NCHRP

REPORT 535

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Predicting Air Quality Effects of Traffic-Flow Improvements:

Final Report and User's Guide

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OF THE NATIONAL ACADEMIES

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Predicting Air Quality Effects of Traffic-Flow Improvements:

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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In the final report, Dr. Stopher prepared major portions of Chapter 2, "The Impacts of Traffic Improvements on Emissions." Ms. Gail Payne prepared Section 3.3, "Modeling Non-Motorized Travel," and Section 3.4, "Modeling Truck Traffic." Dr. David Gillen prepared the majority of Chapter 6, "Land Use Models." Dr. Alexander Skabardonis prepared major portions of Chapter 8, "Traffic Operations Models." Dr. Robert Ireson prepared the majority of Chapter 9, "Mobile Emission Models."

The following research team members provided advice and review at key stages of the research: Dr. Alan Horowitz, University of Wisconsin, Milwaukee; Dr. John Bowman, Massachusetts Institute of Technology; Dr. Elizabeth Deakin, University of California, Berkeley; and Mr. Robert Dulla, Sierra Research.

FOREWORD

By Martine Micozzi
Staff Officer
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This report contains a user's guide and case studies, providing a recommended methodology to predict the long- and short-term mobile source emission impacts of traffic-flow improvement projects. Guidance is provided to evaluate the magnitude, scale, and duration of such impacts for a variety of representative urbanized areas.

The report is based on an in-depth exploration of methodologies used to estimate the impacts of traffic-flow improvement projects on mobile source emissions. It evaluates varying strategic approaches used to develop such methodologies, reviews advanced methodologies used by leading metropolitan planning agencies, and offers suggestions to improve conventional travel models.

With major metropolitan areas striving to meet increasing travel demand while improving mobility and maintaining conformity with air quality regulations, this report offers guidance of special interest to metropolitan planning agencies, transportation engineers, urban designers, and public officials and policymakers.

The report offers analysts considering a proposed traffic-flow improvement a comprehensive methodology composed of five modules to assess potential impacts on air quality.

The analysis of the effects of traffic-flow improvements on mobile source emissions focuses on four areas: operational improvements, travel time savings impacting traveler behavior, travel time savings increasing total demand for travel, and travel time savings stimulating growth and new development in specific areas within the metropolitan region.

This report, prepared by Dowling Associates, features a sound methodology that was created, applied, and tested in a dozen case studies. This methodology improves the prediction model for assessing impacts of corridor-level transportation projects and provides an effective tool for estimating the range of impacts possible when traffic-flow improvements are considered in metropolitan areas.

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FINAL REPORT

USER'S GUIDE

Final Report

PREDICTING AIR QUALITY EFFECTS OF TRAFFIC-FLOW IMPROVEMENTS

SUMMARY

The NCHRP 25-21 project identified and investigated most significant impacts of traffic-flow improvements on travel behavior and air quality suspected or known at this point in time. The impacts of traffic-flow improvements on household trip making, destination choice, time-of-day choice, mode choice, and route choice have been considered and included in a recommended comprehensive methodology for predicting the air quality impacts of traffic-flow improvements. The long-term impacts on the redistribution of future economic activity from less accessible areas of the region to more accessible areas have also been considered and incorporated into the methodology.

Only two identified impacts of traffic-flow improvements on air quality have been intentionally excluded from the methodology: the potential direct impact on the overall growth of a metropolitan region and the potential indirect impact of traffic-flow improvements on actual or perceived accessibility (via nonmotorized modes) for transit, pedestrian, and bicycle modes. Both impacts were excluded because of the lack of necessary data and limitations of project resources.

The NCHRP 25-21 methodology was applied to a series of case studies, and the results were compared with more general results reported in the literature. The facility-specific results showed travel time and volume changes that were consistent with theory and expectation.

However, it was harder to validate the methodology's predictions for system-level (i.e., regionwide) performance. Some of the results fell within the broad range of results that have been reported in the literature. Other results fell outside the range of results reported in the literature. Indeed, application of the methodology to the same traffic improvement at different locations in the region showed a wide range in predicted systemwide impacts. The same type of project (adding an HOV lane, for example) resulted in net benefits or disbenefits to regional emissions, depending on its location.

The NCHRP 25-21 methodology was applied to 10 case studies. The impacts of individual traffic-flow improvement projects on regional daily vehicle-miles traveled (VMT) were on the order of a few hundredths of 1 percent. A 30-year improvement program impacted regional VMT by less than 1 percent. The impacts varied from a

reduction in emissions to an increase in emissions, depending upon the specifics of each case study. The case study results suggest that more applications of each traffic-flow improvement type in different facilities, in different area types, and at different congestion levels are needed to better understand the conditions under which traffic-flow improvements contribute to an overall net increase or decrease in vehicle emissions.

CHAPTER 1

INTRODUCTION

This report presents the results of the research for the National Cooperative Highway Research Program (NCHRP) Project 25-21 to develop a methodology to predict the long- and short-term mobile source emission impacts of traffic-flow improvement projects.

1.1 ORGANIZATION OF THIS REPORT

This first chapter outlines the structure of this paper and reviews the research project objectives. The second chapter provides an overview of the theory and evidence for the impact of traffic-flow improvement projects on mobile source emissions. Chapter 3 presents a review of the state of the practice at typical planning agencies. That chapter outlines the methodologies used to forecast the emission impacts of transportation projects used by some of the more advanced metropolitan planning organizations (MPOs) in the United States. A lengthy critique of the shortfalls of current practice is included in that chapter.

Chapter 4 presents an overview of the available methodologies in the literature for improving current practice. Chapter 5 describes current methodologies in the literature for conducting sketch-planning analysis, such as the Highway Economic Requirements System (HERS), the Surface Transportation Efficiency Analysis Model (STEAM), and the Spreadsheet Model for Induced Travel Estimation (SMITE). Chapter 6 discusses the state of the art in land-use forecasting. It delves into current land-use modeling practice, its shortfalls, and two of the more promising models currently available (the Highway Land Use Forecasting Model [HLFM] and UrbanSim).

The next three chapters consider potential state-of-the-art improvements to conventional travel models. Chapter 7 presents some of the more promising advances in the field of travel demand forecasting (the Portland Tour-Based Model, the Transportation Analysis Simulation System [TRANSIMS], and the Short-Range Transportation Evaluation Program [STEP]). Chapter 8 presents vehicle operations models (*The Highway Capacity Manual* and Corridor Simulation [CORSIM] are highlighted) and describes techniques for linking travel demand models to these vehicle models. Chapter 9 presents mobile source emission models: Mobile 6, Georgia Tech's Mobile Emission Assessment System for Urban and Regional Evaluation [MEASURE], and the NCHRP 25-11 modal emission model.

Chapter 10 evaluates various strategic approaches to the development of a methodology to predict the emission impacts of traffic-flow improvement projects. Chapter 11 presents the recommended methodology.

The next five chapters (Chapters 12–16) present the derivation and testing of the individual modules of the methodology.

Chapter 17 presents the results of various investigations into the validity of the methodology.

The final chapter, Chapter 18, summarizes the results of the research and presents a recommended program for disseminating the results to the professional community.

1.2 SUMMARY OF PROBLEM BEING RESEARCHED

With the passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and its reauthorization, the Transportation Equity Act for the 21st Century (TEA-21), increased emphasis has been placed on informed decision making regarding the full range of environmental, system performance, financial, and other implications of statewide and metropolitan transportation plans and programs. A major component of providing accurate impact assessments centers on effective data collection and analytic methods to support decision makers.

The total air quality effects of transportation projects, especially those designed to improve traffic flow, are not fully understood. Projects may result in beneficial or detrimental impacts over the short or long term. For example, traffic-flow improvement projects may have a short-term air quality benefit by reducing congestion and increasing speed yet have a negative effect by facilitating additional travel. Also, transportation actions such as high-occupancy vehicle (HOV) projects, tolling strategies, and reduction in parking availability may have long-term air quality benefits by reducing trips and VMT, yet might make air quality worse in the short term by increasing congestion and queuing. Research is needed to improve the information available to support decision making in project evaluation, selection, and priority programming. Further, more accurate and objective information is needed by transportation decision makers regarding the full range of effects and impacts associated with traffic-flow improvement projects over the life of those projects.

1.3 OBJECTIVES OF THE RESEARCH

The objective of this research has been to develop and demonstrate, in case study applications, a methodology to predict the short-term and long-term effects of corridor-level, traffic-flow improvement projects on carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO_X), and particulate matter (PM). The methodology should evaluate the magnitude, scale (such as regionwide, corridor, or local), and duration of the effects for a variety of representative urbanized areas.

This project will result in analytical methods for assessing long- and short-term air quality and other effects; however, it is hoped that a visionary approach can be applied to the broadest range of issues and options.

The research will focus on analytical methods that can be implemented in a broad range of existing software used for travel demand modeling.

The potential audience for this research will be broad, including both technical and nontechnical interests. The final product will become a tool for effective decision making in investing transportation resources and should provide both qualitative policy direction as well as a "state of the practice" methodology for analyzing emission impacts.

There is no expectation for the research to predict pollutant concentrations or ozone formation resulting from traffic-flow improvement projects. Rather, the research is expected to use the best available emission factors and vehicle operations and activity data to estimate net changes in emissions of ozone precursors, particulates, and carbon monoxide.

1.4 OVERVIEW OF THE WORK PLAN

The work plan consists of seven tasks:

- **Task 1. Literature Review:** The objective of this task was to conduct a review of transportation and air quality literature to determine previous and current research studies that will support the objectives of and provide tools for the research.
- **Task 2. Devise Methodology:** The objective of this task was to devise a methodology to predict short-term (less than 5 years) and long-term (more than 10 years) air pollutant emission effects (and consequently the air quality effects) of completed traffic-flow improvement projects. The methodology should evaluate those effects at the local, corridor, and regional scales. Projects include, for example, added freeway lanes, arterial widenings, intersection channelization, access management, HOV lanes, signal coordination, transit improvements, ramp metering, and park-and-ride lots. The methodology should include consideration of secondary effects of traffic-flow improvements, including possible changes in emissions resulting from project impacts on (1) safety and accessibility for pedestrians, bicyclists, and transit users and (2) land use. To the extent possible, the methodology should be designed to use data sources commonly available in the transportation planning process.
- **Task 3. Develop Case Study Criteria and Candidate Projects:** The objectives of this task were to (1) develop, for panel review and comment, criteria to select case studies and (2) identify a variety of project types and urbanized areas (e.g., high- and low-growth areas and areas with heavy and light congestion) for which there are available appropriate data. This task presented potential case study project types and urbanized areas that meet the criteria developed in this task.
- **Task 4. Interim Report:** The objective of this task was to prepare an interim report covering the work performed and the findings from Tasks 1 through 3. The interim report recommended any necessary work plan modifications for panel review and approval.
- **Task 5. Test and Validate Methodology:** This task involved the selection of a variety of traffic-flow improvement projects and testing and validation of the methodology. This task identified deficiencies in the analytical approach. A brief technical memorandum was developed summarizing the findings and recommending improvements in the methodology for review by the panel.
- **Task 6. Refine Methodology:** This task refined the methodology based on the comments of the panel and the validation results from the previous task.
- **Task 7. Final Report:** This task documented in the final report the results of the research, including both the methodology and the results of the case studies. A user's guide was produced describing the recommended methodology and providing example problems (i.e., case studies) illustrating the application of the methodology.

CHAPTER 2

THE IMPACTS OF TRAFFIC IMPROVEMENTS ON EMISSIONS

This chapter presents a selective review of the literature and the general knowledge of how traffic-flow improvements affect mobile source emissions. This chapter focuses on a basic understanding of the subject. Later chapters will look at the state of the practice and will review potential methodologies in the literature for improving the ability to predict the impacts of traffic-flow improvements on emissions.

2.1 PROBLEM STATEMENT

Within the past decade, transportation professionals have reluctantly accepted that many of the transportation projects that are implemented affect the level of travel demand. Most importantly, following a landmark court case in the San Francisco Bay Area,[1] the existence of induced demand for travel has been recognized and must be dealt with in planning transportation facilities. Induced demand, however, is not the only effect that changes to transportation facilities will have. The context within which induced demand has surfaced is that of the addition of capacity, usually through widening an existing, congested roadway. However, also of importance is the effect of a myriad of transportation demand and supply management and low-cost investments, many of which are aimed at achieving the opposite of induced demand, namely the reduction of vehicular travel.

One of the primary driving forces in looking at demand and supply strategies that might reduce vehicular travel is that of conforming to air quality standards in metropolitan areas. Although technology has made major strides in reducing per-vehicle pollutants, increases in vehicular travel may eventually outpace the ability of technology to reduce pollutants. The result is that many metropolitan areas have found it difficult to achieve reductions in emissions from vehicles. During the late 1980s, and throughout the 1990s, many agencies have invested time and effort into a variety of strategies aimed at reducing vehicular travel, increasing occupancy of private vehicles, and shifting travel into public transit or non-polluting modes like bicycle and walking.

The major question that needs to be addressed with respect to these strategies, and which is the focus of the current research project, is that of how much these various strategies are able to impact the level of travel. The question is asked as to which strategies are effective and by how much can they change vehicular traffic, in both the short run and the long run. Included in the types of projects and strategies to be considered in this respect are added freeway lanes, arterial widening, intersection channelization, access management, HOV lanes, signal coordination, transit improvements, ramp metering, and park-and-ride lots. It is also desired that the methodology developed to assess the impacts of such projects be capable of assessing not only the primary, direct effects, but also the secondary effects, such as changes in safety and accessibility for pedestrians, bicyclists, and transit users, and also for land-use changes.

2.1.1 Theories of Change in Travel Demand

Economic theory is clear that if all other factors are equal, a change in the price of a commodity will result in a change in the quantity demanded by consumers. The application of such economic theory to travel demand has long been established as appropriate (Oi and Shuldiner,[2] Wohl and Martin,[3] and others). Of potentially more concern is what constitutes "price" in the context of travel demand. A number of studies in the late 1960s and early 1970s, aimed at putting a value on travel time, established fairly clearly that time and monetary costs make up price (Quarmby,[4] Lisco,[5] Haney,[6] Groneau,[7] Hensher,[8] and Watson[9]). In addition, another researcher, de Donnea,[10] established that the circumstances under which the time was spent, i.e., the comfort, convenience, and other attributes, also affected the value of the travel time and therefore the price. A further contribution in this debate, and one on which much of the later work relied, was that of Lancaster,[11] who postulated that economic price could contain a number of attributes of a commodity that contribute to the satisfaction or enjoyment of the consumer.

In spite of this work, and the recognition of a downward-sloping demand curve for travel and the activity to which a person traveled, the transportation planning profession was slow to accept the notion that a change in the transportation facilities, such as the addition of capacity under conditions of congestion, might actually result in a net increase in travel. Such a conclusion was pointed out by P. R. Stopher and A. H. Meyburg (*Urban Transportation Modeling and Planning,* Lexington Books, D.C. Health and Co., Lexington, Massachusetts, 1975, pp. 220–221), but largely ignored by the profession, because of the complexities and expense of accounting for such changes in demand. It is now, however, much more widely accepted in the profession that changes in transportation supply will, all other factors being equal, result in changes in the level of demand. Thus, adding new capacity to an existing congested roadway in the hopes of reducing pollutants from vehicles caught in stop-and-go driving conditions could actually have the reverse effect if the level of induced traffic is such as to more than offset the pollution reductions obtained from speeding up the traffic. In some cases, the amount of additional traffic generated or diverted may be such as to exceed in pollutants the pre-capacity addition situation, thereby leading to a worsening in air quality.

As Stopher[13] pointed out, there are several possible reactions that transportation users may have to a change in transportation facilities. Stopher's arguments applied specifically to capacity increases, but also apply equally well to a wide range of other transportation system changes. The principal reactions are

- Change route of travel;
- Change time-of-day of travel;
- Change mode of travel;
- Change destination of travel;
- In the longer term, change work place location or home location, i.e., make substantial and significant change to repeated origins and destinations; and
- Change amount of travel.

Only the last one of these reactions is actually a change in the level of demand (induced traffic if the change is an increase in trips, and suppression of travel if the change is a reduction). The other reactions result in diverted trips. In theory, then, when a change is made to transportation facilities, a range of possible results can occur, in which traffic is diverted away from a facility that loses capacity and to a facility that increases capacity. A combination of diversion and either induced or suppressed travel is what will give rise to changed volumes on the facility that has experienced the change.

2.1.2 Estimation of Demand Changes

The next issue is to consider if it is possible to estimate or forecast the extent of such changes. To a large extent, diversions of trips can be forecast or estimated provided that the travel-forecasting models are sensitive to both travel time and congestion. Probably, a model that includes only travel time will underestimate diversion because it does not take into account the circumstances under which the time is spent. Congested travel is considered more onerous than uncongested travel of the same duration. If capacity is increased for a transportation facility, all other factors being equal, congestion will be reduced and travel diversion will take place as a result of both the reduced travel time afforded by the capacity increase and the improved circumstances under which the travel takes place (i.e., a reduction in the level of congestion). Conversely, if capacity is reduced or price of travel increased for some alternatives, then travel diversion will take place, all other factors being equal, as a result of increased travel times or prices and potentially increased congestion. The increase in congestion will likely cause a larger diversion of travel away from the facility that has been changed than would be estimated by travel time effects alone.

Estimating induced or suppressed travel and changes resulting from a change in home or work location are more difficult to estimate or forecast. In the case of changes in residence or work place, it may be possible to gain some idea of the magnitude of such long-term changes through a transportation-sensitive land-use model. However, most land-use models use transportation accessibility measures that are rather aggregate and insensitive. It can be expected that the true extent of such locational changes is underestimated by current land-use models, with the possible exception of UrbanSim.[14] Induced or suppressed travel is largely missing from the capabilities of most current models, although some recent developments have provided some means to estimate these changes. The real problem here is that traditional trip generation models, which are the ones that should provide such estimates, have limited sensitivity to the transportation system and therefore will not produce a change in the estimated amount of travel. The only source in conventional models for such a change would have to come through feeding new travel times into the land-use models and finding some change in the distribution of land use that resulted in a change in trip generation. Such changes are generally quite small.

The method that is used most commonly at this time is to apply an estimated elasticity to the total level of trip making.[15] According to Noland and Cowart, elasticities of VMT (a measure of the total level of demand) and travel cost (including time) are of the order of −0.5 to −1.0, while the elasticity of VMT with respect to lane-miles of roadway appear to be in the range of 0.2 to 0.5 in the short term, and 0.7 to 1.0 in the long run. Such elasticities have to be applied outside the conventional model system, because there is nowhere in the models for this to operate to increase or decrease total levels of demand.

2.1.3 Transportation Facility and Demand Changes

Much of the literature has concentrated on the issue of increased highway capacity (Noland and Cowart,[15] Fulton et al.,[16] Noland,[17] Litman,[18] Marshall,[19] Chu,[20] Stopher[13]). Adding or removing a lane of a multilane facility, or adding lanes to a two-way, two-lane facility represent major transportation changes in the corridor of the affected roadway and can be expected to produce quite substantial demand changes.

However, these are by no means the only transportation facility changes of interest. Of considerable importance are the introduction of HOV lanes, changes in traffic signalization and channelization, and improvements to transit services, among others. Often, the changes in travel times and costs produced by these types of facility changes are small. The ability of the models to reflect the demand changes, particularly given that the models probably tend to underestimate the changes resulting from travel time changes, is probably quite small to nonexistent. This situation has been troublesome for those who champion the cause of such changes as HOV lanes, transit improvements, and traffic signal improvements.

Although theory is clear that these changes in facilities will create some level of demand change and diversion, the models are not sufficiently sensitive to estimate the magnitude of the changes. In addition, as is discussed later, the nontransportation changes occurring in the metropolitan areas where these transportation changes are implemented are so large that they may overshadow the transportation changes. The effects of the transportation changes may be noticeable only in the very short term. Most transportation networks are sensitive principally to changes on the order of not less than 1 minute in travel times. A typical signalization improvement may result in only a number of seconds of travel time change. Of course, changes will again take place in the levels of congestion perceived by the user, but these changes are not taken into account in any models.

2.1.4 THE TROUBLE OF ASSUMING "ALL OTHER THINGS BEING EQUAL"

Rarely are all other things equal, and they certainly do not remain so for very long if they are equal at all. The fabric of the country is in continual change. Equilibrium is a useful construct in theory but does not happen for any significant period of time in reality. The earlier statements about diversion and induced or suppressed demand are all conditioned on no other change taking place in the system. To see the problems that this condition raises, it is necessary only to consider a few limited examples.

Consider the situation in Baton Rouge, Louisiana, between 1997 and 1999. A section of Interstate 10 and Interstate 12 were to be widened, with Interstate 10 being widened from three lanes in each direction to four and Interstate 12 being widened from two lanes to three in each direction from their point of confluence/divergence, and for a distance of a few miles on each side of that point. The project began in mid-1997 and was completed at the end of 1999, thus taking a period of 2.5 years to complete. One would like to measure the effects of this widening on travel on the Interstates and parallel surface streets. While the project was being completed, two intersections of surface streets in the close vicinity of the Interstates were modified to add new turning lanes. During the 2.5-year period, the population of Baton Rouge grew by about 5 percent, with most of the growth concentrated in areas that are likely to be served at least in part by the widened freeways. Gasoline prices declined to an all-time low price in Baton Rouge (in inflation-adjusted dollars), with the price drop being on the order of 25 percent over the construction period. Unemployment declined by about 2 percentage points over the period. The local economy grew significantly. Under any definition, this does not describe the conditions implied by all other factors being equal. On the contrary, each of the changes mentioned is likely to affect travel on the widened freeways.

Consider now the situation that exists almost 1 year after completion of the project. Gasoline prices have risen by almost 40 percent, population growth has continued at an annual 2 percent, and the economy continues strong with very low unemployment. Surface road projects in the vicinity of the widened freeways continue to be undertaken. Again, the situation clearly does not meet the concept of all other factors being equal.

Under these conditions, how does one determine the effects of each of these different changes on the levels of traffic on the widened facilities? One could possibly argue for building some type of linear model, but such a model would assume that all of these factors were linearly additive in their effects on the amount of travel on the facilities, an assumption that seems rather improbable. There is little theory and no empirical evidence available to explain how all of these factors might combine to change traffic flows, particularly because none of the listed factors except population increase are taken into account in conventional travel demand modeling. Yet, it is clear that each of these factors affects levels of travel in a corridor.

The situation described here is by no means unique, but rather probably describes the type of situation that will arise in many highway widening projects. Of course, in some instances, the changes will be in the opposite direction, which will lead to the suspicion, if these changes are not accounted for, that widening roadways does not lead to any significant change in demand levels.

Potentially, the situation is worsened further because the changes in population, employment, gasoline prices, the economy, etc., are described in global terms (at least on a metropolitan area level), while the effects to measure are corridor specific. Not all of the changes discussed take place, and certainly those that take place do not do so at the same levels, within what one might define as the influence area of the widened roadways. This brings into view the question of the geographic limits of the factors to be examined. For example, in the case of the Baton Rouge freeways, does the widening of Interstate 10 affect traffic that is passing through the area, possibly diverting traffic from Interstate 20 (200 miles to the north of Interstate 10)? Because diversion of travel from other routes and destinations is one of the posited effects of the widening, from how far away may those diversions occur? How much diversion may occur from a parallel surface street that is itself undergoing reconstruction or widening, but that is experiencing exacerbated delays due to construction, after the opening of the widened freeways? How far away must one look at surface streets to capture the majority of the effects and to determine how much VMT is diverted and how much actually increased?

These issues are clearly difficult to resolve, but must be resolved to meet the goals of this project and be able to measure the extent of the effects of a variety of factors on congestion, VMT, and vehicular emissions. Some attempts have been made to put some sort of an estimate together of some of these effects, and these are reviewed next.

2.1.5 Attempts to Estimate Demand Changes

Since the landmark San Francisco Metropolitan Transportation Commission (MTC) case in 1989 and the passage of the Clean Air Act Amendments of 1990 and ISTEA in 1991, there has been an increasing level of interest and effort in trying to determine if certain projects, such as road widening, affect demand for travel. Most of the attempts that have been made to date are based on existing data, not on new data collected for the specific purpose of estimating the effect of transportation facility changes on travel demand. Most of the extant and recent studies on the topic have focused on (1) using VMT as a measure of demand and (2) analyzing aggregate data for metropolitan areas across the country.

2.1.5.1 VMT as a Measure of Demand

At first glance, VMT appears to be a reasonable measure of demand. It focuses first on vehicles, which are certainly the elements of concern in estimating emission and congestion levels. Also, it is a reasonably available and easy-to-use measure, as is noted by Noland and Cowart.[15] However, it is in other respects not a particularly good measure. It is not the principal measure of concern in estimating vehicle emissions. Although emission factors are multiplied by VMT, the factors themselves are highly dependent on vehicle speed, which is the major determinant of both emission levels and congestion. Slow-moving vehicles and vehicles in stop-and-go conditions generate substantially higher emissions per vehicle-mile than do vehicles traveling at cruising speeds of 50 to 70 mph. Also, it is known that travelers in the urban context are largely insensitive to distance. They are, however, highly sensitive to travel time, which is a derivative of speed and VMT. In general, however, people budget time, not distance, in deciding what travel to undertake. Thus, travel time is almost certainly the measure that captures congestion and to which people respond when capacity is increased.

There is a further problem in the use of VMT as a measure of demand. In early discussions among researchers, induced travel was defined very specifically to be the new travel that was not undertaken before the improvement. By deciding to focus on VMT as a measure of demand, researchers have, in effect, redefined induced travel to be any increase in travel distance, whether arising from changes in route, shifts in mode, changes in destination, or changes in the number of trips made. At the same time, the revised definition excludes time-of-day shifts. The decision to use VMT as a measure has required the definition of induced travel to change to meet what VMT is capable of measuring. However, if one is to be complete in estimating the air quality effects of transportation facility changes, then all changes, including time-of-day shifts, become significant. If one is simply interested in estimating how many new trips take place, then the number of trips—not VMT, travel time, or speed—should be the measure of interest.

In summary, VMT confounds diverted and induced demand, but does not completely measure diverted demand. Some elements of route diversion and all aspects of time-of-day diversion are ignored by VMT. It is also possible that some destination diversion might not be captured if the new destinations do not add significantly to VMT. In this regard, time-of-day shifts may be more important than some of the other aspects of induced and diverted demand because of the potential impacts on speeds of shifts between peak and off-peak times. VMT is not the major influencing variable on emissions, which are more subject to change because of speed than because of VMT. Also, VMT is not what people are intrinsically demanding. They demand travel time (or, perhaps, reductions in travel time). Elasticities of VMT with respect to capacity change are not helpful to modelers. VMT is only an incidental output of the modeling process and does not feature as a significant input or output of any step of the modeling procedures. Elasticities of VMT are not helpful to the modeler in establishing amounts of induced travel. Thus, equating induced travel with VMT is confusing and unhelpful. Travel time and speed changes are far more germane to the issue, as is also the number of trips. The largest problem by far in the modeling process is that trip generation is unaffected by price of travel in even its most general sense, so that it remains invariant with increases or decreases in transportation capacity. This is the problem that needs to be addressed from the modeling standpoint. Any changes in quantity of trips forecast in trip generation will then be correctly picked up in trip distribution, mode choice, and assignment to reflect diversions among destinations, modes, and routes, and the new speeds of travel can be output readily from the assignment process, thereby leading to estimation of emissions consequences.

2.1.5.2 VMT and Travel Time Budgets

Zahavi[21] was probably one of the first researchers to propose that people have a travel time budget. His work was largely ignored because of problems perceived in his examination of very aggregate data. More recently, his work has begun to be accepted as having some considerable merit as modern activity analysis seems to bear out his contention of travel time budgets (Stopher and Metcalf,[22] Gordon and Richardson[23]). In essence, the notion of a travel time budget proposes that out of each 24 hours, people have a limited amount of time that they are willing to spend on travel. In most investigations, this seems to amount to somewhere in the region of 1.25 to 1.5 hours, although there may be some significant variation around these mean figures. The notion of a travel time budget has significant implications for the analysis of the response of demand to transportation facility changes.

In the event that a transportation facility were improved so that users experienced a travel time saving, then much of that travel time saving would be used elsewhere in travel. If the user did not use the travel time saving elsewhere, then the user's total travel time expenditures would decrease. Consider now the tracking of VMT. If VMT were to increase inelastically with capacity increases, there could be net travel time decreases to users because, while users would travel farther, they may take less time overall. If this were to happen, then the travel time expenditure would decrease progressively below the person's travel time budget, as each new capacity increase occurred. Eventually, this trend would seem to lead to the absurd notion of no travel time being expended. It seems then that the elasticity of VMT with respect to capacity increases should be fairly close to unity in order for people to continue to use their travel time budgets. However, the ability to continue using travel time budgets also somewhat depends on the proportionate travel time changes.

It seems, then, that the notion of a travel time budget is further evidence that VMT is not the correct measure. It also seems that interpretation of elasticities of VMT with respect to capacity may have relatively little meaning.

2.1.6 Empirical Measurement

The Travel Model Improvement Program (TMIP) conference on "The Effects of Added Transportation Capacity" in 1991 addressed the issues of empirical measurement in some detail. Much of the discussion in the conference proceedings[24] on measurement appears to be germane to the present situation and has not been superseded by any significant experience or change in design issues. This conference identified three primary categories of experimental approach: the case study, attitudinal and preferential surveys, and longitudinal panel surveys. It was noted that these options are not mutually exclusive, but may offer opportunities for composite designs and studies that would take advantage of the particular merits of each approach.

2.1.6.1 Case Studies

Case studies are seen as perhaps the most obvious method to track the effects of capacity changes on travel demand. The TMIP conference proceedings suggested that the case study is the most useful starting point to consider the issues in an empirical design. The suggestion from the conference proceedings appears to necessitate a series of surveys, with a before survey taking place prior to any construction or other changes in the subject corridor so as to measure the baseline. The conference proceedings recommended a series of after surveys taking place from 1 year following completion of the project to up to 10 years after, to measure the long-term effects. Even 10 years is likely to be insufficient to measure some of the long-term land-use changes that may result. The proceedings also recommended that the surveys include residents, employers, and developers, at a minimum.

The problems of case studies are numerous, however:

- How to sample—identifying both the users and potential users, as well as those whose travel on other facilities may be affected by the capacity change in question. Of particular difficulty here is measuring in the before survey those who might decide to travel on the facility after the capacity expansion has taken place. Without measuring these individuals before the capacity change, there is no valid way to determine the induced travel of such people in the after surveys only.
- The time frame—there are many other changes that will take place during the more than 10 years that the surveys need to span. These changes will impact the amount of travel. Controlling for these impacts or disentangling their effects poses enormous problems.
- Measuring change—there are also problems in measuring change because of the baseline of the change of interest. Ideally, the change in travel demand to be measured after the capacity change should be compared with the change in travel demand that would have resulted had the capacity change not taken place. Such a comparison is measurable only if one can find a parallel situation to use as a control.

In ensuing discussion at the TMIP conference, several comments were made. The first was that there is a tendency to focus on a single case study, where in fact valid results are obtainable only from multiple case studies. Analyzing multiple case studies would require a systematic design for the case studies that could be applied to multiple case studies. Conference members further suggested that researchers should not simply choose five cases at random, but rather should use cluster analysis and the development of topologies of capacity addition problems. Other problems noted included the difficulty of identifying parallel routes, conceptualizing the data collection scheme, and maintaining the data over the lifetime of the project. A final problem that was noted is that of anticipatory development, or development that is spurred by the expectation of a capacity addition. Anticipatory development may occur many years in advance of the commencement of construction, thus making it even more difficult to define when the before study should be done. An example was quoted of the Bay Area Rapid Transit (BART) system, which had discussions for 20 years before construction began, but during which time anticipatory developments took place.

2.1.6.2 Attitudinal and Preferential Studies

Some discussion at the TMIP conference focused on what is now generally described as stated preference (SP) techniques. Conference members suggested that preferential studies would be preceded by setting up focus groups to help design the survey. The focus groups should consider the hypothetical situations of both a capacity addition and no change in capacity but worsening congestion.

Attitude surveys of developers and employers may also be a necessary component of the SP survey to determine the air quality impacts of highway capacity improvements. The attitude surveys would elicit information about stated intentions if capacity were to be added or if congestion were to worsen.

The TMIP conference proceedings note several advantages and disadvantages to the SP approach. The attitude and stated preference surveys do not need a specific project setting in which to be conducted, nor do they necessarily involve complex sampling. Nevertheless, the SP surveys should be undertaken with travelers who are presently experiencing some level of congestion on an identifiable highway so that situations described in hypothetical questions can be realistic enough to be meaningful. For example, it would not be useful to ask a person living in Baton Rouge about congestion increasing above levels that are only commonly experienced in, say, Los Angeles, nor would it be sensible to talk about major capacity additions in a corridor where there is no space for such additions. The conference proceedings also note that the focus groups can help substantially to design the survey, and other questions can be included that will control for externalities that complicate the before-and-after survey.

There are also some disadvantages to the SP approach. First, in the absence of revealed preference data, it is difficult to scale the coefficients in a derived model from SP data, so that the actual elasticities with respect to capacity addition are probably not derivable. Second, there are still some significant issues with respect to the accuracy of behavioral intent measurement. Third, some of the items that may need to be included may not be easily quantified or described for inclusion in the survey. It was observed in the conference proceedings that the long-term reliability of SP results has not been ascertained. This observation is still true today.

At the TMIP conference, there was considerable discussion of the attitudinal and preference approach, also. First, it was suggested that the changes ensuing from a capacity increase were sufficiently complex that it would be impossible to remove the attitudinal and preference modeling from computer modeling and simulation. It was also pointed out that it is difficult for people to visualize a future condition, especially if this condition will affect their behavior or their attitudes. If the change presented is too simple, it may be meaningless, while if too complex, it may not elicit the responses desired. It was suggested that video technology could be used to overcome part of this problem. A second problem that was raised is that people are willing to provide a response as long as it does not cost them anything. It was suggested that cost changes could invalidate results.

2.1.6.3 Longitudinal Panels

A longitudinal panel is selected at the beginning of the process and is re-interrogated at intervals after the completion of the project to measure changes in behavior. Survey methodology is clear on the advantages that accrue from panels as a means to measure change. However, a panel must be established in one or more control areas to determine how much change will likely take place in the absence of a behavior-changing project. Measuring system performance is also necessary and would also be required of a case study, using cross-sectional samples. This requirement poses some problems because of the lack of good performance measurement of the highway system. It was also noted in the TMIP conference that the panel approach applies more to residents than to employers and developers.

The idea of longitudinal panels engendered more discussion than either case studies or SP studies. The benefits of panels were mentioned a number of times, both in terms of measuring change and also in terms of maintaining updated data generally. It was noted that the make-up of the panel is critical. New households need to be added, and households that move should be retained in the panel population. The ability to get information about households that move to new locations, it was felt, would provide useful insights on the changes caused by the capacity change itself. Keeping track of households, however, also can make panels much more expensive to maintain.

The length of time that the panel would need to remain active was also discussed. It was noted that the panel would need to be in place for some years, which also causes conditioning effects and fatigue. It was also noted that the type of information obtained from a panel may not be sufficient to provide satisfaction to a legal court.

2.1.6.4 Conclusions

From the TMIP conference, no clear method of measuring the effects of added capacity emerged. In fact, a review of the discussion suggests that there remain very substantial problems, not least of which are the need for a control area and the issue of controlling for externalities that change travel demand along with a capacity change. Defining the extent of the study area also poses problems unless one is willing to (1) set up panels or other measurement techniques in various locations where capacity additions are not currently planned and (2) hope to intercept some capacity increases in the future. This approach, however, appears to be much too expensive and is unlikely to be considered feasible. Issues of how long measurements must continue to capture longer-term changes, such as home and job relocation, and new development that may follow are also unanswered.

2.2 RELATIONSHIP BETWEEN TRAFFIC-FLOW IMPROVEMENTS AND EMISSIONS

A complex chain of effects connects traffic-flow improvements to mobile source emissions (see Figure 1).

Traffic-flow improvements, by definition, improve overall vehicle operating speeds and reduce congestion. Reduced congestion means fewer and less extreme vehicle acceleration and deceleration events for the facility. These first-order effects (see Box 1 in Figure 1) usually mean a change in the vehicle emission rates for the facility. Fewer acceleration and deceleration events will result in lower emission rates. Higher speeds may increase or decrease the vehicle emission rates.

However, there are second-order effects as well. The higher speeds mean lower travel times. Lower travel times may encourage vehicle drivers to make more trips, make longer trips, and change their mode, route, and time of day for making their trips. These second-order effects usually occur fairly soon (within a year) of the facility improvement.

Traffic-flow improvements for one mode may also adversely affect accessibility and travel times for other modes. For example, a street widening may improve auto speeds, but will increase pedestrian crossing times. Thus, an improvement may adversely affect one mode at the same time as it benefits another.

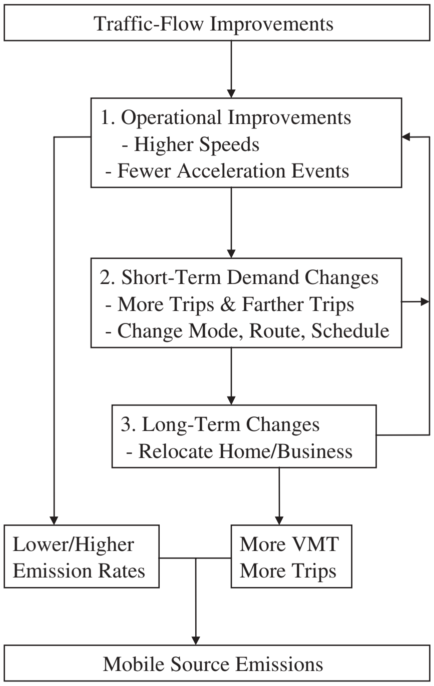


Figure 1. Chain of effects tying flow improvements to emissions.

Longer-term, third-order effects take many years to occur (see Box 3 in Figure 1). These effects involve individuals and businesses relocating to take advantage of the better travel times.

The second- and third-order effects increase the demand for the facility and reduce its first-order travel time savings and emission reduction benefits. These effects will feed back until a theoretical equilibrium is reached and there is a final estimate of the mobile source emission impacts of the traffic-flow improvement.

Conventional analyses of the impacts of traffic-flow improvements usually focus on only the first-order (operational improvement) effects while neglecting the very real second- and third-order effects. Some advanced analyses, using a modeling process called feedback or equilibration, have been able to take into account some but not all of the second-order effects. They take into account the geographic distribution, mode choice, and route choice effects of the improvements, but often fail to take into account increased trip making. A few very advanced analyses have been able to take into account the longer-term, third-order effects, but only at the cost of very large investments in the analysis process, thus discouraging the application of these analyses for all but the most extensive traffic-flow improvement projects.

The remainder of this chapter reviews the current state of knowledge regarding the various ways that traffic-flow improvements affect demand and ultimately emissions. The reader will note that there is a great deal of literature on the impacts of traffic-flow improvement on demand, but the vast majority of the literature stops short of evaluating the impacts on emissions.

2.3 EMPIRICAL STUDIES OF THE IMPACT OF HIGHWAY IMPROVEMENTS ON TRAVEL DEMAND

Empirical studies of the impact of highway improvements on travel demand have tended to be macroscopic statistical studies of how regional vehicle activity (almost always measured in terms of daily VMT) has correlated with changes in highway capacity (often measured in terms of lane-miles added).

Statistical studies of the impact of highway improvements on travel demand are in essence “uncontrolled” experiments. The observer looks at changes in aggregate behavior but is unable to interrogate the users as to why they made their change in behavior. Thus, while the observer can identify the correlation, the observer cannot determine how much of the correlation is due to increased capacity and not due to other changes.

When reviewing the results, one must take into account the precise definition of induced demand and the model forms used in each study before extrapolating the results to broad conclusions. Most of the studies have taken a great deal of care to control for extraneous factors and effects, but almost all suffer from being limited to a subset of the entire urban area transportation system. Thus, their elasticity results include the broad scale shifting of traffic from the local street system to the state highway system that would be expected to occur when the state highway system is improved. The measured increases are subsystem but not regional changes in VMT.

Still, the statistical studies serve a valuable purpose. They point investigators to the conclusion that highway capacity and demand are closely correlated and that demand-modeling practices need to take this correlation into account.

2.3.1 U.S. Conferences and Committees

The U.S. Department of Transportation has sponsored several conferences and committee sessions to review the impacts of highway capacity improvements on travel demand. The most recent federal effort was a special session at the 1998 Transportation Research Board (TRB) Annual Meeting sponsored by the Federal Highway Administration (FHWA).[25] Four papers on the subject representing different viewpoints were presented at this session. They include a summary paper by Kevin Heanue of FHWA on this topic. All of the papers are syntheses of past work. The session participants identified several high-priority areas for future research on inducted traffic:

- The development of simplified procedures to account for induced traffic in benefit-cost analyses of highway improvements;
- More basic research on travel behavior oriented toward understanding the role of changes in travel times and costs on the amount of travel by households and businesses;
- Retrospective studies, which compare observed volumes in highway corridors with forecasts; and
- Before-and-after studies of major improvements in highway capacity.

A special committee was appointed by TRB to study the impacts of highway capacity improvements on air quality and energy consumption in 1995. The committee's report covers contributions of motor vehicle transportation to air pollution and energy consumption, traffic-flow characteristics, travel demand, and land-use and urban form. Some of the key conclusions are that major highway capacity additions vary over time, and the effects of highway capacity additions on emissions highly depend on the state of vehicle design, automotive and motor fuel technology, and emission controls. The report notes that initially, adding highway capacity under heavily congested traffic conditions tends to reduce emissions and energy use by smoothing traffic flows, all else being equal. However, the travel time savings from congestion relief can stimulate travel demand and, over the long term, set the stage for development and travel growth if other conditions are present. The greatest probability of large development and travel impacts occurs where major highway capacity additions provide access to developable land in outlying suburban areas.

TRB Special Report 245[26] suggests that the range of disagreement between highway proponents and opponents on the subject of induced travel has narrowed considerably. The report also notes that there are widely differing elasticities of travel demand with respect to capacity reported in the literature summaries. A review of empirical studies contained in an appendix to the TRB committee report summarized the elasticities of VMT found in the literature for various transportation supply measures (see Table 1).

The U.S. Department of Transportation[27] sponsored a special conference on the subject in Bethesda, Maryland, in 1991. The topics covered at the conference included effects of added capacity on system performance, travel, and development; institutional and financial context; environmental effects; forecasting models; and experimental design. Some noteworthy conclusions include the following:

- Longitudinal panels can provide information on changes in income, behavior, and facility use that would be valuable in assessing congestion and capacity impacts.
- The effect of added capacity on freight movement needs to be part of the research agenda.
- The effects on nonwork travel and off-peak travel need to be considered.
- "Backcasting" could provide information on how effective land-use and transportation modeling efforts have been.
- It is important to consider redistributive impacts of transportation facilities on land development (as opposed to increased total growth).

One of the papers at the U.S. Department of Transportation conference notes that the most appropriate way to forecast a derived demand is to forecast the demand for the final good or activity at the trip end.

Progress[28] published by a consortium of pro-environment, anti-road advocacy groups, examines the emerging evidence that building roads generates traffic and the corollary that a more balanced set of transportation choices can reduce congestion and improve the local economy. Several short *Progress* articles, synthesizing the reports of others, provide selected information on effects of increasing or decreasing capacity.

The Bureau of Transportation Statistics (BTS) assembled a series of articles on the traffic impacts of the Los Angeles

TABLE 1 Estimated elasticities of VMT

Transportation Supply Measure	Elasticities
Average Highway Speed	+0.58 to +1.76
Total lane-miles of highway	+0.13 to +0.15
Seat-miles of transit service	-0.0098

Source: *TRB Special Report 245: Expanding Metropolitan Highways*, Transportation Research Board, 1995.

Northridge earthquake in 1994. This collection of articles provided an example of the effects of catastrophic capacity reductions in the United States. A special issue of the BTS *Journal of Transportation Statistics*[29] includes articles on transit, highway, goods movement, and transportation-related economic losses due to the temporary closure of the Interstate 10 Santa Monica freeway and other road closures caused by the January 1994 Northridge earthquake. The earthquake provided a unique opportunity to examine travel behavior responses in an emergency. An important limitation of this work was that it focused on the short-term responses, but it provided support for the contentions found in other short-term studies. The key conclusions were as follows:

- Change in trip scheduling was the largest single impact on travel of the loss of capacity: in the Interstate 5 corridor, almost 30 percent of commuters said they left from home earlier or later because of the earthquake. Work schedule changes (such as 4/40 [4 days, 40 hours] and 9/80 [9 days, 80 hours]) were reported by significant numbers of people: 7 to 8 percent depending on the corridor.
- Route changes in affected corridors were quite high: 31 percent.
- Modal shift effects were more modest, but the most frequently found modal shift was from drive alone to carpool/vanpool; depending on the corridor, between 4 and 6 percent of surveyed commuters indicated this response. It was countered by a shift of some motorists from carpool to driving alone, perhaps due to disruptions of schedules.
- Shifts from drive alone to transit were very small: less than a fraction of a percent in all corridors.

2.3.2 The Standing Advisory Committee on Trunk Road Assessment Study and Related U.K. Research

The U.K. Standing Advisory Committee on Trunk Road Assessment (SACTRA) prepared a series of reports about statistical correlation between capacity and demand. They were prepared by an independent advisory committee to the U.K. Department of Transport (DoT). The purpose of the initial report[30] was to inform the DoT about evidence of "the circumstances, nature and magnitude of traffic redistribution, mode choice and generation [resulting from new road schemes], especially on inter-urban roads and trunk roads close to conurbations; and to recommend whether and how the Department's methods should be amended, and what if any research or studies should be undertaken." Trunk roads in Britain are intended to serve long-distance through travel, but may include two-lane roads as well as freeways (i.e., motorways).

The principal conclusions of the SACTRA report were the following:

- Induced traffic can and does occur, probably quite extensively, though its size and significance is likely to vary widely in different circumstances.
- The economic value of a scheme (i.e., plan) can be overestimated by the omission of even a small amount of induced traffic.
- Induced traffic is of greatest importance when the network is operating close to capacity (or will in the future), where traveler response to changes in travel times or costs is high, and where an improvement causes large changes in travel costs.

The SACTRA report makes a number of recommendations, including the use of variable-demand methods (rather than fixed trip tables), improved monitoring, and project appraisal that includes induced traffic in environmental and economic analyses. The SACTRA report includes case studies (of both traffic volume and land-use changes) based on the openings of new highway projects in Britain.

The SACTRA report, done by highly credible consultants and academics, has been widely cited by the environmental community as supporting the notion that induced demand is significant, but is being ignored by highway advocates. However, critics have questioned the applicability of the report to the United States. Britain, despite being an industrialized country, has a relatively poor system of high-performance roads. Other differences with the United States include a greater degree of traffic congestion in urban areas, an extensive urban and intercity railway network, a less developed airway network, and a high density of development (i.e., there is little open land legally or physically suitable for development). The critics question if these factors—reminiscent of patterns in the United States at the dawn of the freeway-building era—are really applicable to the kind of marginal changes in highway network improvements being proposed in most U.S. cities today. National spending by Britain on major roads is relatively low by U.S. standards: about $55 per year per capita; FHWA's current budget is approximately three times this, not to mention considerable spending by state governments. Major new freeway investments, such as the M25 motorway circling London, have made dramatic improvements in highway accessibility in the affected corridor. Projects of this magnitude are not likely to occur in many U.S. cities.

The DoT staff prepared its own brief (21-page) response to the SACTRA report.[31] The response states the following:

- Much of the added traffic growth that SACTRA has attributed to induced travel is more properly attributed to increased economic growth rates (particularly in the 1980s).
- The negative effect on road benefits is smaller than claimed by SACTRA. Further, SACTRA did not consider some of the benefits that occur to nonproject motorists, in terms of redistribution and retiming.

- DoT will develop methods to allow, where necessary, variable-trip matrix analysis to be carried out as a matter of course.

Coombe and his co-authors[32] looked at the opposite effect generated by capacity reductions. Their article looks at empirical evidence of trip reductions due to reductions in highway capacity. The study included the theoretical framework for the analysis of travel behavior in the face of reduced road space and practical ways of estimating the traffic impact of selective withdrawal of highway capacity. Evidence from over 100 locations was collected, with more than 60 providing primary case study material. Available evidence showed a wide range of results. Coombe et al. note some general caveats and problems of interpretation. They also conclude that reductions in traffic only occur given certain network conditions, that behavioral responses partly depend on natural variability in behavior, and that behavioral changes vary over time. The authors make points about considerations and model practices that should yield the most accurate results, although the authors do not provide examples of applications to real data. Where generalized cost changes as a result of a capacity reduction are significant, the authors argue for an "elastic" assignment that allows for changes in the generation rates and distribution of traffic.

Goodwin[33] and his co-authors also looked at capacity decreases. They prepared a paper that examines the effect on traffic flows of 100 cases of capacity reductions in Britain that were caused by re-allocation of existing capacity to buses or pedestrians, maintenance, or natural disasters. The cases fell into three broad groups: cases where, on closer examination, there was no actual capacity decrease; cases where there was a real capacity reduction on the treated route but there was spare capacity on alternate routes; and cases where the capacity reduction actually happened and there was no spare capacity on alternate routes. The latter cases were the only ones where traffic was found to decrease on the routes being studied.

2.3.3 Research Authored and Co-Authored by Noland

Noland, with the use of his carefully crafted lagged effect statistical models, has contributed greatly to refining the definition and measurement of induced demand. The following studies of his have meticulously separated demand inducement from other effects in the available data.

Noland and Lem[34] reviewed the literature, theory, and definition of induced travel and attempted to clarify much of the confusion in the literature by defining induced travel to be an increase in VMT for the entire region that is "attributable to any transportation infrastructure project that increases capacity." Changes in number of trips are excluded from the definition of induced demand. Noland and Lem cited various VMT elasticities with respect to travel time decreases and with respect to lane-mile increases from several studies in the United States and Great Britain. Short-run elasticities range from 0.3 to 0.6 for VMT with respect to lane-miles, while long-run elasticities range from 0.7 to 1.00 for VMT with respect to lane-miles. The authors concluded that the theory of induced travel—namely, that increased capacity contributes to substantial increases in demand—is confirmed by the various studies and suggest that much of the benefits of highway projects may come from redirection of urban growth rather than from congestion reduction.

Noland and Cowart[35] fitted various cross-sectional time-series models to 14 years of daily VMT and lane-mile data for arterials and freeways located in 70 metropolitan areas in the United States. Fixed effects were included across urbanized areas and across time. The authors also applied a "two-stage, least-squares" approach to address the issue of causality bias (do planners build capacity in response to demand increases, or do increases in capacity cause increases in demand?).

The models that Noland and Cowart constructed employed variables to isolate the effects of population growth, income growth, fuel costs, and population density changes from the effects of capacity increases. The authors found short-run capacity elasticities of around 0.7 for demand. However, the elasticities varied from 0.3 to 0.7 depending upon the variables included in each model. Two-stage least squares generally improved the fit of the models to the data, but also yielded elasticities that ranged from 0.3 to 0.8. The authors went on to identify the proportion of metropolitan VMT increases that could be attributed to capacity increases and found that the proportions varied widely by region, ranging from a low of 7 percent to a high of 34 percent.

Noland and Cowart initially attempted to extend their analysis to the entire road system within each metropolitan area but found conflicts between sources and gaps in available data. Thereafter, they focused on arterials and freeways where the data were more reliable. Unfortunately, this approach means that an unknown portion of the VMT increases that the authors detected may simply be traffic shifted between the local roads and the arterial or freeway system in each region. Thus, the actual metropolitan area VMT increase is probably lower than what the authors measured. The authors noted that the arterial and freeway systems included in their study accounted for an average of 64 percent of the daily VMT and 28 percent of the lane-miles in each metropolitan area.

Noland[36] estimated the correlation between statewide VMT and lane-miles. He computed elasticities based on several econometric specifications. Lane-miles were found to generally have a statistically significant relationship with VMT. He found elasticities of between 0.3 and 0.6 in the short run and between 0.7 and 1.0 in the long run. Elasticities are larger for models with more specific road types. This is one of the few studies that claims (from empirical data) to find unit elasticities. The author believes that about 25 percent of VMT growth can be attributed to lane-mile additions, assuming historical rates of growth in road capacity. The principal shortcoming of the paper (as far as drawing conclusions useful to urban areas) is that it is highly aggregative. Statewide data are used, so California and Rhode Island are considered comparable units of analysis.

2.3.4 Research by Others

Several researchers have also analyzed the available field data in the United States. Some have even used the same data as Noland and have come to moderately different conclusions on the magnitude of the effect.

Marshall[37] used the same 70 metropolitan area Texas Transportation Institute (TTI) data set as Noland and Cowart to evaluate induced demand. However, Marshall focused on only a single year's data (1996) and performed a cross-sectional analysis of it for daily VMT per capita and lane-mile per capita changes solely on freeways and arterials. The only non–lane-mile factor included in Marshall's model was area encompassed by each metropolitan area. Marshall's elasticities of 0.8 to 0.9 without long-term effects are high compared with other research results.

Fulton et al.[38] evaluated induced demand at the county level for the states of Maryland, Virginia, North Carolina, and Washington, D.C., using Highway Performance Monitoring System (HPMS) data that dated back to 1969. The lane-mile and daily VMT data were limited to the state-maintained highways in each county. The county data for Virginia excluded any data for incorporated cities within each county for that state. Induced demand was defined in this study as an increase in each county's daily VMT on the state-maintained highways that was caused by an increase in the lane-miles of state-maintained highways within that county.

Fulton et al. fitted a series of models to the data. A fixed-effects model was found to have demand elasticities of between 0.3 and 0.6 for each county in each state. A "first differences model" was found to have a slightly wider range of demand elasticities (between 0.15 and 0.61). A distributed lag model was found to result in short-run elasticities of between 0.1 and 0.4 and long-run elasticities of 0.5 to 0.8.

Fulton et al. found that population growth had an equal or greater effect on VMT than capacity had (because Fulton et al. were predicting total VMT, not VMT per capita, like Noland). Income had a comparatively minor effect on VMT. Fuel cost effects were not directly evaluated.

A Granger test of precedence found that lane-mile growth precedes VMT growth (thus indirectly addressing the question of causality). A follow-up test of the hypothesis that congested areas are more sensitive to capacity increases than uncongested areas are yielded inconclusive results.

Note that because Fulton et al. limited themselves to same-county impacts of lane-mile increases, the mitigating effects of traffic decreases from other counties are missed. The result is the potential for an unknown amount of overestimation of the elasticities.

Chu[39] performed a cross-sectional study of 391 urbanized areas in the United States. He fitted a static equilibrium demand model to data obtained from the HPMS and the FHWA's 1997 Highway Statistics Report. He measured demand inducement in terms of the change in traffic density (daily VMT per lane-mile) on all nonlocal roads in each region. Local roads were excluded because of data reliability problems. He tested several models for each facility type and concluded that congestion/capacity elasticities ranges from 0.03 to 0.37, depending on the facility type and the amount of lane-miles of each facility type already present in the urbanized area. The absolute value of the elasticities for freeways and minor arterials increased significantly with increasing lane-miles already in place.

Chu studied a more comprehensive set of facility types (only local roads were excluded) than Noland and Fulton did and obtained similar or lower cross-sectional elasticities than Noland or Fulton did. Chu, however, was unable to estimate long-term effects with his cross-sectional approach.

Hansen[40] prepared an article that summarizes previous work in the field. He noted that, "conventional wisdom aside, we simply don't know whether new highway capacity affects travel behavior and, hence, traffic volumes." He provided a lucid review of problems in measuring this effect, especially the direction of causality ("do roads generate traffic or does traffic generate roads?"). He noted that although cross-sectional estimates of VMT with respect to highway capacity have been in the 0.13–0.7 range, the studies yielding estimates in the lower end of this range have controlled for more variables.

In order to avoid problems associated with causality (i.e., simultaneity), Hansen used a distributed lag model to estimate VMT growth at the county and metropolitan levels in 30 California urban areas. He concluded that a 1-percent increase in lane-miles soon induces an immediate 0.2-percent increase in traffic, building to a 0.6-percent increase within 2 years after the lane-miles are added. At the metro level, he noted that the elasticity could be 0.9 percent after as little as 4 years. The major limitations of this work are that they apply to VMT on state highways only and do not separate diverted traffic (i.e., traffic from route shifting). Hansen's study also makes the assumption of constant elasticity, which seldom holds for most other economic goods except in the case of small changes in the explanatory variable.

Distributed lag models have been criticized by Brian Field in his book, *Forecasting Techniques for Urban and Regional Planning* (ULC Press, 1992):

> The level of complexity of these [distributed lag] models masks an underlying theoretical inadequacy. The *causal structure* is poor and the independent variables [VMT] may conceal numerous specific causal factors linked in different ways to the dependent variable [lane-miles of capacity]. It also seems unlikely that the parameters will remain constant—as required

> for forecasting. There are also problems which arise from the statistical requirements for using the technique—the independent variables must be normally distributed and independent (p. 35).

Brodahl[41] looked at the effect of a major new freeway opening in the Los Angeles area. His study reports on traffic volume and travel time data collected on the Interstate 105 Glenn Anderson Freeway (formerly known as the Century Freeway) in Los Angeles. The freeway was a major new facility opened in October 1993. Traffic volume data are presented not only for the new freeway, but also for parallel and feeding major surface streets.

The largest impact noted by Brodahl was a reduction in traffic volumes on the Route 91 freeway, located about 4 miles south and parallel to Interstate 105. Parallel surface streets generally showed decreases in volumes, with the largest decreases occurring nearest the new freeway; the numbers vary widely from one location to another. Many of the cross (perpendicular) streets showed either large increases or substantial decreases in traffic volumes. Streets having freeway access (i.e., interchanges) showed the largest increase. A considerable amount of backup statistical information was presented with this report.

Downs[42] provides an early insight into the subject. His paper is noteworthy primarily for its early date of publication (1962), just as Interstate/high-performance highway construction was getting into full swing. Downs posits that "on urban commuter expressways, peak-hour traffic congestion rises to meet maximum capacity." Because of its early publication date, the paper does not distinguish between such important concepts as generated versus diverted traffic. Although the arguments put forward in favor of the hypothesis are persuasive and compelling, they are based primarily on what happened with the opening of early expressways and freeways and two hypothetical case studies. Also, the work was completed before the planned high-performance highway network was completed (and in fact, the planned network has not been completed in most U.S. urban areas today).

2.4 BEHAVIORAL STUDIES OF THE IMPACT OF TRAVEL TIME ON TRAVEL DEMAND

Behavioral studies look at travel behavior at the disaggregate household or individual traveler level in order to identify the response of the individual traveler to capacity increases or differences in accessibility. Many of these studies relate to the development of a new class of travel demand models called "activity-based models." Activity-based models seek to predict travel behavior as a derived demand from the scheduling of daily activities both within and without the home. These studies strive for a better understanding of how people use their time and how they trade off time spent on various activities each day or week.

2.4.1 Study of Travel Time Elasticity

Barr[43] performed a cross-sectional study of 27,000 households surveyed in the 1995 National Personal Transportation Survey. He defined induced demand as a change in annual household VMT due to a change in the trip travel time. He found that the elasticity of VMT with respect to trip time ranged from 0.3 to 0.5. The advantage of his approach is that it includes all VMT generated by the household, regardless of the facility type, so all substitution effects are accounted for. His approach also accounts directly for the expected effect of highway capacity on demand, through reductions in travel time. Capacity changes that do not affect travel time will not affect demand as well. His results, however, cannot be directly compared with other lane-mile–based elasticities, because Barr's elasticities are for travel time, not lane-miles. Also, Barr was unable to determine long-term effects because of his use of cross-sectional rather than longitudinal data.

2.4.2 Econometric Model of Travel Behavior

Kockelman[44] fitted a system of utility theory consistent demand equations to the 1990 San Francisco Bay Area Travel Survey of 10,000 households. She tested two model specifications and found that the elasticity of discretionary travel time was generally less than 1 (ranging from 0.4 to 1.0, depending on the model specification and trip length). She also used the models to test various hypotheses on the sensitivity of travel demand to travel time and cost:

- **Hypothesis 1: Total time spent traveling by a household is independent of trip time.** This hypothesis was rejected based on the calibrated model results. The resulting effects of trip time changes were mixed, though. Kockelman noted that total time spent traveling increased as trip time to closer activities increased, indicating the inelastic nature of demand for these activities. However, as trip times to distant locations increased, total time spent traveling by households decreased as closer activities were substituted for more distant activities.
- **Hypothesis 2: The total number of household trips is independent of trip time.** This hypothesis was also rejected based on the calibrated model results. However, Kockelman found that the relative magnitude of the change in trips with respect to trip time changes was comparatively negligible. Higher trip speeds seemed to imply longer-distance trips more so than more trips, although both effects were observed.

2.4.3 Studies of the Use of Time and Travel Time Savings

Use of time studies attempt to get at the heart of the expected relationship between traffic-flow improvements and travel demand. Traffic-flow improvements affect demand by changing travel times. If researchers can understand better how people respond to travel time changes, researchers can better understand how these travel time changes affect travel demand.

Robinson and Godbey[45] produced landmark research on how people in the United States have changed their use of time over the years. Their study shatters many preconceived notions on the use of time in the United States. They observe that, contrary to popular wisdom, Americans have gained 1 hour of free time each day of the week since 1965, while at the same time feeling more harried for time than ever before. Robert Putman, in his forward to the book, observes that the extra free time has come in small packets and has therefore been spent on television (where small packets of time can be most easily spent) rather than on more satisfying leisure activities.

Robinson and Godfrey found that the amount of time each week that women spend traveling has increased by almost 2 hours per week while it has held almost constant over 30 years for men. They attribute this to a large increase in the participation of women in the labor force between 1965 and 1995.

Robinson and Godfrey's research found that people do not automatically invest increased free time (whether it comes from labor-saving devices, shorter work hours, or better roads) into more travel to more out-of-home activities. The vast majority of extra free time comes in packets too small to be used in new activities, and it is therefore used to *extend* existing activities in the home or out of the home.

Dowling and Colman[46] conducted an SP survey of 676 adults in California to identify how travelers would respond to various increases or decreases in trip times. Participants were questioned in detail on their prior day's activities. Each prior day's trip was then reviewed with the respondent and they were asked what they would have done differently if the trip time had been increased or decreased by a randomly selected amount of time (the maximum amount of change was capped at 50 percent of the total trip time to preserve realism).

Dowling and Colman found that the traveler's willingness to change travel behavior varied according to the amount of trip time savings or increase offered (see Figure 2). With travel time changes of plus or minus 5 minutes, more than 90 percent of the respondents indicated they would make no change at all in their previous day's trip. The predominant response from participants was that they would change their trip start time to compensate for any changes (increase or decrease) in trip travel time. The percentage of respondents indicating they might make an extra stop did not rise to 5 percent until the time savings approached 20 minutes. The large number of "other" responses shown in the chart for trip time increases was respondents who indicated they would try to find some way to avoid the trip time increase.

The results of Dowling and Colman are interesting in that most respondents did not consider the travel time savings that they were offered to be significant enough to warrant changes in their previous day's travel patterns. They might have responded differently to larger time savings, but the experimental design intentionally limited the amount of time savings offered to participants to an amount that bore some realistic relationship to their current trip times.

This restriction in the design of the survey was required because realism is the key to a reliable SP survey. SP surveys allow the experimenter to structure the experiment very

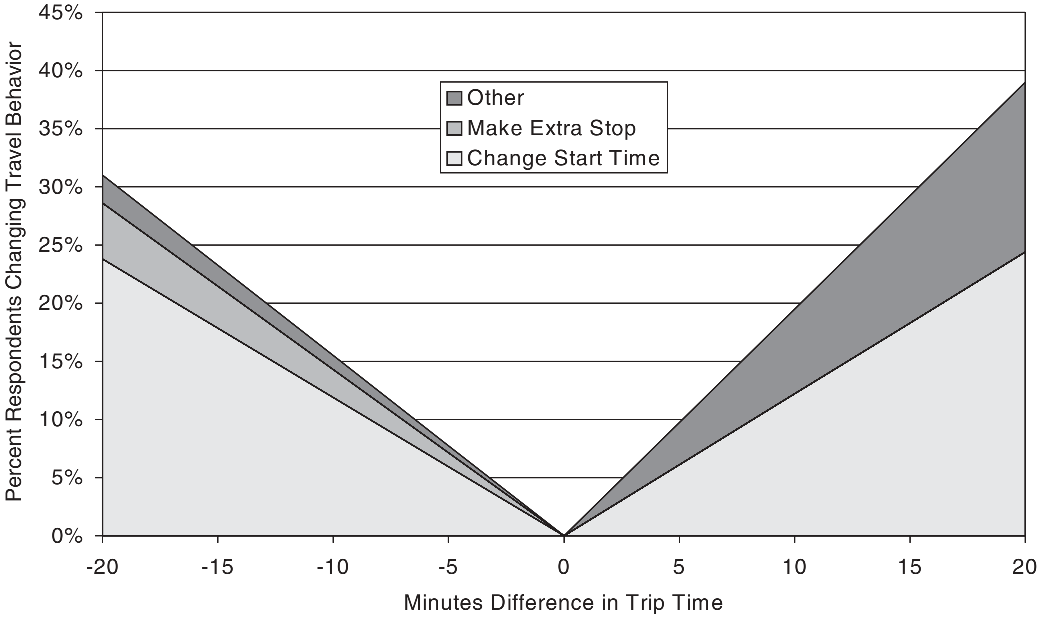


Figure 2. Traveler response to trip time changes.

precisely and thus better understand the decision-making process (and therefore hopefully the behavior) of travelers. However, SP surveys may have problems. As aptly put by Ben-Akiva and Lerman,[47] "People often do not actually do what they say they would do under hypothetical circumstances. These biases can be reduced through a careful experimental design that maximizes the realism of the questions." Ortuzar and Willumsen[48] grant the many experimental advantages of SP data when the experiment is carefully designed. However, they recommend that revealed preference data be used in combination with SP data (rather than relying exclusively on SP data) for model development. Fujiwara[49] identifies bias problems occurring with longitudinal panel SP surveys and recommends means for dealing with them.

A **San Jose State University** study[50] analyzed household survey data collected by Caltrans in 1991 as part of the California Statewide Travel Survey. Only urban households, encompassing about 6,200 dwelling units, and 64,000 person trips, were used for analysis. After geocoding household locations, the authors tested the hypothesis that freeway accessibility, as measured by the proxy of the number of freeway interchanges within a 3-mile radius, would be positively correlated with the number of private vehicle trips made by a household after controlling for demographic variables. In other words, all other things being equal, a household living closer to a freeway ramp would be more likely to make private vehicle trips as a result of the increased mobility afforded by close access to a freeway (or freeways). The San Jose researchers concluded that freeway access, at least as measured by the proxy variable of interchanges within 3 miles, does not play a very strong role in determining how many vehicle trips the household makes. Households in low-density areas (under 2,500 persons per square mile) with no freeway access within 3 miles averaged nearly the same private vehicle trip generation rate as those with freeway access. Because freeway spacing is often closer in high-density areas, the researchers note a problem with the possible multicolinearity of survey data.

2.5 STUDIES OF THE URBAN FORM IMPACTS OF TRANSPORTATION IMPROVEMENTS

There is a great deal of literature in the field of economics on how transportation infrastructure in theory affects urban development. Although it is recognized that the spatial location of transport facilities is a significant predictor of development patterns in a growing area, the effects of highway capacity improvements within an already developed urban area are less clear. This review focuses on three studies that attempted to measure actual impacts on urban form of transportation improvements in a built metropolitan area.

Pernot's[51] retrospective study of urban growth attributed urban sprawl primarily to increased financial well-being, which causes people to buy more land. Highways had a lesser effect. In the case studies of the Interstate 294 and Interstate 88 freeways in the Chicago area, Pernot found that major population gains occurred 10 years before the asphalt was poured.

An **American Association of Bay Area Governments (ABAG)** study[52] of the sensitivity of land development patterns to differing highway investment strategies in the San Francisco Bay Area found mixed results. ABAG undertook an analysis of the land-use implications of the 1989 Transportation Improvement Program (TIP) in the Bay Area using the Projective Optimization Land Use Information System (POLIS) model. Two tests were performed: The first test used existing land-use policies and ABAG's *Projections '90* land uses as the basis for the analysis of the travel time network on growth distribution. The second test looked at the impacts of the transportation network scenarios on growth distribution, relaxing the constraint of local development policies.

Various corridors where major transportation improvements were planned in the TIP were analyzed under "build" and "no build" conditions. The model results suggest that the effects of capacity increases may be highly location specific. In most cases, the relative magnitude of shifts was not great, but in certain less developed areas (e.g., Half Moon Bay), the unconstrained land-use test and highway improvements led to substantial growth. However, in Marin County, highway improvements tended to keep growth from spreading to the less congested northern part of the county (Novato). A similar conclusion was reached in Sonoma County in the North Bay: ". . . the existing transportation network—independent of the build–no build scenarios—will probably facilitate already existing development pressure to further decentralize jobs into the northern [less developed] portion of the [101] corridor." The central Interstate 80 corridor (Vallejo-Vacaville-Fairfield) was the area found to be most sensitive to highway improvements. In the build scenario, this area would have 50,000 jobs in the year 2010, while under the no-build it would have 46,000 jobs. Still, this difference is only about 10 percent.

The general conclusion of the ABAG study is that highway improvements in the core area have little effect on development in the core area, but highway improvements on the fringes attract more development to the fringes. An important qualification to this study was the inability of the POLIS model at that time to distribute land development between counties in the nine-county Bay Area (this distribution had to be done manually). POLIS only distributes development to smaller areas within a county based on county control totals.

TCRP Report 16: Transit and Urban Form[53] observes that there is "little evidence of land-use impacts from the construction and operation of busways in California, Washington State, and Washington D.C."; however, "busways that provide service comparable to rail systems can influence urban form." This report also notes, "In most urban areas where transit operates, its comparative advantage in the reduction of individual trip times is only felt on selected trips. Thus models that forecast land use on the basis of travel impedance are not sufficiently sensitive to transit's contribution to increasing accessibility, especially in downtown areas."

The TCRP report identified the following four mechanisms by which rail transit influences urban form:

- Rail transit influences the value of adjacent land and its improvements.
- Rail transit influences the intensity of development (especially for nonresidential development).
- Rail transit influences urban structure (i.e., urban versus suburban development).
- Rail transit influences the timing of development.

The TCRP report cites several case studies for each mechanism (Philadelphia, San Francisco, Washington D.C., Atlanta, San Diego, Boston, Los Angeles, Miami, Sacramento, and San Jose) as well as a few cases where urban form impacts were not observed (these cases were usually slower, lower-capacity rail systems).

2.6 EXAMPLES OF THE IMPACTS OF TRAFFIC-FLOW IMPROVEMENTS ON EMISSIONS

Prior sections have addressed pieces of the entire chain of events connecting traffic-flow improvements to emissions. This section attempts to look at the entire picture and define better the size of the target for the current research. This section borrows results from some selected conventional and advanced studies to illustrate the magnitude of the emission impacts that might be expected from traffic-flow improvements and shows the required degree of precision for the current research effort.

2.6.1 A Typical Conventional Analysis: The San Francisco Metropolitan Transportation Commission's Long-Range Transportation Plan

MPOs routinely apply conventional travel demand models to estimate the impacts of their long-range transportation plans on mobile source emissions. In fact, it is so routine that few examples make it into the research literature. The following example exemplifies the hundreds of analyses routinely conducted each year in the United States.

The San Francisco Metropolitan Transportation Commission (MTC) evaluated the impacts of $17 billion of transportation infrastructure improvements contained in its 20-year updated 1998 regional transportation plan (RTP).[54] The improvements would add 706 lane-miles of capacity to the regional highway network (an increase of 4 percent) and would increase transit system capacity in the region by 346,028 peak-period transit seat-miles per hour (an increase of 11 percent).

MTC applied a relatively advanced travel demand model (see Chapter 3 for a description) to the analysis of the impacts. However, the trip generation component of the model is not directly sensitive to travel costs, and the emission factors (EMFAC7g) were applied to average speeds, not mode of vehicle operation. The analysis concluded that the RTP would cause very minor reductions in VMT in the region and significantly greater reductions in emissions (see Table 2).

The increase in highway capacity was apparently compensated by the transit capacity improvements, thus resulting in a net reduction in vehicle activity. This result shows how even large-scale highway and transit improvement plans for a region often represent a very small change for the region as a whole (considering the magnitude of the transportation system already in place) and (at least by conventional forecasting techniques) result in miniscule changes in vehicle activity. Interestingly, though, the miniscule vehicle activity changes were magnified into larger-scale mobile source emission reductions, which suggests the need for extreme precision in predicting vehicle activity changes.

2.6.2 NCHRP 8-33 Impacts of Transportation Control Measures on Emissions

Recent research for NCHRP Project 8-33 provides an illustration of the impacts of transportation system improvements on mobile source emissions that can be expected when a more advanced analytical tool is applied to the analysis. The NCHRP 8-33 investigators[55] developed an advanced tour-based modeling approach for the Portland urbanized area (described in a later chapter) and used this model to test the effectiveness of various transportation control measures

TABLE 2 Impacts of MTC long-range transportation plan on emissions

Performance Measure	Impact	% Change
Number of Vehicles in Use	No Change	0%
Daily VMT	- 154,000 per day	< 1/10 of 1%
Engine Starts	- 4,000 per day	~1/100 of 1%
Daily Vehicle Trips	- 3,000 trips	~ 2/100 of 1%
Reactive Organic Gasses	- 3.1 tons/day	8% reduction
Carbon Monoxide	-76.2 tons/day	11% reduction
Nitrous Oxides	-8.5 tons/day	6% reduction
PM 10	No change	0% reduction

Impacts of 4-percent increase in highway lane-miles and 11-percent increase in peak-period transit capacity.

(TCMs) for reducing regional VMT. The impacts of TCMs on emissions are of interest because TCMs are almost the inverse of traffic-flow improvements (in that they usually either make highway travel more difficult, or they make alternative non-vehicle options more attractive) and thus give us an idea of how emissions respond to traffic-flow changes in general.

The TCM policies evaluated by NCHRP Project 8-33 using its advanced tour-based model include the following:

- **Pricing auto travel:** Double the long-term parking cost in downtown area and have an SOV toll of one dollar for all peak-period travel within the metropolitan area (excludes urban growth area).
- **Telecommuting incentives:** Double the percentage of workers working at home.
- **Transit improvements:** Within the metropolitan area (excludes growth areas), cut transit fare in half for all times of day and double bus service frequency at all times of day.

Table 3 shows the forecasted impacts of the TCMs on emissions. The combined impact of all of these TCM policies was to reduce travel and mobile emissions by less than 5 percent, as shown in the table.

The NCHRP Project 8-33 investigators also looked at TCM policies that influence residential location. They used the results of Portland's household SP survey to predict locational responses to policies (improved shopping opportunities, transit service, better safety, better schools in the city center, etc.). Based on the SP survey, the researchers predicted that the TCM policies would increase the forecasted number of households locating in the urban center by 16 percent. Four percent of the households in the region would move from the outer suburbs to within the urban growth area. The effect of these relocations of households was found to be a 2-percent *increase* in auto trips and a 1-percent *increase* in daily VMT. The effect of moving suburban families to downtown was to increase the number of trips generated per downtown household.

2.6.3 The Sacramento Area Council of Governments Integrated Land-Use Transportation Model Study

Rodier et al.[56] demonstrate the effect of using an integrated land-use and transportation model to predict the emission impacts of various transportation improvement scenarios in the Sacramento metropolitan area. The Marcial Echenique Plan (MEPLAN), an integrated land-use and travel forecasting model, was used to predict the travel behavior and emission impacts of four transportation improvement scenarios over a 15-year time frame. These results were then compared with the results obtained when using an advanced conventional travel forecast model, the Sacramento Metropolitan Travel Demand Model (SACMET), without a land-use modeling component. Table 4 shows the results for the HOV scenario (i.e., expansion of the existing 26 lane-miles of HOV lanes to 179 lane-miles). Forecasted land-use changes caused by the increased mobility provided by the expanded HOV system resulted in a significant change in daily VMT, however; the decrease in the number of trips resulted in no difference between the models in predicted increases of total organic gasses and CO and modest reductions in the predicted increases of NO_X and PM.

Putman et al.[57] describe a parallel study of integrating a land-use model with the Sacramento SACMET model but do not report numerical results. A series of maps are presented illustrating the land-use impacts (over a 30-year period) of the transportation improvement measures studied in the report. According to the authors, "The results of these analyses show small but significant differences in the outcomes of the several scenarios examined."

2.6.4 Implications for Current Research Effort

None of the above studies take into account all of the known short-term and long-term effects of traffic-flow improvements on demand and therefore emissions, but they illustrate a key point for the current research. The impacts of typical traffic-flow improvement projects on travel activity are miniscule (less than 10 percent when compared with regionwide travel activity), but these miniscule impacts are magnified several-fold when translated into mobile source emissions. Changes in peak-period activity have significant effects on mobile source emissions. The challenge for the current research effort will be to predict vehicle activity changes resulting from minor changes to a built network accurately enough to reliably predict their effect on emissions.

TABLE 3 NCHRP Project 8-33 forecasted impacts of TCMs on emissions

Type of Impact	Forecasted Impact
Impact on Daily Trips	- 1 %
Impact on Daily VMT	- 2 %
Impact on AM Peak VMT	- 4 %
Impact on AM Peak VOC	- 3 %
Impact on AM Peak NO_X	- 3 %
Impact on AM Peak CO	- 3 %

TABLE 4 Projected changes in emissions over baseline for HOV system expansion

Type of Change	SACMET (no land effects)	MEPLAN
Daily Trips	+0.2	-0.6%
Daily VMT	+1.9%	+6.3%
Mean Trip Speed	+2.0%	+2.1%
Total Organic Gasses	+1.3%	+1.3%
CO	+1.6%	+1.6%
NO_X	+3.0%	+2.3%
PM	+1.3%	+0.3%

2.7 CONCLUSION

This chapter reviewed some of the attempts that have been made to measure induced travel and ideas for measuring induced travel in the future. First, induced and diverted traffic occur as a result of transportation system facility changes. There appears to be no dispute in the profession at this point on this issue; rather, it seems to be widely accepted that such changes occur and need to be estimated. Second, there have been a number of recent attempts not only to establish that induced travel takes place as a result of capacity changes, but also to estimate the elasticity of this demand. However, these attempts have largely concentrated on using VMT as a measure of the induced travel demand and have estimated the elasticities of VMT with respect to capacity changes or changes in lane-miles.

The notion of using VMT as a measure of induced demand has been called into question. First, VMT confounds elements of induced and diverted traffic without completely measuring the latter. Second, VMT is not the most important component of demand that impacts emissions. (This component is vehicle speed.) In addition, it is argued that people do not demand VMT, and so measuring an elasticity of VMT with respect to capacity changes is a rather barren concept. Rather, it is suggested that people have a travel time budget. If a capacity increase is implemented that increases speeds on a facility, then the amount of a person's travel time budget that must be consumed in existing travel that used that facility or that can be diverted to that facility is reduced. This reduction leaves spare travel time within the individual's budget that can be used for additional travel (i.e., more trips), changing an existing destination to a further location, changing time of day of travel, changing mode of travel, or changing the route of some travel. In the longer run, a reduction in the amount of travel time required from a person's budget may lead to either a change in residence or a change in job location to take advantage of the lower expenditures required and to live or work in an area that is considered more desirable.

The emissions implications are greatly varied. If people divert from a congested route to a less congested route, the increase in speed will most likely lead to a reduction in emissions. Similarly, some people may divert from a destination that requires driving on congested roadways to a further destination that requires less congested driving, although a longer distance may be traveled. If the speed is sufficiently increased, the longer distance may be offset in its impacts on emissions by the improved speeds. Diversion from transit modes, or nonmotorized modes, to automobiles will necessarily result in increased emissions. Changes in time of day of travel may add to emissions, decrease emissions, or result in no change. Added trips will almost certainly result in increased emissions, no matter when or where these trips take place.

This chapter contains an extensive review of statistical studies of highway capacity increases or decreases. These statistical studies suffer from the common weakness of all uncontrolled experiments. Correlations are found, but it is difficult to go beyond the statistical conclusion of correlation to a causal mechanism. It is impossible to isolate the specific effects of the traffic-flow improvement from the effects of other changes in the environment. However, the effects all illustrate a point. Traffic-flow improvements impact travel demand, and the impacts are on the order of a 10-percent increase in daily VMT for every 10-percent increase in lane-miles of new capacity. Table 5 summarizes the conclusions of the most recent research of this type.

The statistical studies suggest that every 10-percent increase in capacity is absorbed by a 10-percent increase in demand. However, this trend applies to only the higher-speed subsystem of the entire regional transportation network.

The behavioral studies indicate that the vast majority of time savings that Americans have received over the last 30 years (whether from new freeways or from labor-saving devices) has gone to nontravel activities. Nevertheless, while these behavioral studies may contradict the magnitude of impacts suggested by the statistical studies, they confirm the basic conclusions of the statistical studies that travel time savings (and therefore traffic-flow improvements) result in increases in travel demand.

Using VMT changes to estimate the induced and diverted traffic is clearly deficient. Such use does not capture the complexity of the changes outlined here, nor does it relate directly to the estimation of emissions effects of the transportation facility changes.

One of the thorniest problems to be resolved in measuring the effects of changes in the transportation system is the condition of "all other factors being equal." This condition, made throughout the economics of demand and supply and very much of importance in considering both induced and diverted demand, assumes that everything else remains the same during the period of interest in which the transportation facility change is being made. Unfortunately, it is almost guaranteed that nothing remains unchanged while the capacity change or other facility change is implemented. This reality is particularly true when the change being implemented will have long-term consequences or when the change requires a significant time to implement. In such circumstances, there are likely to be changes in population, the economy, the supply of jobs, participation in the work force, fuel prices, the existence of destination opportunities in new locations, etc. Thus, to be able to measure the effects on existing travel demand of a transportation facility change requires the analyst to be able to control for, or estimate the separate effects of, all the other changes that take place. This requirement poses a very difficult problem to solve, one that does not appear to have been solved to date.

This chapter then considered issues of the empirical measurement of induced travel. Three methods have been proposed for empirical measurement. Two of these are closely related and are case studies and longitudinal panels. Case studies usually involve a series of cross-sectional surveys of

TABLE 5 Comparison of recent induced-demand study results

Source	Definition of Induced Demand	Data Source	Model Type	Results
Noland, Robert B., and William A. Cowart, "Analysis of Metropolitan Highway Capacity and the Growth in Vehicle Miles of Travel," *Transportation*, Vol. 27, No. 4 (2000), 363-390.	Increase in daily VMT per capita on freeways and arterials in a metropolitan area due to increase in lane-miles per capita on those facilities.	TTI congestion report data on 70 U.S. metropolitan areas from 1982 to 1996. Panel (longitudinal) data.	Distributed lag, with fixed effects.	Short-run elasticity = 0.3. Long-run elasticity = 0.9.
Marshall, Norman, "Evidence of Induced Demand in the Texas Transportation Institute's Urban Roadway Congestion Study Data Set," Pre-Print CD-ROM, Transportation Research Board Annual Meeting, Washington, D.C., 2000.	Increase in daily VMT per capita on arterials and freeways in a metropolitan area due to increase in lane-miles per capita on those facilities.	TTI congestion report data on 70 U.S. metropolitan areas for 1996 only. Cross-sectional data.	Regression model (only noncapacity factor included is area).	Elasticities of 0.9 for freeways and 0.8 for arterials.
Noland, Robert B., "Relationships between Highway Capacity and Induced Vehicle Travel," *Transportation Research A*, Vol. 35, No. 1 (2001), 47-72.	Increase in statewide VMT on nonlocal roads due to increase in statewide lane-miles on those facilities.	FHWA Highway Statistics 1984-1996 for 50 states.	Distributed lag, with fixed effects.	Short-run elasticities = 0.3–0.6. Long-run elasticities = 0.7–1.0.
Fulton, Lewis M., Robert B. Noland, Daniel J. Meszler, and John V. Thomas, "A Statistical Analysis of Induced Travel Effects in the U.S. Mid-Atlantic Region," *Journal of Transportation and Statistics,* Vol. 3, No. 1 (2000), 1-14.	Increase in daily VMT on state-maintained highways within a county that is due to an increase in lane-miles on those facilities within that same county.	HPMS systems for Virginia, Maryland, North Carolina, and Washington, D.C. Panel data for 220 counties, 1969 to present.	Fixed effects: first difference: distributed lag:	0.3–0.6 elasticity. 0.15–0.6 elasticity. Short run = 0.1–0.4. Long run = 0.5–0.8.
Chu, Xuehao, "Highway Capacity and Areawide Congestion," Pre-Print CD-ROM, Transportation Research Board Annual Meeting, Washington, D.C., 2000.	Increase in urbanized area traffic density (daily VMT per lane-mile) due to increase in lane-miles on nonlocal roads.	FHWA Highway Statistics and HPMS. Cross-sectional data for 391 urbanized areas for 1997.	Static equilibrium model.	0.03–0.4 elasticities depending on facility type and extent of lane-miles already present in each urbanized area.
Barr, Lawrence, "Testing the Significance of Induced Highway Travel Demand in Metropolitan Areas," Pre-Print CD-ROM, Transportation Research Board Annual Meeting, Washington, D.C., 2000.	Increase in annual household VMT due to reduction in travel time. (Not limited by facility type, only includes capacity improvements that affect travel time.)	Cross-sectional study of 27,000 households surveyed in 1995 NPTS.	Regression model.	Elasticities of 0.3–0.5 (with respect to time, not lane-miles).

Note: most elasticities shown in this table are with respect to lane-miles of capacity or some variation of that measure (see "definition of induced demand" column for indication). HPMS = Highway Performance Monitoring System.

the affected population, and longitudinal panels repeat measurements with panel members over some period of time. The chapter identified numerous problems that arise with either of these two methods, including the difficulty of defining the area in which affected residents, employers, and developers may be found; identifying the affected persons in the before period; and obtaining a control sample that is similar to the main sample, unaffected by the transportation facility change (or any transportation facility change), but equally affected by the population, demographic, fuel price, and other changes that affect the main sample. A number of other problems and issues were also identified for each of these methods. No effective solution was identified for these problems.

The third empirical method that was discussed is attitude and preference surveys. These surveys have the potential to get around some of the difficulties of case studies and panels, in that they allow for inclusion of, and control for, some of the externalities. In addition, these surveys do not necessarily require that a specific project is contemplated in order to obtain some measurements. However, in the absence of revealed preference data, the actual magnitude of elasticities cannot be determined. Acquiring the revealed preference data and controlling for the externalities raise the same problems as for the case studies and panels.

The chapter also noted that any type of empirical measurement, especially if it is intended to determine the long-term impacts of transportation facility changes, would need to be conducted over a substantial period of time. This period may need to last at least 10 years after the change has been fully implemented, which would lead, in many cases, to a total period of 13 to 15 years at least. The difficulty of maintaining consistent data collection over such a period is considerable, as is clearly evidenced by the difficulties that arise for most MPOs with budgeting for a single cross-sectional survey and by the almost complete lack of panels for transportation measurement. The studies of the impacts of transportation improvements on urban form in already built urban areas suggest that the long-term impacts will be hard to distinguish from other factors.

The examples of past conventional and advanced efforts to study the emission impacts of traffic-flow improvements suggest that the magnitude of the impacts will be quite small on a percentage basis compared with basinwide activity. The current research will require an exceptionally precise tool to isolate the emission impacts associated with traffic-flow improvements.

CHAPTER 3

STATE OF THE PRACTICE

This chapter reviews the travel demand and emission-forecasting procedures used by MPOs and other practitioners to evaluate the impacts of traffic-flow improvements in the United States.

3.1 REVIEW OF CONVENTIONAL PRACTICE

This section describes the current demand-modeling and emission-estimating procedures used by seven leading MPOs in the United States. The procedures illustrate intermediate to relatively advanced practices and indicate the resources that might be available for an advanced methodology for predicting the emission impacts of traffic-flow improvements. This section details the phases, or "steps," of the procedures.

3.1.1 Portland, Oregon

This section describes the currently operational travel demand model developed by Metro for the Portland, Oregon, metropolitan area. (Note that a later chapter describes the experimental activity-based model currently being tested in Portland. The experimental model, however, is not currently used for production work by the MPO.) The Portland metropolitan area has a population of 1.8 million people and covers a land area of 6,954 square miles (18,080 square kilometers). The population estimate was taken from the 1990 Official Census count, based on 1992 definitions of the consolidated metropolitan statistical area (CMSA). The definition, and thus the population figure, may differ from that actually included in the regional model area.

The Portland Metro model was calibrated against a 1994/1995 household activity and a behavior survey of 4,500 households.

The input data for this model are as follows:

- Socioeconomic and land-use data
  - Households cross-classified by four income categories, four age-of-household-head categories, and four household size (persons per household) categories (a total of 64 cells)
  - Employment (retail and other)
  - Land use (residential acres, industrial acres, and other acres)
- Access measurement data
  - Degree of mixed land uses in zone
  - Retail and other employment within 1 mile of zone
  - Density of local intersections in zone
  - Total employment within 30 minutes via transit from zone
- Special generators data
  - Shopping center floor area
  - Hospital staff
  - College students and staff
  - Weekday zoo attendance
  - Weekday attendance at the Oregon Museum of Science and Industry (OMSI)
- Other data
  - Average weekday traffic volumes at external stations
  - Household and transit coverage factors (percent within zone that are within 1/4 mile of bus line or 1/2 mile of light rail line)
  - Zones with park-and-ride lots

The steps of this model are as follows:

- **Pre-Generation.** This step of the model consists of three independent multinomial logit models: a worker model, a children model, and an auto ownership model. The worker model estimates the proportion of households in each zone that have 0, 1, 2, or 3+ workers. The children model estimates the proportion of households with 0, 1, 2, or 3+ school age children. The auto ownership model estimates the proportion of households in the zone that own 0, 1, 2, or 3+ autos. These models are sensitive to the household size and the age of the head of household. The worker and auto ownership models are sensitive to the household income. The auto ownership model is sensitive to the density of local street intersections in the zone, the degree of mixed uses in the zone, and the transit accessibility to employment of the zone (i.e., the number of jobs accessible within 30 minutes via transit).
- **Trip Generation.** Trip generation is estimated for six purposes (home-based work, home-based school, home-based college, home-based other, non–home-based work,

and non–home-based other). A combination of cross-classified tables of trip generation rates and linear regression equations are used to predict daily person trip productions and attractions. The trip generation rates and regression equations are sensitive to household size, workers per household, autos per worker, retail employment, and other employment.

The school trip generation estimates are sensitive to household size (persons per household) and children per household. The college trip production estimates are sensitive to household size (persons per household) and the age of the head of the household. The college trip attraction estimates are sensitive to special generator data gathered for each college.

A separate modeling process is used to predict trips to the Portland International Airport.

- **Trip Distribution.** A multinomial logit model is used to distribute the trips. The model is sensitive only to the number of attractions in the destination zone and the travel time between zones (the same as a standard gravity model). Special district-level (a geographic grouping of zones) adjustment factors (*K*) are applied to certain trip interchanges to better match the household survey trip distribution. These factors vary by district pairs and are constant.
- **Mode Choice.** Mode choice is performed in two steps. First, the bicycle and walk trips are separated out. Then, the remaining trips are split between vehicle modes.

The proportions of trips using walk mode and bike mode are computed using multinomial logit equations that vary by trip purpose and by mode. The mode split equations are sensitive to trip distance, cars per worker, local street intersection density, and the mix of land uses.

School trip mode split is not computed using the logit equations; instead, the mode split is obtained from a table. There is a set of mode splits for each of four major areas within the metropolitan area.

The walk and bike mode computations are constrained by the following maximum allowed distances for these modes:

Trip Purpose	**Maximum Walk Distance (miles)**	**Maximum Bike Distance (miles)**
Home-Based Work	5	15
Home-Based Other	4	6
All Other	3	5

The motorized mode person trips are then split among the vehicular modes according to multinomial logit equations. The one exception is trips generated by 0-car households. These trips are split between transit and car passenger modes based on fixed percentages.

Home-based work trips and non–home-based work trips are split among drive alone, shared ride, walk to transit, and auto to transit modes. All other trip purposes are split between auto and transit modes.

The vehicle mode splits are sensitive to access time, in-vehicle time, cost, workers per household, cars per worker, trip distance, residential density, and employment density. A central business district dummy variable is employed to account for the special transit usage characteristics of the downtown. A special adjustment process is used to shift some bus trips to light rail to account for the observed light rail ridership.

Fixed auto occupancy rates by trip purpose are used to convert auto trips and shared-ride trips to equivalent vehicle trips.

- **Time of Day.** Fixed percentages by trip purpose, direction of trip (production to attraction, or attraction to production), and peak period are used to predict the number of trips made during the AM peak 2 hours, the AM peak hour, the PM peak 2 hours, and the PM peak hour.
- **Traffic Assignment.** Portland has a 1,244-zone network. The auto and truck vehicle trip tables are assigned to the highway network using a multiclass equilibrium assignment. Trucks are assigned in terms of their passenger car equivalents to account for their greater consumption of capacity. The truck table is developed through a separate process that is independent of the development of the auto trip table.

Transit trips are assigned using a multipath assignment. Transit speeds are a function of the auto volumes on each link.

- **Feedback and Equilibration.** No formal procedure was documented in the user's guide or model description.

3.1.2 San Francisco, California

This section describes the travel demand model developed by the Metropolitan Transportation Commission (MTC) in 1997 for the San Francisco Bay Area.[59] The San Francisco Bay Area has a population of 6.3 million and a land area of 7,368 square miles (19,150 square kilometers).

The model was calibrated against a 1990 household travel survey of 9,359 households. Another 1,479 households were surveyed for multiday (three weekdays) travel patterns.

The steps of this model are as follows:

- **Pre-Generation.** Demographic and socioeconomic forecasts for the region are based upon national, state, and local trends. The POLIS model is used to spatially allocate the forecasts. These forecasts are performed by ABAG, which is separate from the MTC. A nested logit model is used by the MTC to predict the distribution of workers per household and vehicles per household based on the socioeconomic forecasts provided by ABAG. The top level of the nested logit model predicts the proportion of households with 0, 1, or 2+ workers per household. The second level of the model predicts the conditional proportion of households with 0, 1, or 2+ cars per household given the number of workers per household.

- **Trip Generation.** Daily person trip generation is estimated for the following trip purposes: home-based work, home-based social or recreation, home-based school, home-based other, and non–home based. Trip generation is estimated using linear regression equations that are sensitive to workers per household, household income, employment density, retail employment, service employment, vehicles per household, and household size.

  School trips are divided into grade school, high school, and college subpurposes. The number of trips produced is a function of the school age population. School attractions are a function of enrollment.
- **Trip Distribution.** Trips are distributed using a gravity model based on a blend of peak and off-peak travel times. For each trip purpose, the peak and off-peak travel times are weighted according to the percentage of trips of that purpose that occur during peak and off-peak periods. The result is a table of weighted mean zone-to-zone travel times for each trip purpose.

  Home-based work trips are stratified by household income quartile. Each income quartile is distributed with its own friction factor curve.

  Fixed adjustment (*K*) factors are applied to specific trip interchanges to account for variations in trip making not adequately explained by the gravity model.
- **Mode Choice.** A set of nested logit models is used to forecast mode choice by trip purpose. For the home-based work trip purpose, the top level of the model separates trips by bicycle, walk, and motorized modes. The next level divides the motorized trips by drive-alone auto, two-person shared-ride auto, three-person shared-ride auto, and transit. Then the transit trips are further divided at the third level into auto access trips and walk access trips. The other trip purposes employ less extensive nesting and fewer modes.
- **Time of Day.** A binomial logit model is used to predict the proportion of home-to-work auto person trips that are made during the 2-hour morning peak period. The model is sensitive to delay and household income. All other trip purposes and modes of travel are assigned to the peak period using fixed percentages.
- **Traffic Assignment.** The MTC uses a 1,099-zone system plus 21 external gateways. The highway network has about 31,000 one-way links. The transit network has 25 transit operators and over 700 transit lines. Static user optimal equilibrium is used to assign vehicle trips to the highway network.
- **Feedback and Equilibration.** A feedback procedure has been used by the MTC for years. Depending on the model run (e.g., existing versus future), between three and eight iterations are required for closure. Closure is based primarily on professional judgment. The direct method (rather than averaging previous runs) is used.

3.1.3 Dallas–Fort Worth, Texas

This section describes the travel demand model process currently being used in the Dallas–Fort Worth area by the North Central Texas Council of Governments (NCTCOG).[60] The Dallas–Forth Worth area covers 9,105 square miles (23,670 square kilometers) and has a population of more than 4 million.

This model was calibrated against a 1984 home interview survey. The NCTCOG maintains land-use and socioeconomic data in a 5,000+ traffic survey zone system; however, this zone system is aggregated to 960 regional analysis areas and 61 external gates when used with the travel demand model. The steps of this model are as follows:

- **Pre-Generation.** The Disaggregate Residential Allocation Model (DRAM) and Employment Allocation Model (EMPAL) are used to predict land use in 5-year increments for 191 super districts. The super-district forecasts are disaggregated to the 5,000+ zone system. Nevertheless, the travel model cannot operate on such a large number of zones, so before trip generation is computed the necessary socioeconomic data are first aggregated from the 5,000+ traffic survey zone system to the 960 regional analysis area system. Household income distribution curves, which are derived from 1980 Census data, are used to compute the proportion of households within each zone that fall into each income quartile. The curves relate the proportion of households in each quartile to the zonal median income. A similar process, which uses distribution curves from the Census, computes the proportion of households by household size as a function of the mean household size for each zone.
- **Trip Generation.** Four two-dimensional, cross-classification tables of trip rates (one for each trip purpose) are used to compute daily person trip production for home-based work, home-based other, non–home based, and other (external, truck, and taxi vehicle trips) trip purposes. The “other” trip purpose rates per employee vary by employment type and area type. The home-based and non–home-based trip rates per household vary by income quartile and household size. The home-based work trip productions are divided into four household income quartiles. Home-based work attractions are computed separately for each income quartile. A series of cross-classification tables are used to compute the zonal attractions as a function of the employment in the zone (basic, retail, and service). Trip generation for regional malls, colleges, hospitals, airports, and regional recreational facilities are estimated separately as special generators.

- **Trip Distribution.** A gravity model is used to distribute trips. A Bessel function is used for the friction factors. The home-based work trips for each income quartile are distributed separately, each with its own Bessel function. Intrazonal travel times are computed by dividing each zone into 13 concentric squares and by computing the average distance from the zone centroid to the perimeter of each square. A table of speeds by area type and time of day is used to compute the mean intrazonal travel time from the average intrazonal trip distance. *K* factors are used to account for trip behavior not adequately modeled by the gravity model. External-external vehicle trips are added to the "other" trip purpose trip table.
- **Mode Choice.** Multinomial logit models are used to predict mode choice by trip purpose (home-based work, home-based other, and non–home based). Home-based work trips, which are stratified by income quartile, are split between drive alone, two-person shared ride, three-plus–person shared ride, transit with walk access, and transit with auto access. Similar modes are used for the other two trip purposes, with the exception that the two shared-ride modes are collapsed into a single two-plus–person shared-ride mode.
- **Time of Day.** A fixed set of time-of-day factors by trip purpose is used to estimate peak-hour volumes from daily trips.
- **Traffic Assignment.** An incremental capacity restrained assignment process is used. Link impedances used in the assignment process are a function of not only the link travel time, but also the link length and the link travel cost. Exponential functions are used to predict the impact of traffic volumes on link travel times. The exponential functions are capped so that the link speed never drops below 1 mile per hour. Different functions are used for the daily assignment and for the AM and PM peak-hour assignments.

  The highway network is coded using eight link types and centroid connectors. The link free-flow travel time is estimated by dividing the posted speed limit into the link length and adding the estimated control delay due to stop signs and signals on the link. Between 4 and 12 seconds of control delay is added depending upon the area type and the functional class of the link. Link capacities vary by number of lanes, median type (divided or not), area type, and functional class.
- **Feedback and Equilibration.** The mainframe-based regional model uses final link speeds that are fed back to trip distribution and mode split until the change in the VMT-weighted highway assignment speed difference is less than 5 percent for each facility type. A direct method is used, i.e., the results from the previous iteration(s) are not combined with the current iteration to obtain a new overall solution. Rarely have more than one iteration been required.

3.1.4 Philadelphia, Pennsylvania

This section describes the travel demand process used by the Delaware Valley Regional Planning Commission (DVRPC) for the Philadelphia metropolitan area.[61] The region encompasses 5.2 million people in two states.

The model was calibrated against a 1987–88 survey of 2,500 households. The DVRPC maintains socioeconomic data for 1,395 zones. There are 114 external gates. The steps of this model are as follows:

- **Pre-Generation.** Pre–trip-generation models are not employed.
- **Trip Generation.** Daily person trip generation is forecasted for home-based work, home-based nonwork, and non–home-based trip purposes. Fixed-trip rates by area type and by vehicle ownership category are used to estimate trip generation. Vehicle trips made by external trips, trucks, and taxis are estimated using separate rates.
- **Trip Distribution.** Gravity models are used to distribute the person trips and the truck, taxi, and external vehicle trips.
- **Mode Choice.** The mode choice is predicted using a binary probit model that splits the person trips into auto and transit modes. An auto-occupancy model is used to predict drive-alone and shared-ride trips. The transit trips are assigned to submodes (commuter rail, subway/elevated, and surface bus) during the assignment process according to the shortest transit path.

  The person trip table is stratified into 18 tables according to the trip purpose (home-based work, home-based nonwork, and non–home based), the transit submode that is used by the transit shortest path (commuter rail, subway/elevated, and surface bus/trolley), and the household auto-ownership type (zero cars and one or more vehicles). Binary-mode choice (transit or auto) is computed for each of the stratified trip tables.

  The auto-occupancy model predicts the mean number of persons per vehicle for home-based work trips and for home-based other trips. It consists of a pair of linear equations that are a function of only the highway travel time. The linear equations are subject to allowable maximum and minimum auto-occupancy values.
- **Traffic Assignment.** Traffic assignment is performed using static user equilibrium. A standard Bureau of Public Roads equation is used to predict the impact of traffic on travel speeds. Transit trips are assigned to the single shortest path.
- **Feedback and Equilibration.** No formal procedure is included in the user's guide or model documentation.

3.1.5 Chicago, Illinois

This section describes the travel demand model developed by the Chicago Area Transportation Study (CATS) for the Chicago area.[62] The CATS region includes the Illinois counties of Lake, McHenry, Cook DuPage, Kane, Kendall, Grundy, and Will and the Indiana county of Lake. The CMSA includes 8.2 million people in 6,931 square miles (18,000 square kilometers).

The model was calibrated against a series of household surveys, the latest of which occurred in 1990 and consisted of 19,000 households. The land-use and socioeconomic data are tabulated for a system of 1,640 traffic analysis zones. The steps of this model are as follows:

- **Pre-Generation.** The households in each traffic analysis zone are stratified into 21 categories according to the estimated number of workers per household and the estimated number of persons per household. Survey-developed distribution curves, which plot the percentage of households in each category as a function of the mean persons per household or the mean workers per household, are used to estimate the percentage and number of households falling in each category for each zone.
- **Trip Generation.** Daily home-based person trip generation is computed using trip rates in a cross-classification table stratified by workers per household in one dimension and by persons per household in the other dimension. The number of trips generated by workers in the household is added to the estimated number of trips generated by the remaining persons in the household to obtain the total trips generated by each category of households. Trips are generated for three purposes: home-based work, home-based other, and non–home based.

  Linear regression equations, which are sensitive to seven employment categories and the total number of households in a zone, are used to predict trip attractions and trips produced outside of the homes in each zone.

  Special floor space–based trip generation rates are used to predict trip generation for the central Chicago area. A separate model is used to predict truck trip generation.
- **Trip Distribution.** Chicago uses an "intervening opportunities" model (similar to a gravity model) to distribute trips. Separate friction factor curves are used for each trip purpose and for each of 15 different districts within the region. Vehicle trip tables for through trips, visitor trips, school trips, truck trips, and taxi vehicle trips are estimated separately.
- **Mode Choice.** A binary logit model is used to split person trips into auto and transit modes. A unique Monte-Carlo simulation approach is used to trap the impact of variances in parking costs and the income of the traveler on mode split. The mode split probability is computed for each individual trip between zones, and a random number generator is used to select a parking cost and income for that trip. The results of this simulation are then summed over all trips between the pair of zones to obtain the transit trips going between the zones.
- **Traffic Assignment.** The transit network has 642 transit lines coded.
- **Feedback and Equilibration.** No formal feedback or equilibration procedure is included in the user's guide or model documentation.

3.1.6 Washington, D.C.

This section describes the travel demand model currently being used by the Metropolitan Washington Council of Governments (MWCOG) for the Washington, D.C., area.

The socioeconomic data are stored in a system of 1,972 traffic analysis zones that are aggregated to 333 districts for the trip generation and distribution steps. Then the district-level trip table is proportionally disaggregated to the zone level for the mode split step. The steps of this model are as follows:

- **Pre-Generation.** A household vehicle ownership model is applied at the district level to estimate the number of homes in each district owning 0, 1, or 2+ vehicles.
- **Trip Generation.** Motorized person trips are generated for home-based work trips only. Vehicle trips are generated for three noncommercial purposes (home-based shop, home-based other, and non–home based) and two truck purposes (medium weight and heavy weight). Linear equations, which are sensitive to households by auto ownership category and by five categories of employment, are used to forecast trip productions and attractions for all six purposes.
- **Trip Distribution.** Trip distribution is computed using the gravity model. A preliminary assignment of vehicle trips is made to obtain "first cut" congested travel times for use in distributing home-based work trips.
- **Mode Choice.** The mode choice model is applied only to the home-based work trips. Home-based work trips are split between low-occupancy vehicle, high-occupancy vehicle, and transit modes.
- **Traffic Assignment.** Traffic assignment is performed using an incremental capacity restraint algorithm.
- **Feedback and Equilibration.** Congested highway travel times are fed back to the trip distribution model only for home-based work trips. This cycle is repeated twice. Other trip purposes are assumed to be unaffected by traffic congestion.

3.1.7 Seattle, Washington

This section describes the travel demand model that is currently being used by the Puget Sound Regional Council (PSRC) for the Seattle area.[63] The Washington CMSA population is over 3 million with a land area of 7,224 square miles (18,780 square kilometers). The PSRC has been gathering a longitudinal panel household travel behavior data set for

1,700 households since 1989. The panel has been surveyed eight times since 1989. Approximately 50 percent of the original households are still in the panel. New households have been recruited to replace those leaving the region so that the current panel remains at about 1,700 households. The steps of this model are as follows:

- **Pre-Generation.** The PSRC uses a linear regression model to predict the regional control totals for households and employment. The regression model is not sensitive to changes in accessibility. The DRAM/EMPAL models then are used to allocate the regional totals to 219 districts, which are then further disaggregated to 832 traffic analysis zones.
- **Trip Generation.** Daily motorized person trip productions and attractions are estimated for home-based work, home-based other, and non–home-based trip purposes, plus college student trips, school trips, and commercial vehicle trips. Productions are estimated using cross-classification tables that, for home-based work, home-based other, and non–home-based trips, are sensitive to household size and the number of workers in the household. College and school productions are sensitive to the number of college age students and school age students per household. Commercial vehicle trips are factored from the non–home-based trips. Linear regression equations are used to predict attractions. Trip generation is not sensitive to travel time, access time, or auto ownership.

  The PSRC currently is testing an update of its model that includes nonmotorized modes in the trip generation step. The new model also splits out home-based shop trips from the home-based other category and groups home-based work trip productions and attractions by income quartile.
- **Trip Distribution.** Trip distribution is done using a gravity model with *K* factors to correct for underestimates or overestimates by the gravity model.
- **Mode Choice.** A logit mode choice model is used to predict the percentage of home-based work, home-based other, and non–home-based trips that are transit with walk access, transit with auto access, and automobile. Home-based work auto trips are further split into carpool and single-occupancy (noncarpool) person trips. AM peak-period travel times are used to estimate home-based work mode choice. Midday travel times are used for predicting the mode choice for the other trip purposes. The auto operating costs are included in the mode choice analysis for transit trips with auto access. The PSRC currently is testing a combined mode choice and trip distribution model that includes walk and bike mode choices.
- **Time of Day.** The daily trips by mode are split into trips made during the 3-hour AM peak period and the 3-hour PM peak period using fixed percentages. The remainder of the trips are midday and off-peak trips.
- **Traffic Assignment.** Single-occupancy auto, carpool, and commercial vehicle trips are assigned to the highway network using multiuser equilibrium assignments. The auto access portions of transit and auto access trips are also assigned to the highway network. Transit trips are assigned using EMME/2's capacity constrained algorithm.
- **Feedback and Equilibration.** Travel time results are routinely fed back to the trip distribution and mode split steps. Major changes in the transportation system are fed back to the DRAM/EMPAL land-use allocation step.

3.2 CRITIQUE OF CONVENTIONAL PRACTICE

Litman[64] has criticized conventional travel demand models for underestimating the demand-inducing impacts of highway capacity increases. He is one of many voices to criticize the current state of the practice.

As noted by Deakin and Harvey[65] in their review of the state of the practice, the quality of models in practical use varies significantly. Merely bringing all MPOs up to current standard practice would be quite an improvement. The key shortcomings of current practice that they identified include

- Omission of key variables for predicting travel behavior (household income, parking and auto operating costs, and number of workers per household);
- No trip generation variables beyond auto ownership and income (e.g., household size would be a good predictor);
- Inadequate representation of trip attractions;
- Omission of transit and walking accessibility in trip distribution models;
- Lack of peaking information by trip type and market segment;
- Simplistic representation of socioeconomic variables affecting travel behavior; and
- Simplistic characterization and modeling of nonwork travel.

Deakin and Harvey also note that many MPOs are not gathering the data they need to develop and maintain adequate travel models. They recommend regular collection of land use, land-use regulations, travel behavior surveys, network, and monitoring data. They also recommend additional staffing to maintain and operate the models.

Stopher[66] has noted that current travel demand models sufficiently predict the impact of travel cost changes on mode choice, but not the impact of cost on overall demand for travel. The typical problems of conventional travel demand models are that

- They cannot reflect changes in trip making per household,
- They lack feedback (i.e., equilibration of demand with supply),

- They fail to use land-use models to reflect the impacts of transportation changes on land use,
- They have large aggregation errors with large zones, and
- They cannot accurately predict real-world travel speeds.

Many of the advanced MPOs described in Section 3.1 have already addressed many of the above problems. Stopher's observations still apply to the vast majority of MPOs that have not yet addressed these issues.

Stopher observes that only a subset of TCMs, those that are quantifiable, could be reasonably evaluated using conventional travel demand models. The primary quantifiable TCM strategies that can be evaluated with conventional travel demand models are

- Price-related TCMs (transit fare subsidies, parking costs, and tolls),
- HOV lanes,
- Transportation system management (TSM) improvements that have measurable impacts on speeds and capacities,
- Transit service improvements (exclusive of reliability changes), and
- Park-and-ride lots.

Examples of nonquantitative TCMs are informational, promotional, and marketing TCMs.

Stopher and Fu[67] identified a set of improvements that could be made in the short term to improve the accuracy of conventional travel demand models and the accuracy of mobile emissions produced from demand model output. The following improvements are identified:

- **Pre-Trip Distribution Diurnal Factoring.** It is proposed that the factoring of daily trips to time of day be moved to immediately after the trip generation step. Thus, the model will run the distribution, mode split, and assignment steps for five time periods using the travel times and costs appropriate for that time of day.
- **Link-Specific Capacities.** It is proposed that more precise capacities be computed on a link-specific basis rather than relying on general capacity values based on the area type and the number of lanes.
- **More Realistic Speed-Flow Curves.** It is recommended that modelers adopt more realistic speed-flow curves that show a much steeper drop in speeds when demand exceeds capacity.
- **Feedback.** Congested travel times should be fed back to the trip distribution step.
- **Seasonal and Day of Week Factoring.** Seasonal and day of week factors should be developed to convert the average weekday volumes produced by models into specific season and day of week data needed for air quality analyses.

Feedback, or equilibration of travel times with the assumed travel times, is a major issue for all travel models. A report by the Comsis Corporation[68] for the U.S. DOT TMIP identifies conditions when feedback should be used, explains how it can be implemented, and describes its effects on model results. Harvey Miller[69] has prepared a guide on maintaining internal consistency within travel models that presents the basic theory of transportation system equilibrium and describes the various types of equilibrium (i.e., user optimal, dynamic user, and stochastic user). The appendixes provide the formulas and properties for network and market equilibria.

Replogle[70] recommends additional data collection, including panel surveys, traffic counts, time and delay studies, supply inventories, pricing data, goods movement data, special generator data, and land development inventories. Replogle also makes the following recommendations for model methodology improvements:

- The trip generation models must predict person trips not vehicles trips, be sensitive to changing demographics and urban structure (i.e., access time), be sensitive to trip chaining, and consider job/housing balance in forecasting land use and external trip patterns.
- Trip distribution models must use travel times internally consistent with later stages of the model, integrate multimodal factors, and provide for departure time choice.
- Mode choice analysis must improve treatment of transit access options, better represent auto access to transit, better represent nonmotorized access modes to transit, become sensitive to variations in pedestrian and bicycle friendliness, and become sensitive to auto ownership.
- Networks must have increased zone and network detail, and intersection capacity and delay must be separated from link capacity and delay.
- Models must be sensitive to alternative land-use scenarios.
- Models must be able to represent transportation demand management (TDM) programs.

From the perspective of statewide travel forecasting, Horowitz[71] identifies appropriate methodologies for differing analysis needs. One of the several methodologies he presents is a **four-step modeling procedure** for forecasting statewide passenger travel:

1. Trip generation,
2. Trip distribution,
3. Mode choice, and
4. Vehicle assignment.

Although Horowitz's original model includes four steps, some applications of the model have elaborated on the basic four steps, adding such steps as pre-generation and time of day. Thus, the applications included in this chapter include more than four steps, although they follow Horowitz's original four-step model structure.

3.3 MODELING NONMOTORIZED TRAVEL

Relatively few models take into account nonmotorized travel. Only some of the more advanced research models have attempted to explicitly model nonmotorized travel. This section is a condensed version of the FHWA 1998 overview titled *Guidebook on Methods to Estimate Non-Motorized Travel: Overview of Methods* (Publication No. FHWA-RD-98-165) and also refers to an article by Thomas Rossi of Cambridge Systematics. The term "nonmotorized travel" refers mostly to bicycling and walking, yet also could include inline skating, scooting, skateboarding, or horseback riding.

This review discusses the various methods that are used to predict future demand of nonmotorized travel. Other methods are available that support demand forecasting such as the usage of land-use and population data, before-and-after studies, preference surveys, facility and environment characteristics, and geographic information systems (GIS). This review only covers demand estimation methods of discrete choice and regional travel models because these approaches reflect the state of the art of nonmotorized demand estimation techniques.

Thomas Rossi[72] prepared a paper on methods for incorporating nonmotorized vehicle modes (bike and pedestrian) into travel behavior models. He identifies four reasons for incorporating nonmotorized travel in models: better modeling of mode choice, analysis of transportation demand management measures, analysis of alternative land-use patterns, and prediction of transit access.

Rossi describes three examples of nonmotorized models: the Central Artery/Tunnel project, the Land Use Transportation Air Quality (LUTRAQ) project, and Philadelphia. The Central Artery/Tunnel model is a submodel of the regional model system and is focused on downtown Boston. A special pedestrian trip generation, distribution, and assignment model was developed along with a pedestrian network. The Portland LUTRAQ model extended the preexisting pedestrian/bicycle modeling capabilities of the Portland model. Pedestrian environment variables and data were added to the Portland model, which enabled more sophisticated auto ownership and mode choice forecasts. The Delaware Valley Regional Planning Commission (DVRPC of Philadelphia) added nonmotorized trips to the trip generation model and then separated them out using a binary mode choice model prior to trip distribution.

Rossi notes several limitations with pedestrian environment variables: They are, of necessity, limited to zones, since that is the smallest analysis unit within travel behavior models. A significant amount of time is required to develop and update environmental variables for each zone. Many of the components of the pedestrian environment variables are subjective, making it difficult to ensure consistency between model operators and between calibration and forecasting. Rossi concludes that environmental variables have been successfully applied, but do require a great deal of care.

3.3.1 Discrete Choice Models

Discrete choice models predict individuals' choice of mode or route as a function of variables such as parking availability or the traffic level. The model is used to estimate how travelers would respond to a specific policy change or facility improvement like increased bicycle parking at transit stations. The underlying data set of the model consists of the following characteristics: individual attributes such as age and income, alternative route or mode choices, geographical location, and individual trip decisions. These data sets are developed from revealed and SP surveys. Revealed preference surveys quantify actual behavior, whereas SP surveys illustrate the choices that travelers would make given different scenarios. The results are limited by the questions asked in the SP survey. The possible outputs include the probability of an individual to choose bicycling or walking for each scenario, elasticities that show the percent change of bicycling or walking when one variable changes, and the total number of travelers who are expected to change for each scenario. The results could be incorporated into regional travel models as bicycle and pedestrian submodels.

3.3.1.1 Work Trip Mode Choice

In the late 1970s and early 1980s, the Wisconsin Department of Transportation (WisDOT) developed a series of work trip mode choice models to determine the impacts of transportation policy in urban areas throughout the state. The bicycle variables included the presence of bike lanes, street surface quality, and street traffic. The pedestrian variables included the presence of sidewalks, season, and distance to work. The presence of bicycle lanes on all the applicable streets caused a 39-percent increase in summer bicycle trips. A deterioration of pavement quality from smooth to rough caused a 42-percent reduction of summer bicycle trips. These results remained fairly constant for the four urban areas that the model covers. The calibration process showed a reasonable correspondence between the model estimates and actual travel behavior.[73]

3.3.1.2 Transit Access Mode Choice in Chicago

The Chicago Transit Authority (CTA) developed discrete choice models to predict the travel impacts of bicycle and pedestrian improvements at rail stations. CTA used two nested logit models: one to measure the access mode to the commuter rail and the other for the rapid rail. These models used the following variables to estimate changes in mode split:

travel time, parking availability for autos, parking costs, other costs, number of buses, and bicycle and pedestrian improvements. The bicycle variables that had high statistical significance include debris, bicycle parking, curb lane width, and slow traffic. The presence of bicycle facilities was not statistically significant. The pedestrian variables included sidewalks, recreation paths, slow traffic, no turn on red, crosswalks, pedestrian lights, and walk islands. The model was used to prioritize stations, select case study locations, identify design improvements, and estimate the cost-effectiveness of improvements.[74]

3.3.2 Regional Travel Models

Regional travel models use existing and future land-use data, transportation networks, and human behavior to predict future travel patterns. The traditional four-step approach of trip generation, trip distribution, mode choice, and network assignment typically has been oriented toward autos and transit. More sophisticated models predict nonmotorized mode splits and route choice. Models specifically for bicycling and walking also exist.

The primary factors that are assumed to influence bicycling and walking are trip distance or time, trip purpose, individual characteristics, and environment factors. The different environment factors cover the following: sidewalk availability, terrain, land-use mix, building setbacks, transit stops, street crossings, and bicycle infrastructure. The model outputs include the nonmotorized trip generation of each traffic analysis zone and the trip distribution between the zones.

The advantage of regional travel models is that they exist in every major metropolitan area in the United States. With sufficient nonmotorized infrastructure and demand data, these models represent the state-of-the-art method for nonmotorized travel demand estimation. The disadvantages of regional travel models include insufficient data on nonmotorized travel patterns, inadequate knowledge about the nonmotorized network characteristics, inability to consider recreation trips, and a level of detail that is too coarse to analyze shorter trips.

3.3.2.1 Edmonton Transport Analysis Model

The Edmonton Transport Analysis Model includes bicycling and walking as separate modes and uses bicycle network characteristics to predict nonmotorized travel. A link was coded as a facility with a bicycle path, a bicycle lane, or mixed traffic. Time-equivalent penalties were given for each facility type. SP surveys showed that bicyclists would ride 1 minute on mixed-use facilities, 2.8 minutes on bike paths, or 4.1 minutes on bike lanes. Feedback loops made it possible for the model to show the affects of bicycle network improvements on trip generation, trip distribution, and mode choice.[75]

3.3.2.2 Pedestrian-Bicycle Environment Factor Models

Pedestrian-bicycle environment factors such as sidewalk and bikeway availability help predict nonmotorized trips. These factors describe the attractiveness of an area to bicyclists and pedestrians. The Portland regional model used the following pedestrian environment factors: sidewalk availability, ease of street crossing, connectivity of street and sidewalk system, and terrain. Each zone was ranked according to its quality of pedestrian environment. The mode choice step included a motorized versus nonmotorized option, which was a function of the pedestrian environment, travel distance, ratio of cars to workers in households, and employment within 1 mile of the zone. The Maryland–National Capital Park and Planning Commission developed a nested logit mode choice model that included bicycle and pedestrian variables in its environment factor. The walk/bike mode was used to determine transit access.[76]

3.4 MODELING TRUCK TRAFFIC

3.4.1 Literature Review: Freight Flow Models

The freight flow model literature review is a condensed version of the summary provided by Cambridge Systematics titled *Review of Current Freight Flow Models (Draft)*, which was prepared for the Florida Department of Transportation Freight Model Development Project in September 2000. The review provides a discussion of vehicle-based and commodity-based models and includes descriptions of existing truck models that use the respective techniques.

Modeling truck movements separately from passenger cars is a relatively new phenomenon. Most truck models have focused on the statewide level. A few models have been developed for urban areas (e.g., Portland, Phoenix, and Sacramento), but they generally operate independently with limited interfaces to the conventional travel demand models already present in the region.

Models of truck movements in an urban area approach the problem in either of two ways: they model the truck traffic flows directly or they model the flows indirectly by modeling the movements of commodities and then deriving the truck flows necessary to carry the commodities.[77] Commodity flow models are sensitive to many economic variables that affect the amount of goods that must be moved; however, they often exclude the various truck trips not associated with the movement of goods (such as service trips). Truck flow models can only indirectly predict the amount of truck traffic through land-use proxies, but have the advantage of modeling all truck trips.

The ideal regional model would use both the vehicle-based and the commodity-based model approaches. The advantage of the vehicle-based model is that it includes service-oriented trucks such as distribution and air express delivery movements. Commodity-flow models are better at estimating long-haul truck movements. The Southern California Association of Governments (SCAG) model, which is described under the commodity-based model section, provides the best example of this combined approach.

3.4.2 Vehicle-Based Models

3.4.2.1 Background

Vehicle-based models are based on three of the four steps used in the traditional person transportation modeling process: trip generation, trip distribution, mode choice, and vehicle assignment. The mode split step is not necessary since the model only focuses on one mode. Trip generation applies trip rates to traffic analysis zone employment or household data. Special generators such as seaports, airports, and intermodal rail yards are also considered. External stations include the effect of long-distance truck trips. The trip distribution step uses the gravity model and considers truck trip lengths. The vehicle assignment step focuses on a subset of roads that consists of the highway network and other truck routes. Other modifications include revisions to the network's speed, capacity, and toll rates. Two sample vehicle-based models include the New Jersey and Phoenix truck models shown below.

3.4.2.2 New Jersey Statewide Truck Model

The New Jersey statewide truck model was developed to establish more accurate truck trip tables. The previous truck model used a commodity flow approach that did not adequately reflect service-oriented truck trips. Truck trips are estimated based on information from a variety of sources like cordon-line and facility-specific surveys as well as state border crossing count data. Separate gravity models exist for medium- and heavy-truck types and for trip end types such as internal/internal (I/I) and external/internal/external (E/I/E). Truck trips are assigned to the truck routes along with auto trips. This model is used to estimate the impacts of toll changes, road construction, and major new developments.

3.4.2.3 Phoenix Truck Model

The Phoenix truck model also uses three of the four steps of the person transportation modeling process. Different trip generation and distribution models exist for the following truck types: less than 8,000 pounds, 8,000–28,000 pounds, and more than 28,000 pounds. The truck generation models are based on a survey of daily truck trips. The trip distribution step uses weight class-specific gravity models, which are calibrated to observed trip length distributions and their averages.

3.4.3 Commodity-Based Models

3.4.3.1 Background

Commodity-based models forecast freight flows usually for statewide transportation networks using commodity flow data for at least two modes: truck and rail. Commodity data come from the nonproprietary U.S. Census's *Commodity Flow Survey* or from the proprietary sources of Reebie and Associates or TRANSEARCH. Trip generation rates derived from population and employment data are used to better understand annual or daily travel flows. Future changes in the highway network are also considered.

The zone system is at the county level and typically includes fewer than 200 zones. The trip distribution step consists of gravity models that are based on five or six commodity groups. Using tons per truck or railcar for each commodity type, a conversion from commodity flows to vehicle flows is possible. After the trip distribution step, conversion to trucks by size and weight occurs. The vehicle assignment method is an all-on-nothing procedure since trucks have limited route alternatives. The following five models reveal the different variations that are possible using the commodity-based modeling approach.

3.4.3.2 Indiana Statewide Freight Model

The Indiana statewide freight model uses both nonproprietary and proprietary data to forecast the freight flows of trucks and rail within the state of Indiana. The freight flow data come from the latest U.S. Census's *Commodity Flow Survey*. The existing and future county-level population and employment data come from the databases of Woods and Poole Economics, Inc. (www.woodsandpoole.com). The latest edition of the Interstate Commerce Commission's (ICC's) *Rail Waybill Sample* is used to convert commodity flows to vehicle flows for railcars. The conversion for heavy trucks is assumed to be 40 percent of railcars.

3.4.3.3 Kansas Statewide Agricultural Commodity Model

The Kansas statewide agricultural commodity model forecasts the flows of five major agricultural commodities by truck, rail, and barge. The model uses nonproprietary data and new data collected specifically for the model effort, such as mail surveys, telephone reports, base year traffic counts, and field interviews. The highway network acts as the starting point with revisions for link grades and toll rates. The data are tabulated in mode- and commodity-specific trip tables. Gravity models are based on origin/destination data. The model is able to test changes to the existing transportation system, yet has a limited forecasting capability.

3.4.3.4 Michigan Statewide Truck Model

The Michigan statewide truck model uses a variety of national and international data to develop base year truck trip tables. To obtain projections, the model uses data from the Bureau of Economic Affairs (BEA) and from a proprietary source, Regional Economic Models, Inc. Interindustry Forecasting at the University of Maryland (Inforum) forecasts truck movements between the United States, Canada, and Mexico. The model is highly compatible with the person transportation model, yet has limited forecasting abilities except for route choice.

3.4.3.5 Portland Commodity Flow Model

The Portland commodity flow model has two major components: the strategic model database (SMD) and the tactical model system. The SMD analyzes the existing and future freight flows. It covers eight modes of travel, including private truck, less-than-truckload, truckload, intermodal, rail, barge, sea, and air. Seventeen commodity groups are included, as well as five origin and destination areas such as northern and southern United States. The SMD is based on both proprietary and nonproprietary data. The tactical model system is a more in-depth analysis of heavy-truck trips. It uses data provided in the SMD and relies on the Portland regional person travel model to do the following: summarize the heavy-truck flows, allocate their origins and destinations, simulate reloading and terminal usage, convert commodity flows to heavy-truck trips, add empty trailer and tractor trips, add through truck trips, and assign heavy-vehicle trips to the highway network. The model forecasts changes in the transportation infrastructure, yet lacks sensitivity to changes in transportation policy and private-sector costs.

3.4.3.6 Southern California Association of Governments Regional Heavy-Duty Truck Model

The Southern California Association of Governments (SCAG) regional heavy-duty truck model consists of three submodels to forecast transportation and air quality in the Los Angeles region:

- **The intraregional model** is not commodity based due to the lack of commodity data for the 1,300 internal zones. Instead, population and employment data are used to estimate existing and future light-heavy, medium-heavy, and heavy-heavy truck trips. Gravity models are developed for the three truck classes.
- **The external-internal/external-external model** combines multiple commodity flow data sources at the county level.
- **The special generator model** predicts truck trips as opposed to commodity flows at shipping ports and airports within the SCAG region.

The submodel results are combined and converted from daily to hourly trip tables and then are assigned to the highway network. Six trip tables are provided: three truck-type tables for external-internal truck trips and three for internal truck trips. The models focus on truck types, time period, and trip-end type allowing for congestion and truck flow analyses.

3.5 NCHRP PROJECT 8-33 RECOMMENDATIONS FOR IMPROVED PROCEDURES

NCHRP Project 8-33, "Quantifying Air Quality and Other Benefits and Costs of Transportation Control Measures," is a research project to develop and test an improved framework for analyzing the air quality impacts of TCMs. This project was completed December 1999 and as such is a predecessor to the current research effort.

NCHRP Project 8-33 investigated the current state of the art for analyzing TCMs and concluded that while the conventional modeling approach of linking models works, "serious reservations exist concerning the accuracy of these results, the robustness of the underlying data, and whether the correct set of variables are captured in the model systems representing current practice."[78]

The Project 8-33 researchers recommended that a new modeling framework consisting of the following modules be developed for the purpose of evaluating TCMs:

- **Disaggregate and activity-based demand.** These newly emerging modeling approaches focus on the individual, the household, the vehicle, and the trip, rather than the aggregate groups of households used in more traditional approaches. A daily activity plan by hour of day (including trip making) is developed for each person or household in response to the characteristics of the person, the household, and that person's environment (accessibility to jobs and other activities, etc.). Nonmotorized trips are included explicitly in the daily activity plan.
- **Household sample enumeration.** Rather than aggregating households by traffic analysis zone within the region and then predicting the mean trip patterns for that group, individual persons or households are randomly selected, and their individual travel patterns are predicted. These individual trips are then expanded and summed to represent total travel of all households in the region. Individual trip-making patterns and linkages are preserved with the sample enumeration method.
- **Incremental analysis.** Incremental analysis involves comparing the "changes" produced by specific strate-

gies rather than the absolute magnitude. The philosophy behind this approach is that behavior models tend to be more accurate at predicting changes in travel behavior than at predicting the total magnitude of travel. The models that predict "changes" or "deltas" are then added to the "well-calibrated" base-year trip table (obtained from some other source than the travel demand model) to obtain the future trip table.

- **Traffic microsimulation.** Traffic microsimulation is needed to obtain accurate modeling of congestion effects (i.e., speed, delay, queuing, and volume) and to output vehicle operating mode predictions (i.e., acceleration, cruise, deceleration, and idle).
- **Household travel survey data with SP data to support policy analyses.** Extensions include information on characteristics of vehicles used (model, year, type, and odometer reading), seasonal variation of travel patterns, time of day, weekend trips, SP responses to potential TCMs, and panel surveys to track longer-term responses and to monitor the reliability of SP responses.

The Project 8-33 researchers also recommended various improvements to current emission models, including

- Update the Federal Test Procedure,
- Update speed correction factor test cycles,
- Improve the speed correction factor methodology, and
- Develop link-specific emission rates.

Specifically, the researchers noted that the Federal Test Procedure and the speed correction factor test cycles need to be reviewed and updated in light of new information on how people actually drive their vehicles. The current speed correction factor methodology considers only the mean speed of the trip. It does not consider the underlying distribution of speeds and acceleration that vary by facility type and degree of congestion. Trip-based emissions are not appropriate for estimating emissions for improvements to individual segments of the roadway system.

Recognizing that all of these improvements will take time to research and implement, NCHRP Project 8-33 researchers have also developed a series of improvements that can be implemented in the mean time (see Table 6).

3.6 ENVIRONMENTAL PROTECTION AGENCY ANALYSIS

The Environmental Protection Agency (EPA) has issued reports on appropriate travel activity methodologies for the analysis of intelligent transportation systems (ITS)[79] and pricing measures to reduce transportation emissions.[80] The EPA's ITS analysis report identifies the need for two major methodological improvements to evaluate the emission impacts of ITS measures:

- Modal emission models that can predict second-by-second tailpipe emissions under a variety of conditions and
- Travel demand models linked to microsimulation models with feedback from simulation back to trip generation, distribution, and mode choice.

The EPO proposes that a range of modeling approaches and analytical processes would be required to analyze ITS components since the different components affect different aspects of the transportation system at differing levels of spatial aggregation. A series of candidate analytical tools are considered

TABLE 6 Short-term improvements identified by NCHRP Project 8-33 researchers

Area of Improvement	Recommendation
Feedback Linkage	Incorporate a feedback linkage that equilibrates congested travel time predictions with assumed travel times used in trip distribution and mode choice
Land-Use Model	Adopt a formal land-use model that provides capability to assess changes in location in response to transportation system changes
Vehicle Ownership Model	Provide a policy-sensitive model of vehicle ownership choice
Trip Generation/Distribution	Add nonmotorized modes
Mode Choice	Provide a nested logit, add a nonmotorized mode, and access modes
Time of Day	Provide a time-of-day choice model or a peak spreading model sensitive to predicted congestion levels
Route Choice	Incorporate the effects of tolls
Household Surveys	Add TCM-related SP questions
Household Sample Enumeration	Aggregate individual household trip patterns, rather than forecasting aggregate trip making for aggregates of households
Traffic Microsimulation	Link the travel model output to microsimulation models
Network Coding	Increase the coverage and precision of the network
Emissions Analysis	Configure the EPA vehicle emission factor model (MOBILE) for operating mode corrections (cold start, hot start, or stabilized), develops trip-based emission estimates (separate start emissions from running exhaust emissions), and links mode of travel (auto, transit) to vehicle class (cars, light-duty trucks, heavy-duty trucks, motorcycles, etc.)

in the report: INTEGRATION, Traffic Network Simulation (TRAF-NETSIM), Air Quality (AirQ), MOBILE6, CMEM, MEASURE, Transportation Analysis Simulation System (TRANSIMS), Mitretek's travel demand modeling process, and Short-Range Transportation Evaluation Program (STEP).

The EPA's pricing measures report focuses on recommendations regarding the appropriate analysis methodologies for evaluating the emission reduction potential of the following: parking pricing, modal subsidies, at-the-pump charges, emission fees, and roadway pricing. The pricing report notes that the conventional four-step travel forecasting process was not designed for testing pricing policies. The conventional process has shortfalls for testing pricing policies:

- Pricing is not rigorously included in the model's structure (usually pricing is only considered in mode choice);
- The accuracy of the pricing relationships that are included in models is uncertain because of the lack of in-place pricing policies for validating the relationships;
- The income effects of traveler response to pricing rarely are included in models;
- The use of zonal averages in the models restricts the pricing detail that can be considered in the models; and
- Models are not set up to predict the impact of pricing on through trips or commercial trips.

The recommended improvements revolve around the inclusion of cost (or its equivalent in time impedance units) in the computation of vehicle ownership, vehicle trip generation, trip distribution, mode choice, and route choice. The STEP model is presented in the appendix of the EPA report as an example of an advanced modeling approach.

CHAPTER 4

AVAILABLE METHODOLOGIES

This chapter presents an overview of the leading available methodologies for estimating the emission impacts of traffic-flow improvement projects.

4.1 TYPOLOGY

It is useful to categorize the various methods and models in the literature according to the portion (or portions) of the total air quality estimation process that each method is designed to address. As shown in Figure 3, the entire process is divided into five major analytical steps: land-use forecasting, travel demand estimation, transport system operations analysis, emissions estimation, and air quality forecasting. This research will focus only on the first four steps and will leave air quality forecasting to others.

Each analytical step in the process can be considered a "link" in the analysis chain. When all the links are completed and connected, they form a comprehensive and complete procedure for analyzing the emission impacts of any policy or investment option for the air basin. Each link is defined as follows:

- The land-use step forecasts growth in population and demographic and socioeconomic changes and spatially allocates people, households, and commercial activity within the air basin.
- The travel demand step converts the locational data generated by the land-use model into estimates of travel activity.
- The systems operation step estimates the impacts of the forecasted travel activity on the operation of the region's transportation system. This step predicts travel time, speed, delay, and vehicle modal activity. The travel times predicted in this step influence the prior steps, land use and travel demand.
- The pollutant emissions step uses the vehicle modal activity data to make emission predictions, which are in turn fed into an analysis of the basin's air quality.

It is useful to add a second dimension to the typology by establishing the level of aggregation for which each method is designed to be applied. The research objective and the nature of the air quality analysis problem is such that the ability to evaluate policy and investment options at a microscopic level will be a valuable attribute of any methodology considered in this research project. The levels of aggregation are as follows:

- **The areawide level of aggregation** is typical of sketch-planning models. These models and the methodologies behind them are designed to require and produce only basinwide averages of VMT, delay, and emissions.
- **The traffic analysis zones level of aggregation** is an intermediate level of aggregation typical of most transportation forecasting models in the United States. Households and commercial activity are aggregated into geographic units, or zones. The real-world transportation system is represented by a subset of key facilities and coded as "links." The models work with and produce results that reflect averages for each zone and link. An air basin is typically split into no more than 1,500 geographic analysis zones that are often aggregates of census tracts (a few regions with GIS capabilities store their socioeconomic data at a smaller level of disaggregation, but travel models rarely can employ that full level of detail).
- **The individual or household level of aggression** is the lowest level of analysis. Each household or each person within the household is evaluated separately, and the results are summed to obtain estimates of aggregate behavior. In most cases, the household-level behavior forecasts are made for only a random sample of households in the region and the results are expanded by a factoring process to represent all households in the region.

4.2 OVERVIEW OF AVAILABLE METHODS

Figure 4 presents a graphic overview of the available methodologies most relevant to this research project. They are classified according to the analytical processes they contain and their target level of aggregation for application. The best methodologies for accomplishing the NCHRP 25-21 objectives will tend to lie at the lower (i.e., individual) level of the chart and will have the broadest horizontal coverage. The following sections provide a brief summary of each methodology.

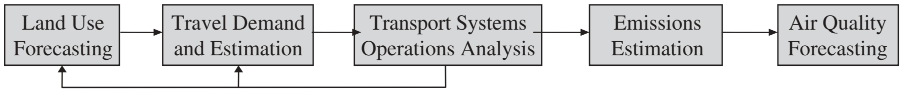


Figure 3. Land-use/transportation/air quality chain.

4.2.1 Areawide Analysis Tools

At this level of analysis, the available methodologies predict the changes in areawide VMT caused by transportation improvement projects or transportation control measures. These methodologies do not generally consider the implications of shifting traffic between routes or between types of facilities. The standard error of the vehicular activity estimates produced by these models is generally greater than the predicted benefits of any individual transportation improvement project.

TCM Tools is a sketch-planning methodology designed to estimate the change in vehicle activity and emissions resulting from any one of a couple dozen TCMs. The methodology works at the regional or areawide level of aggregation. It does not track link- or location-specific impacts. It does not deal with long-term land-use impacts. The software user must identify the percentage of travelers likely to respond to or participate in the TCM. The methodology does not deal with the synergistic effects of multiple TCM projects.

Highway Economic Requirements System (**HERS**) is a highway program investment tool that computes the likely areawide benefits of different program investments by computing the highway operation and air pollution impacts of improvements made to a sample of highway links (the HPMS system) within urban areas. HERS has the same modeling capabilities (demand, supply, and emissions) as TCM Tools. HERS uses elasticities to estimate the likely magnitude of latent demand for each improvement project.

SMITE and Sketch-Planning Analysis Spreadsheet Model (**SPASM**) are various economic and latent demand estimation models developed by Patrick deCorla Souza of FHWA. These models are primarily sketch-planning models designed to yield estimates of areawide changes in VMT due to transportation improvement projects. The models generally employ demand elasticities of approximately one-half of those used in HERS. Their capabilities are similar to those of TCM Tools.

STEAM is primarily an economic benefit assessment model designed to function as a postprocessor at the end of a traditional four-step demand model process. STEAM is designed to improve on the system operations analysis methods contained in conventional travel demand models.

4.2.2 Land-Use Forecasting Tools

This section discusses the available land-use analysis tools that function at the zonal and disaggregate level. Land-use

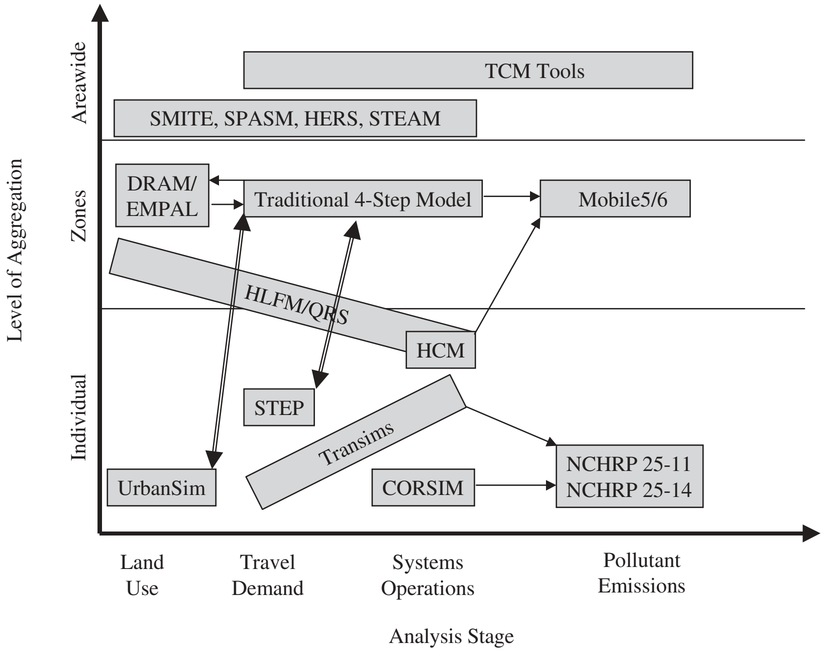


Figure 4. Analytical breadth and level of aggregation of available methodologies.

models translate demographic, natural resource, and infrastructure data into forecasts of land use.

DRAM/EMPAL is the most widely applied set of land-use models in the United States. DRAM allocates households within the region, and EMPAL allocates employment. Both models are Lowry-type models that allocate households and jobs according to accessibility. Land availability is taken into account, but land prices are not. The models do not forecast growth; they merely spatially allocate it. DRAM/EMPAL must be manually interfaced with a travel demand model to obtain zonal accessibility data. These models generally perform better (i.e., produce fewer irrational results requiring manual intervention) when applied to large aggregations of analysis zones (typically no more than 100 land-use allocation districts for the air basin).

HLFM is a simplified Lowry type allocation model that has been integrated with a travel demand model process called the Quick Response System (QRS). The combined HLFM/QRS model is one of the few if not the only model to provide full equilibration between route choice, mode split, trip distribution, and land-use location. However, it does not have the capability of predicting time of day or new generated trips effects of different land-use patterns.

UrbanSim is a dynamic metropolitan area land-use forecasting model. It was developed in 1996-1998 as part of Oregon's Transportation and Land-use Model Integration Project (TLUMIP). Unlike more traditional approaches to land-use modeling, UrbanSim does not seek a cross-sectional equilibrium between the demand for and supply of land. UrbanSim models land-use changes as a dynamic process where people and businesses have certain price and accessibility demand functions but are not perfectly mobile so as to take full advantage of available land supply opportunities. UrbanSim shows how changes in land-use policies and transportation supply affect the movement of households and businesses on a year-by-year basis. Moving costs and other constraints delay the response of the actors to changes in land supply, price, and accessibility.

4.2.3 Travel Demand Estimation

This section describes travel demand methodologies at two levels of aggregation, the traffic analysis zone level and the disaggregate household level.

Conventional four-step travel demand models function at the link and zone level of aggregation. TRANPLAN, EMME/2, MINUTP, TRANSCAD, and TP+ are examples of software that implement analytical methodologies at this level of detail. The vehicle activity results are considered to be more accurate than can be obtained from sketch-planning approaches; however, the results are still averages and overlook much of the temporal and individual trip variation present in a typical urban area.

Conventional four-step travel demand models divide people's complex travel behavior decision-making process into four sequential steps for the sake of computational convenience: trip generation, destination choice, mode choice, and route choice. A fifth step is often added: time-of-day choice, although this step frequently consists of "hard wired" percentages that are not sensitive to changes in traffic congestion (see Figure 5).

Disaggregate methodologies analyze travel behavior and vehicle activity at the individual traveler or household level. This level of detail allows the greatest ability to trap all possible effects of transportation improvements, but often comes at the cost of excessive data requirements and computation requirements.

STEP is a comprehensive disaggregate demand-forecasting tool, identified by the EPA as a promising tool for evaluating the air quality impacts of ITS projects. STEP operates at the household level directly off of household survey databases. These databases are usually collected by MPOs as part of the MPOs' calibration every 10 years of the MPOs' traditional four-step travel demand models. STEP contains trip frequency, trip destination, mode choice, and vehicle ownership models that are sensitive to the travel time and cost changes caused by traffic-flow improvement projects.

The **Portland Tour-Based Model** is a disaggregate model, like STEP, that is applied at the household level. However, unlike STEP, which employs a variation of the traditional four-step procedure, the Portland model uses a tour-based approach to predict travel activity. A nested multinomial logit model is used to predict each person's decisions about daily activities, whether the activities are performed inside or outside of the home, whether the person stops along the way to the destination, the time of day the person will make the trip, and the person's choice of destination and mode of travel. This model is still undergoing development and is not yet used in Portland's day-to-day planning process.

TRANSIMS is a multiyear project of the FHWA and the University of California Los Alamos National Laboratory (LANL) to develop a travel demand model that retains the identity of individual "synthetic" travelers throughout the entire travel demand forecasting and traffic operations analysis process of the model. TRANSIMS incorporates tour-based

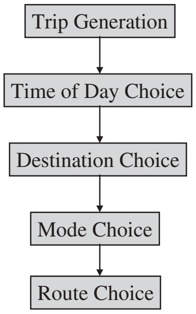


Figure 5. Conventional travel demand model.

travel demand, intermodal trip planning, traffic microsimulation, and air quality analysis, all with a single unified program architecture.

TRANSIMS simulates the demand patterns of individual travelers (rather than the households used in the STEP model). However, in order to microsimulate traffic operations for a large region, TRANSIMS has adopted a traffic microsimulation approach (called cellular automata) that is slightly more aggregate than Corridor Simulation (CORSIM) (thus, TRANSIMS is "tilted" in Figure 4). TRANSIMS currently requires an order of magnitude increase in the data collection resources and computer processing capabilities of MPOs, although this requirement will change as TRANSIMS is further refined for the commercial market.

4.2.4 Transportation System Operation Simulation

Travel demand models always include a very crude transportation system operation component so that the interrelationship between demand and route choice can be modeled. This crude transportation system operation component is often a speed-flow curve, which is not a very good predictor of mean vehicle speeds, but is sufficient to produce reasonable demand estimates for each link of the transportation system. Speed-flow curves, many of which are based on a Bureau of Public Roads (BPR) equation, generally underestimate the impact of congestion on travel speeds and thus contribute to underestimates of vehicular emissions. In particular, the use of link-based estimates of speed such as the BPR equation miss the impacts of cross-street demand on signalized intersection delays.

The ***Highway Capacity Manual*** (HCM) provides one basis for improving vehicle operation forecasts. The manual contains a series of procedures for predicting the steady-state traffic conditions at a macroscopic level. Traffic performance in terms of mean delay, mean travel speed, and mean density are predicted for the peak 15-minute period within the peak hour. Dynamic effects such as the build-up of traffic queues over several time periods and the impact of one time period on the following time period are not explicitly considered (although a few of the procedures allow users to manually account for these effects). Modal activity (acceleration, deceleration, idle, and cruise) is not predicted by the HCM procedures. QRS is one travel demand–modeling software package that has implemented the HCM procedures within the demand-modeling context.

CORSIM is an example of disaggregate transportation supply simulation model. It requires that overall demand be fixed within each subperiod of analysis and has no capabilities for revising the demands in response to simulated traffic congestion. It has the capability to show the build-up and dissipation of congestion over the analysis period and generates emission estimates using Mobile 5 data. Microsimulation software such as CORSIM tends to be so data-intensive as to be unworkable for basinwide applications. It is generally limited to segments of facilities no more than 10 miles long.

4.2.5 Mobile Source Emission and Air Quality Models

A variety of air quality–modeling approaches can be used to assess the effects of transportation projects. Air quality models can be characterized according to the methods they use for the "source term" and the "dispersion term." Spatial and temporal variability in emissions, as well as release conditions (temperature, stack heights, and velocities) are all potentially important elements of the source term. The dispersion term may include both pollutant transport and dispersion based on meteorological conditions, the effects of terrain and street canyons on dispersion, and chemical transformation and removal processes.

MOBILE5 and **MOBILE6** are emission factor models developed by the U.S. EPA. MOBILE6 was released in 2002. Emission rates are produced for different vehicle classes and age distributions for specified calendar years. MOBILE5 produces a single set of speed-dependent running emission rates (in grams per mile), whereas MOBILE6 produces different speed-dependent emissions for arterials and freeways, along with non–speed-dependent rates for ramps and local roadways. Emissions associated with "trip-ends" (i.e., excess emissions during starts and evaporative emissions from hot soak, diurnal, and resting loss) can be obtained from these models to assess the effects of changes in the number of trips.

At the time of the NCHRP Project 25-21 research, the Hybrid Roadway Intersection Model (**HYROAD**)[81] was undergoing final revisions under **NCHRP Project 25-6**. HYROAD is a disaggregate emission model that models the geographic dispersion of CO emissions in the vicinity of an intersection. The vehicle demands are given to the model, which then disaggregates the activity data by vehicle type, modal activity, and distance from the intersection.

At the time of the NCHRP 25-21 research, NCHRP Project 25-11 was producing a modal emission model capable of responding to second-by-second operating conditions for light-duty vehicles. The model can be used to investigate the effects of congestion on emissions in ways not treated by the cycle-based approaches used in MOBILE. In particular, it is sensitive to power demand, including the increased likelihood of vehicles going into power enrichment with mild acceleration under high-speed, low-congestion conditions.

At the time of the NCHRP 25-21 research, NCHRP Project 25-14 was producing analytical tools for predicting the effects of various transportation planning policies on heavy-duty vehicle activities and the associated emissions. The first phase of this research involves the inventorying of heavy-duty vehicle usage patterns. This project was still active as of April 2003.

CHAPTER **5**

SKETCH-PLANNING APPROACHES

This chapter reviews macroscopic sketch-planning approaches for predicting the impacts of highway capacity improvements on traffic volumes. Some investigators have proposed that the elasticities used in sketch-planning models could provide a quick solution to conventional travel models. The elasticity factors would be used to factor-up the forecasts produced by conventional four-step models. This chapter presents some of the sketch-planning approaches that employ the use of an elasticity to account for the demand-inducing effects of new highway capacity.

5.1 HERS

The FHWA has developed the Highway Economic Requirements System (HERS),[82] which uses data from the Highway Performance Monitoring System (HPMS) segments to estimate the investment requirements for the urban areas of the United States. HERS was recently updated to include a procedure for estimating induced demand on a link-by-link basis and for including that effect in the computation of the consumer benefits. Douglass Lee et al.[83] developed a methodological framework that splits induced demand into short- and long-term components (see Figure 6). Lee et al. deal with some of the important measurement issues with calculating elasticity, which are often given scant treatment in other papers. For example, capacity may be a poor explanatory variable because it is actually changes in travel speed (or travel time) that drive increases in travel demand (widening a free-flowing facility presumably would do little to directly stimulate demand). Lee et al. conclude that long-run elasticities (over 5 years or more) are probably in the range of –1.0 to –2.0, about double the short-run elasticities, which are in the range of –0.5 to –1.0. The elasticities have the same magnitude as those identified by R. Noland.[84]

Although HERS looks at specific links, it looks at only a sample of links and thus cannot distinguish between new travel in the region and diverted (i.e., reassigned) travel between links or facilities. Its results are reliable for areawide analyses of broad program investment decisions, but not for evaluating the impacts of specific improvement projects.

5.2 TRAVELER RESPONSE TO TRANSPORTATION SYSTEM CHANGES INTERIM HANDBOOK, TCRP PROJECT B-12

The Traveler Response to Transportation System Changes Interim Handbook[85] provides a comprehensive, interpretive documentation of how travel demand and the usage of transportation facilities and services are affected by various transportation system changes. An interim handbook was released in March 2000 (via the web) that makes available seven topic areas that were completed under TCRP Project B-12. They include HOV facilities, vanpools/buspools, demand-responsive services, transit scheduling/frequency, bus routing changes, transit pricing/fares, and parking pricing/fares.

Although TCRP Project B-12 provides a possible model to emulate in terms of report format and interpretation, the material presented has little overlap with that in NCHRP Project 25-21. TCRP Project B-12 is intended for use by transportation planners as an aid in the development and screening of alternatives and quick preliminary assessments. The report emphasizes nonhighway modes (e.g., a transit planner might want to know, for a specific transit market, what the likely patronage impact is of changing the headways on a bus route from 30 minutes to 20 minutes). TCRP Project B-12 provides excellent guidance on this topic.

TCRP Project B-12 is not intended to cover general-purpose highway capacity increases, nor is it intended to provide guidance on entirely new facilities (as opposed to changes in existing facilities). The closest that TCRP Project B-12 comes to general-purpose highway capacity increases is in the HOV facilities section. Throughout most of the report, considerable use is made of elasticities; thus, baseline ("before change") demand levels must be a known value. In some cases, before-and-after market shares and percent changes are used. The transportation system changes dealt with in this handbook are principally not single-occupancy vehicle (SOV) modes; the final version of the report will include park-and-ride facilities, busways, light rail transit, commuter rail, transit information, road value pricing, land use and site design, pedestrian/bicycle facilities, parking management, and TDM.

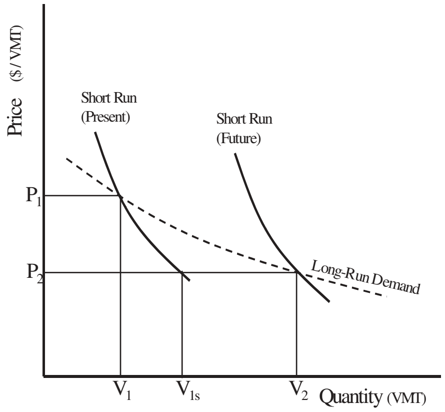


Figure 6. Short- and long-term demand effects.

5.3 SPASM, SMITE, AND OTHER SKETCH-PLANNING TOOLS

DeCorla-Souza and Cohen[86] and Cambridge Systematics[87] have developed a series of sketch-planning models that treat demand inducement using elasticities. Their elasticities tend to be about half those of HERS, the rationale being that the latter model is predicting route shifts from non-HPMS segments, while the former models deal with entire urban networks and predict only net increases in demand, not shifts in routes.

SPASM[88] is a spreadsheet-based, sketch-planning model appropriate for "screening analysis" of alternatives. It provides first-cut estimates of public capital and operating costs, employer costs, system user costs and benefits, air quality and energy impacts, performance, and induced demand. Induced demand is based on an elasticity of demand (i.e., trips) with respect to travel time of –0.5. This elasticity was chosen because of its use in *TRB Special Report 245*, but this value can also be changed by the user.

Another sketch-planning model is **SMITE**, which was developed for estimating travel increases caused by capacity increases. The model predicts the change in VMT as a function of travel time change. It is particularly useful where a traditional four-step travel forecasting model is not available, or where comparing alternatives would be too resource intensive in the four-step environment. A paper by DeCorla-Souza and Cohen[89] demonstrates the application of SMITE. In their hypothetical case study, a 50-percent increase in capacity (widening a freeway from four lanes to six lanes) induces an increase in VMT of 5–8 percent, depending on the initial level of congestion. Even with a unit elasticity (–1.0), VMT increases range between 9 and 11 percent corridorwide due to the project.

Denvil Coombe et al.[90] point out several problems with using simple elasticities. **COBACHECK** is a model similar to HERS for evaluating the economic value of transportation improvement decisions. The paper by Coombe et al. critiques the Metropolitan Transport Research Unit's COBACHECK method for computing economic benefits of road improvements and counting as a "disbenefit" all induced traffic. COBACHECK assumes a long-run elasticity that is twice the value of the short-run elasticity. The article concludes that COBACHECK's method of reducing benefits due to induced demand is inaccurate and that only a model using trip matrices (rather than aggregate demand) can accurately be used to evaluate project benefits.

Austin et al.[91] developed a workbook of sketch-planning techniques for estimating the emission reduction and travel activity impacts of TCMs. The method estimates direct reductions in trip generation, indirect increase in trip generation, temporal shifts, trip length shifts, and speed shifts.

The California Air Resources Board and Caltrans[92] have developed a manual of sketch-planning methods for evaluating the cost-effectiveness of new bus service, vanpools, shuttles, signal coordination, bicycle facilities, telecommuting programs, and ridesharing/pedestrian facilities. The manual does not deal with secondary demand effects of the projects. The user must input the primary mode choice effects of the projects.

TCM Tools is a sketch-planning methodology designed to estimate the change in vehicle activity and emissions resulting from any one of a dozen transportation control measures. It works at the regional or areawide level of aggregation. It does not track link- or location-specific impacts, nor does it deal with long-term land-use impacts. The software user must identify the percentage of travelers likely to respond to or participate in the TCM. The methodology does not deal with the synergistic effects of multiple TCM projects. Crawford and Krammes[93] provide more information about this and other sketch-planning tools.

Commuter is a pivot point logit model methodology for estimating the emission reductions from (1) voluntary mobile source emission reduction and commuter choice incentive programs contained in the state implementation plan and (2) employer-based commuter choice programs.[94] Commuter predicts the impacts of these programs on the commute mode split and the percentage of commute trips shifted to off-peak periods. However, Commuter is not designed for transportation control measures that are massive enough to affect travel speeds and does not predict the impacts of the measures on trip lengths (except what occurs when shifting modes).

5.4 SKETCH-PLANNING POSTPROCESSORS

Sketch-planning postprocessors are specialized analysis tools designed to work with the trip tables and transportation networks produced by a typical regional planning model. The base case trip table and network produced by the planning model are modified by the postprocessor to reflect the impacts of street improvements or ITS improvements. The postprocessors have the advantage of working with a richer database than is available to typical sketch-planning tools, and they save on the expense of adapting and rerunning the traditional regional models for the purposes of evaluating the impacts of specialized projects.

STEAM is a corridor sketch-planning tool, sponsored by FHWA, that uses output from conventional four-step travel forecasting models to generate more accurate forecasts of speeds, volumes, and benefits for highway capacity improvements.[95] STEAM recomputes the link speeds given the forecasted volumes and capacities contained in the base model network. It performs a risk analysis and outputs systemwide results of net present worth and benefit/cost analyses.

The ITS Deployment Analysis System (IDAS) performs a similar postprocessing function as STEAM, but is designed for analyzing the costs and benefits of ITS projects.[96] IDAS contains routines for recomputing vehicle speeds and vehicle demand based upon estimated changes in travel time and costs resulting from various ITS project strategies. IDAS computes mode shifts, temporal shifts, route shifts, and induced or foregone demand. IDAS also computes fuel consumption and air pollution impacts.

5.5 ASSESSMENT

The sketch-planning approaches are appealing because of their simplicity. However, with the exception of STEAM and IDAS, sketch-planning models do not produce the level of detail required for mode of operation emission estimates without interfacing them with more detailed travel models.

A further criticism is that the sketch-planning models incorporate fixed elasticities instead of behavioral models, so it is difficult to know if one is not double-counting demand effects when mixing a sketch-planning model with a conventional travel demand model that also accounts for some demand effects. This problem is a concern even when applying STEAM and IDAS.

For these reasons, sketch-planning models will not be considered further in the development of the NCHRP 25-21 methodology.

CHAPTER 6

LAND-USE MODELS

There are a variety of methods for examining the impacts of the transportation system on land use, including informal methods such as simple judgment, expert judgment and Delphi panels, formal modeling approaches such as simple regression models, economic frameworks, and complex transport/land-use models. The decision to use one method instead of another for assisting planning policy depends on a number of criteria, including the relevance of the indicators, the validity of the method, the plausibility of the results, and the contribution of the results to the needs of the regional planning process. Still et al.,[97] for example, list four criteria for any forecasting model of land-use changes in response to a transport investment:

- The model must be intuitive and internally consistent, with clear and supportable assumptions and recognition of key sensitivities.
- The model must be able to yield forecasts of households, populations (including workers), and employment indicators.
- The zoning disaggregation must be fine enough for planning detail, but capable of aggregation up to planning units and political jurisdictions.
- The method and results must be transparent to be as accessible as possible to a wide audience and to increase credibility.

The complex transport and land-use models are able to satisfy the last three criteria, but do not fully satisfy the first criterion. What seems to be missing from this list is the capacity of the model for policy analysis over the range of alternatives facing planners. Policy instruments link to policy objectives, so models should be capable of assessing the ability of these policy instruments to achieve the policy objectives. The objectives stem from current transport policy issues, including congestion, energy use, safety, environmental degradation, accessibility for disadvantaged and challenged persons, social inequality, fiscal restraint and privatization. These issues give rise to one or more of the following policy instruments: zoning and traffic restrictions, gas taxes, transit subsidies, infrastructure investment, transit investments, transportation system and demand management options, road pricing, privatization, and deregulation. There will be ranges of weak and strong linkages between these policy objectives and the list of instruments just cited.

The selection of a methodology to evaluate the outcomes of changes in transportation management options, investments, and policies in a variety of network settings requires a balance between detail and flexibility. The principal purpose in developing this framework is for broad applicability, yet at the same time the need for accuracy leads one to adopt a finer grid of spatial detail. In the end, it may not be possible to develop a methodology that fits all users, but the level of detail should reflect a balance of benefits and costs of portability across issues, options, and sizes of urban areas.

Before undertaking a detailed assessment of the alternative models, the question arises, Are the land-use effects large enough or predictable enough to be a necessary part of the modeling effort? Hunt et al.,[98] for example, state, "The existence of a relationship between land use and transportation is axiomatic. The need to consider land use and transportation as important determinants of air quality is also well established, both practically and legally." The authors go on to claim that air quality depends not only on travel activity but also on urban form and the distribution of population and employment. However, they point out that the nature of the relationship is not well understood. Pickrell,[99] however, argues that the past influence of transportation on urban land is unlikely to be replicated in the future. In the past few years, innovations and investments in transportation facilities have had a diminishing effect on land-use changes. Also, he argues, the influence of land-use patterns themselves on travel behavior is modest. The statistical relationship between travel and land-use measures is weak and unreliable. Thus, Pickrell claims, "the lack of compelling evidence of these relationships means that the changes in land-use patterns likely to be fostered by metropolitan planning cannot be relied upon to alter the volume or geographic pattern of urban travel in predictable ways, despite planners' frequent assertions to the contrary." Pickrell is concerned that land-use planning will be used as a substitute for rational investment levels and pricing policies.

The decision to include or not include land-use effects should be based on an assessment of the role the land-use model plays in the modeling framework. The assessment should examine what benefits the model yields and what costs it imposes. Several models are being evaluated on a number of different dimensions, including Integrated Transportation and Land Use Package (ITLUP, also referred to as DRAM/EMPAL), Marcial Echenique Plan (MEPLAN), New York Metropolitan Transportation Council Land Use Model (NYMTC-LUM), and UrbanSim. The evaluation focuses on the current state of practice using these models. The models are examined in terms of their treatment of time, land, space, transportation networks and services, and the economic agents, as well as in terms of their behavioral relationships, how they undertake the spatial allocation process, what policies can be modeled using the models, and the performance of the models.

6.1 INTEGRATED LAND-USE AND TRANSPORTATION MODELS

NCHRP Report 423A: Land-Use Impacts of Transportation: A Guidebook provides a comprehensive review of the current state of the art in land-use models.[100] This is the first volume of a two-volume report on the development of the UrbanSim model (the second volume will be a user's guide for UrbanSim). The first volume reviews current land-use forecasting practice and available tools and recommends improvements.

The following formal land-use models are reviewed in the NCHRP report:

- DRAM/EMPAL;
- MEPLAN;
- TRANUS (an integrated land-use and transportation model developed by Dr. Tomas de la Barra (formerly known as "Transporte y Uso del Suelo," or "Transportation and Land Use");
- MetroSim;
- The Highway Land Use Forecasting Model (HLFM II+);
- The Land Use Transportation Interaction Model (LUTRIM); and
- The California Urban Futures (CUF).

Among these models, DRAM/EMPAL has seen widest use, particularly in the United States. TRANUS and MEPLAN have not seen application in the United States (although TRANUS is currently being tested in Sacramento, California; in Baltimore, Maryland; and in the state of Oregon).

DRAM/EMPAL consists of three components: the disaggregate residential allocation model, the employment allocation model, and a set of travel demand models (MPOs usually substitute their own travel models). DRAM/EMPAL has seen widespread use in the United States. DRAM/EMPAL is based on the Lowry gravity model, which assumes that accessibility is the prime explanatory variable of locational choice. The user provides forecasted employment and population control totals for the region, plus vacant "developable" land (the user must decide what is "developable"). DRAM/EMPAL then allocates the growth to districts within the region.

NCHRP Report 423A notes that the DRAM/EMPAL models "do not perform well with very disaggregate zonal systems or where there is sparse activity within certain zones." Development has ceased on DRAM/EMPAL. A new modeling system, the Metropolitan Integrated Land Use System (METROPILUS), is currently under development.

HLFM II+ is also based on a Lowry gravity model and (like DRAM/EMPAL) assumes that accessibility and land availability are the key explanatory variables of locational choice. HLFM (like all Lowry models) is a full equilibrium model. It does not predict land use for a given year but rather identifies where the region should be given the land supply and what the accessibility situation is like. A more detailed description is provided later in this chapter.

MEPLAN and TRANUS are two closely related model systems that have seen little practical application in the United States. Both models use discrete choice logit models to predict choices of household and business location and trip making (i.e., trip generation, distribution, and mode choice). The models use the concept of markets for (1) land (floor space and housing); (2) transport; and (3) labor (and other economic factors of production). Input/output modeling is used to represent interactions between economic sectors, households, and land markets. Demand and supply are balanced in each market by adjusting prices. Accessibility and prices lag demand. These models are therefore temporally "dynamic" rather than "equilibrium."

A noteworthy feature of TRANUS is its use of an exponential model to predict the variation of travel demand as a function of travel cost. TRANUS presumes that the number of trips between zones will decrease from a maximum (if travel cost is zero) to a minimum as travel cost goes to infinity. The theory is that there is always a minimum number of trips that must be made regardless of cost, and there is also a finite limit on demand regardless of how cheap it is to travel. Stated in formula form,

$$T_{ij} = Q_{ij} * \left[a + b * \exp\left(-B * c_{ij}\right)\right] \qquad \text{Equation 1}$$

Where:

T_{ij} = the number of trips between zone i and zone j (a separate computation is performed for each trip purpose, trip purpose index not shown);

Q_{ij} = a measure of the potential travel demand (for example, the number of jobs in zone j filled by workers living in zone i);

a = the minimum number of trips per unit of Q_{ij} (for example, trips per worker) that must occur;

b = the number of trips per unit of Q_{ij} that would be affected by trip cost;

B = the calibration parameter (set to zero for work trips, which always must be made, regardless of cost. Nonzero for other purposes.); and

c_{ij} = the generalized cost to go from zone i to zone j.

The maximum number of trips between zones i and j would be $Q_{ij} * (a + b)$. The minimum number of trips between zones i and j is $Q_{ij} * a$.

MetroSim, LUTRIM, and CUF are models that were under development at the time of this report and have seen little practical application anywhere. MetroSim was being developed by Alex Anas at the State University of New York at Buffalo. LUTRIM was being developed by William Mann. CUF was being developed by John Landis at the University of California.

NCHRP Report 423A notes that users of all of these land-use models generally complain about the difficulty of applying any of these models, specifically the high staff time costs, the extensive data requirements, the need to hire the developer of the model to calibrate it, the inaccuracy of results, the lack of integration with transportation models, and the insufficient documentation.

The NCHRP report notes that the models based on Lowry gravity models assume that accessibility is the key explanatory variable of locational choice. The models generally do not adequately represent nonaccessibility factors that influence household and firm location choice.

The report provides a conceptual description of the general framework and mechanisms of the land market and comes to the following conclusions regarding needed improvements to current land-use models:

- The models must have measures of accessibility that reflect the complex decision making of households and firms (i.e., consider access to services, recreational opportunities, school, etc., as well as traditional work location).
- The models must recognize that affordability and other factors may be just as or more important than accessibility.
- The models must recognize the limitation of public policies for shaping the pattern of development.
- The model must recognize that in-fill and redevelopment can accommodate a significant share of growth (i.e., the model must not overestimate the demand for vacant land).

Both the NCHRP report and Mark Harvey[101] note that one problem with all of these models is obtaining longitudinal data (i.e., panel data gathered over a long period combining time-series and cross-sectional data) for calibration. Most models have been calibrated using cross-sectional data rather than longitudinal data. This implies that they might be valid for shorter periods consistent with the cross-sectional data used to calibrate them.

The NCHRP report also notes that the models tend to perform poorly at the disaggregate level. Even the TRANUS/MEPLAN disaggregate models perform poorly if the zone system is too detailed.

Other noteworthy reviews of land-use models are those by Rosenbaum and Koenig for the EPA, Southworth for the Oak Ridge National Laboratory, Berechman and Small of the University of California, and Oryani and Harris for the Delaware Valley Regional Planning Commission.

Rosenbaum and Koenig[102] assess the ability of currently available land-use models and integrated land-use and transportation models (DRAM/EMPAL, MEPLAN, and TRANUS) to evaluate the impact of land-use policies and strategies designed to reduce travel demand. The authors looked at the ability of the models to predict the impacts of zoning and land regulation incentives on travel patterns. They noted problems with the minimum size (i.e., aggregation) of zones required for these models. DRAM/EMPAL does not reflect land-use zoning impacts as well as MEPLAN and TRANUS do. DRAM/EMPAL is also insensitive to monetary incentives to encourage mixed use or higher densities.

Rosenbaum and Koenig recommend the following improvements to standard land-use and transportation modeling tools so as to facilitate their use in evaluating the impact of land-use strategies and policies:

- Development of data and procedures to allow land-use analysis at fine spatial resolutions, such as census tracts;
- Development of data to determine the relationship between special land-use features of interest (e.g., pedestrian-friendly environments and mixed land-use development) and neighborhood attractiveness;
- Development of data and procedures to allow incorporation of pedestrian and bicycle modes, as well as public transit, into travel demand models;
- Development of data to determine the relationship between mixed use development and travel mode selection;
- Development of data and procedures to allow incorporation of trip chaining into travel demand models; and
- Development of data and procedures to allow incorporation of temporal choice into travel demand models.

Southworth[103] reviews the state of the art in operational urban land-use and transportation simulation models. Models reviewed include DRAM/EMPAL, ITLUP, Projective Optimization Land-Use Information System (POLIS), MEPLAN, Kim's Chicago model, MASTER model, and the Dortmund model. Southworth provides mathematical descriptions of the models and identifies several practical issues related to the applications of these models (their analytic complexity, their significant data requirements, and their significant demands on computational resources).

Berechman and Small[104] note that modelers must choose between tractability and suitability. Most tractable models exclude agglomeration economies and lack a dynamic structure suitable for handling rapid disequilibrium growth.

Oryani and Harris[105] reviewed three candidate land-use models for the DVRPC: DRAM/EMPAL, MEPLAN, and MetroSim. The authors interviewed other MPOs' experience with using DRAM/EMPAL and evaluated two case studies (Orlando and Tampa) of the application of DRAM/EMPAL.

They recommended that DVRPC implement the DRAM/EMPAL model and provided cost and data collection needs for the implementation.

Although POLIS is part of a three-tiered modeling system, it is the only tier that is directly sensitive to accessibility and congestion. The MTC/ABAG POLIS model uses a sophisticated mathematical programming process that allocates land uses to zones based on cost minimization (i.e., microeconomic theory). The model includes a travel time matrix provided from the regional travel model. The objective function of the model is to develop a "solution" of job, household, and labor distribution that maximizes "locational surplus" associated with a specific location, subject to the policy and economic constraints associated with each time period. Population, new housing units, employment (five sectors), number of work trips (by mode and zone pair), and shopping trips (by mode and zone pair) are distributed to 107 zones in the MTC region. The model was calibrated using Census Bureau household and business data between 1964 and 1980.

The following sections provide more detailed technical information on two models: HLFM and UrbanSim. HLFM is an example of an equilibrium Lowry land-use model similar to the widely applied DRAM/EMPAL model, but somewhat simplified. HLFM is notable for its tight integration with travel model software. UrbanSim is an example of an advanced practice dynamic microscopic land-use model currently being tested in Oregon and Washington that bears a resemblance to the MEPLAN and TRANUS models in their use of discrete choice models and economic markets. UrbanSim is designed to interface with external travel demand software. These two models bracket the range of available land-use model applications.

6.2 THE HIGHWAY LAND-USE FORECASTING MODEL

The Highway Land-Use Forecasting Model (HLFM) was developed by Dr. Alan Horowitz. It is based on the Lowry-Garin land-use model first described in 1964–66. HLFM uses information on the highway system, land uses (existing and proposed), demographic data, and socioeconomic data to predict the amount of employment and population likely to locate in each zone within an urban area. HLFM extends the Lowry-Garin model by taking into account the availability of land by activity type.

HLFM is a very long-term "equilibrium" land-use model. The model predicts the land-use demand and supply equilibrium toward which the urban area is heading. HLFM is intended to give a good indication of the global trends in urban development, not detailed land-use information at the zonal level. HLFM will not predict land use for any given year or for the base year (if the urban area is currently substantially out of equilibrium).

The data requirements of HLFM are substantially less than those of DRAM/EMPAL. Since HLFM integrates with QRS, it is sensitive to the impacts of both highway and transit on land use, as well as the effects of traffic controls.

HLFM is designed to be integrated with a travel demand/supply model. The travel times and costs are computed for all pairs of districts (i.e., aggregations of traffic analysis zones) in the urban area. The Lowry-Garin model is then used to allocate population and employment to the districts. The population and employment allocations are fed into a travel demand model that predicts the resultant travel demand, traffic volumes, and travel times. The new travel times are fed back into the Lowry-Garin model to compute new population and employment allocations. The process is repeated until the travel patterns are "unchanged."

6.2.1 Allocation Process

To start, the Lowry-Garin model requires the location and amount of basic industry employment in the region. Basic industries are industries that choose their location primarily according to their proximity to needed natural resources and urban infrastructure. Once the model has this initial information, the allocation process is then begun.

First, the conditional probabilities are computed for worker resident locations and for service employment locations. The model then computes the total employment in each district and the population residing in each district. The model revises the relative attractiveness of each district based upon the results of the current iteration. This process is iterated in the HLFM model until the user-specified maximum number of iterations has been reached.

6.2.2 Conditional Probabilities Equation

Three conditional probability matrices are computed: the probability of a person working in district *j* residing in district *i* (matrix *A*); the probability that an employee working in district *j* is served by another employee working in district *i* (matrix *H*); and the probability that an individual living in district *j* is served by an employee working in district *i* (matrix *B*).

The conditional probabilities are computed using singly constrained trip distribution equations with an exponential deterrence function (these equations are mathematically identical to logit models).

$$a_{ij} = \frac{w_i * \exp\left(-\beta * t_{ij}\right)}{\sum_i w_i * \exp\left(-\beta * t_{ij}\right)} \qquad \text{Equation 2}$$

Where:

a_{ij} = the conditional probability that an individual working in district *j* will live in district *i*;

w_i = the attractiveness of district i;

t_{ij} = the travel cost, time, or disutility of travel between districts i and j (from travel model); and

β = a calibration parameter.

The attractiveness (w) of a district is specified in terms of the net developable area for the computation of residential location probabilities (matrix A). Net developable area for service industries is used for computing the other two location probability matrices (B and H).

6.2.3 Employment Location Equation

The key equation for finding employment in each district is

$$E = E_B + E_R + E_W \qquad \text{Equation 3}$$

Where:

E = the vector of total employment in each district;

E_B = the vector containing the amount of basic employment in each district;

E_R = the vector of employment that service residences (people); and

E_W = the vector of employment that serves workers (or other businesses).

Since E_R and E_W are functions of total employment, it is necessary to solve this vector equation for total employment E to eliminate E_B from the right side. The following equation is used to simultaneously compute the total number of jobs in every individual district as a function of basic employment in all districts individually:

$$E = (I - GBQA - HF)^{-1}\, E_B \qquad \text{Equation 4}$$

Where:

I = the identity matrix; a diagonal matrix of 1's, all other values of the matrix being 0;

A = the matrix of a_{ij}; the conditional probability that an individual working in district j will live in district i;

B = the matrix of b_{ij}; the conditional probability that an individual who lives in district j will obtain services from a job located in district i;

H = the matrix of h_{ij}; the conditional probability that an employee working in district j is served by another employee located in district i;

F = a diagonal matrix containing the ratio of service employment to all employment for each employment district, usually set uniformly to the regional average;

G = a diagonal matrix containing the ratio of total employment to population for each residential district, usually set uniformly to the regional average; and

Q = a diagonal matrix containing the ratio of population to employment in each residential district.

The F, G, and Q matrices contain the information typically associated with base multipliers for a region.

6.2.4 Adjustments to Attractiveness

The attractiveness weights (w) that will be used in the next model iteration to compute the conditional probability matrices are based upon the remaining net developable area resulting from the current model iteration.

6.3 THE URBANSIM MODEL

The UrbanSim model is a dynamic metropolitan area land-use forecasting model (see Figure 7). It was developed in 1996-1998 as part of Oregon's Transportation and Land-Use Model Integration Project (TLUMIP).[106]

Unlike more traditional approaches to land-use modeling, UrbanSim does not seek a cross-sectional equilibrium between the demand for, and supply of, land. UrbanSim models land-use changes as a dynamic process where people and businesses have certain price and accessibility demand functions but are not perfectly mobile so as to take full advantage of available land supply opportunities. UrbanSim shows how changes in land-use policies and transportation supply affect the movement of households and businesses on a year-by-year basis. Moving costs and other constraints delay the response of the actors to changes in land supply, price, and accessibility.

UrbanSim does not have a transportation model integrated within it to compute accessibility. UrbanSim obtains accessibility statistics from a separate transportation model, thus allowing users to interface UrbanSim with most any metropolitan transportation planning model and software. A more integrated version of UrbanSim is under development for Honolulu.

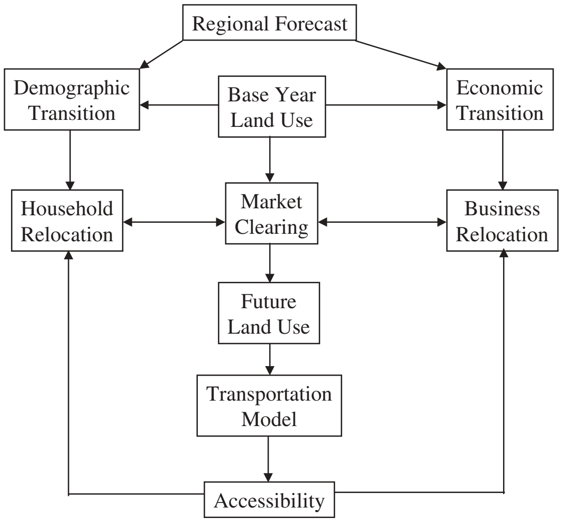


Figure 7. UrbanSim flow chart.

The basic philosophy behind UrbanSim is that urban development over time and space is the outcome of the choices and actions of four sets of actors: households, businesses, developers, and government. The different actors make their location decisions within different time frames. Household and business location decisions are assumed to occur within 1 year of a change in conditions. Building construction decisions by developers take longer, and infrastructure decisions by government take the longest.

UrbanSim requires the following input data:

- Base year land use,
- Population,
- Employment,
- Regional economic forecasts,
- Transportation system plans,
- Land-use plans, and
- Land development policies (such as density constraints, environmental constraints, and development fees).

The "Demographic Transition Module" and "Economic Transition Module" predict temporal changes in the distribution of household and business types (e.g., age, income, and industry type) for the region. These predicted changes are based upon the user input regional population and employment forecasts.

The model then predicts the location of businesses, households, new construction, and the price of land/buildings. The Household Mobility and Location Module simulates household relocation decisions (stay or move; if move, then to where and what housing type). The Business Mobility and Location Module simulates business relocation decisions (stay, move, building type, and location). The characteristics of the household and the businesses influence the choices taken.

The land development component simulates developer choices to convert vacant or developed land to urban uses (including type of improvement and density). The model takes into account profit expectations and governmental constraints (e.g., zoning and infrastructure).

The market clearing is simulated by adjusting the land prices in response to competing demands. The ratio of demand to supply is used to proportionally adjust the land price. The new land prices affect the demand for the following year.

The model produces information on land uses, prices, density, and the distribution of population and employment that can be input to a transportation model for any desired forecast year.

6.3.1 Household and Economic Transition Models

For businesses, the economic transition model is

$$B_{nst} = \sum_{\forall s} B_{nst-1}(R_{nsi} - R_{nso}) \qquad \text{Equation 5}$$

Where:

B_{nst} = the regional total number of businesses of industry n, size s, at time t or $t-1$;
R_{nsi} = the rate of business formation in the region and immigration to region for type n, size s businesses; and
R_{nso} = the rate of business closure in the region and exodus from region for type n, size s businesses.

The rate of business formation is computed as follows:

$$R = \left[\frac{B+E}{B}\right]^{1/n} - 1 \qquad \text{Equation 6}$$

Where:

R = the rate of business formation,
B = the number of businesses in the base year, and
E = the number of business events (formations in this case) forecasted to occur over the n-year time period.

The rate of business closure is computed similarly. The rates are adjusted to achieve specific target values for businesses for target years.

For households, the demographic transition model is

$$H_{ht} = \sum_{\forall h} H_{ht-1}(R_{hi} - R_{ho}) \qquad \text{Equation 7}$$

Where:

H_{ht} = the regional total number of households of type h at time t (t is in units of 1 year),
H_{ht-1} = the regional total number of households of type h at time $t-1$,
R_{hi} = the rate of household formation in the region and immigration to region for type h households, and
R_{ho} = the rate of household death or dissolution in the region and exodus from the region for type h households.

The household rates are computed similarly as for businesses.

6.3.2 Household and Business Relocation Models

The following models first determine how many households or businesses in each zone are likely to move that year and then determine which buildings and zones they will move to.

6.3.2.1 Mobility Submodel

The following logit choice model is used to predict the probability that a household or business will move in a given year:

$$p(m) = \frac{1}{1+\exp(V_m)} \qquad \text{Equation 8}$$

Where:

$p(m)$ = the probability of a business or household moving in a given year and
V_m = the utility of moving.

For businesses the utility of moving is

$$V_m = \beta_1 + \beta_2 i + \beta_3 s \qquad \text{Equation 9}$$

Where:

β_n = the calibration parameter vectors,
i = the industry type, and
s = the size of business.

For households, the utility of moving is

$$V_m = \beta_1 + \beta_2 a + \beta_3 c + \beta_4 i + \beta_5 s \qquad \text{Equation 10}$$

Where:

β_n = the vectors of calibration parameters,
a = the age group of the head of the household,
c = the dummy variable (0,1) for presence of children in the household,
i = the household income level, and
s = the size of household.

6.3.2.2 Location/Building Choice Submodel

The number of moving businesses is added to the net increase in businesses in the region to obtain the total number looking for a new location. A nested logit model is used to predict the probability of a particular building type and location (i.e., zone) being selected by the businesses looking for a new location. The zone choice is the lowest level of the choice model. The zone selection is conditional upon the building type selection. Buildings are grouped into four types: industrial, wholesale, retail, and office. To compute the marginal probability of choosing building type b, use the following equation:

$$P(b) = \frac{\exp(V_b + \mu V_b')}{\sum_{b'} \exp(V_{b'} + \mu V_{b'}')} \qquad \text{Equation 11}$$

Where:

$P(b)$ = the marginal probability of choosing building type b,
V_b = the utility of building type b,
V_b' = the logsum of the conditional choice of location l, and
μ = the logsum calibration coefficient.

To calculate the logsum of the conditional choice of location l, use the following equation:

$$V_b' = \ln \sum_l \exp(V_l) \qquad \text{Equation 12}$$

Where:

V_1 = the utility of choosing the location l.

The conditional probability of choosing a particular location (or zone) is given by the following equation. If the available data do not support a nested logit form (e.g., $\mu = 0$), then a multinomial logit specification is used that simultaneously combines the location and building type choice.

$$P(l|b) = \frac{\exp(V_l)}{\sum_{l'} \exp(V_{l'})} \qquad \text{Equation 13}$$

Where:

$$V_l = \mu(C_{hl} - p_l + \ln S_l) \qquad \text{Equation 14}$$

And where:

V_l = the utility of choosing the zone l,
μ = the calibration scaling factor for utility,
C_{hl} = the bid function for consumer h for lots in zone l,
p_l = the price of lots within the zone l, and
S_l = the size of the choice of lots within the zone l.

The bid function is a linear function of density, number of available housing units, income, travel time to the central business district, general accessibility to employment and retail opportunities, and other factors. Similar factors with some variations appropriate to businesses are used to predict business location choice. Accessibility, Access$_i$, is measured with the following accessibility index:

$$Access_i = \sum_j^J A_j \exp(\beta L_{ij}) \qquad \text{Equation 15}$$

Where:

A_j = the amount of activity (e.g., jobs) in zone j,
L_{ij} = the travel time, cost, or composite utility for travel between zone i and zone j, and
β = the utility scaling parameter.

There is some concern about whether the use of a scaling parameter for utility violates the theoretical basis for logit discrete choice models.

6.3.3 Market Clearing Model

The market clearing model sets the land price. Each business type has its own bid function which is a function of zonal characteristics (lot density, employment density for that industry, population, income, presence of freeway access, etc.) and building types (available building stock, age of buildings, etc.).

Household bid functions are stratified by income and the presence of children in the household. Variables included in the household bid function are accessibility, net building density, age of housing, and housing type (single family, quadplex, or multifamily).

Land prices are adjusted in response to differences between the current vacancy rate and the normal vacancy rate for each building type:

$$P_{lbt} = P_{lbt-1}\left[\frac{(1+\alpha_b - V_{lbt}) + \lambda(1+\alpha_b - V_{bt})}{1+\lambda}\right]^{\beta} \qquad \text{Equation 16}$$

Where:

P_{lbt} = land price at location l for building type b and year t,
P_{lbt-1} = land price at location l for building type b and year $t-1$,
α_b = the normal vacancy rate for building type b,
V_{lbt} = the current vacancy rate (for location l, building type b, at year t),
V_{bt} = the current mean vacancy rate for the region (for building type b at year t),
λ = the weighting parameter, and
β = the scaling parameter.

A Land Development/Redevelopment Module interfaces with the market clearing model to determine how the supply of buildings responds to the changes in land prices. Projects are assumed to be constructed until the user-specified "normal" vacancy rate for each building type is reached. Developers are assumed to construct first the projects that yield the greatest profit. The expected profit of a project is computed by subtracting land cost, hard construction cost, and soft construction cost (impact fees, permit costs, demolition costs, service extension costs, etc.) from the expected sales price of the building project. The new supply of building space is assumed to become available in the following year.

6.4 THE IDEAL MODEL

The ideal model would include markets for land development, residential housing, commercial floor space, and labor in which the demand and supply functions are well defined and equilibrium is established through price signals. The explicit modeling captures evolving behavior over time. The demographics of the model should be endogenous to ensure that the population characteristics are representative over time and are at a level of detail to complement the behavioral relationships in the housing and transportation models. The impact of regional economies should be endogenously modeled so urban consumption and production both influence and are influenced by land and transport market outcomes. The travel demand component should be activity based to provide a level of disaggregation to ensure that policy instruments can be adequately molded. Finally, the auto ownership decision should be explicitly modeled and linked to the travel demand component.

Such an ideal model is represented in Figure 8, where the core behavioral components are shown in the shaded area. A key idea here is that location choice and land development are distinguished, as is the supply side of the land market.

The four major drivers of the urban system are demographics, the regional economic makeup and level of activity, government policy (including zoning, taxation, regulation, and macro variables such as interest rates), and the transport system (which proxies the supply side of the network).

Each component of such an ideal model involves a complex series of submodels. Even if the market-based demand and supply relationships are at a more aggregate level, the key issue is to correctly model the interactions of the economic agents. Failure to properly model the demand-supply interactions may mean that the dynamic evolution of the urban system will not be properly captured. Certainly, in all the models reviewed below and others not included (e.g. Australian and Japanese models), a key setoff assumption is the strong separability between transportation demand and the demand for other parts of the consumption bundle. In an ideal model, the full range of consumption activities would be modeled.

Two broad categories of transport and land-use models have been developed. The first category is simulation models, which attempt to replicate the land-use patterns by simulating the process of urban development and transportation investment that produces the land-use patterns. Figure 9 illustrates a typical structure of a simulation model.[107] The second category of model is an optimization model, which represents an equilibrium between an urban area's transportation system and the land market. These models are used to

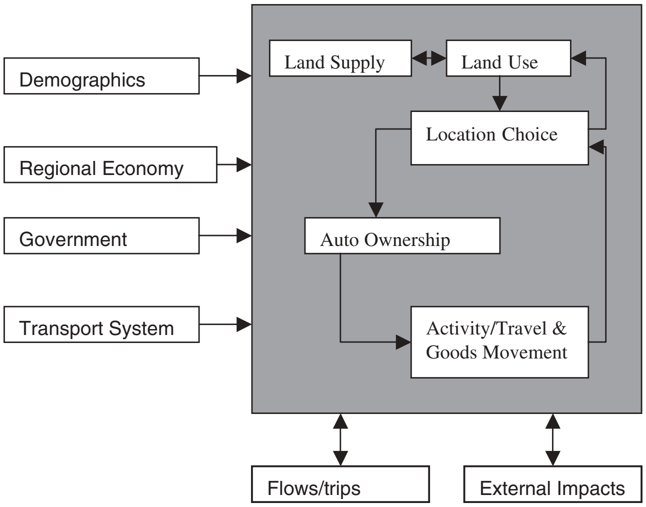


Figure 8. Idealized transport land-use model.

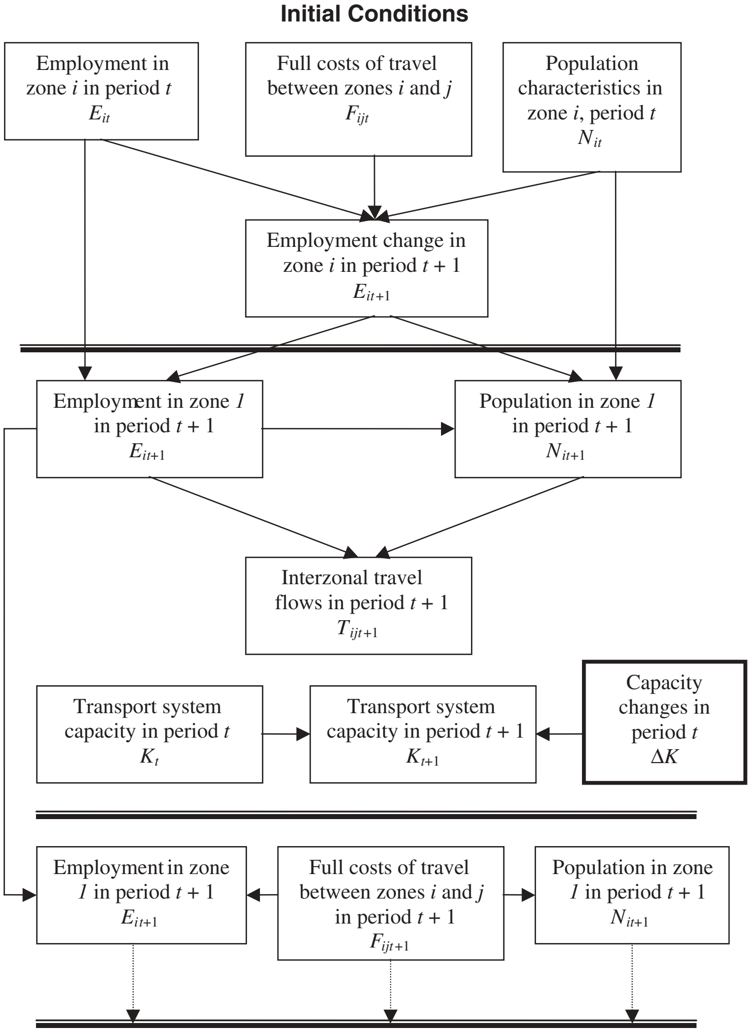


Figure 9. Land-use simulation model.

establish the optimal distribution of land uses in an urban area or flows over the transportation network. Interestingly, simulation models have been used much more in practice to investigate the interaction between transportation changes and land use and to support plans of urban areas while optimization models have been used for research purposes.

The Lowry-Mills type represents land-use simulation models. In the group reviewed here, ITLUP represents the Lowry-Mills type. Optimization models generally use some mathematical programming or assignment techniques to establish the equilibrium of different land uses within the urban area.

6.5 MODEL REVIEW

The review in this section draws heavily from other work.[108] The models considered here fall into two categories. ITLUP is an operational package with a relatively long history of application in the United States and elsewhere. MEPLAN, NYMTC-LUM and UrbanSim, however, have a shorter history of application, but they have a current set of operational applications and detailed representations of land markets in which price provides the equilibrating mechanism.

6.5.1 ITLUP

ITLUP was developed at the University of Pennsylvania, has a 25-year history, and is the most widely used spatial allocation framework used in the United States. It includes a number of submodels, including DRAM (Disaggregate Residential Allocation Model) and EMPAL (Employment Allocation Model). It is a Lowry-type model with four population income levels, four types of employment, and travel patterns for public and private transport.

A multinomial logit model is used to determine mode split while trip generation and distribution are developed within DRAM. Household location is established concurrently with trip generation and distribution. A considerable amount of detail can be added to this model, since DRAM and EMPAL can be used separately in conjunction with other travel demand forecasting models such as Tranplan; Urban Transportation Planning System (UTPS); and Equilibre Multimodal, Multimodal Equilibrium (EMME/2).

A significant benefit of this model is that the data required are not large in comparison with other models and the data are generally readily and easily available. The data relate specifically to population, household, and employment data. A major weakness of this model is that it does not account for the land market clearing process.[109]

The program originated in Formula Translation (FORTRAN); however, it has been maintained, running on a personal computer (the personal computer version is called Metropolis) under an Arcview shell, providing linkages to Arcview GIS.[110]

6.5.2 MEPLAN

MEPLAN is contained in proprietary software developed in the United Kingdom. It has developed over a 25-year span, and the principal has significant expertise in the area. It has been applied in a number of regions of the world, including the United States (Sacramento and Oregon) and Canada (Edmonton).

MEPLAN is highly flexible and has an aggregate perspective. Space is divided into zones with quantities of households and economic activities allocated to the zones. Flows of interactions among the factors in the different zones give rise to travel demand. The distinguishing feature of this model is the use of an input-output matrix, which is spatially disaggregated. This matrix provides a means of overcoming (to some degree) the assumption of strong separability between transportation and other components of the consumption bundle contained in other models. This social accounting matrix includes variable technical coefficients, labor sectors, and space sectors. All economic activities, including household activities, are treated as producing and consuming activities. The spatial disaggregation is achieved by having further production arise to satisfy consumption allocated among the zones according to a discreet choice model, which responds to price levels for such production. Travel demand gives rise as a result of this interaction. Temporal change is modeled by considering sequential points in time.

Space in each zone is fixed at each point in time. Space, both land and commercial floor space, cannot be moved between zones. Space must therefore be consumed in the zone in which it is produced. In order to reach equilibrium, the technical coefficients for the consumption of space (i.e., demand for housing) are elastic with respect to price. Prices equate demand with supply and are endogenously determined at each point in time. Prices for outputs in other sectors are also determined endogenously by the consumption-production relationship reflected in the social matrix. Travel demand, which arises from the interaction in the land, goods, and housing market, is determined for each point in time. This travel demand is allocated to modes and the network on the bases of nested logit models for mode and route choice. This allocation accounts for congestion in full costs. Any disutility in the transport sector feeds back into the next time period as response lags.

Exogenous demand provides the initial impetus for economic activity and changes in the study area demands. It also provides the amount of space in each zone from one time period to the next, thus driving economic change. These changes are allocated to the different zones under equilibrium conditions.

MEPLAN is personal computer based, but it is proprietary.

6.5.3 NYMTC-LUM

NYMTC-LUM reflects the work of Anas[111] over the past two decades. It is a simplified version of Metropolis, which is the PC version of ITLUP. Like Anas's earlier work, NYMTC-LUM is anchored in microeconomic theory where demand and supply interactions determine the equilibrium price. The model simultaneously shows the interactions between residential housing, commercial floor space, labor, and nonwork travel markets with explicit representations of demand and supply in each market. Housing prices, floor rental rates, and wages are all endogenously determined in the model and serve as the arbiter between demand and supply in their respective markets. Finding prices and wages that balance demand and supply in the markets of interest generates static equilibrium in the forecast year. This final equilibrium is not path dependent and therefore does not require solutions in a sequence of years.

The model uses traffic zones as the geo-statistical unit of observation and therefore provides a fine level of detail for policy analysis. For example, the application in New York has 3,500 zones. However, at present the model does not have significant disaggregation in households, employment, and buildings. This fact could be changed with added data and some level of complexity.

The land-use component is not integrated with the travel demand model. Rather, it is connected to the existing MTC travel demand model in that it receives model utilities as inputs from the mode choice model. This connection is similar to the case of UrbanSim and ITLUP models.

NYMTC-LUM's adaptability is illustrated in the application in New York, where the primary interest is in evaluating transit programs, investments, and strategies. Features of the model, which facilitates its application in the New York context, include small traffic zones, integration of the detailed transit network, and use of the mode choice models. The microeconomic foundations provide a range of economic evaluation measures, including property values and consumer and producer surplus.

NYMTC-LUM works on a PC platform and is written in FORTRAN. It is commercially available through Anas.

6.5.4 UrbanSim

UrbanSim is an operational model that was originally developed for Hawaii, Oregon, and Utah, but is currently being further developed at the University of Washington. It is an operational model of urban land and floor space and is integrated with a traditional four-step model. The unique feature of the model is that it has been placed in the public domain and is accessible via the Internet site for both software and documentation.

The most notable features of UrbanSim are the level of detail for both spatial disaggregation and disaggregation across households, employment, and land use. The model is grounded in microeconomic theory and emphasizes theoretical consistency and rigor. The model operates as a disequilibrium model in which stock supply and demand are built incrementally over time. Demand for building stock (commercial floor space in other models) is based on willingness to pay (WTP) or bids (observed prices, since WTP is difficult to observe). Buyers are utility maximizers who attempt to maximize their consumer surplus (i.e., the residual between WTP and price paid), whereas sellers maximize price paid per unit. Suppliers of building stocks are profit maximizers given observed demand. Markets are assumed to be competitive. Building stock prices are determined within a market clearing process, which occurs at the submarket level of the traffic analysis zone and property type.

UrbanSim works as a path-dependent model, requiring a solution in each year, and operates in dynamic disequilibrium in each year. The profit-maximizing supplier provides parcels for development based on expected profit. This profit uses expected revenue from the previous year prices, and new construction choices are not supplied to the market (for occupancy) for the subsequent year. Demand is based on lagged prices, and current supply and prices adjust to the balance of demand and supply in each submarket of each year.

The demand side of the market uses traffic analysis zones as the spatial unit of analysis. The level is highly disaggregated in all current applications, offering a fine level of detail. On the supply side, the model uses individual land parcels as the unit of land development. This feature is unique to this model. All other models treat a more aggregate level for the land supply function. The level of disaggregation carries over to the economic agents. For example, in some applications it has used 111 household types.

The model is based on policy scenarios of varying levels of detail that include comprehensive land-use plans and growth management regulations, such as mixed densities, green areas, and environmental restrictions. The model has also been developed to assess pricing policies and instruments associated with a range of infrastructure and transportation policies.

6.6 ASSESSMENT

Tables 7 though 17 provide a comprehensive examination and comparison, across a number of dimensions, among the four models. The models differ widely in some respects and are quite similar in others. The extent of their operating experience varies dramatically. This variation in some ways reflects the evolution of the models. The models are all PC based and are an outcome of a consultancy and are therefore proprietary, except UrbanSim. Three of the four are static equilibrium models that leap directly to the year-end equilibrium or are moved to it in 5-year steps. The exception, again, is UrbanSim, which operates on a 1-year time step and does not assume equilibrium.

All the models are zone based, and the older models have a coarse zone; NYMTC-LUM uses traffic zones and is fairly detailed. UrbanSim has two levels of detail: the traffic zone for the demand side and the parcel for the land supply side.

The transportation system in all models is some form of a multimodal network model. MEPLAN has integrated network capacity. NYMTC-LUM and UrbanSim are connected to stand-alone, four-step modeling systems, while ITLUP can operate either in conjunction with the four-step modeling systems or on its own. In all cases, the information passed from the transportation model to the land-use model are based on random utility models. In nested models, the logsum is used to transfer utility. In MEPLAN, the composite utilities from the mode choice model are used as inputs into the land-use model. The land-use model uses these utilities in simulating spatial economic flows in determining the trip origin-destination (OD) table. The remaining models use the composite utility derived from destination choice models in the land-use model and simulate the OD tables within the transportation model. These differences affect the capability of the models to analyze transportation policy. The integration of transportation and land use does not affect this capability as much as the quality of the four-step transportation model.

The range of transportation policy or management options depends primarily on the travel demand model. All models can handle transit issues, albeit at a coarse level. Goods movement is handled only by MEPLAN. Other issues such as HOV, carpooling, and other ITS applications are not handled in the models.

The interaction and integration of the various economic agents (persons, households, firms, and public authorities) differs slightly among the models. The models are all household based, and developers and carriers are explicitly identified because of the role they play in the interaction between transportation and land use. Interestingly, none of the models treat the “person” except the individual trip generated in the transportation model. This feature also shows up on the production side, where, for example, the models (except UrbanSim) deal directly with the location of employment but not with firms. All models except ITLUP have an explicit representation of the building supply development process.

All the models have a strong basis in economic theory; however, the ways in which the eight potential markets are handled differ among the models. The housing markets in all

TABLE 7 Time, land, and developed space

Model	Time	Land	Developed Space
ITLUP	Equilibrium established at each step, 5 years generally. There are information lags from the previous step. Transport costs at time *t* are the basis of employment allocation at time *t*. Household allocation of time is based on transport costs and employment costs.	Zone based with generally larger units. Developable land is exogenous. No micro scale is represented.	No explicit representation of buildings or floor space.
MEPLAN	Equilibrium established at each time step. Information lags exist for previous time steps. Transport disutilities at time *t* are the basis of time allocation in $t + \Delta t$ where Δt is set exogenously, generally 5 years.	Zone based, typically large zones. Technical coefficients for production and consumption become unrepresentative for smaller zones. Land categorization is needed in the model. Developable land is exogenous.	Model is flexible enough to include the causal chain running from land→buildings→activity→representation of floor space category. Includes floor space, prices, and density.
NYMTC-LUM	Direct step to equilibrium for horizon year but can be used with multiple time steps with equilibrium calculated at each time step.	Small zone based. Land area categorized by housing type, basic industry (exogenous), nonbasic industry (endogenous) and vacant land.	Housing by category – number of units, floor space, by zone, basic and nonbasic floor space by zone. Number of categories limited by data only. Prices are explicitly calculated.
UrbanSim	Dynamic disequilibrium, 1-year time step with lagged responses to price signals.	Demand side uses traffic zone and property types. Supply side uses parcel for land development or redevelopment. Developable land is exogenously specified. Land-use plans, regulations and environmental constraints are integrated at the parcel level.	Explicit representation by housing type, nonresidential floor space by type, density, price, and age of development.

models (except ITLUP) include demand and supply. Also, the models (except ITLUP) treat the commercial floor space market with well-defined demand and supply functions. The labor markets differ across the models. In UrbanSim, the travel demand work trip distribution model determines worker-job linkages, while in MEPLAN the labor market is explicitly modeled. In ITLUP, little distinction is made between the housing and labor market.

The personal transportation travel demand predicted by MEPLAN arises out of the spatial consumption-production process. In ITLUP, three trip purposes are generated and distributed simultaneously with the spatial allocation of households. In all other models, the conventional four-step model travel demand model is used. Auto ownership and transportation infrastructure markets are treated exogenously. The demand for infrastructure is implicit in the travel demand model.

The objective functions for the different markets are conventional utility functions or profit maximization functions. The travel demand models and housing markets have logit or nested logit models. Supply functions are generated by profit-maximizing pursuits. The equilibrium is determined

TABLE 8 Transportation network and services

Model	Transportation Network	Transit Representation	Goods Movement	Other Transport Services
ITLUP	Uses road network for assignment of travel costs. Accessibility is specified exogenously by DRAM/EMPAL (it can be endogenous or via link to exogenous travel demand forecasting model). Since it is a composite model, iterations between transportation and land-use models require data transfer between independent sub-structure models. Can link to exogenous demand-forecasting models. Population/employment distribution independent of work trip distribution developed in travel demand model.	Inherent in general accessibility term. Depends on travel demand model used. Commonly auto-only access is used.	Not present.	Inherent in general accessibility term. Not explicitly considered in the endogenous travel demand model.
MEPLAN	Multimodal networks used. Integrated interactions between land use, modal split/assignment. Assignment is static not dynamic. Course network an issue. Can interface with external travel demand models but different zone systems an issue. Nested logit used for mode-split.	Explicit transit representation exists with submodels for rail and bus. Includes transit capacity representation. Links can carry different modes. Course network restricts level of detail for transit.	Explicit goods movement by all relevant modes in considerable detail. Terminal costs explicit, shipping costs included.	Taxi included for some applications. Flexible enough to consider other modes and allocate costs to users.
NYMTC-LUM	Accessibilities imported from separate four-step travel demand model.	Depends on travel demand used. Transit effects enter via mode choice model log sum terms. Small zone system gives good transit system sensitivity.	Not present.	Depends upon modal split model used. Incorporated in accessibility term.
UrbanSim	Connected with travel demand models – generally activity based. Uses composite utility to develop access measures to activities as part of business and household location models. Workplace choice is predicted within the travel modes.	Depends on travel demand model used. Transit effects enter via mode choice log sum term. Small zone system provides good transit system sensitivity.	Implicit in use of auto accessibility terms as proxy for congestion costs on shipping and affecting employment location decisions. Does not model flows of goods.	Depends on modal split model used. Incorporated in accessibility term.

TABLE 9 Economic agents

Model	Persons	Households	General Establishments	Developers	Carriers	Public Authorities
ITLUP	Not explicit. Total population is exogenous.	Household based. Generally four income bands. Aggregate number of households per zone.	Aggregate number of jobs/zone. Typical categorization by four basic industry groups but Standard Industrial Classification (SIC) is possible. Firms not explicitly represented.	Not explicit.	NA	Exogenous policy inputs (transportation system, developable land). No taxation effects considered. No endogenous public-sector responses.
MEPLAN	Person-trips generated by households. No explicit representation of person or their attributes.	Household based. User-specific categorization – income, occupation of household head. Aggregate number of households/type/zone.	Explicit outputs of production processes. Represented by various proxies such as employment.	Space is developed or redeveloped as function of prices and availability. Developers are implicitly represented by total space by type to be developed/ redeveloped. Exogenous input.	Implicit in multimodal framework representation. Cost structure is explicit.	Exogenous policy inputs re: serviced land, zoning, transport network, land tax. No endogenous public-sector response except some transit frequencies change with demand.
NYMTC-LUM	Not explicit. Can adjust equations for multiworker households.	Household based but no categorization by household type. Average household income in each zone determined by allocation of workers from workplace to residential zone.	No explicit representation of firms. Employment is explicit by zone. Lowry concept of basic and nonbasic industry is used. This division is used to keep track of land use and floor space.	Supply of building stock in each zone responds to market values for buildings of type by zone subject to available land.	NA	Transport network or services are exogenous inputs. No sensitivity to zoning or other land-use controls. Some land-use policy is sensitive on a scenario basis determined by exogenous inputs of population and nonbasic employment totals.
UrbanSim	Not explicit at present. Future versions to include workplace choice.	Detailed representation of households; 11 household types. Model predicts births, deaths, moves, building type and location choices.	Business establishments are explicit. User classified by industry and number of employees. Model predicts births, deaths, moves, and building type and location choice. Major buildings can be excluded from simulation to reflect low mobility and lack of information.	Developers explicit as decision-makers. Currently, simulates development/ redevelopment at the land parcel level based on expected profitability. Number of policy inputs used in determining feasibility and cost. Revenue from current market prices. Can handle large multiyear projects.	NA	Explicit policy inputs include land-use plans, density constraints, growth boundaries, environmental constraints, transportation infrastructure, pricing, and service levels.

TABLE 10 Behavioral framework

Model	Housing Market	Floor Space Market	Goods and Services Market
ITLUP	Demand for land explicit, allocates households to zones by type. Supply is implicit but defined by exogenous constraints. There is no price mechanism or signal, static equilibrium.	Supply implicit. No price signal or mechanism.	NA
MEPLAN	Supply function, developers allocate from exogenous total. Housing allocation by type to zones based on prices and current capacity. Includes dynamic lagged response. Demand for housing integrates the idea that the amount of space consumer per household is elastic with respect to price in zone. In a time period, prices are adjusted by zone until there are no vacancies: amount of space consumed per household and distributed among zones is in balance with supply.	Same as housing market except with production processes producing labor.	Explicit based on input-output framework with variable technical coefficients. Elastic with respect to price, logit style substitution. Households maximize utility subject to budget constraint (dual used in model).
NYMTC-LUM	Supply of housing by type by zone is a function of housing prices, interest rates, and development costs. Demand for housing by type by zone is determined by a logit model of worker joint choice workplace and place of residence. Choice is a function of wage in employment zone, price of housing in residential zone, accessibility terms, and other variables. Housing prices are determined by equilibrium.	Similar to housing market except demand for nonbasic floor space is a function of rent of floor space and demand for nonbasic floor space located in a given zone.	NA
UrbanSim	Uses bid rent model but does not impose equilibrium. Demand is based on willingness to pay, or bid function. Consumers are assumed to maximize surplus (bid-price). Households are price takers with price adjusting between 1-year price steps based on aggregate demand and supply within each submarket (traffic zone or property type). Developers produce supply, maximizing profit based on current market conditions. Supply is assumed inelastic within each 1-year time step but is elastic between time steps. The short time step facilitates seeking model equilibrium, but retains rigorous microeconomic foundations.	Identical to and integrated with housing market. Land parcels developed into most profitable use that regulation will allow. This provides a realistic representation of competition between residential and commercial land uses within the constraints of the land policy or zoning laws.	Exogenous levels of employment by sector, endogenous mobility, and location of businesses. Location choice incorporates access to labor market, localization, and inter-industry linkages. Strength of the locational influence of inter-industry links and localization is determined empirically during estimation of each sector.

TABLE 11 Behavioral framework

Models	Labor Market	Personal Transportation Market	Goods Movement Market
ITLUP	Implicitly modeled in that the jobs-housing market is one process. The demand for labor is determined exogenously to the submodels (i.e., employment per zone is known). The spatial distribution of labor (where workers live) is determined by the spatial allocation model. No labor price (wage) mechanism.	Endogenous (within ITLUP) or exogenous linkages to external demand models. Practically, there is no feedback to the activity system.	NA
MEPLAN	Labor supplied by households as demanded by production activities. Generally, labor costs paid by employers are the costs faced by households – households must give up leisure time to earn income. The framework is sufficiently flexible to allow the simulation of a market process, where wages are set endogenously (practical application generally treats wages exogenously).	OD demands arise from the spatial distribution of flows from consumption to production. This includes all types of trips. Includes all modes. There is feedback if the model is iterated with flows assigned to networks with congestion. Feedback to travel decision occurs in same time period, feedback to activity location lagged one period.	NA
NYMTC-LUM	Demand for labor in each zone is a function of wage level.	External travel demand model. If the model is used with instantaneous feedback, the equilibrium between travel and land use occurs. Place of residence-place of work linkages and residence – nonwork activity location linkages are determined within the model. Not currently used in transportation demand management model.	NA
UrbanSim	Location of jobs and workers determined as households and firm location choices, with firm location affected by access to labor market and household location affected by access to jobs. Direct linkage of individual workers to individual jobs is not currently implemented.	External travel demand model. Instantaneous feedback within the travel model; lagged feedback effect to the household and business location choice model.	NA

by an endogenous price, which equates demand and supply. UrbanSim differs in this respect in that it is a dynamic model that moves to equilibrium but does not necessarily achieve it.

Demographics are important model attributes that are treated exogenously. UrbanSim is moving in the direction of treating demographics endogenously.

All the models can handle a range of pricing- and infrastructure-related prices. This ability is unsurprising, since the models were developed for this purpose. The models have not been flexible in handling emerging policies, however. The models cannot, for example, handle regulatory policies or policies associated with transportation management or

TABLE 12 Behavioral framework

Model	Transportation Infrastructure Market	Auto (Vehicle) Market
ITLUP	Exogenous supply, from public authorities (or other providers of transportation infrastructure). Demand is implicit in the travel demand forecasting models.	Not considered explicitly in ITLUP, although could be reflected in DRAM trip generation rates, modal splits, and vehicle occupancy rates. An exogenous travel demand model could include an explicit auto ownership choice submodel.
MEPLAN	Exogenous supply. Demand is implicit in the travel demand forecasting models.	Can have categorization of households by auto ownership level, with exogenous transition among categories.
NYMTC-LUM	Exogenous supply. Demand is implicit in the travel demand forecasting model.	Exogenous travel demand model could include auto ownership choice submodel.
UrbanSim	Exogenous supply. Demand is implicit in the travel demand forecasting model.	Can categorize households by auto ownership level, with exogenous transition among categories, or can have an auto choice submodel in travel demand model.

ITS options. These limitations reflect weaknesses in the standard four-step, travel demand–modeling system. The problem is not with integrated models, but with improving the travel demand models.

6.7 SUMMARY AND RECOMMENDATIONS: LAND-USE MODELS

This chapter's review of four representative models, which range across the state of the art in integrated land-use and transportation demand models, illustrates that no model is ideal. One model that stands out for a number of reasons is UrbanSim. First and foremost, UrbanSim is the most disaggregate of the frameworks. It models land development at the parcel level and travel demand at the traffic zone level. Second, while most frameworks are based on strong equilibrium assumptions, UrbanSim takes a dynamic approach. Third, while most applications are temporarily aggregate and use up to 5-year steps, UrbanSim calculates changes in 1-year steps and thus provides a framework for ongoing assessment of policy instruments. Fourth, while other models are proprietary, UrbanSim is a public domain model and is accessible by a broad group of practitioners. It will therefore progress in a way that reflects the attempts to find solutions to current shortcomings. This progression will form part of an evolving literature. The other models, because they are proprietary, will progress only to the extent that urban areas provide these questions and resources to the firms owning the software.

The current models all have, to different degrees, strengths in a number of areas. They are based on solid microeconomic foundations with well-developed housing and land and floor space markets. They provide logical frameworks for assessing interactions between transportation and land use. In all, the transportation network is multimodal, so a number of substitution possibilities can be considered.

At the same time, all the current models have shortcomings in terms of excessive spatial aggregation, excessive reliance on strong equilibrium assumptions, aggregate representation of households and firms, and failure to explicitly represent the individual decision maker. These shortcomings mean that aggregation is not flexible across different dimensions. The models all suffer from the lack of endogenous demographic processes, auto-ownership processes, and the heavy reliance on four-step, travel demand–modeling techniques. A significant deficiency in all the models is the failure to integrate transportation and housing choice into the broader consumption bundle. The current set of models implicitly treats housing and transportation choice as strongly separable from the rest of people's consumption activities. Changes in relative prices in the other areas will have no impact, as the models are presently structured, on the demand for housing or transportation or both. Even the specifications in the transportation-housing choice utility linkages have a maintained hypothesis of weak separability.

On balance, however, UrbanSim has the least number of shortcomings, and the model's remaining shortcomings are evolving in the direction of the ideal model.

On the downside, UrbanSim is complex and data hungry. It requires expertise to populate it with data as well as to run it and translate the output to make it transparent to policy makers and transportation managers. But this requirement is not unique to UrbanSim.

At this point, one needs to ask how UrbanSim satisfies the research objectives. The key points of the research objectives are to use the case studies to illustrate the methodology and to develop recommendations for the evolution of an analysis framework. In both cases, UrbanSim is a good candidate. First,

TABLE 13 Spatial allocation processes

Models	Housing Supply	Housing Demand	Floor Space Supply	Floor Space Demand
ITLUP	Implicit in the model; allows zone- or sector-specific constraints that correspond to zoning and planning regulations and other land-use policies. Density constraint processes being tested in Metropolis.	Logit allocation model for households, given known workplaces.	Implicit.	Implicit.
MEPLAN	Total development is exogenous in each time period and is allocated among zones as a function of price in the previous time period and of the availability of space. (Uses log-linear form of utility function.)	Households containing workers demanded in zone *j* are allocated among zones according to logit functions. The utility function includes costs of location in zone *i* + travel disutility from *i* to *j* + the alternative specific constant. Set of explanatory variables can be expanded although rarely done in practice. Household type can include alternative-specific constants. Costs of locating in zone *i* include costs of consumption to produce in zone *i*.	Same as housing supply.	Same as housing demand.
NYMTC-LUM	Number of housing units per zone is a function of market value (as a function of price, interest rates) and development costs).	Logit model is a function of household income, housing price, accessibility to work and goods/services, and other variables.	Same as housing supply.	Function of demand for nonbasic services and rent.
UrbanSim	Developers convert vacant parcels or redevelop parcels with existing development on the basis of expected profit using market prices and development costs. Housing supply is inelastic within 1 year, but elastic from year to year. Price triggers changes in the profitability of development.	Household choices of moving, building type, and location may be modeled as connected choices in a nested logit or may be separated into mobility choice and joint choice of building type and location. Location choice is a function of consumer surplus, and bids are a function of housing type, density, access to jobs and shopping, age of housing stock, housing supply, zonal income distribution, land-use characteristics, and proximity to central business district.	Same as housing supply.	Same formulation as housing demand, with bids a function of access to labor, localization effects, inter-industry linkages, building types, density, age, zonal land-use mix, presence of highway, and proximity to central business district.

TABLE 14 Spatial allocation processes

Model	Goods & Services Supply	Goods & Services Demand	Labor Supply/Demand	Demographic Processes
ITLUP	Implicit in nonwork person trip allocation model.	Implicit in nonwork person trip production model.	Treats job and housing market effectively as one and the same without differentiating between the two (i.e., housing location decisions that are conditional on workplace choice decisions and that tend to be dominated by the workplace decision).	Exogenously specified total households by income category, which are then allocated by zone, in each time period.
MEPLAN	Explicit in production-consumption processes as modeled in input-output framework.	Same as supply.	Same as ITLUP.	In practice, little or no demographics. Unemployed/retired households exogenously specified or are implicitly in labor to household ratios.
NYMTC-LUM	Implicit in nonbasic employment, which is determined by residential demand for these services.	Residence-nonwork linkages submodel estimates the number of nonwork trips from each residential zone to each nonbasic employment zone as a function of travel impedances, accessibilities, income, and other socioeconomic attributes.	Supply of labor jointly determined from workers household residence by logit model. Model is a function of wage rate by zone, travel impedances, and other variables. Demand for nonbasic labor is a function of wages, rent, and demand for nonbasic goods as determined by the residence-nonwork linkage model.	No explicit demographic processes within the model structure. Total population for the forecast year is an exogenous input, as are other demographic attributes.
UrbanSim	Implicit in nonwork trip attraction model.	Implicit on nonwork trip production model.	Household and business location processes modeled independently, but with information about the lagged access to jobs or labor market. Links determined by trip distribution model. Model is not workplace driven.	Full range of demographic transitions is envisaged (birth, death, aging, household dissolution, in/out migration). However, current model has static transition probabilities.

case studies by their very nature are highly focused and disaggregate, and these characteristics are features of UrbanSim. Second, the nature of policies to be examined will require an evolution in a direction that UrbanSim is moving in.

UrbanSim also compares favorably with most of the more specific NCHRP 25-21 methodology requirements:

- UrbanSim is a good candidate for evaluating short-term impact analysis, since it provides outputs on a yearly basis. Although the model is not as good of a candidate for the long term because it is not an equilibrium model, UrbanSim provides a sense of direction. UrbanSim's inability to provide a final outcome is not a major weakness, since a manager has flexibility to respond to changes in a dynamic setting.
- UrbanSim operates at the required level of disaggregation.
- Although UrbanSim does not satisfy the objective that the model not require new data collection activities, this objective is at odds anyway with the other objectives. Meeting the objective of not requiring new data collection activities would have a significant cost in terms of higher levels of aggregation and the consequent inability to examine projects and policies.

TABLE 15 Policy capabilities of current models—land use

Policy Category	Specific Policy	ITLUP	MEPLAN	NYMTC-LUM	UrbanSim
Land Use					
Pricing	Taxation	N	E	E	E
	Subsidies	N	E	E	E
	Development Charges	X	E	E	E
Infrastructure and Services	Public Housing	N	E	E	E
	Servicing Land	X	E	E	E
	Government Buildings	N	E	E	E
Regulations	Zoning	X	E	E	E
	Urban Design	N	N	N	E
Transportation					
Pricing	Road Tolls	I	E	I	I
	Gas Taxes	I	E	I	I
	Subsidies	N	N	N	N
	Transit Fares	X	E	I	I
	Parking Prices	X	E	I	I
Infrastructure and Services	Build Roads	E	E	E	E
	Build Rail/Transit Ways	X	E	E	E
	Operate Transit	X	E	E	E
	ITS	I	N	N	N
	Parking	I	N	N	N
Regulations	Parking Regulations	N	N	N	N
	Traffic Regulations	X	E	E	E
	Nonpricing Transportation Demand Management	N	N	N	N
	Licensing	X	N	N	N
	Inspection/Maintenance	N	N	N	N
Other					
Pricing	Auto Tax	N	N	N	N
	License Charges	N	N	N	N
	Income Redistribution	N	E	E	E
Infrastructure and Services	NA				
Regulations	Air Quality Standards	N	N	N	N
	Emission Standards	I	E	I	I
	Noise	I	I	I	I
	Safety	I	I	I	I
	Technology Standards	N	N	N	N

E = explicit and can normally be done in model, N = no, I = implicit, X = can respond but only with exogenous parameter changes.

- Because UrbanSim is not proprietary, contributors from the academic community can develop the model and software in the direction of the ideal model.
- Regarding the ability to model heavy vehicles, only MEPLAN handles goods movements. One method of integrating the use of heavy vehicles into UrbanSim is through the consumption of goods and services by households and a submodule that translates this demand into truck emissions. The same submodule can be used to assess different emission reduction policies by changing the relative prices of goods.
- UrbanSim is the only model evaluated herein that provides a direct linkage between worker and jobs. In MEPLAN and the other models, there is little distinction between the labor market and housing market.

The Integrated Land Use, Transportation, Environment (ILUTE) , being developed as a joint project among four universities in Canada, shows great promise.[112] The model is closer to UrbanSim than to the traditional ITLUP model. It is presently in the development stage, but should be monitored closely as a candidate model for environmental assessment.

6.8 DEMOGRAPHICS: A BRIEF DISCUSSION

Demographics are key components of any microsimulation model. Transportation and housing choices are influenced to a great extent by age, gender, education, household makeup, and the spatial distribution of the population with its attendant attributes. In discussing the ILUTE model that is being developed for Canadian cities, Miller and Salvini[113] note that the first step in any modeling effort is to accurately represent the population of interest in the study area. This step requires detailed demographic attributes on a highly disaggregated basis. This step provides the base population from which the simulations are made.

Population synthesis procedures generally use some sort of Monte Carlo procedure to draw the representative population from aggregate population data. Miller and Salvini describe a relatively new procedure to create a synthetic baseline population—a two-step iterative proportion-fitting procedure. The procedure estimates the multiway distributions for each census tract in a public use area, such that each distribution satisfies the marginal distribution for the census tract and has the same overall correlation structure as the public-use data multiway distribution.

TABLE 16 Performance of current models—applicability

Models	Scope	Theoretical Consistency	Spatial Precision	Temporal Precision	Validation	Transit Representation
ITLUP	Partially integrated/partially connected with transport model. Spatially distributed only if totals are exogenously specified. No supply, no prices.	Over-reliance on equilibrium; at best quasi-dynamic.	Determined by data availability; in practice this means that large zones tend to be used.	Five-year step. Smaller increments are possible if supported by data.	History of validation and recalibration.	Typically, no direct land-use sensitivity to transit, auto-only trips are considered. Transit trip making centers on travel demand model.
MEPLAN	Integrated with transport model. Full representation of production and consumption with fully endogenous prices.	Over-reliance on equilibrium; at best quasi-dynamic. Use of IO framework at such a small spatial scale is questionable.	Use of aggregate IO coefficients limits how small the zones can be while still being representative of the economic processes.	Five-year step. Smaller increments are possible if supported by data. One-year lag used in land-use model.	Some validation.	Explicit representation of transit services. Accessibility includes transit effects and can influence land use. Conversion of transit OD times/costs to larger land-use zones an issue.
NYMTC-LUM	Connected but not integrated with transport model.	Over reliance on equilibrium. Microeconomic consistency throughout.	Developed at traffic zone level.	Current implementation: one step to forecast end-year equilibrium. Could use 5-year steps for full equilibrium at each step.	None for current version. Some experience with earlier versions.	Transit trip making and land-use sensitivity to transit demands on travel demand model used.
UrbanSim	Connected but not integrated with transport model.	Less stringent equilibrium conditions. Model uses nonequilibrium dynamic framework with one-year time increments.	Demand side is implemented at the traffic zone level. Supply side is implemented at the parcel level.	One-year steps. Interaction with travel model may be annual or set at a level to represent significant changes in the transport system.	Process underway.	Transit trip making representation and land-use sensitivity to transit depends on travel demand model used. Current applications have detailed transit network and mode choice model.

IO = input-output.

Related to the development of the above procedure is the process by which the population is "aged" over time. This process is part of the evolution of the urban area. A model is required that will process births, deaths, aging, in-migration, out-migration, marriages, divorces, employment changes, auto ownership, residential mobility, household formation, and household dissolution. This module will vary in complexity and will require some flexibility within the overall modeling framework to reflect both the availability of data and the desired level of aggregation.

The model being developed by Miller and Salvini is a composite of the traditional ILUTE model and UrbanSim. Miller and Salvini's model has a sophisticated evolutionary process engine.

TABLE 17 Performance of current models—feasibility/usability

Models	Data Requirements/Implementation	Technical Requirements	Output Presentation
ITLUP	Simpler model structure means modest data requirements and calibration effort.	Expert support is generally required.	Arcview shell provides presentation capabilities and has a link to external analytical and graphical displays in Windows.
MEPLAN	Complex model structure leading to significant data requirements and calibration effort.	Set-up requires expert, ongoing support.	Full economic evaluation model—prices, consumer surplus, and flows for volumes and times.
NYMTC-LUM	Since it is a static model, data for one point in time is required for calibration. At a minimum, census journey-to-work and income data and nonwork trip linkages are required for calibrations. Housing floor space data are not necessary for calibration.	Unknown.	Population and employment distributions by zone. For residence-work and residence-nonwork trip linkages, include outputs of wages, rents, average income by zone, and consumer and producer surplus for economic evaluation. Format for this information is not clear.
UrbanSim	Requires the following data: parcels with land and improvement values, area, housing units and nonresidential square footage, business establishment inventory, census data, land-use plans, and environmental constraints. Calibration requires use of standard regressions for bid functions and a logit for location models.	Not implemented, currently being implemented in three cities.	Model outputs include household and business distributions by zone, land use, property values, and housing and nonresidential floor space. Results can be transferred to spreadsheet programs. There is a visualization component.

CHAPTER 7

TRAVEL DEMAND MODELS

This chapter highlights three candidate modeling approaches for the NCHRP 25-21 methodology: TRANSIMS, the Portland Tour-Based Model, and STEP.

7.1 TRANSIMS

Transportation Analysis Simulation System (TRANSIMS) is a multiyear project of the FHWA and the University of California Los Alamos National Laboratory (LANL) to develop a travel demand model that retains the identity of individual "synthetic" travelers throughout the entire travel demand forecasting and traffic operations analysis process of the model. TRANSIMS incorporates tour-based travel demand, intermodal trip planning, traffic microsimulation, and air quality analysis, all within a single unified program architecture.[114] TRANSIMS is a rapidly evolving transportation modeling system for which any written description is soon out of date. Interested readers should consult the TRANSIMS homepage at http://transims.tsasa.lanl.gov to obtain the most current information on this system of programs.

7.2 PORTLAND TOUR-BASED MODEL

This section describes an advanced model form that employs tour-based analysis and sample enumeration and that is currently being developed and tested for Portland, Oregon.[115, 116] Currently under development, this model is not fully operational in that it has not been used yet by the MPO for its planning tasks (the currently operational model in Portland is described in Chapter 3). This section describes the model as it existed near the end of 1998. Figure 10 provides a flow chart for the advanced model. The subsections below describe each of the modules (i.e., boxes) in the model.

For the Portland model, it was necessary to back off from some of the ideals of tour-based models in order to achieve reasonable computer memory requirements and model run times (no more than 6 hours per model run on the fastest available microcomputer). Specifically, the Portland tour-based model

- Simplified time of travel to five time periods per day,
- Limits the number of stops on tour to one outbound and one inbound,
- Allows only one "main" mode for the tour (rather than segment-specific modes),
- Does not perform microsimulation of traffic congestion, and
- Does not provide vehicle class information (by emission type).

7.2.1 Input

The Portland Tour-Based Model requires the following input data:

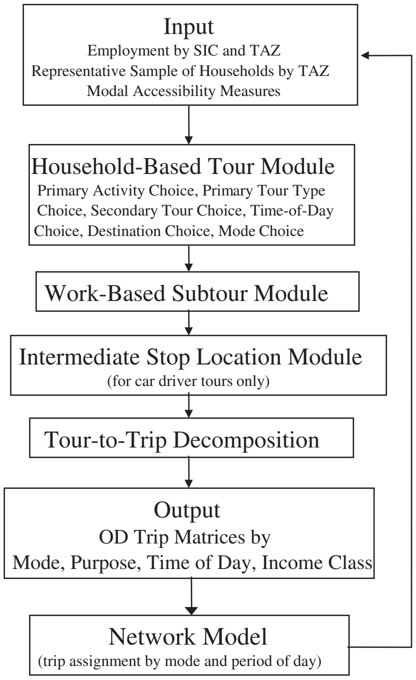
- Households by traffic analysis zone (stratified by persons per household, income, and age of the head of the household),
- Employment by Standard Industrial Classification (SIC) code and traffic analysis zone, and
- Modal accessibility measures.

7.2.1.1 Household Data

The Portland Tour-Based Model employs a sample enumeration technique to develop aggregate travel results. The activity patterns are predicted for a sample of households and are then expanded (with expansion factors) to represent the entire population in the region.

In the case of Portland, a synthetic sample of 120,000 persons (about 50,000 households) was created from the U.S. Census Public Use Microdata Sample (PUMS). This synthetic sample was chosen rather than a 4,451-household survey that Portland had available because of the desire to have a larger sample size for generating a statistically reliable trip table for use in traffic assignments. The majority of analyses were conducted using 10 percent of the synthetic population sample (approximately 12,000 persons).

Households were stratified into 64 bins or cells consisting of four household size categories, four income categories, and four age-of-head-of-household categories. For each traffic analysis zone, households were drawn randomly from the 5-percent PUMS from the relevant Public Use Microdata Area (PUMA).



SIC = Standard Industrial Classification.
TAZ = traffic analysis zone.
OD = origin-destination.

Figure 10. Portland Tour-Based Model flow chart.

A maximum of one household is selected for each of the 64 household type bins, for each individual traffic analysis zone within the region. For Portland, this selection means a maximum sample size of about 80,000 households (about 200,000 persons) (1,244 zones by 64 household categories per zone).

When a household is selected, all persons 16 years or older are included in the sample used in the analysis.

The existing auto ownership for each sample household is pulled from the PUMS. The future auto ownership is predicted using an auto ownership submodel.

7.2.1.2 Employment and Modal Accessibility Data

Existing and forecasted employment by SIC code must be provided for each traffic analysis zone.

Network (i.e., zone to zone) travel times by mode, access times by mode, and cost by mode must be provided for each possible pair of origin and destination zones, by time period of day.

7.2.2 Household-Based Tour Module

The Household-Based Tour Module is nested logit and predicts household-based tour activity for the weekday (see Figure 11). A household tour is a sequence of trip segments in which the entire tour starts and ends at home. The Nested Logit Choice Module is organized according to the following hierarchy:

1. Primary Activity Choice (first row [i.e., top row]),
2. Primary Tour-Type Choice (second row),
3. Secondary Tour Choice (third row),
4. Time-of-Day Choice (fourth row),
5. Destination Choice (fifth row), and
6. Mode Choice (sixth row [i.e., bottom row]).

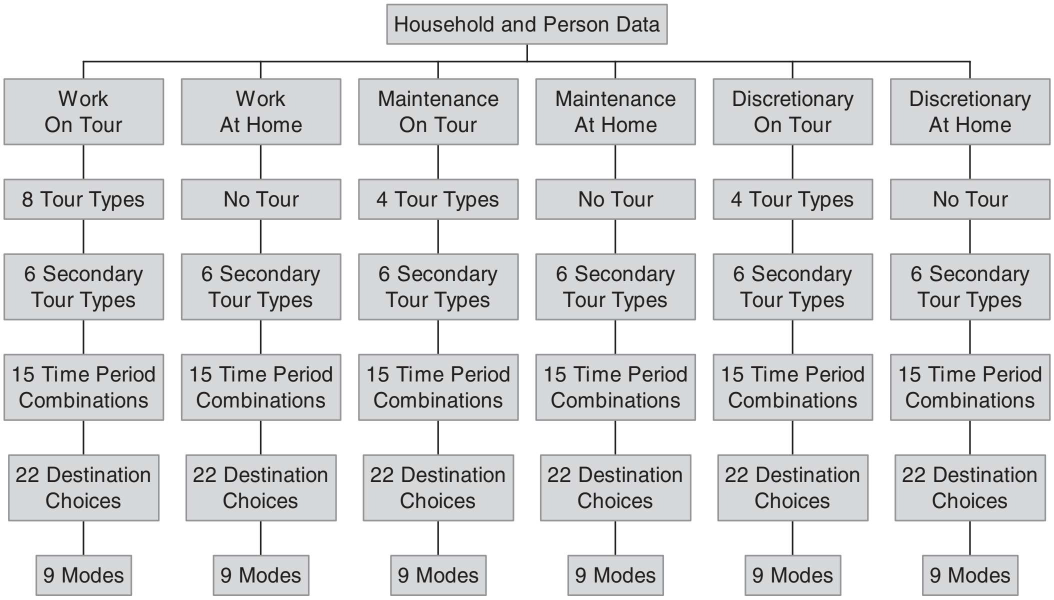


Figure 11. Portland's Household-Based Tour Module.

The choice probability at each level is conditional upon the choices in the levels above it. The following paragraphs explain each level of the nested logit model.

7.2.2.1 *Primary Activity Choice*

The top level of the nested logit model selects the primary daily activity for each person in the household. Three activity types are available (work [which includes school], household maintenance, or discretionary activities), and for each primary activity type, the person can choose to do it outside the home (i.e., on tour) or at home. Thus, six choices are available at this level:

1. Work On Tour,
2. Work At Home,
3. Maintenance On Tour,
4. Maintenance At Home,
5. Discretionary On Tour, and
6. Discretionary At Home.

Work on tour (with intermediate stops or workplace subtours) account for about half of all trips made in the Portland urban area.

7.2.2.2 *Primary Tour-Type Choice*

The three primary activities that take place outside of the home are then divided into four or eight tour types, depending on the number and sequence of intermediate stops. (A maximum of one stop is allowed for each direction of travel [outbound and inbound] to the home except for work tours, which are allowed one extra stop during working hours.)

For nonwork (i.e., maintenance or discretionary) tours outside of the home, the following four tour types are available:

1. Home to destination, return home (no intermediate stops);
2. Home to intermediate stop, continue to tour destination, return home (one intermediate stop);
3. Home to destination, make intermediate stop on way home, return home (one intermediate stop); and
4. Home to intermediate stop, continue to tour destination, make intermediate stop on way home, return home (two intermediate stops).

For work tours outside of the home, the above four types of choices are available plus the additional option of running (or not running) an errand during working hours (i.e., when a person leaves and returns to work). Thus, for work tours outside of the home, a total of eight tour types are available (HWH, HOWH, HWOH, HOWOH, HWOWH, HOWOWH, HWOWOH, HOWOWOH, where "H" is home, "W" is work, "O" is other intermediate stop, and the letter sequence gives the sequence of tour stops).

At this level, there are 16 tour types possible for the tours that leave the house, plus 3 primary activities that do not leave the home; thus, there are 19 possible tour types (a combination of primary activity and the tour type).

7.2.2.3 *Secondary Tour Choice*

For each of the 19 possible tour types, 6 secondary tour choices are available:

1. No secondary tour,
2. A single household maintenance tour,
3. Two or more household maintenance tours,
4. A single discretionary tour,
5. Two or more discretionary tours, and
6. A single household maintenance tour and a single discretionary tour.

The model trades off extra stops on the primary tour against additional secondary tours to and from the home. At this level, there are now $19 * 6$ (114) possible branches of the choice tree for each person in the household. Note that, unlike the primary tour model, which is a logit choice model, the secondary tour model uses fixed percentages obtained from the Portland survey data.

7.2.2.4 *Time-of-Day Choice*

At the time-of-day choice level of the nested logit model, each of the 114 possible primary and secondary tour types is then assigned a starting and ending period probability. The weekday is divided into five time periods (Early, AM Peak, Midday, PM Peak, and Late). For Portland, the following limits were selected for these time periods:

- Early (3 AM to 7 AM),
- AM Peak (7 AM to 9:30 AM),
- Midday (9:30 AM to 4 PM),
- PM Peak (4 PM to 7 PM), and
- Late (7 PM to 3 AM).

Since there are five starting periods and five ending periods, a total of 25 combinations are possible; however; overnight trips have been ruled out, so the resulting available starting and ending choice combinations decreases to 15.

All intermediate stops occurring on a tour are assumed to occur in the same period as the half-tour to which they are assigned. Thus, an intermediate stop on the way to work is assumed to occur in the same time period when the person leaves the home.

7.2.2.5 Destination Choice

At this level, the probability of choosing one of 22 possible zone destinations is computed for each alternative. The possible choice list of 1,244 zones in the Portland area was reduced to a "feasible" subset of 22 zones to improve computational efficiency of the model. The total 1,244 possible destination zones are stratified according to their distance from the tour origin zone and the employment. The 22 "feasible" destination zones for each origin zone are sampled from the 1,244 possible destinations so as to reproduce the actual distribution of chosen destinations.

Separate sets of models are used depending on the tour purpose (work [including school], maintenance, or discretionary).

7.2.2.6 Mode Choice

For each of the 22 feasible destination zones, the model computes the conditional probability of choosing each of 9 modes. Each selected mode will be the main mode for its respective tour (segment-specific mode choice was ruled out by computation constraints). The 9 main tour modes are

1. Drive Alone,
2. Drive with Passenger,
3. Passenger in Car,
4. Light Rail via Auto Access,
5. Light Rail via Walk Access,
6. Bus via Auto Access,
7. Bus via Walk Access,
8. Walk, and
9. Bicycle.

There are 22 ∗ 9 (198) possible mode/destination types for each tour.

Note that by assigning a single main mode to a tour, the model does not distinguish between a casual carpooler who hitches a ride to work and takes the bus home from a person that takes a bus going both to and from work. Main modes are generally assigned to each tour with the intent that, as much as possible, they reflect (within the available nine modes to choose from) the auto VMT generated by the tour while recognizing that some detail and precision on non–auto use will be lost.

7.2.3 Work-Based Subtour Module

For home-based tours that are predicted to have a work subtour (running an errand during working hours), the work-based subtour model predicts the mode and destination of the subtour. Fixed fractions from the household survey are used to identify the time period when the subtours occur. The time-of-day fractions are conditional upon the time of day when the person's home-to-work tour begins and ends.

Time of travel is not taken into account. Subtours are assumed to be completed within the same time period as when they started.

7.2.4 Intermediate Stop Location Module

The Intermediate Stop Location Module predicts the location of the one intermediate stop (the module currently cannot account for multiple stops) visited between the home and the primary tour destination (conditional upon the main mode, location, and timing of the primary tour activity). This module is applied only to tours predicted to have intermediate stops and only to tours that are made by car. This module is applied at a more aggregate level than other modules are. Time of travel is not taken into account. The intermediate stop is assumed to occur in the same time period as when the tour started (if it is an outbound stop) or when the return trip started (if the stop is made on the return trip home).

Two separate modules are used: one for intermediate stops on work tours and another for intermediate stops on nonwork tours.

7.2.5 Tour-to-Trip Decomposition

The Tour-to-Trip Decomposition Module decomposes tours into trips. The origin, intermediate stop, destination, work subtour stop, destination, intermediate stop, and return to origin of the tour become the beginning and end points of trips. The model outputs person trip 1,244 ∗ 1,244 zone origin-destination tables for two tour purposes (work and nonwork), four time periods, nine modes, and three household income classes of the traveler.

7.2.6 Output Module

The Output Module of the Portland Tour-Based Model produces OD trip matrixes by mode of travel, trip purpose, time of day, and income class.

7.2.7 Network Module

The Network Module of the Portland Tour-Based Model is responsible for assigning the OD matrixes to the highway network and producing OD travel times by time of day.

7.2.8 Shortfalls of Current Portland Tour-Based Model

The NCHRP 8-33 investigators (who were also the developers of the Portland Tour-Based Model) noted that they had to overlook a few theoretical shortfalls in order to keep the computation requirements of the model within reason. Specifically, they noted the following shortfalls as of the November 1998 implementation of this model:

- The model uses an aggregate traffic analysis zone system rather than a 1-acre grid system.
- Time of day is limited to five time periods (not hour by hour).
- Tours are limited to one stop outbound and one stop on the return trip.
- The model predicts primary mode of tour, but not segment-by-segment mode.
- Intermediate stops are aggregated.
- Work subtours are not fed back to other activity choices.
- Time and space constraints on activities were not implemented in the model to account for the dependency between activities.

7.3 THE STEP MODEL

The Short-Range Transportation Evaluation Program (STEP) was originally developed by Greig Harvey of Deakin-Harvey-Skabardonis. This section summarizes materials that Harvey and others prepared for the California Energy Commission.[117]

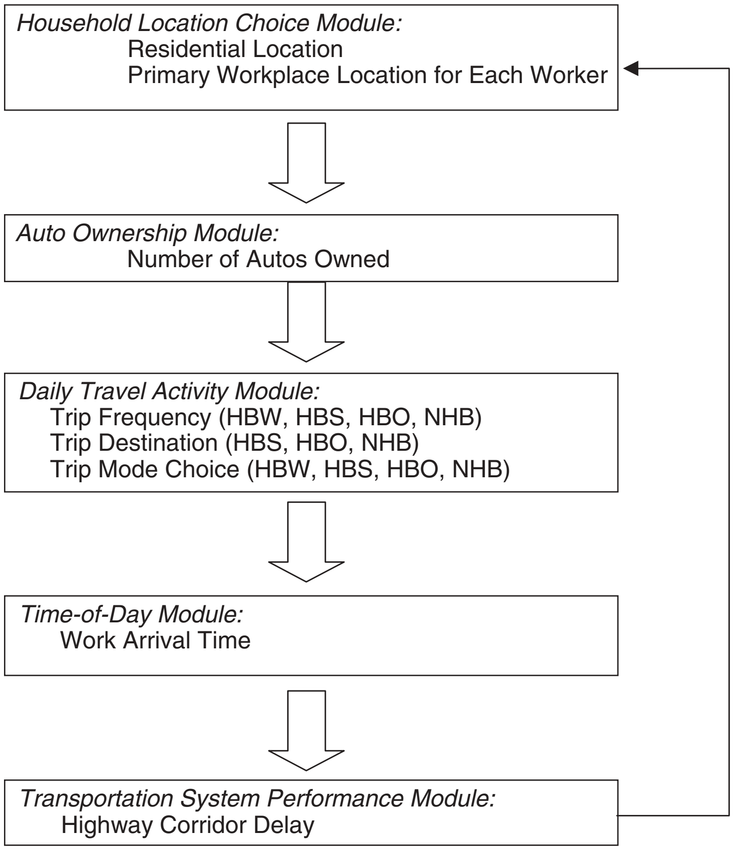
STEP is a package of microscopic household-level travel demand models designed for planning applications and policy analysis. The STEP model can predict the influence of travel time and cost on residential household location, primary work location, vehicle ownership, trip frequencies, trip destinations, mode choice, and time of day.

The STEP model is composed of 5 modules (see Figure 12):

- Household Location Choice Module,
- Auto Ownership Module,
- Daily Travel Activity Module,
- Time-of-Day Module, and
- Transportation System Performance Module.

The results of the Transportation System Performance Module are fed back into the Household Location Choice Module.

STEP uses sample enumeration to obtain aggregate forecasts. STEP is applied to a sample of households within the



Note:
HBW - Home-Based Work Trips
HBS - Home-Based Shopping Trips
HBO - Home-Based Other Trips
NHB - Non-Home-Based Trips

Figure 12. Flow chart of STEP model.

region (typically 5,000 households). The results are then expanded to represent total regional travel activity. STEP outputs daily VMT, fuel consumption, and mobile emissions.

7.3.1 Input Data Requirements

The required input data for STEP are

- Socioeconomic data (the socioeconomic characteristics of a sample of households in the region obtained from a household travel survey or the U.S. Census PUMS),
- Land-use data (population, number of households, and employment by category located by zone or district in the region), and
- Transportation level-of-service data (travel times and costs).

7.3.2 Household Location Module

The Household Location Module uses a multinomial logit model to predict the probability of a household locating in a district. The probability is sensitive to the relative housing costs, ethnic makeup, crime rate, tax rate, quality of schools, and the accessibility to jobs for each location. Household location districts are typically the U.S. Census PUMAs. The probability that a household will choose to live in district i can be calculated as follows:

$$P_i = \frac{\exp(U_i)}{\sum_{i=1}^{n} \exp(U_i)} \qquad \text{Equation 17}$$

Where:

P_i = the probability that a household will choose to live in district i,
U_i = the perceived utility of district i as a residence, and
n = the number of districts in the region.

The perceived utility of district i as a residence (U_i) can be calculated as follows:

$$\begin{aligned} U_i = {} & b_1\left[\frac{\text{price}_i}{f(\text{income})}\right] + b_2(\text{ethnicity}_i) \\ & + b_3(\text{crime}_i) + b_4(\text{tax}_i) + b_5(\text{school}_i) \\ & + b_6(\text{mode}_i) \end{aligned} \qquad \text{Equation 18}$$

Where:

price_i = the mean monthly price of the household's current type (rent, own, single, multi) for district i,
$f(\text{income})$ = a nonlinear transformation of the household's income,
ethnicity_i = the percentage of households in district i with this household's ethnicity,
crime_i = the rate of serious and violent crime per 100,000 residents at location i,
tax_i = the property tax on a home of average value at district i (homeowners only),
school_i = the average per-pupil expenditure in location i (households with children only),
mode_i = the sum of the log of the denominator of the mode choice model for work trips from district i for each worker in the household across all modes, and
$b_1, \ldots, b_6$ = parameters fitted by estimation.

The parameters (b) vary by the number of workers in the household. A land price model is used to reflect the effect of supply constraints on price and therefore demand.

7.3.3 Vehicle Ownership Module

Two logit models are used to predict the probability of a household owning 0, 1, or 2+ vehicles. One model is used for households with workers and the other for households without workers.

Both models take the following form:

$$P_v = \frac{\exp(U_v)}{\sum_{k=1}^{2+} \exp(U_k)} \qquad \text{Equation 19}$$

Where:

P_v = the probability of choosing vehicle ownership level v,
U_k = the household's utility for vehicle ownership level k,
U_v = the household's utility for vehicle ownership level v, and
k = the set of vehicles ownership levels (0, 1, 2+).

The variables and coefficients for the three utility functions (for 0, 1, and 2+ auto households) are shown in Table 18. For example, the utility of owning one auto is

$$\begin{aligned} U_1 = {} & 4.989 + 0.3935\,\text{sin fam} - 0.05419\text{eden} \\ & - 2.689\frac{\text{autos}}{\text{hhsize}} + 0.06814\text{twork}_1 \\ & + 0.7919\ln(\text{rinc}_1) \end{aligned} \qquad \text{Equation 20}$$

The nonworker household vehicle ownership model has the same form as the worker model. The utility specifications and coefficients are shown in Table 19. For example, the utility of owning one auto for a zero worker household is

$$U_1 = -0.8695 + 0.3188x\ln\left(\frac{\text{dinc}}{\text{hhsize}}\right) \qquad \text{Equation 21}$$

TABLE 18 Variables and coefficients for worker households with 0, 1, and 2+ autos

Coefficient Value	Variables in the Utility			Explanation
	0 Vehicle	1 Vehicle	2 or More Vehicles	
4.989		const		1 vehicle ownership constant.
5.689			const	2+ vehicle ownership constant.
0.3935		sinfam		Constant for single-family detached unit.
1.342			sinfam	Constant for single-family detached unit.
-0.05419		eden	eden	Workers per acre in the home zone.
-2.689		autos/hhsize	autos/hhsize	Autos per person in household. The variable "autos" has the value 1 for $v = 1$ and 2.25 for $v = 2+$.
0.5608	tshop			A measure of the quality of transit service from the home zone for nonwork trips, defined as the sum of transit utilities divided by the sum of auto utilities for the shopping destination/mode choice model.
0.06814	twork_0	twork_1	twork_2+	A measure of the quality of transit service from the home zone for work trips, defined as the household head's work trip transit utility divided by the sum of work trip drive and work trip shared-ride utilities.
0.7919	$\ln(\text{rinc}_0)$	$\ln(\text{rinc}_1)$	$\ln(\text{rinc}_2+)$	Natural log of the remaining income after housing, auto ownership, and commuting expenses subtracted.

7.3.4 Daily Travel Activity Module

The Daily Travel Activity Module predicts trip frequency, distribution, and mode choice as a function of travel time and cost plus other variables using multinomial logit models with varying utility functions.

7.3.4.1 Home-Based Work Trip Distribution Model

Once the residence location i and auto ownership have been determined, a logit model is used to predict the probability of working in zone j:

$$P_d = \frac{\exp\left[\ln(w_d) + 1.811\sum_{v=1}^{2+}\left(P_v * E\left[U_{m|vd}\right]\right)\right]}{\sum_{i=1}^{\text{nzones}}\exp\left[\ln(w_i) + 1.811\sum_{v=1}^{2+}\left(P_v * E\left[U_{m|vi}\right]\right)\right]} \quad \text{Equation 22}$$

Where:

P_d = the probability of choosing destination d as the workplace;

w_d = the total number of workers attracted to (or jobs available in) zone d;

w_i = the total number of workers attracted to (or jobs available in) zone i;

$E[U_{m|v\,d}]$ = the expected utility of work mode choice to destination d, given auto ownership level v (the expected utility is defined here as the natural logarithm of the sum of the utilities for travel to destination d, via each mode m, given auto ownership level v);

$E[U_{m|v\,i}]$ = the expected utility of work mode choice to destination i, given auto ownership level v (the expected utility is defined here as the natural logarithm of the sum of the utilities for travel to destination i, via each mode m, given auto ownership level v);

TABLE 19 Variables and coefficients for nonworker households with 0, 1, and 2+ autos

Coefficient Value	Variables in the Utility			Explanation
	0 Vehicles	1 Vehicle	2 or More Vehicles	
-0.8695		const		1 vehicle ownership constant.
-8.357			const	2+ vehicle ownership constant.
-0.0682			popden	Population density in home zone (persons per acre).
0.3188		$\ln\left(\frac{\text{dinc}}{\text{hhsize}}\right)$		Natural log of the household disposable income per person.
1.227			$\ln\left(\frac{\text{dinc}}{\text{hhsize}}\right)$	Natural log of the household disposable income per person.
0.5608	tshop			A measure of the quality of transit service from the home zone for nonwork trips, defined as the sum of transit utilities divided by the sum of auto utilities for the shopping destination/mode choice model.

P_v = the probability of choosing household auto ownership level v; and
nzones = the number of zones in the region.

Greig Harvey, in his description of STEP, equates the expected value of a utility function across several alternatives with the natural logarithm of the sum of the utilities for the alternatives. However, the mathematical equivalence could not be confirmed. Nevertheless, Harvey's use of the term "expected value" for the logsum has been retained in this discussion.

Note that this model is not constrained by the number of available jobs in the destination zone, although the number of jobs influences the likelihood of a worker going to that zone.

7.3.4.2 Home-Based Work Mode Choice Model

The probability of a mode being selected for a home-based work trip is multinomial logit, with the utility of each mode defined in Table 20. For example, the utility for drive-alone trips is

$$\begin{aligned} U_a = {} & -2.512 - 0.00000714\text{dinc} - 1.067\text{cbd} \\ & - 0.0244\text{ivtt}_a - 0.077\text{walk}_a \\ & - 21.43(\text{cost}_a/\text{inc}) + 1.958\,\text{autos} \\ & + 0.677\text{head} \end{aligned} \qquad \text{Equation 23}$$

The auto occupancy for shared-ride, home-based work trips is computed according to the following equation, which is constrained to have a value greater than 2:

$$\text{srocc} = \text{Max}[(2.542 * 0.00004717\text{dinc} + 0.01116\text{ivtt(s)}), 2.0] \qquad \text{Equation 24}$$

Where:

srocc = the shared-ride occupancy;
dinc = the household disposable income; and
ivtt_s = the shared-ride, in-vehicle time.

7.3.4.3 Home-Based Shop Trip Frequency Model

The daily frequency of home-based shop trips is determined according to the following nonlinear regression equation:

$$\text{hbshop} = \frac{0.8194}{0.0766 + \exp(U_{hbs})} \qquad \text{Equation 25}$$

Where:

hbshop = the daily frequency of home-based shop trips;
U_{hbs} = –0.34174 (household size) – 0.51512 (income/100) – 0.52681 $E(U_{dm})$ + 0.1146 ln(1 + employment density); and
$E(U_{dm})$ = natural logarithm of the denominator of the home-based shop destination and mode split model.

7.3.4.4 Home-Based Shop Trip Destination and Mode Choice Model

Home-based shopping trips are distributed and split between modes using a multinomial logit model that defines each possible combination of zone destination and mode choice as a separate alternative. The basic model form is as follows:

$$P_{dm} = \frac{\exp(U_{dm})}{\sum_{j=1}^{\text{nzones}} \sum_{i=a,t} \exp(U_{ji})} \qquad \text{Equation 26}$$

Where:

a = auto mode;
t = transit mode;
U_{ji} = the traveler utility for the destination j, mode i combination;
P_{dm} = the probability of taking a shop trip to destination d by mode m; and

TABLE 20 Variables and coefficients for drive alone, shared ride, and transit

Coefficient Value	Variables in the Utility by Mode			Explanation
	Drive alone	Shared ride	Transit	
-0.00000714	dinc	dinc		Household disposable income.
-1.067	cbd			Constant for central business district.
-0.347		cbd		Constant for central business district.
0.327		nwork		Number of workers in household.
-0.0244	ivtt_a	ivft_s	ivtt_t	In-vehicle travel time (minutes).
-0.077	walk_a	walk_s	walk_t	Walk time (minutes).
-0.045			waitl	Transit initial wait (minutes).
-0.0428			Xferwait	Transit transfer wait (minutes).
-21.43	cost_a/inc	cost_s/inc	cost_t/inc	Cost (cents)/household income.
1.958	autos			Number of autos in household.
1.763		autos		Number of autos in household.
1.389			autoslaac	Number of autos for auto access.
-1.237			aac	Constant for auto access to transit.
0.677	head			Constant for head of household.
-2.512	const			Drive-alone constant.
-3.473		const		Shared-ride constant.

U_{dm} = the traveler utility for the destination d mode m combination.

The utility equations are linear with variables and coefficients as defined in Table 21. For example, the utility of the auto mode (U_a) is

$$\begin{aligned} U_a = & -0.8631 + 0.2563\text{cbd} \\ & + 5.053(\text{autos/hhsize}) \\ & - 0.000202(\text{time}_a * \text{inc}) \\ & - 0.2447\text{cost}_a + 0.0005995\text{rden} \\ & + \ln(\text{rjobs}) \end{aligned} \qquad \text{Equation 27}$$

7.3.4.5 Home-Based Social or Recreational Trip Destination and Mode Choice Model

Home-based social or recreational trips are distributed and split between modes using a multinomial logit model that defines each possible combination of zone destination and mode choice as a separate alternative. The basic model form is the same as for shopping trips. The utility functions are linear, with coefficients and variables as defined in the Table 22. For example, the utility of the auto mode (U_a) is

$$\begin{aligned} U_a = & \ 1.844 - 0.215\text{cbd} \\ & + 2.167(\text{autos/hhsize}) + 0.3368\text{rautos} \\ & - 0.0001097(\text{time}_a * \text{inc}) \\ & - 0.0256\ \text{cost}_a + 0.0609\text{rden} \\ & + 0.0244\text{popden} \\ & + 0.6998\ \ln(\text{pop/rjobs}) + \ln(\text{rjobs}) \end{aligned} \qquad \text{Equation 28}$$

7.3.4.6 Home-Based Social or Recreational Trip Frequency Model

The daily frequency of social or recreational trips is a function of household characteristics, home zone characteristics, and destination characteristics (as embodied in the expected utility for social or recreational destination/mode choice). The trip frequency model is as follows:

$$\begin{aligned} \text{hbsr} = & \ 0.1398 * \exp[0.4671 * \ln(\text{hhsize})] \\ & + 0.005055 * (\text{hhsize} - \text{nwork}) \\ & + 0.3963 * \ln(\text{inc} \div 100) \\ & + 0.06785 * E[U_{dm}] \\ & - 0.3213 * \ln(\text{seden} + 1) \end{aligned} \qquad \text{Equation 29}$$

TABLE 21 Home-based shop trip destination and mode choice variables and coefficients for auto and transit

Coefficient Value	Variables in the Utility		Explanation
	Auto	Transit	
-0.8631	const		Auto constant.
0.2563	cbd		Constant for central business district.
0.8912		cbd	Constant for central business district.
5.053	autos/hhsize		Autos per person in household.
-0.000202	time_a*inc	time_t*inc	Door-to-door travel time (minutes) weighted by income.
-0.02447	cost_a		Cost (cents).
-0.02299		fare*hhsize	Transit fare (cents) weighted by household size.
0.0005995	rden	rden	Retail density (employees per population serving acre).
1.0	ln(rjobs)	ln(rjobs)	Natural log of retail workers in zone.

TABLE 22 Home-based social or recreational trip destination and mode choice variables and coefficients for auto and transit

Coefficient Value	Variables in the Utility		Explanation
	Auto	Transit	
1.844	const		Auto constant.
-0.215	cbd		Constant for central business district (destination).
1.19		cbd	Constant for central business district (destination).
2.167	autos/hhsize		Autos per person in household.
0.3368	rautos		Autos not used for work trips.
-0.0001097	time_a*inc	time_t*inc	Door-to-door travel time (minutes) weighted by income.
-0.0256	cost_a		Cost (cents).
-0.0108		fare*hhsize	Transit fare (cents) weighted by household size.
0.0609	rden	rden	Retail density at destination (employees per acre).
0.0244	popden	popden	Persons per acre at destination.
0.6998	ln(pop/rjobs)	ln(pop/rjobs)	Natural log of population per retail job at the destination.
1.0	ln(rjobs)	ln(rjobs)	Natural log of retail employment in the destination zone.

Where:

hbsr = the number of daily home-based social or recreational trips per household;
hhsize = the number of persons in the household;
nwork = the number of workers in the household;
inc = the household income (dollars per year);
$E[U_{dm}]$ = the expected utility from the social or recreational destination/mode choice model, defined as the natural log of the denominator of that model's logit equation; and
seden = the service employment density, in workers per gross acre.

All other trip purpose frequencies (home-based work, non–home-based trip) are kept constant in STEP.

7.3.5 Time-of-Day Module

A nested logit Time-of-Day Module is used to predict the starting time of work trips during the morning peak period. (This module had not been implemented at the time of Harvey's description. The description provided here is more of a conceptual guideline rather than an actual module.)

The top level of the Time-of-Day Module estimates the binary probability that a worker has a regular schedule (e.g., a work start time between 5:30 AM and 10:30 AM) or an irregular schedule. This probability is a function of household income, household size, and the ratio between AM peak and offpeak highway travel time.

For regular schedule workers, the conditional probability is then computed that a regular-schedule worker will start work during any one of the five morning hours between 5:30 and 10:30 AM. This conditional probability is a function of household size and the ratio of AM peak to offpeak travel.

7.4 ASSESSMENT

TRANSIMS is still in its early stages of development and, as such, is more a philosophical approach to travel demand modeling rather than an actual model. As criticisms are leveled at specific steps, the problems are fixed and TRANSIMS becomes a different model. Efforts are currently underway to replace TRANSIMS's simplistic Travel Pattern Selection Module with a more theoretically sound Travel Behavior Module based upon the Portland Tour-Based Model.

In essence, the basic philosophy of TRANSIMS is employing unlimited computing power for the microscopic simulation of the second-by-second movements of individual people through the region. As such, the resources required to feed and operate such a model is beyond the range of feasible options for NCHRP Project 25-21. Additional refinements to TRANSIMS (such as recent work to make much of the required traffic control information endogenous to the model) and further improvements in personal computers will no doubt improve the model's feasibility, but the model is not currently a viable option for NCHRP Project 25-21.

The Portland Tour-Based Model, in contrast to TRANSIMS, has already been trimmed back from its idealized activity-based theoretical foundations to ensure feasible application on current computer facilities. As such, the Portland Tour-Based Model is a possible option for NCHRP Project 25-21, although some travel demand responses will have to be cut from the model to ensure feasible operation. Since there is little experience with this modeling approach outside of the Portland area, there is concern over its application to other regions. For example, demand responses, which occur infrequently in Portland and thus could be replaced with fixed factors, may be more important in other areas. Then again, demand responses might be equally unimportant elsewhere. It is simply not known at this time. The bottom line, however, is that Portland represents a significant improvement in demand-modeling capabilities and thus should be tested in NCHRP Project 25-21.

The STEP model was once the leading state-of-the-art approach to modeling the impacts of transportation supply changes on demand. Its groundbreaking focus on modeling household travel behavior and using sample enumeration to extrapolate household effects to regional effects allowed the consideration of more detailed demand effects than possible for more aggregate models. However, the analytical heart of STEP is several years old. The demand models it is based on have been gradually replaced with more up-to-date nested logit models. The concept of modeling household behavior is still as valid as (if not more so than) when Harvey created STEP; however, the analytical engine needs to be updated. The bottom line conclusion is that the STEP concept is very appropriate for testing in NCHRP Project 25-21, with the actual demand model formulas updated to the latest practice.

CHAPTER 8

TRAFFIC OPERATION MODELS

This chapter reviews methodologies for predicting vehicle mode of operation activity. The methodologies range from the simplistic link-based Bureau of Public Roads (BPR) equation to the *Highway Capacity Manual* to dynamic microsimulation.

8.1 THE BPR EQUATION

The standard BPR (predecessor to the FHWA) equation was developed in the late 1960s by fitting a polynomial equation to the freeway speed-flow equations contained in the 1965 *Highway Capacity Manual*.

The standard BPR equation is as follows:

$$s = \frac{s_f}{1 + a(v/c)^b} \qquad \text{Equation 30}$$

Where:

s = predicted mean speed,
s_f = free-flow speed,
v = volume,
c = practical capacity,
a = 0.15, and
b = 4.

Practical capacity is defined in this equation as 80 percent of the capacity. Free-flow speed is defined as 1.15 times the speed at the practical capacity.

The parameter a determines the ratio of free-flow speed to the speed at capacity. The parameter b determines how abruptly the curve drops from the free-flow speed. A high value of b causes speed to be insensitive to v/c until the v/c gets close to 1.0; then, the speed drops abruptly.

Planners typically use tables based on area type and facility type for assistance in coding free-flow speed and capacity data. These tables allow planners to use simple road maps and aerial photos to code the free-flow speed and capacity information for 5,000 to 10,000 links in a region.

A common error of practitioners has been to overlook that "capacity" in the standard BPR equation is actually practical capacity, which is closer to 80 percent of the actual capacity of the facility.

Table 23 shows practical capacity and free-flow speed. The table was developed by the FHWA[118] for use with the BPR equation.

8.2 HIGHWAY CAPACITY MANUAL

The *Highway Capacity Manual*[119] contains a series of procedures for predicting the steady-state traffic conditions at a macroscopic level. Traffic performance in terms of mean delay, mean travel speed, and mean density are predicted for the peak 15-minute period within the peak hour. Dynamic effects such as the build-up of traffic queues over several time periods and the impact of one time period on the following time period are not explicitly considered (although a few of the procedures allow users to manually account for these effects). Modal activity (acceleration, deceleration, idle, and cruise) is not predicted by the HCM procedures.

The HCM procedures are generally sensitive to the geometric design of the facility (width, grade, number of lanes, etc.), the traffic controls (stop sign, signal, signal timing, coordination, etc.), and the demand (vehicles, vehicle mix, peaking, turning movements, etc.). Demand is assumed to be fixed, peaking by a fixed percentage (selected by the user) within the peak hour.

A key step of all of the HCM procedures is the computation of facility capacity. This computation is normally sensitive to the facility design characteristics. The following equation illustrates the computation of capacity for the approach to a signalized intersection:

$$\begin{aligned} c = g/C * s_0 * N * f_W * f_{HV} * f_g * f_p * f_{bb} * f_a \\ * f_{LU} * f_{LT} * f_{RT} \end{aligned} \qquad \text{Equation 31}$$

Where:

c = the capacity of approach (vehicles per hour),
g/C = the ratio of signal green time to total signal cycle length,
s_0 = the base saturation flow rate (vehicles per hour of green per lane),
N = the number of lanes on the approach,
f_W = the lane width adjustment factor,
f_{HV} = the heavy vehicle adjustment factor,

TABLE 23 Capacities and speeds for BPR equation

<table>
<tr><td colspan="7">Practical Capacity Table for BPR Equation (VPH)</td></tr>
<tr><td>Area Type</td><td>Freeway</td><td>Expressway</td><td>Two-Way Arterial (Parking)</td><td>One-Way Arterial (Parking)</td><td>Centroid Connector</td><td>Two-Way Arterial (No Park)</td></tr>
<tr><td>CBD</td><td>1750</td><td>800</td><td>600</td><td>700</td><td>10,000</td><td>600</td></tr>
<tr><td>Fringe</td><td>1750</td><td>1000</td><td>550</td><td>550</td><td>10,000</td><td>800</td></tr>
<tr><td>Outer CBD</td><td>1750</td><td>1000</td><td>550</td><td>650</td><td>10,000</td><td>800</td></tr>
<tr><td>Rural/ Residential</td><td>1750</td><td>1100</td><td>550</td><td>900</td><td>10,000</td><td>800</td></tr>
<tr><td colspan="7">Free-Flow Speed Table for BPR Equation (MPH)</td></tr>
<tr><td>Area Type</td><td>Freeway</td><td>Expressway</td><td>Two-Way Arterial (Parking)</td><td>One-Way Arterial (Parking)</td><td>Centroid Connector</td><td>Two-Way Arterial (No Park)</td></tr>
<tr><td>CBD</td><td>48</td><td>37</td><td>22</td><td>22</td><td>10</td><td>22</td></tr>
<tr><td>Fringe</td><td>48</td><td>44</td><td>25</td><td>29</td><td>15</td><td>25</td></tr>
<tr><td>Outer CBD</td><td>58</td><td>37</td><td>22</td><td>24</td><td>15</td><td>22</td></tr>
<tr><td>Rural/ Residential</td><td>67</td><td>47</td><td>28</td><td>32</td><td>15</td><td>28</td></tr>
</table>

CBD = central business district.
MPH = miles per hour.
VPH = vehicles per hour.

f_g = the approach grade adjustment factor,
f_p = the parking lane adjustment factor,
f_{bb} = the local bus adjustment factor,
f_a = the area type adjustment factor,
f_{LU} = the lane-use adjustment factor,
f_{LT} = the left-turn adjustment factor, and
f_{RT} = the right-turn adjustment factor.

The delay computation is typically sensitive to the capacity, the demand, and the traffic control characteristics. The following equations illustrate the computation of intersection approach delay for a traffic signal:

$$D = d_u * \mathrm{DF} + d_i + d_3 \qquad \text{Equation 32}$$

$$d_u = (0.50) * C * \frac{\left[1 - (G/C)\right]^2}{\left[1 - (G/C) * \mathrm{Min}(X, 1.0)\right]} \qquad \text{Equation 33}$$

$$d_i = 900 * T * \left[(X-1) + \sqrt{(X-1)^2 + 8 * k * I * X/(T * c)}\right] \qquad \text{Equation 34}$$

Where:

D = the approach total delay, in sec/veh;
d_u = the approach uniform delay, in sec/veh;
d_i = the approach incremental delay, in sec/veh;
d_3 = the residual demand delay caused by queued vehicles at the start of the analysis period, in seconds;
DF = the delay adjustment factor (function of quality of signal coordination);
C = the cycle length, in seconds;
G = the effective green time for the lane group, in seconds;
X = the volume/capacity ratio for the subject lane group;
c = the capacity for the through lane group;
T = the length of the analysis period, in hours;
k = the actuated signal control factor; and
I = the upstream signal factor.

8.3 PLANNING MODEL TO HCM LINK

Many MPOs have attempted to introduce HCM techniques into their estimation of facility capacities, vehicle speeds, and delay. The FHWA[120] has produced a guidebook on innovative techniques for accomplishing this. The guidebook cites postprocessing approaches that have been used to improve speed estimates produced by travel models.

NCHRP Report 387[121] presents procedures for implementing improved link-based speed and delay estimation procedures based on the HCM. These procedures use an improved speed-flow equation based on the Akcelik equation, which was used in the HCM to produce estimates of delay.

Horowitz[122] adapted the 1994 HCM procedures for use in estimating node-based delay for his QRS model. Node delay procedures are generally considered to be more accurate than link-based procedures, since node-based procedures take into account the demands on the conflicting approaches at an intersection. Node-based delay procedures, however, introduce the possibility of multiple solutions to the user optimum equilibrium traffic assignment problem. Horowitz indicates that while this can happen, it has not been a problem.

The 2000 edition of the HCM[123] contains the following link-based procedure for predicting mean vehicle speeds. The mean vehicle speed for the link is computed by dividing the link length by the link traversal time. The link traversal time

(R) is computed according to the following modified Akcelik equation:

$$R = R_0 + D_0 = D_L + 0.25N * T\left[(x-1) + \sqrt{(x-1)^2 + \frac{16J * L^2 * x}{N^2T^2}}\right] \qquad \text{Equation 35}$$

Where:

R = the segment traversal time, in hours;
R_0 = the segment traversal time at free-flow speed, in hours;
D_0 = the zero-flow control delay at signals (equals zero if no signals), in hours;
D_L = the segment delay between signals (equals zero if no signals), in hours;
N = the number of signals on the segment (if no signals, set $N = 1$);
T = the expected duration of the demand (typically 1 hour), in hours;
x = the segment demand/capacity ratio;
L = the segment length, in kilometers; and
J = the calibration parameter.

Note that the zero-flow control delay (D_0) and segment delay (D_L) terms are required because the HCM defines free-flow speed on signalized arterials to *exclude* delays due to signals and segment delays due to close signal spacing.

The segment traversal time at free-flow speed (R_0) is computed from the free-flow speed:

$$R_0 = {}^{L}\!/_{S_0} \qquad \text{Equation 36}$$

Where:

R_0 = the segment traversal time at free-flow speed, in hours;
L = length, in kilometers; and
S_0 = the segment free-flow speed, in mph.

The zero-flow control delay for signalized intersections (if any) (D_0) on the segment is computed using the following equation:

$$D_0 = \frac{N}{3{,}600} * \text{DF} * \frac{C}{2}\left(1 - {}^{g}\!/_{C}\right)^2 \qquad \text{Equation 37}$$

Where:

D_0 = the zero-flow control delay at the signal, in hours;
N = the number of signals on the segment;
3,600 = the conversion from seconds to hours;
g/C = the average effective green time per cycle for signals on segment (default = 0.44);
C = the average cycle length for all signals on the segment (default = 120), in seconds;
DF = delay factor;
= 0.9 for uncoordinated traffic actuated signals;
= 1.0 for uncoordinated fixed-time signals;
= 1.2 for coordinated signals with unfavorable progression;
= 0.90 for coordinated signals with favorable progression; and
= 0.60 for coordinated signals with highly favorable progression.

The segment delay between signals (D_L) is obtained by multiplying the length of the arterial (or segment) for which a speed or travel time estimate is desired by the segment delay per kilometer shown in Table 24.

The number of signals (N) on the facility segment is obvious, except for when there are no signals. When there are no signals on the facility, N is still set equal to 1. This is because N is really the number of delay-causing elements on the facility. Each delay-causing element on the facility adds to the overall segment delay when demand starts to approach and/or exceed capacity at that element or point. Since demand in excess of capacity must wait its turn to enter the facility seg-

TABLE 24 Segment delay between signals (secs/km)

Arterial Class:	I	I	I	II	II	III	III	III	IV	IV	IV
Free-Flow Speed (km/h)	88	80	72	72	64	56	56	48	56	48	40
Signal Spacing (km)	Segment Delay Between Signals (secs/km)										
0.08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	66.9	75.6
0.16	n/a	n/a	n/a	n/a	n/a	n/a	26.3	21.9	38.8	37.5	47.5
0.24	n/a	n/a	n/a	n/a	n/a	n/a	20.1	13.1	23.2	18.8	22.5
0.32	18.1	18.1	18.1	18.1	15.6	13.8	15.7	8.8	17.0	12.5	13.1
0.40	15.0	15.0	15.0	15.0	12.5	10.1	10.7	4.4	12.0	7.5	5.6
0.48	11.9	11.9	11.9	11.9	7.5	4.5	0.0	0.0	0.0	0.0	0.0
0.64	8.8	8.8	8.8	8.8	3.8	1.3	n/a	n/a	n/a	n/a	n/a
0.80	5.0	5.0	5.0	5.0	1.9	0.1	n/a	n/a	n/a	n/a	n/a
1.60	0.0	0.0	0.0	0.0	0.0	0.0	n/a	n/a	n/a	n/a	n/a

Source: 1994 *Highway Capacity Manual*, Table 11-4, Segment Running Time Per Mile, which is being included in the 2000 HCM, unchanged. The above table was computed by subtracting the running time if traveling at free-flow speed from running time shown in Table 11-4 and then converting the result to Standard International (SI) units.

ment, there is always at least one delay-causing element (the segment itself) on a facility, even when there are no signals. The more signals there are on a facility, the more points there are where traffic is delayed along the way.

The duration of demand (T) is usually 1 hour for a peak-hour analysis but can be longer for a peak-period analysis. The total demand for the peak period is divided by the number of hours to arrive at the average hourly demand rate that is used to compute the average demand/capacity ratio (x) for the peak period.

The calibration parameter J is selected so that the traversal time equation will predict the mean speed of traffic when demand is equal to capacity. The values for J, shown in Table 25, reproduce the mean speed at capacity predicted by the analysis procedures contained in the HCM. The data for two-lane rural highways are tentative. They are taken from recent, as yet unpublished research to update the HCM methodology for these facilities. The following equation was used to generate the J parameter values in Table 25:

$$J = \left(\frac{1}{S_c} - \frac{1}{S_f} \right)^2 \qquad \text{Equation 38}$$

Where:

S_c = the mean speed at capacity (km/h) and
S_f = the mean speed when demand is zero (km/h).

8.4 MICROSIMULATION MODELS

There are numerous microsimulation models, many designed for just one type of facility or one type of intersection. Table 26 provides a succinct inventory of the majority of the models classified according to their target facility types and geographic coverage capacity. The following paragraphs provide descriptions of the four italicized models in the table: CORSIM, INTEGRATION, Paramics, and VisSim.

8.4.1 The CORSIM Model

The CORSIM model is a dynamic microsimulation model. Vehicle movements are simulated every second, and statistics are gathered on vehicle operating mode. The CORSIM model is composed of two submodels, FREESIM for the freeway and ramps and NETSIM for the surface street system.[124]

8.4.1.1 FREESIM

FREESIM is based upon the proposition that each vehicle will seek to travel at the driver's desired speed in the absence of other vehicles and geometric constraints (grades, lane drops, ramp merges, and horizontal curves). The desired speed is link and driver dependent. It is determined by the mean speed coded for each link and the driver's aggressiveness level (randomly selected at the time the vehicle first enters the network

TABLE 25 Recommended traversal time *J* parameters

Facility Type	Signals Per km	Free-Flow Speed (km/h)	Speed (km/h) at Capacity	J
Freeway	n/a	120	86	1.05E-05
	n/a	112	85	8.20E-06
	n/a	104	83	5.78E-06
	n/a	96	82	3.38E-06
	n/a	88	80	1.29E-06
Multilane Hwy	n/a	96	88	8.97E-07
	n/a	88	82	7.94E-07
	n/a	80	75	6.37E-07
	n/a	72	67	9.84E-07
Two-Lane Hwy	n/a	110	70	2.70E-05
	n/a	100	60	4.44E-05
	n/a	90	50	7.90E-05
	n/a	80	40	1.56E-04
	n/a	70	30	3.63E-04
Arterial Class I	0.333	80	53	2.21E-05
	1	80	31	1.83E-04
	2.5	80	15	1.30E-03
Arterial Class II	0.5	64	40	4.99E-05
	1	64	28	1.96E-04
	2	64	18	7.91E-04
Arterial Class III	2	56	17	8.74E-04
	3	56	13	1.78E-03
	4	56	10	3.18E-03
Arterial Class IV	4	48	10	3.17E-03
	5	48	8	5.37E-03
	6	48	7	7.11E-03

TABLE 26 Inventory of microsimulation models

SIMULATION	TYPE		OPERATING ENVIRONMENT					
MODEL	MAC/ MIC	D/S	ISOLATED INTERSECTIONS	ARTERIALS	NETWORKS	FREEWAYS	FREEWAY CORRIDORS	RURAL HIGHWAYS
CONTRAM	MAC	D		▨	▨	▨	▨	
DYNASMART	MES	D		▨	▨	▨	▨	
CORFLO	MAC	D/S		▨	▨	▨	▨	
CORSIM	*MIC*	*S*	▨	▨	▨	▨	▨	
EVIPAS	MIC	S	▨					
FLEXSYT	MIC	S	▨	▨	▨			
FREQ11	MAC	D				▨	▨	
INTEGRATION	*MIC*	*D/S*	▨	▨	▨	▨	▨	
METACOR	MAC	D					▨	
PARAMICS	*MIC*	*S*	▨	▨	▨	▨	▨	▨
ROADSIM	MIC	S						▨
SATURN	MAC	D		▨	▨			
TEXAS	MIC	S	▨					
TRAFFICQ	MIC	S	▨	▨	▨			
TRARR	MIC	S						▨
TWOPAS	MIC	S						▨
WATSIM	MIC	S	▨	▨	▨	▨	▨	
VISSIM	*MIC*	*S*	▨	▨	▨	▨		

MAC = macroscopic. MIC = microscopic. MES = mesoscopic. D = deterministic. S = stochastic.
Source: Skabardonis, *"Assessment of Traffic Simulation Models,"* Final Report, prepared for Office of Urban Mobility, Washington State Department of Transportation, May 1999.

from a default or user-specified distribution of driver types). The driver's aggressiveness determines how much faster or slower the vehicle will travel than the coded mean desired speed for the link.

8.4.1.1.1 Car-Following Equations. The presence of other vehicles and geometric constraints trigger acceleration or deceleration events as the vehicle adjusts its speed in response to the constraints.

FREESIM assumes that in the presence of other vehicles, a vehicle will attempt to maintain a constant distance behind a lead vehicle. The desired following distance is a function of the speed of the following vehicle and the difference in speeds of the lead and following vehicles:

$$d = 10 + kv + bk(u - v)^2 \qquad \text{Equation 39}$$

Where:

d = the desired following distance between the back of the lead vehicle and the front of the following vehicle (feet),
k = driver sensitivity for the follower vehicle,
v = the speed of the follower vehicle (fps),
u = the speed of the lead vehicle (fps), and
b = a calibration constant.

Aggressive and nonaggressive drivers will have different desired following distances according to their "driver sensitivity factor" (k). The driver sensitivity factor (k) is one of the main determinants of freeway capacity in FREESIM. Lower k's result in higher capacities.

If the two vehicle speeds are different, then the desire to maintain a constant distance will result in acceleration or deceleration of the following vehicle. The vehicle's acceleration (a) is determined according to the following equation (note that deceleration is the same as negative acceleration):

$$a = \frac{2\left(d - 10 - v(k + T) - bk(u - v)^2\right)}{T^2 + 2kT} \qquad \text{Equation 40}$$

Where:

a = the acceleration rate (fpss),
d = the distance between back of lead vehicle and front of following vehicle (feet),
k = driver sensitivity for the follower vehicle,
v = the speed of the follower vehicle (fps),
u = the speed of the lead vehicle (fps),
b = a calibration constant, and
T = the duration of scanning interval (secs).

The emergency requirement to avoid collisions overrides the acceleration determined by the car-following equation. The following vehicle must be able to stop safely behind the lead vehicle when the lead vehicle decelerates to a stop at the maximum allowable emergency deceleration.

Similarly, the vehicle performance characteristics will limit the acceleration predicted by the car-following equation.

8.4.1.1.2 Geometric Constraints. For lane drops and ramp merges, the vehicle acceleration is computed by comparing the acceleration that would be predicted by the car-following equation (assuming that the lead vehicle is located at the lane drop or merge location and has a zero speed) with the acceleration rate required to come to a complete stop at the lane drop or merge location. The lower of the two acceleration rates is selected, subject to the vehicle's performance capabilities.

Changes in the user-coded mean desired speed between two sequential links will trigger acceleration events as the vehicles change speed between links. If the downstream link has a horizontal curve with a safe speed lower than the user-coded mean speed, the safe speed will override the user coding. Similarly, if the downstream link has a steep grade that results in a sustainable speed for trucks that is lower than the user-coded desired mean speed, the maximum sustainable speed will override the user coding (within the range of allowable grades and speeds in FREESIM, the sustainable speeds of passenger cars are unaffected by grades).

8.4.1.1.3 Lane-Changing Criteria. Changing lanes will also trigger an acceleration or deceleration event in FREESIM. The lane-changing vehicle must either accelerate or decelerate in order to fit between vehicles in the new lane. Vehicles change lanes according to gap acceptance criteria.

An available gap in the desired lane is evaluated according to two acceleration criteria: the required deceleration for the lane changer to safely fall in behind a lead vehicle in the new lane and the required deceleration rate for the following vehicle in the new lane to safely follow the lane changer. A vehicle makes the lane change if the required leader and follower decelerations in the new lane are within the acceptable acceleration range for the driver wishing to change lanes.

The acceptable acceleration varies by the type of lane change. There are three types of lane changes considered in FREESIM: mandatory, discretionary, and anticipatory lane changes. Mandatory lane changes are triggered by lane drops, ramp merges, incidents, and the necessity of exiting the freeway. Anticipatory lane changes occur upstream of an on ramp, when vehicles in the right lane of the freeway shift over one lane to avoid merging with the on-ramp traffic. All other lane changes are "discretionary" and occur when a vehicle seeks to pass a slower vehicle in front of it.

The acceptable acceleration rate for lane changes is highest for mandatory lane changes. It varies by speed for discretionary and anticipatory lane changes.

8.4.1.2 NETSIM

NETSIM, like FREESIM, is based upon the proposition that each vehicle will seek to travel at the driver's desired speed in the absence of other vehicles, traffic control devices, and geometric constraints (e.g., lane drops). The desired speed is link and driver dependent. It is determined by the mean speed coded for each link and the driver's aggressiveness level (randomly selected at the time the vehicle first enters the network from a default or user-specified distribution of driver types). The driver's aggressiveness determines how much faster or slower the vehicle will travel than the coded mean desired speed for the link.

8.4.1.2.1 Car-Following Equations. Unlike FREESIM, NETSIM determines the acceleration of a vehicle according to a car-following equation that employs the maximum emergency deceleration rate for the vehicles and the driver response lag time (two factors that are missing from the FREESIM car-following formulas). In essence, in each second, NETSIM first moves the lead vehicle to its new position and then moves the following vehicle to the closest position behind the leader that will allow the follower to avoid colliding with the leader if the leader should decide to emergency brake in the following 1-second simulation period.[125] The acceleration for the following vehicle is determined by the change in position of the following vehicle in a 1-second time period:

$$a = \frac{(F_1 + T_1) + (F_2 + T_2)}{(F_1 + T_1)t^2 + (F_2 + T_2)^2} \qquad \text{Equation 41}$$

Where:

$$F_1 = 2e_f[d - (c+1)v] + \frac{u^2 e_f}{e_l} - v^2 \qquad \text{Equation 42}$$

$$F_2 = e_f(2c + 1) + 2v \qquad \text{Equation 43}$$

$$T_1 = 2e_f(t+1)\left\{\left[1 + \frac{u-v}{e_l}\right]\left[u + \frac{(u-v)(t+1)}{2}\right] - v\right\} \qquad \text{Equation 44}$$

$$T_2 = (t+1)\left[e_f(2c + 2 + t + 1) + 2v\right] \qquad \text{Equation 45}$$

Where:

a = the acceleration rate (feet per square second, or fpss),
e_f = the maximum emergency deceleration rate for the following vehicle (fpss),
e_l = the maximum emergency deceleration rate for the lead vehicle (fpss),
d = the distance between the front of the following vehicle and the back of the lead vehicle (feet),
c = the driver response time lag to deceleration (seconds),
v = the following vehicle speed (fps),
u = the lead vehicle speed (fps), and
t = the time remaining to change lanes (seconds).

Equation 44 should be used only if the vehicle is changing lanes. Otherwise, T_1 equals 0.

Equation 45 should be used only if the vehicle is changing lanes. Otherwise, T_2 equals 0.

If the computed acceleration rate is greater than the maximum emergency deceleration, the computed acceleration rate is reduced.

The speed of the following vehicle is determined from the equation of motion:

$$v_t = v_{t-1} + aT \qquad \text{Equation 46}$$

Where:

v_t = the speed at time t seconds (fps);
v_{t-1} = the speed at time $t - 1$ seconds (fps);
a = the acceleration rate (fpss); and
T = the duration of the simulation time period (seconds), always 1 second in NETSIM.

8.4.1.2.2 Lane Changing. NETSIM has two types of lane changing: mandatory and discretionary. Mandatory lane changing is due to lane channelization (e.g., right-turn-only lane), lane drop, lane closure, or the need to reach the appropriate lane to make a turn. Discretionary lane changing occurs to pass a slower-moving or stopped vehicle or to move to a lane with a shorter queue.

There is no anticipatory lane changing in NETSIM to avoid a downstream queue or lane drop on a downstream link (such as in FREESIM). FREESIM vehicles can look ahead three links to line up in the correct lane to exit a freeway, while NETSIM vehicles can react only to conditions on the link on which they are located. NETSIM vehicles will not line up in the right lane for a right turn more than one block (i.e., one link) in advance of a turn.

The motivation for a discretionary lane change is computed according to the vehicle speed and headway. The speed that would motivate a discretionary lane change and headway is computed for the vehicle.

8.4.1.2.3 Size Limits of Software. The publicly released version 4.2 of the CORSIM software currently has limitations on network size (see Table 27). With only two parallel facilities, these limits preclude the use of CORSIM for anything larger than a 5- to 10-mile-long corridor.

8.4.1.2.4 Field Validation of NETSIM Modal Activity Forecasts. Hallmark and Guensler[126] compared NETSIM-estimated, second-by-second vehicle speeds and acceleration against field measurements at 30 locations (approach stop bar and midblock) and found that at a signalized intersection, NETSIM predicted much higher fractions of hard accelerations (≥6 mph/s [≥9.7 kph/s]) than were measured in the field. Hallmark and Guensler also found that NETSIM underestimated the variance in vehicle speeds midblock between intersections.

TABLE 27 Size limitations of CORSIM networks

Characteristic	NETSIM	FREESIM
Nodes	250	350
Links	500	600
Vehicles present on network at any one time	10,000	10,000

Source: Table 3-5, Traffic Software Integrated System (TSIS) On-Line Help, Version 4.02, 1998

Chundury and Wolshon[127] compared NETSIM car-following equations to car-following data measured in the field and found generally reasonable correspondence between the predicted and actual car-following distances and speeds; however, they also noted that NETSIM's predicted acceleration and deceleration rates were higher than observed in their field tests.

8.4.2 INTEGRATION

The strengths of the INTEGRATION model are the explicit modeling of integrated freeway and arterial networks under time-varying demands and the ability to model different vehicle classes under various levels of traffic information provision. INTEGRATION appears as the most comprehensive single model for corridor planning and ITS applications. The model includes several options for traffic assignment for several vehicle classes and incorporates the effects of traffic dynamics (i.e., queue formations) into the traffic assignment. Aggregate OD flows are converted into individual vehicle departures, with each vehicle having a unique origin and destination. Vehicle routings are determined through an equilibrium traffic assignment at user-specified intervals and microscopically from the link travel times of earlier departures of simulated vehicles that act as dynamic vehicle probes.

The car-following, lane-changing, and gap acceptance algorithms permit the explicit modeling of freeway and surface street traffic-flow dynamics, traffic signal control, and ramp metering. The model's car-following algorithm is designed to satisfy the link's macroscopic speed-flow-density relationships, in contrast to the rest of microscopic simulation models, which use the driver's target headway and other criteria in the car-following algorithms. INTEGRATION is not a high-end simulator for vehicle movements. It does not provide the detailed modeling of driver or vehicle characteristics through a number of parameters found in CORSIM and other microscopic models. Thus, a number of design and control options are handled approximately. Examples include complex interchange designs, detailed roadway layouts, roundabouts, pedestrians, actuated signal control, transit movements, and signal preemption.

INTEGRATION has been used in several studies in research and practice. Most of the earlier studies involved the assessment of benefits from real-time route information and guidance (e.g., the Travtek experiment in Florida, the National ITS System Architecture Study). Following the conversion of the model into a fully microscopic one, a number of operations studies have been performed concerned with street circulation patterns, interchange redesign, freeway operations, signal control on arterials, and impact studies.

A number of software utilities exist for importing data from travel demand models (e.g., TRANPLAN and EMME/2) into

INTEGRATION. An interface between EMME/2 and INTEGRATION was created as part of the Seattle study conducted by Wunderlich et al.[12] A utility was written by the city of Portland to import data from the GIS Map-Info database into the link data file of INTEGRATION. The model requires OD matrices per time period (15 to 30 minutes each). Usually, the OD matrix produced by the conventional trip generation and distribution planning process is not accurate enough because INTEGRATION requires OD flows per time period instead of a single peak-period OD matrix (the same is true for all the models that require OD flows as input). Numerous adjustments and iterations are required to obtain a representative OD matrix for further analysis. A separate software package (QueensOD) is available to estimate OD matrices from traffic counts.

Input to the model consists of a series of ASCII files and is accomplished through a text editor. There is no graphical user interface available other than the utilities to directly import data from other sources.

8.4.3 Paramics

The major strength of Paramics is its software design for high performance and scalability. It provides for a seamless integrated modeling of networks consisting of freeways, arterials, and minor roads; various intersection types (i.e., signals, stop signs, and roundabouts) and parking garages with no limit on the network size (i.e., number of links and nodes); and the number of vehicles that can be simulated. The user interface with multiple graphical windows for data input and output provides an excellent visualization tool. A companion software (Paramics Analyzer) is available for statistical analysis of the outputs from multiple model runs.

Paramics limitations include (a) lack of equilibrium traffic assignment, (b) limited options in modeling traveler information/guidance (i.e., the model updates the routing instructions at each intersection instead of each path because updating the routing instructions at each intersection may result in myopic travel paths with extensive turns and oscillations); (c) inability to explicitly model a number of control options (e.g., the National Electrical Manufacturers Association [NEMA]/170 controller and bus signal preemption from mixed lanes); and (d) limited user options in modeling incidents and workzones (e.g., specification of lanes occupied by the incident and rubbernecking). The latest version of the model reportedly includes several enhancements to overcome the above limitations, including improved routing algorithm, bus preemption options, and simulation of NEMA controllers.

There are a number of Paramics applications, mostly in Britain, on freeway operations and impact studies. Several reports describe the model validation for British conditions. The U.S. applications are still limited. Currently, Paramics is being used to model the design and impacts of a freeway interchange along Interstate 680 in the city of Pleasanton, California, and alternative roundabout designs in the city of Petaluma, California. An evaluation and application of Paramics at the University of California, Irvine, indicated that the model accurately replicated traffic flow on a single freeway link, but fairly high discrepancies were found between observed and predicted link flows during the simulation of the entire Irvine network. Model developers attributed this finding mostly to improper model application.

Paramics includes utilities for importing existing data from travel demand models (e.g., TRANPLAN and EMME/2) and CORSIM into the model. Other utilities include importing of U.S. Geological Survey maps, AutoCAD drawings, and networks generated from geographical information systems (GIS) packages. Like INTEGRATION, Paramics requires time-dependent OD matrices.

Input to the model is accomplished through a graphical user interface. Alternatively, a text editor is available for data coding. Considerable time and effort is required, even with imported network data, to correctly represent the real-world street layouts into the model. The program includes an application program interface (API) to externally specify algorithms and control options. This API improves the model's flexibility, but the user has to design the control logic through "IF-THEN-ELSE" statements, which may not be straightforward for many traffic operations staff. The model allows for changing model parameters while the simulation is running and for immediately observing the changes through animation, thus cutting the time required during the calibration.

8.4.4 VisSim

The model's primary area of application is detailed modeling of traffic flow on urban networks under different vehicle types, intersection geometries, and control options. The model can be used for freeway operations studies to simulate interchange configurations, merging, weaving movements, and ramp metering (including HOV bypass). VisSim is not suitable for corridor capacity improvements at the regional level or for evaluation of networkwide effects of traveler information/guidance systems in combined freeway and arterial networks. There are no software limits on the size of the network to be modeled, but the practical limit is networks with 60 signalized intersections.

VisSim's particular strength is to explicitly model transit priority (i.e., bus preemption), signal control, pedestrian movements, stop/yield sign control, and roundabouts. Because VisSim's coding scheme is based on links and connectors, the network physical geometry can be explicitly coded (i.e., scaled of imported AutoCAD drawings and aerial photos). Thus, vehicle paths can be explicitly traced (analogous to "railroad tracks"). This ability provides a realistic simulation of vehicle movements, and this realistic simulation is useful in roundabouts, other complex intersection designs, and access control designs. The model can simulate fixed-time, traffic-actuated, and adaptive real-time signal control strategies through the interface of its signal generator program. Recent and emerging enhancements to the model include a dynamic traffic assignment algorithm and sensitivity to grades so it can better model truck performance on grade-separated interchanges.

VisSim provides several performance measures for autos and transit for impacts assessment. Users can define points in the network to (a) collect travel time data from the simulated vehicles or (b) set up queue counters. The model produces time-space and speed-distance diagrams along a route. Its interface with the Traffic Engineering Application Package (TEAPAC) software relates model predictions with HCM measures and level of service. Animation of vehicle movements (especially with background AutoCAD or aerial photos) greatly facilitates the understanding of the impacts of alternative scenarios. The generated outputs on detector calls and signal status would be valuable to signal operations staff working on developing and debugging logic for signal controllers.

In Europe, there are several applications of VisSim primarily on traffic signal control and transit priority. VisSim (or its predecessor model, MISSION) has been used in Germany to study the effects of speeds limits and incidents on freeways. King County Metro is currently using VisSim on transit signal priority studies in Seattle. Several studies in the United States applied VisSim on intersection and interchange design and operations, mostly through consultant projects. The results from these studies are unpublished, so detailed information on the model's features and accuracy in replicating real-world conditions are not readily available.

VisSim requires a fairly significant amount of time to code the input data. Most of the effort stems from the requirement of the link/connector scheme to represent in detail the intersection layouts. Also, the interface and coding of detector/signal logic for signal control (other than fixed-time plans) may require significant effort.

8.5 LINKAGES BETWEEN THE PLANNING MODEL AND THE MICROSIMULATION

There are three recent examples of linkages between planning model output and microsimulation input. Two of these, Skabardonis and Dion et al., involve various strategies for decomposing the planning model output into modal activity data. The third, Fellendorf and Vortisch, is an actual software linkage between planning and simulation models.

Skabardonis[128] developed a travel demand postprocessor for predicting the percentage of vehicle-hours spent in each of four operating modes (cruise, acceleration, deceleration and idle) as a function of the facility type, the physical characteristics of the specific segments of the facility, and the travel demand model predicted volume/capacity (*v*/*c*) ratio for each segment. The procedure consists of a series of tables that convert *v*/*c* ranges into predictions of mean speed and operating mode fraction.

Skabardonis used a series of runs of the NETSIM and Integrated Traffic Simulator (INTRAS) microsimulation models to develop a set of 33 tables. The microsimulation model runs were performed for 12 real-world arterial street networks (with 104 traffic signals and 334 links) and one real-world freeway (a 9.6-km section of the Interstate 880 freeway). In all cases, the results produced by each simulation model data set had been previously validated for each real-world network. The demand levels were then varied on each network to obtain results for a wide range of *v*/*c* ratios.

The tables are stratified into four different facility types. Each facility type was then further subdivided according to the geometric and traffic control characteristics. Table 28 shows the 33 link types identified by Skabardonis.

The 1985 HCM[129] defines arterial classes approximately as follows:

- Class I = suburban high-design facilities with multi-lane approaches, exclusive left-turn lanes, protected left-turn phasing, and free-flow speeds in the range of 64 to 72 km/h (40 to 45 mph).
- Class II = urban/suburban facilities with two to three lanes per approach, some intersection with no exclusive turn lanes (i.e., pockets), and free-flow speeds of 48 to 56 km/h (30 to 35 mph).
- Class III = urban streets with no exclusive turn lanes, permitted left-turn phasing, short signal spacings, and free-flow speeds of 40 to 48 km/h (25 to 30 mph).

TABLE 28 Link type categories

Facility Types	Classification Criteria	Class Values	Number of Link Types
Freeways	Section Type	Basic, Merge, Weaving	12
	Number of Lanes	6, 8, 10	
	Design Speed	60, 70 mph	
Arterials	1985 HCM Arterial Class	I, II, III	9
	Progression Quality	Poor Progression, Uncoordinated, Good Progression	
Ramps	Number of Lanes	1, 2	8
	Configuration	On Ramp, Off Ramp	
	Metering Signal	Yes, No	
Collectors	Number of Lanes	1, 2	4
	Traffic Control	Signal, Stop Sign	

Table 29 shows an example of one of the 33 tables.

Potential problems with the use of tables would be the applicability of tables created for specific conditions to other situations. Little is known about the robustness of these tables for wide application.

Dion et al.[130] propose a method to determine modal emissions from average speeds using regression equations and assumptions. The model determines the number of stops per given average speed and then the time spent in acceleration and deceleration. The regression models were developed using the Oak Ridge National Laboratory (ORNL) database.

According to the authors,

> The fuel consumption and emission rates estimated by the model were compared against the rates estimated by MOBILE5 and the microscopic model used to develop the mesoscopic models. Specifically, fuel consumption and emission estimates were compared for scenarios considering the EPA's standard urban and highway driving cycle, as well as for a series of real-world urban arterial driving cycles. The results of these evaluations indicate that the mesoscopic model estimates fuel consumption and emission rates that are consistent with those produced by the underlying microscopic model in scenarios considering both EPA driving cycles, and those estimated with MOBILE5. The only exception was for the CO estimates, which were significantly lower with MOBILE5. However, it was also found that the MOBILE5 estimates fell between the minimum and maximum emission rates estimated by the mesoscopic model. Finally, the test performed with the real-world driving cycles indicate that the mesoscopic model could significantly overestimate fuel consumption and vehicle emissions in scenarios including a significant number of partial stops as a result of inaccuracies in converting partial stops into a single number of equivalent full stops.

Fellendorf and Vortisch[131] developed a software suite to apply a disaggregate activity-based travel demand model, a dynamic route choice, a traffic microsimulation model, and a vehicle modal emission model, using the VisSim software. According to the authors,

> Four separate models are integrated in one software suite to cover traffic demand, route choice, traffic flow and pollutant emissions. The traffic demand model follows a behavior-oriented, disaggregated approach. It computes the set of trip chains performed during one day in the analysis area. The dynamic route choice is calculated by an iterated simulation of the entire day. Each individual vehicle travels through the road network using the microscopic traffic-flow model of VISSIM. Fuel consumption and exhaust gas emissions of all vehicles in the network are determined based on dynamic engine maps. In addition, the model is capable of considering additional emissions during the warm-up phase of the engine as well as evaporation emissions during parking.

It is unclear whether the model includes feedback of traffic-flow results to the activity model. The authors do not recommend that the model be applied to large areas because of the calibration effort required, data required, and the computational burden.

8.6 ASSESSMENT OF METHODS FOR ESTIMATING MODAL ACTIVITY

The purpose of including a traffic operations model in the recommended NCHRP 25-21 methodology is to predict the VHT by mode of operation (i.e., cruise, idle, acceleration, and deceleration) and by speed and acceleration category. The estimates of vehicle activity are then used with modal emission factors (e.g., University of California, Riverside/NCHRP 25-1) to produce the emissions estimates.

The following sections describe and critique the possible approaches for estimating vehicle activity. The approaches can be classified into two major categories: direct modeling approaches and postprocessing techniques.

8.6.1 Direct Modeling Approach

A direct modeling approach involves the simulation of the entire study area using a modeling tool that would predict the vehicle activity, as well as other performance measures of interest. This simulation can be done at either the microscopic or the mesoscopic level of detail.

Microscopic models predict vehicle activity by processing individual vehicles' trajectories. This information is obtained from the output of microscopic simulation models (e.g., CORSIM, INTEGRATION, Paramics, and VisSim). The process involves the simulation of the entire study area using a microsimulator. This approach provides directly the required vehicle activity data. However, there are a number of issues related to accuracy, data requirements, computational aspects, and implementation into a methodology for use by MPOs.

TABLE 29 Mode of operation fractions and mean speed for basic freeway sections

v/c Ratio Range	Cruise	Acceleration	Deceleration	Idle	Mean Speed
0–0.50	55.90%	22.70%	21.20%	0.20%	57.40 mph
0.51–0.75	54.60%	23.60%	22.40%	0.40%	55.70 mph
0.76–0.90	53.20%	23.70%	22.70%	0.50%	54.30 mph
0.91 and greater	34.60%	31.00%	26.50%	7.70%	32.30 mph

Note: These entries are for a design speed of 60 mph.

Percent entries are percent of total vehicle-hours traveled (VHT) on link that are spent in specific operating mode.

The state-of-the-art microsimulation tools model the movement and interaction of individual vehicles based on car-following, lane-changing, and queue discharge algorithms. These algorithms are based on the "fail-safe" principle; that is, they attempt to maintain a minimum safe distance headway between successive vehicles. Often, the calculated vehicle speed changes are higher than the observed field conditions, and as a result these models tend to overestimate the magnitude and frequency of accelerations and decelerations.

Microscopic simulation models are best suited for operational studies for which the OD patterns or turning movements have been determined from other sources. They are not designed to estimate the amount or mode of travel generated and distributed in the study area. Thus, this approach requires the linkage of a four-step planning model with a microscopic simulation model. The four-step planning models provide the input traffic volumes and turning movements to microscopic network models, which in turn simulate the characteristics of individual vehicles and their trajectories in the network.

A mesoscopic model simulates individual vehicles, but it assumes that all vehicles travel at the same average speed; that is, the model simulates traffic based on macroscopic speed-flow-density relationships. An example of such a model is DYNASMART-P, recently released by the University of Texas at Austin. The model could perform microsimulation of individual trip-maker decisions (route, departure time, and mode); traffic interactions are modeled using macroscopic speed-flow-density relationships.

The advantage of using such a hybrid model is that queuing is explicitly taken into consideration in the traffic assignment process, which leads to improved estimates of traffic volumes and average speeds at reasonable computer costs. The disadvantage is that the model cannot directly produce vehicle activity data by speed-acceleration category. The micro- or mesoscopic model must be linked in some manner to the planning model to produces the demand forecasts.

One possible approach is to sequentially link the four-step planning model with a microscopic model. This process requires detailed operational data and recoding of the network in sufficient detail for the microscopic models. For example, a series of street segments could be coded as a single link in the planning model. Microscopic models, however, require coding at the approach/intersection level, as well as specification of the type and characteristics of traffic control. This approach is best suited for subarea analysis because at present it is computationally infeasible to simulate microscopically traffic conditions in large areas such as urban counties.

Another major drawback of the hybrid approach is that the assigned volumes and turning movements from the planning model are often unrealistic because planning models do not consider queuing in the traffic assignment. Thus, the simulation results can be inaccurate.

An improvement of the hybrid approach is to feed the travel times from the simulation models back into the four-step assignment algorithm. This iterative process improves the accuracy of the planning model's volume and speed outputs. The process involves challenging software development and has the same shortcomings as the sequential linkage approach regarding the data collection requirements, the network coding requirements, and the application to large networks.

8.6.2 Postprocessing Techniques

Postprocessing techniques involve the development and linkage of an Analysis Module that predicts vehicle-activity to the planning model (or methodology) that produces forecasts of traffic volumes and speeds. The accuracy of this approach depends on the accuracy of the predicted traffic volumes and speeds. There is no feedback to the other modules of the methodology. Either microscopic or mesoscopic models may be used.

A microscopic approach involves the estimation of vehicle activity using widely used analytical relationships (e.g., HCM). The approach is called mesoscopic because it involves obtaining microscopic data (i.e., time in cruise, acceleration, deceleration, and idle) using macroscopic relationships. An example procedure illustrates an HCM-based analysis procedure for an arterial link:

1. The researchers have the total link travel time from the volume and speed forecasts from the other modules of the methodology.
2. The researchers use the HCM analysis procedure to calculate the control delay at the signal (as proposed using default values in *NCHRP Report 387*).[132]
3. The researchers develop relationships to determine the spatial and temporal extent of the queue and the number of stops. One approach by Erera et al.[133] is to predict time spent in the queue from the deterministic queuing diagram used in the HCM.
4. The researchers develop typical vehicle trajectories, assuming typical values of acceleration and deceleration rates to determine the time spent in cruise, acceleration, deceleration, and idle mode.

A mesoscopic procedure was developed by Dion et al.[134] A set of regression equations was developed to predict the average speed and the number of stops along arterials. A speed-change cycle was calculated using constant rates of acceleration and deceleration. The emissions were determined using regression analyses. Evaluations against microscopic models indicated that this mesoscopic approach tended to significantly overestimate CO emissions and underestimate hydrocarbons (HC) and NO_X emissions. The major limitation is that this approach does not adequately account for the speed slowdowns (essentially, the model predicts that most delayed vehicles come to a complete stop).

A mesoscopic approach can be readily implemented in a postprocessor to planning models. Its implementation would be particularly straightforward by agencies that have incorporated certain HCM procedures (e.g., node delays) into their planning modeling framework.

A number of assumptions have to be made on vehicle acceleration and deceleration rates to determine the time spent in acceleration, deceleration, and idleness from the total delay. These rates depend on the vehicle and roadway characteristics. Issues to resolve include the following:

- Should different vehicle types be considered, or should average "composite" rates be used?
- What rates should be used (e.g., maximum or normal acceleration rates)? What are typical rates for acceleration at signalized intersections or ramp meters? For example, an EPA study reports that typical acceleration rates at traffic signals are 50 percent of the maximum acceleration rates.
- How should one account for vehicle slowdowns and delays that do not involve complete stops? Should one incorporate a filtering algorithm to estimate total stops based on the amount of delay (similar to the Traffic Network Study Tool, Release #7 [TRANSYT-7F] model)?

The procedure needs to be sensitive to TCM improvements. Therefore, some analytical relationships need to be incorporated between quality of traffic-flow and vehicle activity. For example, the 2000 HCM states that 30 percent of the total delay at the traffic signal is acceleration/deceleration delay and the rest is stopped (idle) delay. However, research findings indicate that the acceleration/deceleration delay is lower than 30 percent of the total delay for arterial links with good progression and much higher than 30 percent on arterials with uncoordinated signals.[135]

The mesoscopic approach does not readily produce vehicle activity by speed-acceleration category. Instead, it produces the total amount of time spent in the acceleration or deceleration mode. It can be modified to produce vehicle activity data by assuming a speed-acceleration relationship (e.g., constant or linear) and calculating the time spent in each speed-acceleration cell.

A sampling approach using a table was developed as part of a California Air Resources Board (CARB) study that involves the stratification of the network links into distinct link types depending on facility type, design, traffic, and control characteristics. The time spent in each mode is estimated from the link volume and travel time outputs from the planning model and the relationships between the link types and vehicle activity. These relationships were developed through simulation in small-scale networks with the selected link types. The relationships in a form of tables are defined by the link type, *v/c* ratio, and free-flow speed. These relationships account for the variation of vehicle activity between facility types, undersaturated versus oversaturated conditions, and characteristics within a link type.

The first step in the CARB study involved the selection of link types. The researchers recognized that it is practically impossible to capture all the variations in the characteristics of the different highway facilities into separate categories. The determination of link types considered the accuracy of the relationships, time and computational resources to develop the relationships, data collection and coding requirements to implement this approach in the planning model, and the link classification schemes commonly employed in regional models. Thirty-three link types were defined (see Table 30).

The test sites used in the simulation experiments consisted of 12 surface street data sets (8 arterials and 4 grid networks), and 2 freeway corridors. The data were coded into the TRAF-NETSIM and INTRAS microscopic models, and several initial runs were performed to verify the accuracy of the coding and the stability of the results. Next, base simulation runs were performed in each site and the outputs were processed through

TABLE 30 Proposed link types for determining vehicle activity relationships

Facility Type	Classification Criteria	Range of Values	# Link Types
Freeways	Section Type	Simple Section/ Merging, Weaving	12
	Number of Lanes	6, 8, 10	
	Design Speed (mph)	60, 70	
Arterials	Arterial Class*	I, II, III	9
	Progression Quality	Poor, Uncoordinated, Good	
Ramps	Number of Lanes	1, 2	8
	Configuration	On, Off	
	Metering/Signal	Yes, No	
Collectors	Number of Lanes	1, 2	4
	Traffic Control	Stop Sign/Signal	

*HCM-85 classification.
1 mile = 1.609 km.

the software to determine vehicle activity. The process was repeated on each site by changing the input volumes to obtain performance estimates for a range of volume-to-capacity ratios. Additional simulations were performed to determine vehicle activity for scenarios not sufficiently represented in the test sites (e.g., different signalization conditions on surface streets and alternative designs on freeway segments). In addition, the trajectories of instrumented vehicles from actual floating car runs on the Interstate 880 freeway were analyzed to compare the measured time spent in each driving mode with the predictions of the INTRAS model. The simulation results were analyzed on each site separately for each link, for each portion of the network (e.g., arterials versus cross-streets), and for the entire network. These relationships were then incorporated in a specially written postprocessor to the MINUTP planning model. This postprocessor could be easily implemented for other four-step regional models. The postprocessor produces the following outputs:

- Tables with time spent in each speed-acceleration category for speeds 0–65 mph (at 5-mph intervals) and accelerations from −7 to 7 mph/sec (at 1-mph/sec intervals), for each link, for each facility type, and for the total network (see Figure 13). This information can be used directly to estimate emissions using modal emission factors.
- A summary of the vehicle activity and traffic performance for each link, for each facility/area type, and for the total network (including VMT, delay, average speed, travel time, and the total time spent in idle, acceleration, cruise, and idle mode). This information can be used to estimate emissions based on simplified modal emission factors (e.g., idle, cruise, stop-to, and stop-from) and speed-based emission rates.

The postprocessor approach can be easily interfaced with a typical four-step planning model used by most MPOs to produce regionwide estimates of vehicle activity data. Recoding of the network is not required except for coding additional fields in the link data file to designate the link types.

The existing tables are not well suited for evaluating a number of TCM strategies (e.g., ramp metering and related ITS measures), because they are based on *v*/*c* ratio and because of basic link characteristics. The tables account for improved signal timing because they include the quality of signal progression on arterials as link type characteristic.

Researchers can overcome the above limitation by performing additional simulation experiments to generate vehicle activity data and to develop relationships between traffic conditions (*v*/*c*), link characteristics, and control/management scenarios.

8.6.3 Subarea Microsimulation

Subarea microsimulation involves using a microscopic simulation to model a selected sample of links in the region and to expand, through sample enumeration, the predicted modal activity for the sample to the region as a whole. This approach requires a substantial amount of software development to ensure compatibility of the entire study area and the sample region to be microsimulated. This requirement means that portions of the network would be designated as "buffers" modeled macroscopically, and at the same time the volumes should be

```
==========================================================================================================
 LINK#:  1202 1230   FACILITY TYPE: 2  AREA TYPE: 4    VHT(Veh-hr):       7.63
    TIME-SPENT(Veh-min) BY SPEED(mph) and ACCELERATION(mph/sec)
"MPH"   -7   -6      -5      -4      -3      -2      -1       0      +1      +2      +3      +4      +5   +6   +7     TOTAL
==========================================================================================================
  0     .0   .0      .0      .0      .0      .0      .0     3.0      .0      .0      .0      .0      .0   .0   .0       3.0
  5     .0   .0      .0      .0      .0      .7     1.6     1.8     1.6      .5      .0      .0      .0   .0   .0       6.2
 10     .0   .0      .0      .0      .5      .9     1.4     1.8     1.8      .5      .0      .0      .0   .0   .0       6.9
 15     .0   .0      .0      .5      .5      .9     1.8     2.7     2.3      .9      .5      .0      .0   .0   .0      10.1
 20     .0   .0      .0      .5      .5      .9     2.3     3.2     2.3      .9      .5      .0      .0   .0   .0      11.0
 25     .0   .0      .0      .5      .5      .9     2.3     3.7     2.7      .9      .0      .0      .0   .0   .0      11.4
 30     .0   .0      .0      .5      .5      .9     2.7     4.1     3.2      .9      .0      .0      .0   .0   .0      12.8
 35     .0   .0      .0      .5      .5      .9     3.2     5.0     3.7      .9      .0      .0      .0   .0   .0      14.6
 40     .0   .0      .0      .0      .5      .9     4.6     5.0     4.6      .9      .0      .0      .0   .0   .0      16.5
 45     .0   .0      .0      .5      .5      .9     4.6     5.5     5.0      .5      .0      .0      .0   .0   .0      17.4
 50     .0   .0      .0      .5      .5      .9    10.5    18.8    10.5      .9      .0      .0      .0   .0   .0      42.5
 55     .0   .0      .5      .5      .5     1.4    26.1    73.7    26.1     1.4      .0      .0      .0   .0   .0     129.9
 60     .0   .0      .0      .0      .0      .9    22.9    73.2    26.1     1.4      .5      .0      .0   .0   .0     124.9
 65     .0   .0      .0      .0      .0      .5     8.7    28.8    11.4      .5      .5      .0      .0   .0   .0      50.3

TOTAL   .0   .0      .5     3.7     4.6    11.7    92.6   230.4   101.3    11.0     1.8      .0      .0   .0   .0     457.5
==========================================================================================================
```

Figure 13. Predicted vehicle activity.

consistent with the subarea to be simulated. The subarea network needs to include all the representative network conditions to permit extrapolation of the sample to the entire study area.

8.7 CONCLUSIONS

The desirability of converting demand model outputs into vehicle modal activity appears clear. As will be discussed in Chapter 9 under mobile emission models, the ability to take into account modal activity effects quadruples the estimated emission benefits of signal coordination.

There is some evidence in the literature, though, that current microsimulation models are not designed to produce realistic acceleration and deceleration behavior. As described in Section 8.4.1.2.4, Hallmark and Guensler, and Chundury and Wolshon found that NETSIM overpredicts hard accelerations and braking. A review of the car-following equations in NETSIM indicates that there is no provision for less than "emergency braking" in NETSIM.

The mesoscopic model by Dion et al. or a more sophisticated extension of Skabardonis's work may be worthwhile modules for the NCHRP 25-21 methodology. Directly linking a planning model to a microscopic simulation model does not currently appear advisable, given the tendency of microscopic simulation models to overpredict hard accelerations and decelerations. Some type of filtering process will be required to reduce the more extreme modal data.

CHAPTER **9**

MOBILE EMISSION MODELS

This chapter discusses the candidate mobile source emission models for consideration in NCHRP 25-21.

9.1 BACKGROUND—VEHICLE EMISSION PROCESSES

Vehicle emissions are a function of vehicle type (light duty, heavy duty, etc.), emission controls (Type 1, Type 2, etc.), the mode of operation of the vehicle (acceleration, deceleration, idle, cruise), the vehicle's operating state (cold start, etc.), the amount of vehicle activity (VMT), and the simple presence of liquid fuel–powered vehicles in the air basin (diurnal and evaporative emissions).

Historically, emissions from on-road vehicles have been calculated and discussed in terms of the grams of emissions per VMT, or simply grams per mile. This approach dates to the first versions of the EPA's MOBILE emission factor model, but necessitates the incorporation of emissions into the composite grams-per-mile rates that are not strictly based on VMT. Reasonable emission inventories could be developed based only on total estimated areawide VMT using this method, provided that the assumed average rates for non–VMT-dependent processes were appropriate for the area of interest. The nature of the changes in vehicle activity caused by traffic-flow improvements (including VMT, speeds and accelerations, number of trips, and time between trips) directly affect emission processes. This effect is not directly proportional to VMT.

There are two major classes of emissions from on-road vehicles: exhaust emissions from fuel combustion and evaporative emissions. It is perhaps simplest to describe the various types of vehicle emissions sequentially, starting with the beginning of the first trip of the day.

9.1.1 Start Emissions

After being parked overnight, a vehicle is started for its first trip of the day, with engine coolant, oil, and catalytic converter all at ambient temperature. The emission control system does not reach full efficiency until the catalyst has reached operating temperature, and other engine systems are operating at nominal conditions for "hot-stabilized" operation. (Note: for definitions of emission terms, see the EPA MOBILE6 User Guide, publication #EPA420-R-03-010, August 2003.) The emission rates during this period are higher for CO, VOCs, and PM. NO_X emissions may be higher or lower than normal. The EPA MOBILE model assumes that a fraction of VMT occurs during "cold-start" conditions and averages the excess emissions during starts into the composite grams-per-mile emission rates. MOBILE6 incorporates a method that is used in California's Emission Factor (EMFAC) model: separate calculation of excess emissions on a grams-per-start basis. In this approach, the magnitude of the excess start emissions is based on the time passed since the end of the last trip, referred to as the "soak time."

9.1.2 Running Exhaust Emissions

When a vehicle has reached "hot-stabilized" operating conditions, exhaust emissions are generally constant over time for given vehicle operations (i.e., following a specific second-by-second speed profile). Because excess start emissions can be measured only by comparing a vehicle's emissions after a cold start with those occurring for the same speed profile under hot-stabilized conditions, running exhaust emissions can be assumed to begin immediately upon the beginning of a trip. A number of factors can influence running exhaust emission rates, including engine load (speed, acceleration, gear, road grade, and air conditioner use, both instantaneous and time history), ambient conditions (temperature and humidity), and fuel formulation. Traffic-flow improvements will primarily affect speed and acceleration along specific roadway segments, but may also influence route choice (i.e., traffic volume on specific roadway segments). To the extent that these changes reduce travel time for trips, there may also be changes in the number and timing of trips, including both new trips and the addition of new intermediate destinations to existing trips (trip chaining). Accurate treatment of the effects of these changes on running exhaust emissions will require explicit treatment of changes in the speed and acceleration profiles, expressed in terms of vehicle-seconds or vehicle-miles accumulated at different speeds and accelerations. Several emission factor models and analytical efforts, including the Comprehensive Modal Emission Model (CMEM), developed under NCHRP Project 25-11, can provide running exhaust emission rates in this form.

Heavy-duty vehicles present additional problems in estimating modal emissions. Emissions testing of heavy-duty vehicles is quite expensive, and databases of existing test results are much smaller than those of light-duty vehicles. NCHRP Project 25-14 is addressing known uncertainties in heavy-duty vehicle emission inventories, and some information has been developed regarding emission sensitivity to speeds and acceleration for NO_X. PM and CO emissions were found to be much more sensitive to transients (e.g., hard accelerations). This work is ongoing and will be reviewed for its applicability to the evaluation of the effects of traffic-flow improvement projects.

Current understanding of running exhaust particulate emissions is less detailed than that of other exhaust emissions because of difficulties in obtaining accurate second-by-second measurements of PM emission rates. This is particularly true for heavy-duty vehicles (especially diesels), whose PM emissions are high relative to the emissions of other vehicle types. CMEM (which is specific to light-duty vehicles) does not address PM emissions. EMFAC2000 (Version 2.02) produces separate start and (speed-dependent) running exhaust emissions, but does not directly address acceleration.

The EPA PART5 model and EMFAC2000 (Version 2.02) also include on-road "fugitive" emissions of road dust and tire and brake wear. Various formulations of rate equations have been developed, with dependence on factors including vehicle weight, roadway silt loading, traffic volume, and in some cases speed. The rates from these models are considered to be quite uncertain. As a result, an ongoing NCHRP project (25-18) includes an empirical investigation of exhaust and fugitive PM emission rates. Although this project should provide some improvement in the accuracy of average rates, it is unlikely to provide any significant advances in understanding of emission rate sensitivity to vehicle operations (i.e., speed and acceleration) on specific roadways. At best, available models and data sets are expected to provide emissions estimates based on VMT and average speed by roadway functional class.

9.1.3 Running Evaporative Emissions

While in operation, gasoline vehicles undergo various changes that influence evaporative losses of fuel. Underhood temperatures increase, resulting in increased permeability of fuel hoses. This is potentially aggravated by the internal fuel pressure of portions of the fuel delivery system in fuel-injected vehicles. Evaporative emissions occurring during vehicle operation are known as running losses and are related most closely to the total time elapsed for a trip. Quantitative studies of running evaporative emissions (i.e., running evaporative emissions) are much more limited than those of exhaust emissions, but running-loss VOC emission rates are comparable in magnitude to those of exhaust VOC. MOBILE composite grams-per-mile rates include running evaporative emissions, and EMFAC (both EMFAC7G and EMFAC2000, Version 2.02) produce grams-per-hour rates as separate emission rates. These rates are known to change with the duration of trips (increasing with time since vehicle start). Vehicle speed and engine load are not considered to be important factors in estimating running evaporative rates.

9.1.4 "Off-Cycle" Emissions

For reasons having to do with the design and operation of current computer-controlled fuel delivery and emission control systems, some vehicle operations can cause significant short-term changes in emission rates. "Power enrichment" events can occur during sustained hard accelerations or during mild accelerations on positive grades. These events are characterized by brief increases in fuel/air ratios and significant increases in CO and VOC emissions. Rapid throttle changes can also cause "enleanment" events and associated increases in NO_X emissions. These effects are a consideration that may or may not be important in the estimation of running exhaust emissions effects of traffic-flow improvements. Urban intersection and arterial projects are unlikely to cause such effects, but the use of ramp metering on freeways can.

9.1.5 Hot-Soak, Diurnal, and Resting Loss Emissions

At the end of a trip when a vehicle is parked and switched off, all exhaust emissions cease, but evaporative emissions continue. During the first hour, evaporative emissions are referred to as "hot soak" emissions. Hot soak emissions from carburetors can be much larger than those of current fuel-injected vehicles. Subsequent to the hot soak, evaporative emissions continue from small seeps at fuel system joints and permeation through fuel lines and seals. In addition, thermal expansion of air and fuel vapors in the gas tank can cause emissions from the carbon canister. Emissions following a hot soak are referred to as either diurnal or resting evaporative emissions, depending on whether the ambient temperature is rising or not. Diurnal emission rates (associated with rising temperatures) are higher than resting loss rates because they include the effects of expanding air and fuel vapors forced out of the fuel tank. However, on a grams-per-hour basis, both are substantially lower than running exhaust or evaporative rates. Carbon canisters can become saturated with fuel vapors, resulting in significant "breakthrough" of VOCs, but this effect is primarily associated with "multiday diurnals" from vehicles that remain parked for more than 24 hours.

9.1.6 Refueling and Carbon Dioxide Emissions

Gasoline vehicle refueling causes VOC emissions because of both displacement of VOC-laden air in fuel tanks and spillage. The delivery of gasoline to gas stations also causes emissions during both tanker loading and unloading. Stage I (gasoline distribution) and Stage II (vehicle refueling) vapor recovery systems are in place in many areas, and these emissions are generally small relative to running emission rates. The rates are effectively proportional to the amount of gasoline sold, so changes in VMT or fuel economy that are the result of traffic-flow improvements will also affect these emissions. Carbon dioxide emissions are also effectively proportional to fuel consumption and are of interest for global climate change.

9.2 MOBILE6

MOBILE6[136] is the update to the MOBILE5 emission factor model being developed by the U.S. EPA. MOBILE6 includes updated basic emission rates, off-cycle driving patterns and emissions, separation of start and running emissions, improved speed correction factors, and updated fleet information.

Emission rates are produced for different vehicle classes and age distributions for specified calendar years. MOBILE5 produces a single set of speed-dependent running emission rates (in grams per mile), whereas MOBILE6 produces different speed-dependent emissions for arterials and freeways, along with non–speed-dependent rates for ramps and local roadways. Both models, however, derive their speed correction factors from emission tests on selected driving cycles. As a result, they cannot be reliably used to assess the effects of projects that tend to “smooth” traffic flow, or otherwise alter the speed/acceleration distributions of traffic (effectively, engine power demands) from those assumed in the use of the specific driving cycles. Emissions associated with “trip ends” (i.e., excess emissions during starts and evaporative emissions during hot soak, diurnal, and resting loss) can be obtained from these models to assess the effects of changes in the number of trips.

9.3 THE MOVES MODEL

Motor Vehicle Emission Simulator (MOVES) is an effort to develop a set of modeling tools for the estimation of emissions produced by on-road and nonroad mobile sources. It is intended to include hydrocarbons, CO, NO_X, PM, air toxics, and greenhouse gases at various levels of resolution needed for diverse applications of the system.

9.4 THE MEASURE MODEL

The MEASURE model is a mobile emission model that estimates the production of carbon monoxide, VOCs, and NO_X both spatially and temporally for a region.[137] The model is GIS based and employs a vehicle mode of operations emission model. The MEASURE architecture has been laid out so that MEASURE can grow in sophistication as better analytical techniques become available.

9.4.1 Engine Start Emissions

Engine start emissions are modeled as “puffs” that occur in the starting zone of the vehicle trip. The grams-per-start emission rates were developed from a re-analysis of the Federal Test Procedure (FTP) database. Later stages of model development will incorporate improvements from studies by the California Air Resources Board (e.g., rates that are a function of soak time and modal activity and allocation of some of the start emissions to the network) and eventually a probabilistic approach with start emission rates modeled as a function of vehicle characteristics, environmental parameters, vehicle activity prior to soak, soak time, driver behavior, and modal activity during the start period.

9.4.2 On-Network Running Exhaust Emissions

The MEASURE model is designed to work with three different emission models: MOBILE5A, an aggregate modal emission model, and a load-based modal emission model still under development. This section describes the aggregate modal emission model that is currently operational within MEASURE.

A hierarchical tree-based regression analysis was performed on the EPA (and other) vehicle emissions database to extract factors that best explained the variations in emissions between drive cycles and vehicles. A total of 700 vehicles and 4,000 vehicle-drive cycle tests were included in the database. The regression equations for predicting emissions include the following variables: acceleration rate, deceleration rate, inertial power surrogate, drag power surrogate, cruise speed, and percent time idling. The percent of variation explained by these equations is currently on the order of 17 percent. There is a great deal of “same vehicle” variability that cannot be explained by the model.

While ingenious in conceptual approach, the use of regression to develop modal emission equations from experiments that lack information on emissions by modal activity unfortunately results in equations of low explanatory power. The advantage of using these equations, though, is that they can be implemented in an aggregate modeling framework. One does not need to resort to traffic microsimulation models to generate the aggregate inputs required by the modal emission equations.

9.4.3 Off-Network Emissions Estimates

The MEASURE architecture is set up for three optional modeling approaches similar to the “On-Network Running

Exhaust" model (MOBILE5A, an aggregate modal emission model, or a load-based model). The Off-Network Module estimates vehicle running emissions that occur off of the typical travel demand model network. These emissions mostly occur on minor collector and local roads not included in travel demand models.

9.4.4 Impact of MEASURE on Emission Estimates

A recent paper by Hallmark et al.[138] illustrates the potential impact of incorporating vehicle modal activity into the emission estimates for traffic-flow improvements. The table from the paper shows that MEASURE predicts about four times the emission reductions for signal coordination (for an individual traffic signal coordinated with adjacent upstream signals) as a traditional analysis using MOBILE5 factors.

9.5 THE NCHRP 25-11 MODAL EMISSION MODEL

At the time of the NCHRP 25-21 research project, NCHRP 25-11 was in the final stages of developing a vehicle emission model that is sensitive to mode of operation.[139] The model is called CMEM.[140, 141] It is designed for integration with microsimulation models (it reads CORSIM output files) but will not replace MOBILE at the regional scale.

The NCHRP project sampled only Tier 0 and Tier 1 light-duty vehicles (cars and small trucks). The CMEM model that was developed as part of that project is based upon 357 sample vehicles (238 cars and 119 trucks; 82 percent of the vehicles were registered in California). Tier 2 vehicles and low-emission vehicles (LEVs) are not included in the sample or in the model. The NCHRP project was completed in December 1999; however, the University of California, Riverside, has other sponsors to extend CMEM to vehicle types not sampled as part to the NCHRP project.

CMEM uses 23 vehicle technology categories (see Table 31).

CMEM is a physical, power demand model. It is composed of six computation modules. The Engine Power Demand Module converts second-by-second data on desired vehicle speed and acceleration into an estimate of engine power demand. The engine power demand is converted to engine speed (revolutions per minute) and air/fuel ratio by the Engine Speed and Air/Fuel Ratio Modules. The engine power demand, engine speed, and air/fuel ratio are then used to compute the rate of fuel consumption in the Fuel Rate Module. The fuel use rate and the air/fuel ratio are used to compute emissions by the Engine-out Emissions Module. The engine emissions and the air/fuel ratio are then used to compute the tailpipe emissions by the Catalyst Pass Fraction Module (see Figure 14).

CMEM is available in three model forms: tables, a batch model, and a graphical user interface (GUI) model. The tables are designed to convert CORSIM microsimulation model output into second-by-second emission estimates. The tables convert vehicle-seconds by speed and acceleration category into estimates of CO, HC, NO_x, and fuel consumption. These tables are considered to be less accurate than the batch model or the GUI model since they do not take into account vehicle activity prior to the second under consideration (activity during the prior second has a significant impact on emissions during the current second).

TABLE 31 CMEM vehicle technology categories

Type of Vehicle	Technology Category
Normal-Emitting Cars	No Catalyst
	2-way Catalyst
	3-way Catalyst, Carbureted
	3-way Catalyst, Fuel Injection, > 50,000 miles, low power/weight ratio
	3-way Catalyst, Fuel Injection, > 50,000 miles, high power/weight ratio
	3-way Catalyst, Fuel Injection, < 50,000 miles, low power/weight ratio
	3-way Catalyst, Fuel Injection, < 50,000 miles, high power/weight ratio
	Tier 1, > 50,000 miles, low power/weight ratio
	Tier 1, > 50,000 miles, high power/weight ratio
	Tier 1, > 50,000 miles, low power/weight ratio
	Tier 1, > 50,000 miles, high power/weight ratio
Normal-Emitting, Light-Duty Trucks	Pre-1979 (≤ 8500 lbs Gross Vehicle Weight)
	1979 – 1983 (≤ 8500 lbs Gross Vehicle Weight)
	1984 – 1987 (≤ 8500 lbs Gross Vehicle Weight)
	1988 – 1993, ≤ 3750 lbs Loaded Vehicle Weight
	1988 – 1993, > 3750 lbs Loaded Vehicle Weight
	Tier 1, Light-Duty Truck 2 or 3 (3751–5750 Loaded Vehicle Weight)
	Tier 1, Light-Duty Truck 4 (6001–8500 Loaded Vehicle Weight)
High-Emitting Vehicles	Runs Lean (High NO_X Emitter)
	Runs Rich (High HC Emitter)
	Misfire
	Bad Catalyst
	Runs Very Rich (Super High HC Emitter)

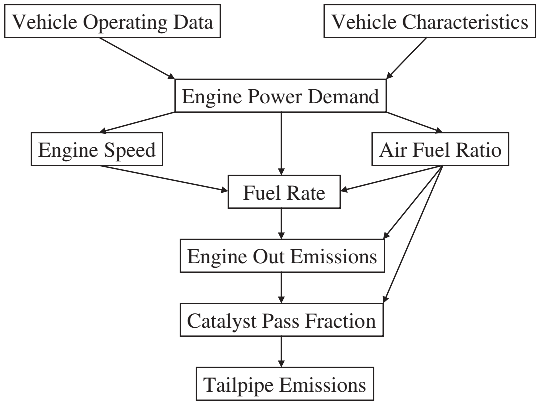


Figure 14. Comprehensive modal emissions model.

The batch model takes second-by-second vehicle trajectory data (speed and acceleration) and grade data and computes total emissions for the duration of the trajectory. The GUI model is similar to the batch model, only it is implemented in Microsoft ACCESS.

CMEM is sensitive to power demand, including the increased likelihood of vehicles going into power enrichment with mild acceleration under high-speed, low-congestion conditions. This result parallels the NCHRP 25-6 finding that power enrichment does not appear to be a significant factor in emissions at congested intersections because of the limitations on acceleration by queued vehicles.

9.5.1 Vehicle Operating Data

Vehicle operating data consist of second-by-second data on vehicle speed, vehicle acceleration, and grade. Also included is the second-by-second power drawn by any accessories, such as air conditioning.

9.5.2 Vehicle Characteristics

Vehicle characteristics include vehicle mass (lb), engine displacement (liters), number of cylinders, coastdown power (horsepower), ratio of engine speed to vehicle speed (rpm/mph), maximum torque (foot-pounds), number of gears, gear ratios, maximum power (horsepower), air/tire drag coefficients, and drive train efficiency as a function of speed.

Note that ignition timing is not a factor in the analysis. It is indirectly accounted for in the characterization of high versus normal emitter vehicles (e.g., misfire) and the other vehicle characteristics related to engine power.

Fuel type is also not directly accounted for in the analysis. It is indirectly accounted for by the engine power and the air/fuel ratio.

9.5.3 Engine Power Demand Module

The Engine Power Demand Module converts vehicle speed and acceleration at time t into estimates of engine power demand, $P(t)$, and engine torque demand, $Q(t)$, at time t. The specific formulas employed in this module are not described in the January 2000 user's guide.

9.5.4 Engine Speed Module

The Engine Speed Module converts engine power demand, $P(t)$, and engine torque demand, $Q(t)$, into an estimate, $N(t)$, of the engine revolutions per minute at time t. It is a function of the engine parameters, which give power and torque by rpm (P[rpm], Q[rpm]); the gear ratios; and the gear shift schedule. The specific formulas employed in this module are not described in the January 2000 user's guide.

9.5.4 Air/Fuel Ratio Module

The Air/Fuel Ratio Module determines the air/fuel ratio at time t. The air/fuel ratio is assumed to be stoichiometric if the power demand is less than the power threshold above which the engine goes into enrichment. The air/fuel ratio is a linear function of the power demand if the power demand goes into enrichment or is negative. The specific formulas employed in this module are not described in the January 2000 user's guide:

$$A/F(t) = \text{stoichiometric ratio (if } 0 \le P(t) \le \text{Pr)} \qquad \text{Equation 47}$$

$$A/F(t) = \text{linear function of } P(t) \text{ for } P(t) < 0 \text{ or } P(t) > \text{Pr} \qquad \text{Equation 48}$$

Where:

$A/F(t)$ = air/fuel ratio at time t,
$P(t)$ = engine power demand at time t, and
Pr = power threshold above which engine goes into enrichment.

9.5.6 Fuel Rate Module

The Fuel Rate Module computes the rate of fuel consumption at time t based upon the air/fuel ratio, friction loss, engine speed, displacement, and power demand:

$$\text{FR}(t) = A/F(t) * 1/44 * \left[k(t) * N(t) * D + P(t)/m\right] \qquad \text{Equation 49}$$

$$k(t) = k_0 * \left[1 + (N(t) - 33)2 * 10 - 4\right] \qquad \text{Equation 50}$$

Where:

FR(t) = fuel use rate at time t,
$A/F(t)$ = air/fuel ratio,

$k(t)$ = friction loss in kilojoules per revolution of engine and per liter of displacement,
k_0 = friction factor,
$N(t)$ = engine speed in rpm,
D = engine displacement in liters,
$P(t)$ = engine power demand at time t, and
m = engine efficiency.

9.5.7 Engine-Out Emissions Module

The fuel rate and the inverse of the air/fuel ratio are used to compute hot-stabilized engine-out emissions:

$$\mathrm{ECO} = [\mathrm{C}_0 * (1 - F/A) + a_{CO}] * \mathrm{FR}(t) \qquad \text{Equation 51}$$

$$\mathrm{EHC} = a_{HC} * \mathrm{FR}(t) + r_{HC} \qquad \text{Equation 52}$$

$$\mathrm{ENOX} = a_{1\mathrm{NOX}} * (\mathrm{FR}(t) - \mathrm{FR}_{\mathrm{NOXr}}) \quad \text{if } A/F(t) < 1.05 \qquad \text{Equation 53}$$

$$\mathrm{ENOX} = a_{2\mathrm{NOX}} * (\mathrm{FR}(t) - \mathrm{FR}_{\mathrm{NOXr}}) \quad \text{if } A/F(t) \geq 1.05 \qquad \text{Equation 54}$$

Where:

ECO = engine-out carbon monoxide emissions per second,
EHC = engine-out hydrocarbon emissions per second,
ENOX = engine-out nitrous oxide emissions per second,
C_0 = calibrated parameter,
F/A = inverse of air/fuel ratio at time t,
a_{CO} = calibrated parameter,
$\mathrm{FR}(t)$ = fuel use rate at time t,
a_{HC} = calibrated parameter,
r_{HC} = calibrated parameter,
$a_{2\mathrm{NOX}}$ = calibrated parameter,
$a_{1\mathrm{NOX}}$ = calibrated parameter, and
$\mathrm{FR}_{\mathrm{NOXr}}$ = fuel use rate at the $\mathrm{NO_X}$ threshold.

9.5.8 Catalytic Pass Fraction

The catalytic pass fraction is determined based upon a set of 10 parameters that determine the relationships between catalyst efficiencies and engine-out emissions and fuel/air ratios under hot-stabilized conditions. The specific formulas employed in this module are not described in the January 2000 user's guide.

9.5.9 Tailpipe Emissions

The tailpipe emissions are determined from the engine-out emissions multiplied by the catalytic pass fraction:

$$\mathrm{TCO}(t) = \mathrm{ECO}(t) * \mathrm{CPFCO}(t) \qquad \text{Equation 55}$$

$$\mathrm{THC}(t) = \mathrm{EHC}(t) * \mathrm{CPFHC}(t) \qquad \text{Equation 56}$$

$$\mathrm{TNOX}(t) = \mathrm{ENOX}(t) * \mathrm{CPFNOX}(t) \qquad \text{Equation 57}$$

Where:

$\mathrm{TCO}(t)$ = tailpipe emissions of CO at time t,
$\mathrm{THC}(t)$ = tailpipe emissions of HC,
$\mathrm{TNOX}(t)$ = tailpipe emissions of $\mathrm{NO_X}$,
$\mathrm{ECO}(t)$ = engine-out emission rate for CO at time t,
$\mathrm{CPFCO}(t)$ = catalyst pass fraction for CO at time t,
$\mathrm{EHC}(t)$ = engine-out emission rate for HC at time t,
$\mathrm{CPFHC}(t)$ = catalyst pass fraction for HC at time t,
$\mathrm{ENOX}(t)$ = engine-out emission rate for $\mathrm{NO_X}$ at time t, and
$\mathrm{CPFNOX}(t)$ = catalyst pass fraction for $\mathrm{NO_X}$ at time t.

9.5.10 Cold-Start Emissions

Cold-start emissions are estimated by applying a subset of seven model input parameters describing both cold-start catalyst performance and engine-out emissions to the above formulas.

9.6 THE NCHRP 25-6 INTERSECTION CO EMISSION MODEL

At the time of the NCHRP 25-21 research, HYROAD, the Hybrid Roadway Intersection Model, was undergoing final revisions under NCHRP Project 25-6. HYROAD is a disaggregate emission model that models the geographic dispersion of CO emissions in the vicinity of an intersection. The vehicle demands are given to the model, which then disaggregates the activity data by vehicle type, modal activity, and distance from the intersection. The model includes three modules: a Traffic Module consisting of a modified version of NETSIM, an Emissions Module that uses regression-derived weights for MOBILE5 driving cycles to generate a speed distribution that most closely matches the speed distribution for the Traffic Module, and a Dispersion Module that incorporates vehicle-induced roadway turbulence on air flow and near-roadway dispersion. The Traffic and Emission Modules can be readily adapted to simulate the emission effects of changes in congestion, subject to the limitations in the underlying emission factor model (currently MOBILE5). However, the Traffic Module produces detailed speed and acceleration distribution information, which can be directly used for emission calculations based a "modal" emission model, such as that being developed under NCHRP Project 25-11. These speed and acceleration distributions are currently disaggregated by location and signal phase, and further stratification by vehicle class can be readily accomplished.

HYROAD was still undergoing refinement and testing, but could provide useful results for assessing second-by-second emissions using simulated or measured vehicle speed and power profiles. In addition, statistical analyses of the vehicle testing database from this project may be used to rank the importance of changes in vehicle operating conditions arising from transportation projects.

9.7 THE NCHRP 25-14 HEAVY-DUTY VEHICLE EMISSION MODEL

At the time of the NCHRP 25-21 research, NCHRP Project 25-14 was producing analytical tools for predicting the effects of various transportation planning policies on heavy-duty vehicle activities and the associated emissions. The first phase of this research involved inventorying heavy-duty vehicle usage patterns.

9.8 ASSESSMENT

Currently, no single model addresses the range of specific emission processes in sufficient detail to capture all of the effects of traffic-flow improvement projects. At the present time, CMEM (from NCHRP Project 25-11) provides the most detailed and best tested estimates of hot-stabilized vehicle exhaust emissions at different speeds and accelerations. Similarly, EMFAC2000 (Version 2.02) provides the most detailed estimates of process-specific evaporative emissions and excess start emissions.

CHAPTER 10

STRATEGIC APPROACH TO METHODOLOGY

This chapter establishes the criteria to be used in development of the NCHRP 25-21 methodology, evaluates current practice against these criteria, and then evaluates various strategic approaches that might be taken by the proposed methodology to accomplish the project objectives.

10.1 PROJECT OBJECTIVE AND REQUIREMENTS FOR METHODOLOGY

The research problem statement for this project gives the following objectives for this research:

> The objective of this research is to develop and demonstrate, in case study applications, a methodology to predict the short-term and long-term effects of corridor-level, traffic-flow improvement projects on carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO_X), and particulate emissions (PM). The methodology should evaluate the magnitude, scale (such as regionwide, corridor, or local), and duration of the effects for a variety of representative urbanized areas.

The research problem statement goes on to identify the following specific requirements for the methodology to be developed by this project:

- The methodology should be able to predict short-term (less than 5 years) and long-term (more than 10 years) air quality effects of completed traffic-flow improvement projects.
- The methodology should evaluate those effects at the local, corridor, and regional scales.
- Examples of traffic-flow improvement projects that the methodology should address are added freeway lanes, arterial widenings, intersection channelization, access management, HOV lanes, signal coordination, transit improvements, ramp metering, and park-and-ride lots.
- The methodology should include consideration of the secondary effects of traffic-flow improvements, including possible changes in emissions resulting from project impacts on land use and on safety and accessibility for pedestrians, bicyclists, and transit users.
- To the extent possible, the methodology should be designed to use data sources commonly available to the transportation planning process.

Discussions between the NCHRP 25-21 panel and the research team during the development of the augmented work plan yielded the following additional guidance on the research objectives:

- While this project will result in analytical methods for assessing short- and long-term air quality and other effects; it is desired that the research team develop a visionary approach that can be applied to the broadest range of issues and options.
- The research should focus on analytical methods that can be implemented in a broad range of existing software used for travel demand modeling. The research report should describe the methods in sufficient detail for analysts to write the necessary job control statements, macros, or software to implement the methods.
- The potential audience for this research will be broad, including both technical and nontechnical interests. The final product should become a tool for effective decision making in investing transportation resources and should provide both qualitative policy direction and a "state of the practice" methodology for analyzing emission impacts.
- There is no expectation for the research team to predict pollutant concentrations or ozone formation resulting from traffic-flow improvement projects. Rather, the team is expected to use the best available emission factors and vehicle operations and activity data to estimate net changes in emissions of ozone precursors, particulates, and CO.
- The use of a modal emission model is a critical element of this project. In addition, this project should include the assessment of heavy-duty vehicle emissions.
- The land-use submodel need not be as geographically comprehensive or as detailed as HLFM/QRS, but it should be superior to STEP in its treatment of household and employment relocation issues.

10.2 METHODOLOGY EVALUATION CRITERIA

Rephrasing the research objectives and breaking them down into questions that can be mostly answered "Yes" and "No" yields the following criteria for evaluating the ability of existing and new methodologies to accomplish the project objectives:

1. Is the methodology suitable for predicting the long-term (10+ years), the short-term (under 5 years), or both effects of corridor-level traffic-flow improvement projects?
2. Is the methodology capable of accurately predicting the magnitude of impacts?
3. Is the methodology capable of predicting the geographic scale of impacts (i.e., regionwide, corridor, or local)?
4. Is the methodology capable of predicting the duration of impacts?
5. Is the methodology suitable for a wide variety of urbanized areas (small, medium, or large; technologically unsophisticated or sophisticated; data rich or poor)?
6. For which of the following types of traffic projects is the methodology suitable: major capacity increases, operational/access management improvements, or alternative mode improvements?
7. Does the methodology take into account the secondary land-use impacts of transportation projects to the extent that the projects affect long-term motor vehicle traffic demand?
8. Does the methodology take into account the secondary safety and accessibility impacts of transportation projects on pedestrians, bicyclists, and transit users to the extent that the projects affect mode share and motor vehicle use?
9. Does the methodology require data that are not commonly available to transportation planners?
10. Can the methodology be implemented in a broad range of travel demand–modeling software?
11. Is the methodology compatible with a motor vehicle modal emission model?
12. Can the methodology assess the impacts of traffic-flow improvement projects on heavy-duty vehicle emissions?

10.3 EVALUATION OF CURRENT PRACTICE AGAINST NCHRP 25-21 OBJECTIVES

Current MPO analytical tools for evaluating the air quality impacts of traffic-flow improvements meet relatively few of the NCHRP 25-21 criteria, even when considering the most sophisticated MPOs (see Table 32). No MPO is set up to analyze vehicle mode of operation emissions. Very few MPOs have models to forecast the impacts of traffic-flow improvements on truck activity. None of them take into account the impacts of traffic-flow improvement projects on pedestrian/bicycle/transit accessibility and safety and their effect on vehicle activity. None of them predict short-term impacts (under 5 years), and all are oriented toward predicting equilibrium effects, not the duration of impacts.

The major shortfalls of current methodologies when compared with the NCHRP 25-21 criteria are as follows:

- Inability to predict short-term impacts under 5 years. For such short time periods in the future, it is best to predict changes from current conditions rather than relying on a model to predict both existing and future conditions.
- Inability to predict the temporal duration of impacts. Models seek equilibrium and do not consider dynamic effects that may accelerate, delay, or prevent equilibrium.
- Difficulty of including land-use effects. Land-use models are available, but are crude and difficult to apply, which discourages their use except for a few major tests.
- Inability to predict the effects of traffic-flow improvements on pedestrian/bicycle/transit access and safety and their consequential impact on vehicle demand patterns.
- Inability to estimate vehicle mode of operation.
- Paucity of models for predicting heavy-vehicle activity effects of traffic-flow improvements.

10.4 EVALUATION OF STRATEGIC APPROACHES

There are three basic strategic approaches to developing a methodology to meet the objectives of NCHRP 25-21. They correspond to three levels of detail with which to attack the research objective (see Figure 15). The first is a macroscopic, areawide sketch-planning approach. The second is a mesoscopic approach equivalent to zones and links level of aggregation used by current MPO modeling technology. The final approach is a microscopic approach that evaluates changes in trip making and emissions at the individual household or person level. These three strategic approaches are evaluated against the NCHRP 25-21 research objectives in the following sections. Table 33 summarizes the discussion.

10.5 MACROSCOPIC SKETCH-PLANNING APPROACH

The macroscopic sketch-planning approach involves the development of a simple set of procedures, like SPASM, SMITE, or HERS, to predict the regional effects of traffic-flow improvements. Sketch-planning methodologies require a very simple set of input data and employ a limited set of variables (which limits the range of policy questions that can be addressed and limits the ability to take into account local variations) to arrive at estimates of regional average results. This approach has the advantage of simplicity, which makes it a tool more likely to be used by decision makers. The sketch-planning approach, however, fails to meet many of the other NCHRP 25-21 objectives that require a greater level of detail than can be provided by a macroscopic approach.

Localized impacts will be difficult to predict reliably with a sketch-planning method that is not sensitive to local conditions. A single elasticity based on an analysis of national data

TABLE 32 Evaluation of current MPO modeling approaches against NCHRP 25-21 criteria

Criteria	Small MPOs (e.g., COFG, MRCOG, and COMPASS)	Medium to Large MPOs (e.g., DVRPC, CATS, and Metro Washington)	Advanced-Practice MPOs (e.g., Portland, PSRC, and MTC)
1. Predicts short- and long-term effects	MPOs and State DOTs and the analytical procedures they use are generally focused on long-term (10+ years) analyses. Very simple growth factor methods are used for short-term (< 5 years) analyses.		
2. Magnitude of impacts	Analysis procedures leave out many second-order effects.	Procedures generally incorporate most second-order effects.	Most sophisticated. Procedures occasionally include third-order effects.
3. Geographic scale of impacts	All: local, corridor, regional.	All: local, corridor, regional.	All: local, corridor, regional.
4. Predicts duration of impacts	Analyses have not typically been concerned with dynamics. They generally predict equilibrium impacts.		
5. Suitable for small and large MPOs	Procedures are suitable, by definition.	Procedures are suitable, by definition.	Procedures are suitable, by definition.
6. Range of projects covered	Few nonhighway projects considered.	All projects.	All projects. Some more sophisticated pricing and land-use measures considered.
7. Includes land-use effects	Not often, if at all.	Manually estimated, some model use.	Generally DRAM/EMPAL type of models used. Not frequently done due to computational resources required.
8. Includes ped/bike/transit access/safety effects	No.	Generally no. Most take into account transit auto and walk access, but both auto access and nonmotorized access are only crudely modeled. No safety effects.	No. One MPO does include mode split effects of nonmotorized accessibility, but does not have procedure to predict how traffic-flow improvements would change accessibility.
9. Uses commonly available data	Yes.	Generally yes, but a few use more sophisticated data.	Most use sophisticated household survey and land-use/accessibility data.
10. Implementable in commonly used software	Yes.	Yes.	Generally yes, but some custom software are used for more sophisticated computations.
11. Compatible with modal emission model	No. Models produce crude mean speed by road segment.	No. Models produce mean speed by road segment.	No. Models produce mean speed by road segment.
12. Heavy-duty vehicle emissions	No.	No.	Some MPOs have truck activity models. Very rare for truck model to be sensitive to traffic-flow improvements.

The numbers in the first column correspond to the numbered items in Section 10.2. Second-order effects are trip generation, distribution, mode choice, route choice, and time-of-day effects. Third-order effects are land-use effects. CATS = Chicago Area Transportation Study, COFG = Council of Fresno Governments (in Fresno, California), COMPASS = Community Planning Association of Southwest Idaho, DVRPC = Delaware Valley Regional Planning Commission, MPO = metropolitan planning organization, MRCOG = Midregion Council of Governments (in Albuquerque, New Mexico), MTC = San Francisco Metropolitan Transportation Commission. PSRC = Puget Sound Regional Commission.

is unlikely to be robust in the face of "non-national average" conditions in the project area. For example, the HERS model elasticities make assumptions of route shifting between the nonsampled segments in the system to and from the highway performance monitoring system (HPMS) sampled segments. This assumption, which is incorporated into the long- and short-term elasticities, would be difficult to modify for project-specific conditions where route shifting is expected to be greater or less than the regional average conditions across the nation.

Sketch-planning approaches have also been traditionally "equilibrium" oriented, rather than dynamic. They are not reliable for predicting short-term, non-equilibrium conditions or the duration of non-equilibrium conditions. HERS has both long-term and short-term elasticities, but in both cases the traffic demand is assumed to reach an equilibrium. Duration of the effects is not predicted.

The strength of sketch-planning methods is their simple data requirements. The downside to its simplicity is that it is difficult to meaningfully test microscopic effects such as

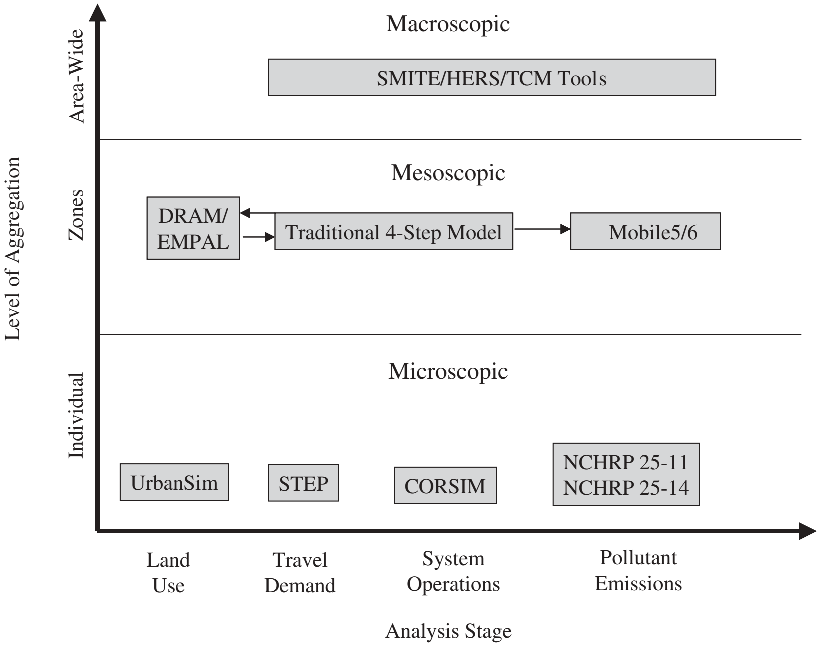


Figure 15. Strategic approaches.

pedestrian and bicycle access effects of traffic-flow improvement projects. It is also impossible to meaningfully predict vehicle modal activity. Heavy-duty vehicle activity predictions would also require more data than typically employed in sketch-planning methods.

Traffic-flow improvement projects tend to be (from the point of view of the entire air basin) a microscopic change to the transportation system. Even 20-year long-range transportation plan (LRTP) improvements tend to affect only a small portion of the transportation system. Minor changes to the regional transportation system are difficult to reliably detect within the expected accuracy of a sketch-planning model. The signal to noise ratio is usually too low.

Sketch-planning approaches are easy to apply and easy for decision makers to use. They meet some of the project criteria for NCHRP 25-21 but are incompatible with modal emission and heavy-duty vehicle emission models. They do not have very many policy-sensitive variables, which limits the range of policies that can be tested. Sketch-planning models have relatively little explanatory power, since the elasticities used in these models combine within them many separate effects. They cannot be calibrated to local or project-specific conditions and, as such, are not sensitive to the impacts of local contexts.

10.6 MESOSCOPIC CONVENTIONAL MODEL APPROACH

A mesoscopic approach to achieving the NCHRP 25-21 research objectives would involve various improvements to current conventional MPO models. The improvements can be incorporated into the models or used as a preprocessor or postprocessor to the conventional model.

A postprocessor, in the style of IDAS or STEAM, is one way to enhance the analytical reliability and capabilities of conventional models to meet NCHRP 25-21 objectives. This approach requires that a regional model produce one or more trip tables and one or more loaded highway networks. The postprocessor then develops heavy-duty vehicle and vehicle modal activity data for each highway link to meet the NCHRP 25-21 emission model objectives. A preprocessor, such as the DRAM/EMPAL land-use models, might be recommended to enhance the long-range forecasting of conventional models.

MPOs may find the preprocessors or postprocessors so valuable that the MPOs will incorporate them directly into the model streams. Nevertheless, this approach has not often been the case in the past. HLFM/QRS is the only example of an integrated land-use and travel forecasting software. Most agencies run their land-use forecasting models separately from their travel demand models and do so only sparingly because of issues with staff training and resource requirements.

The one major disadvantage of pre- or postprocessors, as far as meeting NCHRP 25-21 objectives, is that they cannot conveniently feed back their results to the land-use and household characteristics stage of the travel demand forecasting process. The postprocessor in particular does not have access to the behavior and characteristics of individual travelers and households. The postprocessor works with an aggregated base trip table, which the conventional travel demand model produced from the baseline land-use and household

TABLE 33 Evaluation of general analytical approaches

Criteria	Macroscopic Approach (e.g., HERS, SPASM, and SMITE)	Mesoscopic Approach (e.g., STEAM and IDAS)	Microscopic Approach (e.g., UrbanSim, TRANSIMS, and CMEM)
1. Predicts short- and long-term effects	HERS has separate long- and short-term elasticities. Others have single term.	Yes. Generally better at long-term effects.	Yes. Especially good at short-term effects.
2. Magnitude of Impacts	See Section 2.3 regarding difficulties of developing and applying elasticities. Wide range of elasticities in literature. Regional estimates of demand changes are essentially unvalidatable with field data.	Since postprocessor interfaces with regional model, it has many of the detail and accuracy advantages/disadvantages of conventional models. Since interface is "one-way" (from model to postprocessor), postprocessor does not equilibrate as well as if it were part of an improved model.	More detail implies (but does not ensure) better accuracy. Sensitive to more specific factors than sketch-planning models. Portions of models are validatable against household survey and count data.
3. Geographic scale of impacts	Generally limited to prediction of regional impacts of facility-specific improvements.	All levels: local, corridor, regional.	Ideal for local, good for corridor, very data intensive when applied at regional level.
4. Predicts duration of impacts	No. Assumes demand has reached equilibrium. Not a dynamic model.	No. All conventional demand models are equilibrium models.	UrbanSim can predict duration, being a dynamic model. Others cannot.
5. Suitable for small and large MPOs	Most suitable for small MPOs with limited resources. Also of use to supplement more formal model runs at large MPOs.	Simple way to improve model accuracy (for selected model outputs) for small MPOs. Less useful for large MPOs where some postprocessor functions may already be in MPO model.	Most likely to be feasible for only very large MPOs.
6. Range of projects covered	All projects types, but in less detail than for other approaches. Deviation of local conditions from national average can be problem.	Most all project types. Conventional models will be less adept at forecasting impacts of microscopic traffic-flow improvements.	All project types.
7. Includes land-use effects	Presumably included in long-term elasticity, but no identifiable step for land use alone.	Can be included if the user reruns the regional model that produced the land-use forecasts and takes care of manual feedback of results.	UrbanSim, yes.
8. Includes pedestrian/bike/ transit access/ safety effects	No. Does not forecast impacts of traffic-flow improvement projects on access/safety.	No. Some indirect effects might be included in the mode split model.	Yes possible, but not currently in TRANSIMS.
9. Uses commonly available data	Yes.	Generally yes. Might require some specialized data to evaluate certain projects.	Requires additional specialized data.
10. Implementable in commonly used software	Usually implemented in a spreadsheet.	Usually implemented in a custom program. Not generally implementable within standard demand model software.	No. Requires specialized software.
11. Compatible with modal emission model	No. Completely incompatible.	Can be indirectly linked to modal emission models.	Can be directly linked to modal emission models.
12. Heavy-duty vehicle emissions	No. Generally incompatible. Truck activity not forecasted separately.	Yes, but limited. Truck models are comparatively rare. Truck speeds not isolated from cars.	Yes, but truck modal activity results have not been validated.

The numbers in the first column correspond to the numbered items in Section 10.2. MPO = metropolitan planning organization. PUMS = Census public use microdata samples.

characteristics data. Except for this one limitation, a postprocessor meets most of the NCHRP 25-21 objectives.

One key issue with the design of a postprocessor is to identify which impacts of traffic-flow improvements are to be modeled inside the conventional travel demand model and which impacts are to be modeled by the postprocessor. For example, STEAM assumes that the conventional model produces demand forecasts that exclude some share of demand inducement. STEAM also assumes that the speed estimates produced by conventional models are sufficiently accurate for estimating base demand, but are not sufficiently accurate for estimating induced demand and user benefits. By way of contrast, IDAS assumes that the conventional model base demand and speed forecasts are accurate for the base case. All demand changes computed by IDAS are assumed to be the result only of changes in the supply conditions caused by ITS projects. There is no correction made for "errors" in the conventional model.

The mesoscopic conventional model approach has the advantage of meeting most of the NCHRP 25-21 research objectives, although feedback and equilibration would be difficult. However, this advantage results in a tool that cannot be directly used by most decision makers, but that must be applied instead by modeling experts. The modeling experts then must transmit the results to the decision makers. This limitation may limit the use of the NCHRP 25-21 methodology by small MPOs.

10.7 MICROSCOPIC APPROACH

A microscopic approach involves developing and extending current analytical tools for analyzing the microscopic effects of traffic-flow improvements on individual and household travel behavior and emissions. Examples of microscopic methodologies are UrbanSim, TRANSIMS, STEP, CORSIM, and CMEM.

A microscopic modeling approach is the one most consistent with the NCHRP 25-21 requirement that the methodology employ modal activity emission rates such as those produced by CMEM. Only vehicle microsimulation models produce directly the modal activity data required by CMEM. Other approximate methods are available to generate the necessary modal activity data. The microscopic approach also follows the recommendations identified in NCHRP 8-33.

An improved TRANSIMS model could potentially meet most of the NCHRP 25-21 objectives. The simple household model in TRANSIMS could be replaced with the Portland Tour-Based Model. A heavy-duty vehicle model could be added. TRANSIMS could be linked to UrbanSim to model land-use effects. It could then feed modal activity data to CMEM for modal emissions. Nevertheless, such a massively linked model would be difficult to set up and operate. This massive model would not meet the NCHRP 25-21 objectives of using commonly available data and would not be feasible for medium to small MPOs.

A 100-percent microsimulation approach for NCHRP 25-21 is simply not feasible at this time. It would require a massive amount of data and computer resources. Only the very largest MPOs with sufficiently pressing air quality problems and the staff resources to address them would be even remotely likely to use such a tool.

10.8 A BLENDED MICROSCOPIC/MESOSCOPIC APPROACH

The mesoscopic approach that works with conventional travel forecasting models and improves them has many advantages. Nevertheless, microscopic analysis has the ability to provide greater sensitivity and accuracy at critical points in the analysis. Thus, it appears that there might be some real advantages to blending the mesoscopic and microscopic approaches into a single methodology. Microscopic analysis would be used when sufficient data are available and greater sensitivity is needed. Mesoscopic analysis would be used when one needs to save on analytical and data resources.

The recommended NCHRP 25-21 methodology employs this blended approach. It uses mesoscopic analysis to predict the impacts of traffic-flow improvements on travel time and to predict the changes in modal activity. It uses microscopic analysis to analyze household travel behavior responses and modal activity emission rates. Using this hybrid approach saves on the heavy investment that would be required to microsimulate vehicle activity at the regional level and yet preserves the strength of a household-level travel behavior model.

CHAPTER 11

RECOMMENDED METHODOLOGY

The recommended methodology is designed to answer one fundamental question: "Will a specified traffic-flow improvement contribute to improved or worsened air quality locally and at the regional level, in the short term and in the long term?" Repeated exercise of the methodology on various case studies will answer the question, "Under what conditions will a specified traffic-flow improvement contribute to improved or worsened air quality?"

The methodology is applicable to a broader range of transportation improvement projects besides traffic-flow improvements. The methodology can be applied to transit improvements and projects to reduce traffic capacity.

11.1 RESEARCH OBJECTIVES FOR METHODOLOGY

The research statement for NCHRP 25-21 methodology lays out an aggressive set of objectives for the methodology:

- The methodology must apply to a wide variety of traffic-flow improvement projects at the local, corridor, and regional scales.
- The methodology must predict short-term and long-term impacts.
- The methodology must consider not only primary effects but also secondary effects resulting from accessibility and safety impacts on pedestrians, bicyclists, transit users, and land use.
- The methodology must have exceptional depth of detail, using a modal emission model, and include an assessment of heavy-duty vehicle emissions.
- The methodology should be easy to use and designed to use commonly available data sources (to the extent possible). It should be implementable in a broad range of existing travel demand software.

The objectives go on to state that the final product of this research should become a tool for effective decision making in investing transportation resources and should provide both qualitative policy direction and a state-of-the-practice methodology for analyzing emission impacts. The potential audience for this research will be broad, including both technical and nontechnical interests.

11.2 THEORETICAL FOUNDATION

The recommended methodology proceeds from the fundamental theoretical foundation that "nobody travels for the fun of it." Travel is a derived demand. People travel in order to obtain the ability to participate in activities or to obtain goods that are superior to what they could have done or obtained at their original location. Even sightseers are using the transportation to experience a vista they could not see at home. They may say they enjoyed the drive, but what they really enjoyed was what they could see out of the window. This blanket statement excludes individuals who test their vehicles or are hired to drive a vehicle.

Travel demand is, therefore, not VMT. Travel demand is the schedule of activities by location that travelers would like to pursue that day. In modeling parlance, it is the OD table of person trips for that day by time of day. VMT is merely the most cost-effective method (from the traveler's point of view) for satisfying that demand.

Thus, traffic-flow improvements by reducing average travel times can affect both the total demand for travel and the traveler's choice of the most cost-effective means for satisfying that demand.

In addition, some traffic-flow improvements do not change the average travel time but reduce the variance in travel speeds by smoothing out the traffic flow. Thus, it is possible for a traffic-flow improvement to have no effect on demand or on how that demand is satisfied on the street system and yet still have an effect on air quality by smoothing out the "stop-and-go" nature of the trip itself.

Finally, a series of traffic-flow improvements can make one portion of the metropolitan area more attractive to growth and new development than older, more established parts of the region. The shifting of growth from centrally located developed areas to undeveloped fringe areas can affect both demand and how it is satisfied on the transportation system. This is a very long-term impact. (Extensive transportation capacity investments in one metropolitan area can also increase the net in-migration to the region, but this effect will not be considered in this research.)

Thus, this methodology addresses four basic mechanisms by which traffic-flow improvements can influence mobile source emissions:

- Operational improvements that smooth out traffic flow and thus reduce acceleration/deceleration events,
- Travel time savings and losses on particular routes and modes of travel that influence the traveler's choice of the most cost-effective means for satisfying their demand to travel,
- Travel time savings that increase the total demand for travel, and
- Travel time savings that increase the relative attractiveness and therefore the growth rate of subareas in the region.

The first mechanism, operational improvements, will be called the "operations" effect. Traffic-flow improvements may increase the average speed on the facility, and/or they may increase the capacity of the facility prior to affecting travel behavior. Operational improvements will also affect vehicle mode of operation activity by reducing acceleration and deceleration events. The operations effect occurs on the first day that an improvement is opened for traffic. Travelers have not yet had an opportunity to change their demand schedule in response to the travel time savings provided by the improvement.

The second and third effects of traffic-flow improvements will be combined into a single "traveler behavior" effect. This effect comes in the months following opening day. As travelers become aware of the improvements, they change route, mode of travel, and departure time to take advantage of them. After the improvement has been in place for sufficient time for travelers to change their demand schedule (e.g., the OD table), they will take advantage of the reduced travel costs brought about by the improvement. Traveler behavior effects include changes in destination choice and trip generation (extra trips or stops along the way of a preexisting trip). The result of the behavior effects will be to partially counteract the opening-day travel time improvements. It is assumed that the traveler behavior effects cannot completely eliminate the opening-day travel time improvements, or there is no longer a stimulus to cause the traveler behavior effects.

The fourth effect of traffic-flow improvements is a redistribution of growth (new homes and jobs) to areas within the region that are benefited by the travel time savings attributable to a traffic-flow improvement. This will be called the "growth redistribution" effect. It is possible that the traffic-flow improvement might also enhance the relative competitiveness of the entire metropolitan region for new jobs and new homes, thus influencing overall growth of the region. However, this global effect is beyond the scope of this research project and methodology. It would require a full-blown socioeconomic forecasting model plus some kind of assumption regarding the pace of traffic-flow improvements in other competing metropolitan areas of the United States, Mexico, and Canada.

The research team assumed for the sake of this research project that all competing metropolitan areas have similar policies for implementing traffic-flow improvements and that, thus, a specific set of traffic-flow improvements would likely also be implemented in all metro regions. Thus, the relative competitiveness of the metro regions would be unaffected. The methodology will focus on redistribution impacts within a region, not total growth impacts for the entire region.

The foundation of this methodology is that traveler behavior response and growth redistribution occur *only* if the traffic-flow improvement results in a net change in trip *travel time*. Thus, travel behavior responses and growth redistribution can never completely eliminate travel time savings caused by a traffic-flow improvement.

Other possible effects of traffic-flow improvement not related to travel time such as operating cost improvements will be neglected. Vehicle operating cost (which can also affect travel demand) is correlated to travel time and will not be treated separately here, since the research team is not considering toll changes. The marginal effects of reduced acceleration/deceleration events on vehicle wear and tear (and thus vehicle operating costs) also will be neglected.

11.3 OUTLINE OF METHODOLOGY

The recommended methodology is a blended macroscopic-microscopic approach composed of five modules:

- The "HCM Assignment Module" predicts the highway travel times based upon traffic operations analysis speed-flow curves contained in the 2000 HCM.
- The "Traveler Behavior Response Module" uses elasticities derived from the Portland Tour-Based Model to predict the impact of travel time changes on trip making by peak period and by mode of travel.
- The "Growth Redistribution Module" predicts the impacts of traffic-flow improvements on growth patterns within the region. Subareas within the region that have better than average accessibility improvements will have greater than average growth rates in the region.
- The "Vehicle Modal Activity Module" translates the mean speeds and volumes predicted by the previous modules into a distribution of VHT by speed category and acceleration/deceleration rate category.
- The "Vehicle Emissions Module" translates the modal activity data into estimates of vehicle emissions.

The methodology employs macroscopic approximations of microscopic behavior throughout each of the modules.

The intent is to obtain a practical methodology that can be employed by a wide range of agencies while retaining as much as possible the behavioral accuracy of a microscopic analytical approach.

The proposed methodology predicts the *change in demand and vehicle emissions* caused by traffic-flow improvements at two points in time: short term (5 to 10 years) and long term (25+ years). Figure 16 provides a flow chart overview of the methodology.

The methodology requires as input:

- A set of baseline travel demand tables (OD tables) for AM, PM, and off-peak periods;
- A set of baseline highway and transit networks for the AM, PM, and off-peak periods; and
- The proposed traffic-flow improvement characterized in terms of its impact on mean free-flow speeds and capacities in the baseline networks.

The first round of analysis (base) assigns the baseline OD tables (by mode of travel and time period) to the baseline (no improvement) transportation networks for each time period and mode. The analysis then computes the mean speed and flow for each highway link. This link information is fed to the Vehicle Modal Activity Module, which outputs tables of vehicle activity (VMT) by speed and acceleration/deceleration category. The modal activity information is fed to the Vehicle Emissions Module (VOC, CO, NO_X, and PM), which computes the vehicular emissions.

The second round of analysis (short term) adds the traffic-flow improvement to the baseline network and computes new vehicle trip travel times for the improved network. The new travel times are compared to the baseline travel times to determine the changes in travel times. The changed travel times are entered into the Traveler Behavior Response Module, which modifies the baseline OD tables to produce revised OD tables. The revised OD tables are assigned to the highway network to

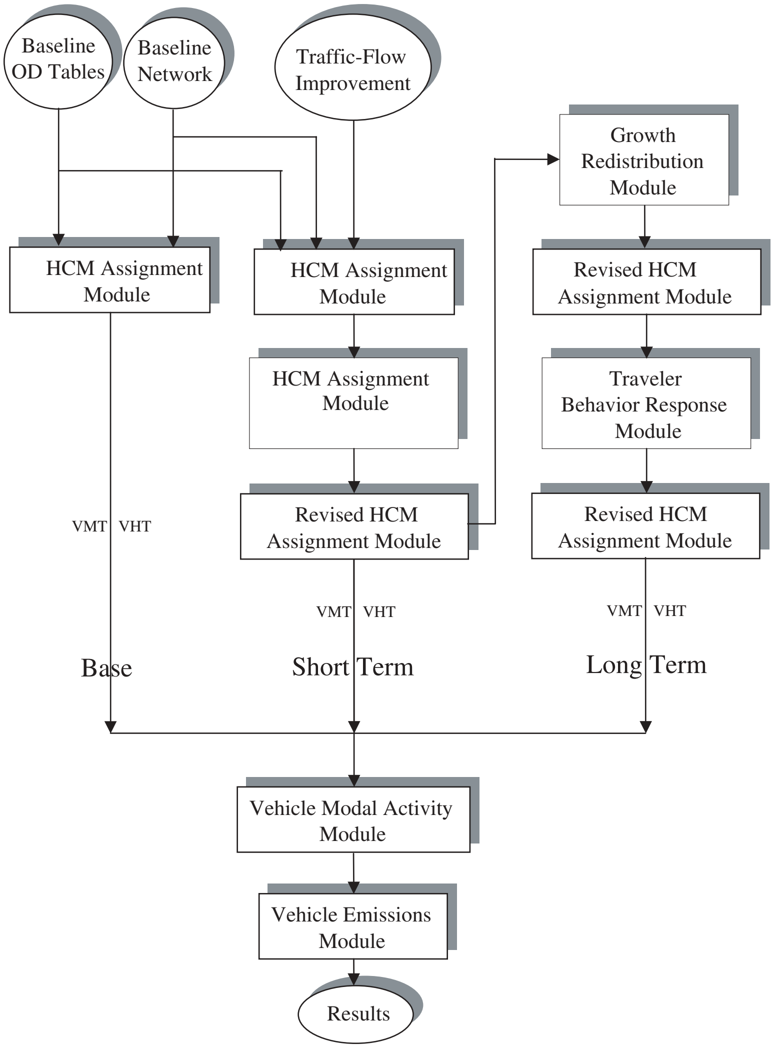


Figure 16. NCHRP 25-21 methodology.

produce mean speed and flow for each highway link. The information is then fed to the Vehicle Modal Activity and Vehicle Emissions Modules to obtain emissions for the short term.

The third round of analysis (long term) feeds the short-term results into the Growth Redistribution Module, which computes the impacts of the traffic-flow improvements on the relative growth rates of zones within the region. The revised growth rates are used to redistribute the origins and destinations of the trips in the short-term OD tables. The revised OD tables are then fed back through the Traveler Behavior Response Module one more time to obtain the mean speed and flow for each highway link. The information is then fed to the Vehicle Modal Activity and Vehicle Emissions Modules to obtain emissions for the long term.

The methodology generally follows the recommendations of NCHRP 8-33. The methodology is designed to predict the changes due to the traffic-flow improvement projects. It does not predict baseline conditions. Baseline conditions (the baseline OD tables) must be input to the methodology.

The methodology does not separately model the demand response of heavy-duty vehicles to traffic-flow improvements. Modeling truck demand response would require a completely separate methodology with separate data requirements. Trucks are presumed to be a fixed percentage of current and future traffic demands in this methodology.

The methodology does not forecast socioeconomic changes, traffic condition changes, or emission changes that are due to factors *other than traffic-flow improvements*. The proposed methodology therefore must be used in conjunction with some other model for predicting future baseline conditions, usually a conventional travel demand model.

11.4 HCM ASSIGNMENT MODULE

On the opening day, drivers will experience the maximum travel time savings provided by an improvement project, before it is diminished by changes in vehicle demand. The improved road section will have higher operating speeds and fewer and milder acceleration/deceleration events. If the improvement also increases peak capacity, then more vehicles will be able to pass through the improved segment during the peak hour and potentially impact downstream capacity bottlenecks.

The HCM Assignment Module predicts the highway vehicle travel time effects of the traffic-flow improvement for a fixed level of demand. Inputting the base demand to the module is equivalent to predicting travel times for the day that a traffic-flow improvement is first opened to traffic. Travelers have not had time to adjust to the travel time savings, so, at this stage in time, there is no demand response. If future demands are input to the module, then the module will predict future travel times and delays for that level of demand. This module has multiple uses in the methodology, being applied to the base case, short-term, and long-term analyses.

The required inputs for the HCM Assignment Module are vehicle OD tables (by mode and time period), the baseline geometric characteristics of the regional highway network (facility type, free-flow speeds, capacity characteristics, and segment lengths), and similar geometric information for the traffic-flow improvement. The module computes the highway link operating characteristics: volume/capacity and mean speed.

The module uses the 2000 HCM Chapter 30 speed-flow curves (these curves are sometimes called the Akcelik curves in the literature) and capacities to estimate the mean speed of traffic on each link of the highway network. A standard static users equilibrium (SUE) assignment of the OD table is performed in this module using the HCM curves for each period of the day (typically AM, PM, and off-peak).

It should be noted that the travel time savings on the improved segment may be partially compensated by increased delays at downstream bottlenecks. This “downstream” effect of traffic-flow improvements are neglected by this module. (Tests showed that this downstream effect was not significant for the conditions of the PSRC, so this effect was ignored in the methodology. See the later chapter on the derivation of the HCM Assignment Module for more details.)

The module computes only highway travel times for mixed-flow and HOV lanes. Transit, bicycle, and pedestrian travel times (if needed) must be computed using some standard travel demand–modeling procedure consistent with the procedure used to estimate the baseline OD tables by time period for each of these non-auto modes of travel.

11.5 TRAVELER BEHAVIOR RESPONSE MODULE

Travelers will adjust their demand schedule for travel in response to changes in the travel time required to reach their daily activity locations. Demand responses may include changes in trip lengths (trip distribution), number of trips (trip generation), time of day (peaking), and mode of travel (mode choice). The Traveler Behavior Response Module predicts how travel demand will react to the travel time savings created by traffic-flow improvements.

The module computes estimated changes in demand for each entry in the OD table for each mode of travel and each period of the day based on the estimated changes in travel times by mode and by time period. The module employs direct elasticities and cross-elasticities derived from the Portland Tour-Based Model. (An example of a direct elasticity is the percentage change in HOV demand for each percentage change in HOV travel time. An example of a cross-elasticity is the percentage change in HOV demand for each percentage change in SOV travel time. Cross-elasticities are also used to account for shifting of travel between peak and off-peak periods for each mode of travel.)

Heavy-duty vehicles (e.g., trucks) are presumed to respond in the same manner as light-duty SOVs respond to travel changes in this module. Thus, heavy-duty vehicles are not modeled separately.

If an MPO already has a tour-based model in place that can predict the impacts of travel time and cost changes on out-of-home trip making, time of day, and mode choice, then that model can be used in place of the simpler Traveler Behavior Response Module described here.

The methodology applies to all trips made in the region. As long as through trips are included in the regional OD tables, then the methodology will adjust in response to travel time savings generated by the traffic-flow improvement projects. If through trips are not included in the base regional OD table, then the methodology will be unable to adjust.

11.6 GROWTH REDISTRIBUTION MODULE

Significant improvements in transportation infrastructure in one part of the urban region will impact the geographic distribution of housing and job growth in the region over the very long term (25+ years). The region's ability to retain current residents and reduce emigration may be affected. The total growth rate for the region may also be affected by changing the attractiveness of the region to migrants from other regions. This last effect, however, requires a model at the national level to properly account for migration between regions. Therefore, the overall effect on total regional growth will be excluded from the methodology.

The Growth Redistribution Module will predict the very long-term impacts of localized travel time changes (caused by traffic-flow improvements) on the geographic distribution of growth in a metropolitan area. There are already several sophisticated land-use models available (such as UrbanSim) that could be used for the purpose of this module. However, these models require a great deal of specialized economic data and effort to set up for a region (which may be beyond the resources of many MPOs). Where such a model exists in a region, it can be used to predict the long-term effects. Where such a model is not available, the simpler Growth Redistribution Module is proposed for use to approximate the long-range land-use effects of traffic-flow improvements.

The Growth Redistribution Module requires that a baseline 20- to 25-year forecast of land-use growth (households and employment changes) be available for the metropolitan area. This baseline forecast should have been prepared either manually or with a model taking into account accessibility changes as well as all of the other factors that commonly affect the distribution of growth within a region. A simple linear regression model is fitted to the baseline land-use forecast. The regression module predicts the change in the growth rate in households and employment in each zone of the region as a function of the relative change of accessibility for each zone. Although not sophisticated enough to predict actual growth, the model should be sufficient to predict how small changes in travel time accessibility can affect the predicted baseline growth rate in specific zones of the region.

The module presumes that total regional growth will be unaffected by traffic-flow improvements (in other words, the model will not be sensitive to the potential effects of differing levels of regional traffic-flow improvements on the competitiveness of regions for attracting new households or jobs). The module predicts only how regional growth might be reallocated from marginally less accessible zones to more accessible zones within the region.

11.7 VEHICLE MODAL ACTIVITY MODULE

The Vehicle Modal Activity Module converts the macroscopic vehicle activity data produced by the previous modules (VHT and VMT by link, mode, and time period) to microscopic modal activity data (VHT by speed and acceleration category). Four tables (Uncongested Freeway, Congested Freeway, Uncongested Arterial, and Congested Arterial) containing percentages are used to determine the proportion of total vehicle-hours on each street and freeway segment that are spent in each speed/acceleration category. These tables were derived from microsimulation of vehicle activity on example real-world sections of freeways and arterial streets using the CORSIM model.

Additional tables for other facility types and varying ITS and traffic management options can be created using CORSIM. The creation of such tables was beyond the resources of this research project and was consequently deferred to future research.

11.8 VEHICLE EMISSION MODULE

The Vehicle Emission Module converts the passenger car modal activity data into estimates of vehicular emissions. The potential impacts of traffic-flow improvements on heavy-duty vehicle and transit vehicle emissions are neglected. (The necessary information on heavy-duty vehicle emission rates by mode of operation was not available at the time of this research.) Modal emission factors from CMEM and EMFAC2000 are used to produce the emissions estimates.

The primary effects of traffic-flow improvement projects are related to speeds and delay along specific corridors. The direct emissions effects include the following:

- Running exhaust emissions (due to changes in vehicle speed and acceleration profiles, as well as changes in VMT due to route choice),
- Running evaporative emissions (due to changes in total travel time), and
- Refueling and CO_2 emissions (due to changes in fuel efficiency).

CMEM was used to produce running exhaust emission rates for the specified speed and acceleration frequency distributions contained in the modal activity data.

There are two secondary effects of traffic-flow improvement projects that influence emissions. First, to the extent that traffic-flow improvement projects reduce total travel time, there may be some increase in the number of trips made, resulting in additional start emissions. Second, both reduced travel time and increased numbers of trips alter the number and timing of hot soak, diurnal, and resting loss periods for the vehicle. Neither of these effects are included in the current version of the NCHRP 25-21 methodology.

Virtually all emission rates are dependent on ambient temperature. This methodology uses an average summer day temperature profile for VOC and NO_X and an average winter day for CO analyses.

11.8.1 Heavy-Duty Vehicle Emissions

Changes in heavy-duty vehicular emissions due to traffic-flow improvements are not explicitly included in the methodology for two reasons: (1) modal emission rate data were not available for heavy-duty vehicles at the time of the NCHRP 25-21 project and (2) the majority of urban area travel demand models do not explicitly model heavy-duty vehicle activity separately from light-duty vehicles. The proposed methodology consequently focuses on modeling light-duty vehicle emission changes.

11.8.2 Changes in Emission Control Technologies

The emission rates used in the NCHRP 25-21 methodology can be replaced with new modal emission rates when they become available. The analyst simply substitutes new rate tables categorized by mean speed and acceleration rate for the original CMEM rates.

CHAPTER 12

DERIVATION OF HCM ASSIGNMENT MODULE

The purpose of the HCM Assignment Module was to improve current methods for estimating the travel delay effects of traffic congestion. The approach taken was to replace the conventional Bureau of Public Roads (BPR) equation method still used in many travel demand models with more up-to-date traffic operations research results contained in the 2000 HCM. The module substitutes the following HCM-based information into the SUE traffic assignment step of the travel demand model process:

- Free-flow speeds by facility type and area type;
- Link capacities by facility type, area type, and other characteristics of facility; and
- HCM-based Akcelik set of speed-flow curves.

A process was also developed for constraining the demands downstream of a bottleneck to the maximum flow rate of the bottleneck. However, testing showed that the improved accuracy in the estimated delays was not worth the cost of additional computer run times. More than 75 percent of the observed improvement in accuracy could be obtained simply by incorporating improved free-flow speeds, capacities, and speed-flow curves without having to incur the cost of a tripling of computer run times required to complete a peak-period assignment. This conclusion is explained in more detail later in this chapter.

12.1 HCM/AKCELIK SPEED-FLOW EQUATION

The mean speed for each segment during the peak period is estimated using the following equations taken from the 2000 HCM. The mean vehicle speed for the link is computed by dividing the link length by the link traversal time. The link traversal time (R) is computed according to the following modified Akcelik equation from the HCM:

$$R = R_0 + D_0 + D_L + 0.25N * T\left[(x-1) + \sqrt{(x-1)^2 + \frac{16J * L^2 * x}{N^2T^2}}\right] \quad \text{Equation 58}$$

Where:

R = the segment traversal time (hours),
R_0 = the segment traversal time at free-flow speed (hours),
D_0 = the zero-flow control delay at signals (equals zero if no signals) (hours),
D_L = the segment delay between signals (equals zero if no signals) (hours),
N = the number of signals on the segment (equals one if no signals),
T = the expected duration of the demand (length of analysis period) (hours),
x = the segment demand/capacity ratio,
L = the segment length (miles), and
J = the calibration parameter.

The computation of the free-flow travel time (R_0) and signal delay terms (D_0, D_L) is explained in the following sections.

The number of signals (N) on the facility segment excludes the signal at the start of the street segment (if present), because this signal should already have been counted in the upstream segment. Streets are often split into segments (links) starting and ending at signalized intersections. The counting convention suggested here avoids double counting of the signals located at the start and end points of each segment.

When there are no signals on the facility, N is still set equal to one. This is because N is really the number of delay-causing elements on the facility. Each delay-causing element on the facility adds to the overall segment delay when demand starts to approach and/or exceed capacity at that element or point. Since demand in excess of capacity must wait its turn to enter the facility segment, there is always at least one delay-causing element (i.e., the segment itself) on a facility, even when there are no signals. The more signals there are on a facility, the more points there are where traffic is delayed along the way.

This means that a bottleneck section of the facility should be coded as a single link and not arbitrarily split into sublinks. The HCM/Akcelik equation (and the standard BPR equation as well) treats each link as a potential delay-causing bottleneck on the network. Splitting one real-world bottleneck into three hypothetical links each with the same demand would triple the estimated delay at the bottleneck.

The expected duration of demand is set equal to the length of the analysis period.

The segment demand/capacity ratio (x) is the ratio of the total demand for the analysis period divided by the total capacity for the period.

The calibration parameter J is selected so that the traversal time equation will predict the mean speed of traffic (averaged over the length L of the link) when demand is equal to capacity. It is computed according to the following equation:

$$J = \frac{(R_c - R_0 - D_0 - D_L)^2}{L^2} \qquad \text{Equation 59}$$

Where:

J = the calibration parameter,
R_c = the link traversal time when demand equals capacity (hours),
R_0 = the free-flow speed traversal time (hours),
D_0 = the zero-flow control delay (hours),
D_L = the segment delay (hours), and
L = the length of the link (miles).

The values for J, shown in Table 34 and Table 35, reproduce the mean segment speeds at capacity predicted by the analysis procedures contained in the 2000 HCM. Tables 34 and 35 use the following definitions of facility types from Chapter 5 of the 2000 HCM:

- **Freeway:** A multilane, divided highway with a minimum of two lanes for the exclusive use of traffic in each direction and full control of access without traffic interruption.
- **Multilane highway:** A highway that has at least two lanes in each direction for the exclusive use of traffic, that has no control or partial control of access, and that may have periodic interruptions to flow at signalized intersections no closer than 2 miles apart.
- **Two-lane highway:** A highway that has only one lane in each direction (with or without occasional passing lanes) for the exclusive use of traffic, that has no control

TABLE 34 Recommended calibration parameter *J* for freeways and highways

SI Units

Facility Type	Signals Per Km	Free-Flow Speed (km/h)	Speed at Capacity (km/h)	J
Freeway	n/a	120.0	85.7	1.11E-05
Freeway	n/a	110.0	83.9	8.00E-06
Freeway	n/a	100.0	82.1	4.75E-06
Freeway	n/a	90.0	80.4	1.76E-06
Multi-Lane Hwy	n/a	100.0	88.0	1.86E-06
Multi-Lane Hwy	n/a	90.0	80.8	1.60E-06
Multi-Lane Hwy	n/a	80.0	74.1	9.91E-07
Multi-Lane Hwy	n/a	70.0	67.9	1.95E-07
Two-Lane Hwy	n/a	110.0	70.0	2.70E-05
Two-Lane Hwy	n/a	100.0	60.0	4.44E-05
Two-Lane Hwy	n/a	90.0	50.0	7.90E-05
Two-Lane Hwy	n/a	80.0	40.0	1.56E-04
Two-Lane Hwy	n/a	70.0	30.0	3.63E-04

U.S. Customary Units

Facility Type	Signals Per mile	Free-Flow Speed (mph)	Speed at Capacity (mph)	J
Freeway	n/a	75.0	53.3	2.947E-05
Freeway	n/a	70.0	53.3	2.003E-05
Freeway	n/a	65.0	52.2	1.423E-05
Freeway	n/a	60.0	51.1	8.426E-06
Freeway	n/a	55.0	50.0	3.306E-06
Multi-Lane Hwy	n/a	60.0	55.0	2.296E-06
Multi-Lane Hwy	n/a	55.0	51.2	1.821E-06
Multi-Lane Hwy	n/a	50.0	47.5	1.108E-06
Multi-Lane Hwy	n/a	45.0	42.2	2.174E-06
Two-Lane Hwy	n/a	65.0	40.2	9.043E-05
Two-Lane Hwy	n/a	60.0	35.2	0.0001385
Two-Lane Hwy	n/a	55.0	30.2	0.0002239
Two-Lane Hwy	n/a	50.0	25.2	0.0003893
Two-Lane Hwy	n/a	45.0	20.2	0.0007484

TABLE 35 Recommended calibration parameter *J* for signalized streets

SI Units

Facility Type	Signals Per Km	Free-Flow Speed (km/h)	Speed at Capacity (km/h)	J
Arterial Class I	0.333	80	53	2.21E-05
Arterial Class I	1.000	80	31	2.04E-04
Arterial Class I	2.500	80	15	1.25E-03
Arterial Class II	0.500	64	40	4.99E-05
Arterial Class II	1.000	64	28	2.00E-04
Arterial Class II	2.000	64	18	7.91E-04
Arterial Class III	2.000	56	17	8.02E-04
Arterial Class III	3.000	56	13	1.78E-03
Arterial Class III	4.000	56	10	3.18E-03
Arterial Class IV	4.000	48	10	3.17E-03
Arterial Class IV	5.000	48	8	4.99E-03
Arterial Class IV	6.000	48	7	7.11E-03

U.S. Customary Units

Facility Type	Signals Per Mile	Free-Flow Speed (mph)	Speed at Capacity (mph)	J
Arterial Class I	1.000	50	33.1	2.21E-05
Arterial Class I	2.000	50	19.3	2.04E-04
Arterial Class I	4.000	50	9.6	1.25E-03
Arterial Class II	1.000	40	24.8	4.99E-05
Arterial Class II	2.000	40	17.8	2.00E-04
Arterial Class II	3.000	40	11.2	7.91E-04
Arterial Class III	3.000	35	10.9	8.02E-04
Arterial Class III	5.000	35	7.9	1.78E-03
Arterial Class III	6.000	35	6.3	3.18E-03
Arterial Class IV	6.000	30	6.1	3.17E-03
Arterial Class IV	8.000	30	5.0	4.99E-03
Arterial Class IV	10.000	30	4.3	7.11E-03

or partial control of access, and that may have periodic interruptions to flow at signalized intersections no closer than 2 miles apart.

- **Arterial:** A signalized street that primarily serves through traffic and that secondarily provides access to abutting properties, with signals spaced 2 miles or less apart. Arterials are divided into classes according to the posted speed limit and signal density criteria shown in Table 36.

12.2 FREE-FLOW SPEEDS

The segment traversal time for free-flow conditions (R_o) is computed from the free-flow speed:

$$R_0 = {}^{L}\!/_{S_0}$$

Equation 60

Where:

TABLE 36 HCM arterial class criteria

Arterial Class	Posted Speed Limit (SI Units)	Signal Density (SI Units)	Posted Speed Limit (U.S. Customary Units)	Signal Density (U.S. Customary Units)
Class I	70-90 km/h	0.3-2.5 signals/km	45-55 mph	0.5-4 signals/mi.
Class II	55-70	0.3-3.1	35-45	0.5-5
Class III	50-55	2.5-6.3	30-35	4-10
Class IV	40-50	2.5-12.5	25-35	4-20

Source: Chapter 15, Urban Streets, HCM.

Note that there may be instances of overlaps in arterial class definitions. The analyst should consult Chapter 15 of the HCM for additional information on the identification of a specific arterial class.

R_0 = free-flow traversal time (hours),
L = length (miles), and
S_0 = the segment free-flow speed (mph).

The free-flow speed is the mean speed of traffic when demand is so low that changes in demand do not affect the mean speed of traffic on the segment. For freeways and multilane highways, free flow is the mean speed observed when volumes are less than 1,300 vehicles per hour per lane. For signalized streets, the free-flow speed is the maximum mean speed of traffic obtained at any point between signalized intersections for low-volume conditions.

The mean speed is computed as the sum of the travel times to traverse the length of the segment, divided into the length of the segment times the number of vehicles in the sample.

The following linear equations can be used to estimate free-flow speed based on the posted speed limit for arterials, freeways, and highways (source: *NCHRP Report 387: Planning Techniques to Estimate Speeds and Service Volumes for Planning Applications*, Transportation Research Board, Washington, D.C., 1997):

For posted speed limits of 50 mph or greater:

$$\mathrm{FFS} = 0.88 * \mathrm{PSL} + 14 \qquad \text{Equation 61}$$

For posted speed limits of less than 50 mph:

$$\mathrm{FFS} = 0.79 * \mathrm{PSL} + 12 \qquad \text{Equation 62}$$

Where:

FFS = free-flow speed (mph) and
PSL = posted speed limit (mph).

12.3 CAPACITIES

Highway link capacities are estimated using the procedures contained in the 2000 HCM. The following subsections summarize the information contained in Chapter 30 of the HCM.

12.3.1 Freeways, Multilane Highways, and Two-Lane Highways

The following equation is used to compute the capacity of a freeway or highway link at its critical point. The critical point is the point on the link with the lowest throughput capacity.

$$c = Q * N * F_{hv} * F_p * F_g * \mathrm{PHF} \qquad \text{Equation 63}$$

Where:

c = capacity (vph),
Q = the passenger car equivalent (p.c.e.) capacity per hour per lane,
N = number of through lanes (ignore auxiliary and "exit only" lanes),
F_{hv} = heavy-vehicle adjustment factor,
F_p = driver population adjustment factor,
F_g = grade adjustment factor, and
PHF = peak-hour factor.

Table 37 provides the HCM-recommended passenger car equivalent capacities per lane (Q). See the HCM for appropriate values for the adjustment factors.

12.3.2 Arterials

The capacity of an arterial is determined by examining the through-movement capacity at each signal-controlled intersection on the arterial link. The intersection with the lowest through capacity determines the overall capacity of the arterial link. The following equation is used to compute the one-direction through capacity at each signal:

$$c = S_0 * N * f_w * f_{hv} * F_g * f_p * f_{bb} * f_a * f_{LU} * f_{LT} * f_{RT} * f_{Lpb} * f_{Rpb} * \mathrm{PHF} * g/C \qquad \text{Equation 64}$$

Where:

c = capacity (vph),
S_0 = ideal saturation flow rate = 1,900 vehicles per hour of green per lane,
N = number of lanes,
f_w = lane-width adjustment factor,

TABLE 37 Passenger car equivalent (PCE) capacities for freeways and highways

Free-Flow Speed	PCE Capacity (passenger cars per hour per lane)		
	Freeways	Multilane Hwys	Two-Lane Hwys
75 mph (112 km/h)	2400		
70 mph (104 km/h)	2350		
65 mph (96 km/h)	2300	2200	1700
60 mph (88 km/h)	2250	2100	1700
55 mph (80 km/h)		2000	1700
50 mph (70 km/h)		1900	1700

f_{hv} = heavy-vehicle adjustment factor,
F_g = grade adjustment factor,
f_p = on-street parking crossing adjustment factor,
f_{bb} = local bus adjustment factor,
f_a = central business district adjustment factor,
f_{LU} = lane-use adjustment factor,
f_{LT} = left-turn adjustment factor,
f_{RT} = right-turn adjustment factor,
f_{Lpb} = pedestrian/bicycle blockage of left-turn factor,
f_{Rpb} = pedestrian/bicycle blockage of right-turn factor,
PHF = peak-hour factor, and
g/C = ratio of effective green time per cycle.

See the HCM for appropriate values for the adjustment factors.

12.4 SIGNAL DATA REQUIRED BY HCM/AKCELIK

The zero-flow control delay and the between-signal delay are required to estimate speeds for signalized arterial streets. The zero-flow control delay (D_0) is computed as follows:

$$D_0 = \frac{N}{3{,}600} * \mathrm{DF} * \frac{C}{2}\left(1 - {}^{g}\!/_{C}\right)^2 \qquad \text{Equation 65}$$

Where:

D_0 = the zero-flow control delay at the signal (hours);
N = maximum of one, or the number of signals on the segment;
3,600 = conversion from seconds to hours;
g/C = average effective green time per cycle for signals on segment;
C = average cycle length for all signals on the segment (seconds); and
DF = delay factor,
= 0.9 for uncoordinated traffic-actuated signals,
= 1.0 for uncoordinated fixed-time signals,
= 1.2 for coordinated signals with unfavorable progression,
= 0.9 for coordinated signals with favorable progression, and
= 0.6 for coordinated signals with highly favorable progression.

If the ratio of green time per cycle for the arterial through movement is not known, a default value of 0.44 can be used. Similarly, if the signal cycle length is not known, then a default value of 120 seconds can be used. A survey of local average signal cycle lengths by area type (e.g., downtown, suburban, and rural) may be desirable to establish appropriate local default values.

The segment delay between signals (D_L) is estimated as follows:

$$D_L = L * \frac{d_L}{60} \qquad \text{Equation 66}$$

Where:

L = The length of the segment and
d_L = The delay per mile, given in Table 38.

TABLE 38 Segment delay between signals

Segment Delay (secs/mile)

Arterial Class:	I	I	I	II	II	II	III	III	IV	IV
Free-Flow Speed (mph)	55	50	45	45	40	35	35	30	35	30
signal spacing (miles)										
0.05										107
0.10							42	35	62	60
0.15							32	21	37	30
0.20				29	25	22	25	14	27	20
0.25	32	28	24	24	20	16	17	7	19	12
0.30	27	23	19	19	12	7				
0.40	17	14	14	14	6	2				
0.50	8	6	8	8	3	0				
1.00	0	0	0	0	0	0				

Segment Delay (secs/km)

Arterial Class:	I	I	I	II	II	II	III	III	IV	IV
Free-Flow Speed (km/h)	88	80	72	72	64	56	56	48	56	48
signal spacing (km)										
0.08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	66.9
0.16	n/a	n/a	n/a	n/a	n/a	n/a	26.3	21.9	38.8	37.5
0.24	n/a	n/a	n/a	n/a	n/a	n/a	20.1	13.1	23.2	18.8
0.32	n/a	n/a	n/a	18.1	15.6	13.8	15.7	8.8	17.0	12.5
0.40	19.7	17.5	15.0	15.0	12.5	10.1	10.7	4.4	12.0	7.5
0.48	16.6	14.4	11.9	11.9	7.5	4.5	n/a	n/a	n/a	n/a
0.64	10.3	8.8	8.8	8.8	3.8	1.3	n/a	n/a	n/a	n/a
0.80	4.7	3.8	5.0	5.0	1.9	0.0	n/a	n/a	n/a	n/a
1.60	0.0	0.0	0.0	0.0	0.0	0.0	n/a	n/a	n/a	n/a

Source: 2000 HCM, Exhibit 15-3, Segment Running Time Per Mile. Table computed by subtracting running time if traveling at free-flow speed from running time shown in exhibit.

12.5 CONSTRAINING DEMAND DOWNSTREAM OF BOTTLENECKS

One criticism of conventional travel demand model practice has been that all demand is loaded on the highway network, even if capacity bottlenecks might prevent the demand from getting through the network before the end of the analysis period. The demand for links downstream of a bottleneck is not reduced to account for demand stored at the bottleneck itself.

If demand is greater than capacity at a bottleneck, the drivers must wait in line at the bottleneck until it is their turn to go through bottleneck. Figure 17 illustrates this process. A total of 5,000 vehicles per hour wish to go from point "A" to point "B." They proceed from point "A" to "B" until they hit Bottleneck 1. This bottleneck can carry only 4,000 vehicles per hour, so 1,000 must wait until the next hour before they can proceed. Meanwhile, the 4,000 that can pass through Bottleneck 1 proceed until they hit Bottleneck 2. Bottleneck 2 can carry only 2,500, so 1,500 must wait until the next hour before they can proceed. The remaining 2,500 vehicles are actually able to get from point "A" to point "B" in the first hour. Excess demand is in essence stored within the network.

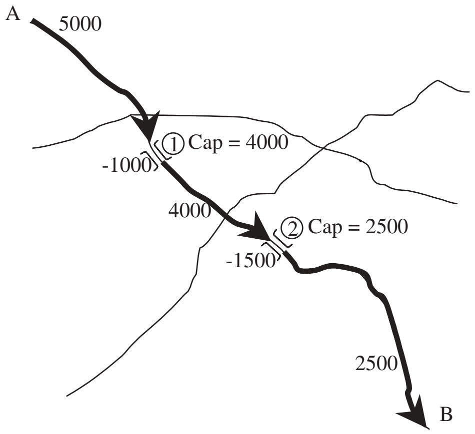
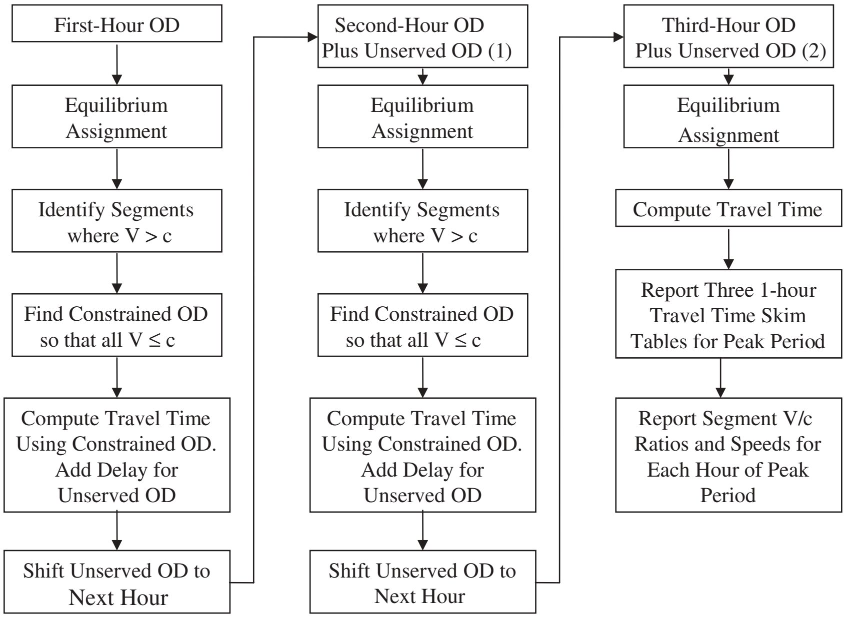


Figure 17. Impact of bottlenecks on hourly OD flows.

It was originally proposed that the HCM Assignment Module identify the magnitude of this excess demand, "store it," and carry it over to the next hour. Each peak period is divided into 1-hour time slices. Only the demand that could physically get through all the network bottlenecks within 1 hour would be assigned to the highway network during each 1-hour time slice. The excess demand that could not be served in the first hour is carried over to the next hour. Results for all the 1-hour time slices are then summed to obtain the overall peak-period results. This process is illustrated in Figure 18.

Following this approach, the module would then be able to identify how capacity increases at one bottleneck affect total origin-to-destination travel times for each hour within the peak period.

The bottleneck constraint option was tested on the Seattle (PSRC) data set. The bottleneck constraint option required 11 hours of computer time to complete two SUE assignments, one for the 3-hour AM peak-period and one for the 3-hour PM peak-period. In contrast, applying the HCM Assignment



V = demand.
c = capacity.

Figure 18. Constraining demand for bottleneck effects.

Module without the bottleneck constraint option required only 1 hour of computer time.

Table 39 compares the predicted VMT and VHT impacts of a hypothetical 20-year RTP when estimated using different traffic assignment approaches:

- SUE using standard BPR speed-flow equations,
- SUE using the HCM/Akcelik speed-flow equations, and
- SUE using the HCM/Akcelik speed-flow equations plus downstream bottleneck constraints.

In each case, the same future-year OD trip tables were loaded on the networks. Even so, there are significant differences in the predicted impacts of the RTP improvements between SUE assignments using the standard BPR equations and the HCM/Akcelik equations. The standard BPR equations predict a 5-percent increase in VMT and a 9-percent reduction in VHT for the RTP improvements. The HCM/Akcelik equations, however, predict a 0.5-percent decrease in VMT and a 48-percent decrease in VHT. Adding the bottleneck constraint option to the assignment process results in only modest changes to the HCM/Akcelik results (a 0.3-percent increase in VMT and a 52-percent decrease in VHT). Although the same demand tables were assigned to the same highway networks each time, the differences in the predicted VMT are due to the differences in the congestion delays predicted by the BPR and HCM equations. The higher congestion delays predicted by the HCM equations cause more traffic to take roundabout routes than predicted by the BPR equations. The result is that the BPR equations predict less VMT than the HCM equations predict for congested conditions.

These results suggest that most of the advantages of the HCM/Akcelik equations can be obtained without having to incorporate the bottleneck constraints.

TABLE 39 Impacts of 20-year RTP as estimated using different assignment techniques

Assignment Technique	Scenario	Peak Period	Vehicle-Miles Traveled	Vehicle-Hours Traveled	Speed (mph)
Standard BPR	RTP Improvements	AM	19,468,400	643,040	30.3
		PM	27,670,300	977,495	28.3
		Total	47,138,700	1,620,535	29.1
	No Improvements	AM	18,459,100	696,708	26.5
		PM	26,472,000	1,088,500	24.3
		Total	44,931,100	1,785,208	25.2
	Difference		2,207,600	-164,673	3.9
	% Difference		+4.9%	-9.2%	
HCM/Akcelik	RTP Improvements	AM	19,618,792	777,708	25.2
		PM	28,400,816	1,625,331	17.5
		Total	48,019,608	2,403,039	20.0
	No Improvements	AM	19,669,446	1,297,723	15.2
		PM	28,597,942	3,344,435	8.6
		Total	48,267,388	4,642,158	10.4
	Difference		-247,780	-2,239,119	9.6
	% Difference		-0.5%	-48.2%	
HCM/Akcelik With Bottleneck Constraints	RTP Improvements	AM	19,666,651	994,131	19.8
		PM	28,326,698	2,019,930	14.0
		Total	47,993,349	3,014,061	15.9
	No Improvements	AM	19,571,285	1,840,165	10.6
		PM	28,264,870	4,419,772	6.4
		Total	47,836,155	6,259,937	7.6
	Difference		157,194	-3,245,876	8.3
	% Difference		+0.3%	-51.9%	

CHAPTER 13

DERIVATION OF TRAVEL BEHAVIOR RESPONSE MODULE

This chapter discusses the derivation of the Travel Behavior Response Module for this study.

The Portland Tour-Based Model was selected as the basis for the travel behavior response model because of its ability to predict both modal and temporal shifts in travel behavior as well as predict the impact on overall out-of-the-home trip making.

13.1 OVERVIEW OF PORTLAND TOUR-BASED MODEL

The Portland Tour-Based Model was originally developed as part of a project to analyze road pricing policy alternatives in Portland. (A full description of the Portland tour-based model is given by Mark Bradley Research and Consulting, A System of Activity-Based Models for Portland, Oregon, Washington, D.C.: Travel Model Improvement Program, U.S. Dept. of Transportation, Report No. DOT-T-99-02, U.S. Environmental Protection Agency, 1998. Consult this reference for details on model structure and coefficients.) An overview of the Portland model within a broader context is shown in Figure 19; the Portland Tour-Based Model proper consists of the blocks within the large rectangle.

A more detailed look at the Portland model is given in Figure 20, which shows information flows between the different submodels. The model system is designed to predict the following:

- A full-day activity pattern (primary activity and, for tour activities, subtour pattern),
- Times of day (outbound, inbound) for home-based tours,
- Primary mode and destination,
- Work-based subtours, and
- Location of intermediate stops.

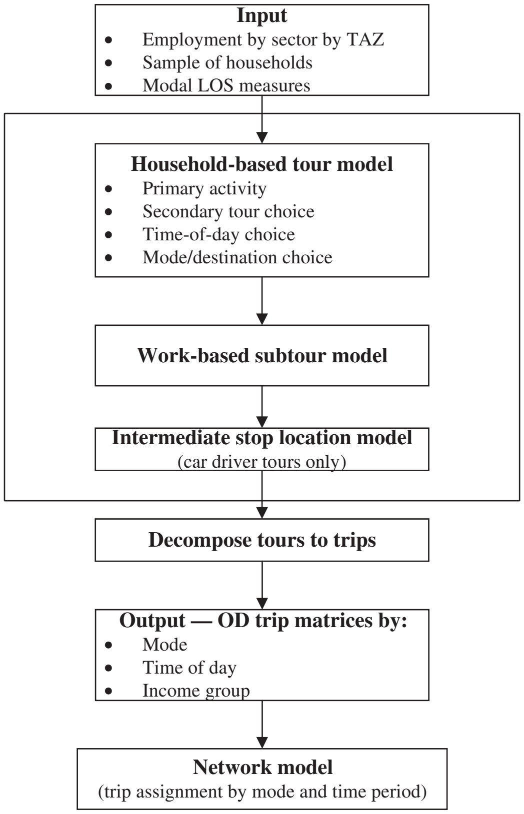
The Portland model is a conceptual descendant of Greig Harvey's STEP model, with considerable additional detail. A description of the STEP model and the theory behind the model is presented by Elizabeth Deakin and Greig Harvey in *Transportation Pricing Strategies for California: An Assessment of Congestion, Emissions, Energy and Equity Impacts: Final Report*, prepared for the California Air Resources Board, 1996. The Portland model has several features that distinguish it from traditional four-step travel models:

- Simultaneous modeling of trip generation, time of day, mode choice, and destination choice. Utilities of lower-level choices (e.g., mode and destination choice) are incorporated into the utilities of higher-level choices (e.g., time of day and primary activity pattern).
- Application of the model to individual travelers. This approach, known as *sample enumeration* when applied to travel survey data and more generally as *microsimulation*, is considered to be at the forefront of the current state of the art in travel modeling. Microsimulation allows the incorporation of detailed household and person characteristics that can significantly affect travel behavior, such as presence of children in the household and competition for available cars in the household for different trip purposes.
- Use of a synthetic sample to develop the base population to which the model is applied. This approach provides the model with a sufficiently large population so that complete trip tables can be produced. Sample enumeration approaches based only on travel surveys generally produce results at a much larger scale, such as superdistrict-to-superdistrict trip movements. The synthetic sampling approach has been used for over 25 years. One early application was the development of a database for research on discrete-choice models. See Gerald Duguay, Woo Jung, and Daniel McFadden, "SYNSAM: A Methodology for Synthesizing Household Transportation Survey Data," Berkeley: Urban Travel Demand Forecasting Project, Working paper no. 7618, September 1976. Synthetic sampling is currently used in the TRANSIMS model and in the current version of the STEP model. An additional advantage of the synthetic sampling approach is that it enables disaggregation of benefit and cost estimates by socioeconomic category, which is often a significant issue in transportation policy analysis.

13.2 MICROSIMULATION MODEL IMPLEMENTATION

13.2.1 Overall Design

The Portland model required nearly 2 years for estimation and implementation. For this study, time constraints limited



LOS = level of service.
TAZ = traffic analysis zone.

Figure 19. Portland Tour-Based Model system flow chart.

what could be done for model estimation and implementation. Hence, the following guided this study's implementation of the model:

- **Model estimation.** The Portland model was applied "as-is" to Seattle without re-estimation of the model steps. Where necessary, choice-specific constants would be adjusted so that aggregate model outputs would be sufficiently close to observed values.
- **Model components.** The model for this study was only used to estimate primary destination, primary mode, and primary activity time of day. The intermediate stop models were not implemented. (In the Portland model, the intermediate stop models were applied as aggregate adjustments to trip tables developed from the primary tour choice models.)
- **Model variables.** A number of variables required by the Portland model were not readily available from current data maintained in Seattle. Because these variables did not change from alternative to alternative, they were assigned default values for all model runs.
- **Expansion of synthetic population sample.** The synthetic sample for the Portland model was developed from forecasts of numbers of households by household size, income, and age of head of household. For application to Seattle, the available socioeconomic forecasts by household type included percentage multifamily households and households by income quartile. Hence, these forecasts were used to develop the synthetic sample for Seattle.
- **Modes.** Two modes in the Portland model—light rail with walk access and light rail with auto access—were not available in Seattle. They were dropped from the mode/destination choice model.
- **Time of day.** The Portland model provides forecasts for five times of day: early, AM peak, midday, PM peak, and late. The PSRC model network is based on two time periods: AM peak and daily. Some network data on auto travel are available for PM peak. The research team therefore made the following assumptions: (1) model results would be reported for three time periods—AM peak, PM peak, and off peak; (2) network levels of service for early, midday, and late time periods would be approximated by daily level-of-service values; and (3) PM peak transit level-of-service matrices were approximated by taking transposes of the corresponding AM peak matrices.
- **Application.** As was done in Portland, the original intent was to apply the model by pivoting the model results around a base trip table to develop forecasts for the transportation alternatives.

Although the scope of the study required the above simplifications, the research team also saw the opportunity to base the model implementation on modern software engineering methods.

- The model was implemented using object-oriented software engineering analysis and design methods. This greatly increased the verifiability, maintainability, and extensibility of the model.
- A high-precision, random number generator was used, as discussed below. This was done in order to minimize the potential for serial correlations between sets of random numbers to confound the model outputs.
- Simulation in the original Portland model is carried out as a "one-shot" process with a fixed synthetic sample. That approach works only if one can assume that a cross-sectional synthetic population sample will produce the same results as those from repeated population sampling, which is a very strong (and probably unwarranted) assumption. (This is roughly analogous to assuming that a stochastic process is ergodic, i.e., the cross-sectional ensemble average is equal to the average over time. For many physical processes, ergodicity is a strong, but reasonable assumption. For socioeconomic processes, it is less clear that ergodicity holds. See Julius S. Bendat and Allan G. Piersol, *Random Data: Analysis And Measure-*

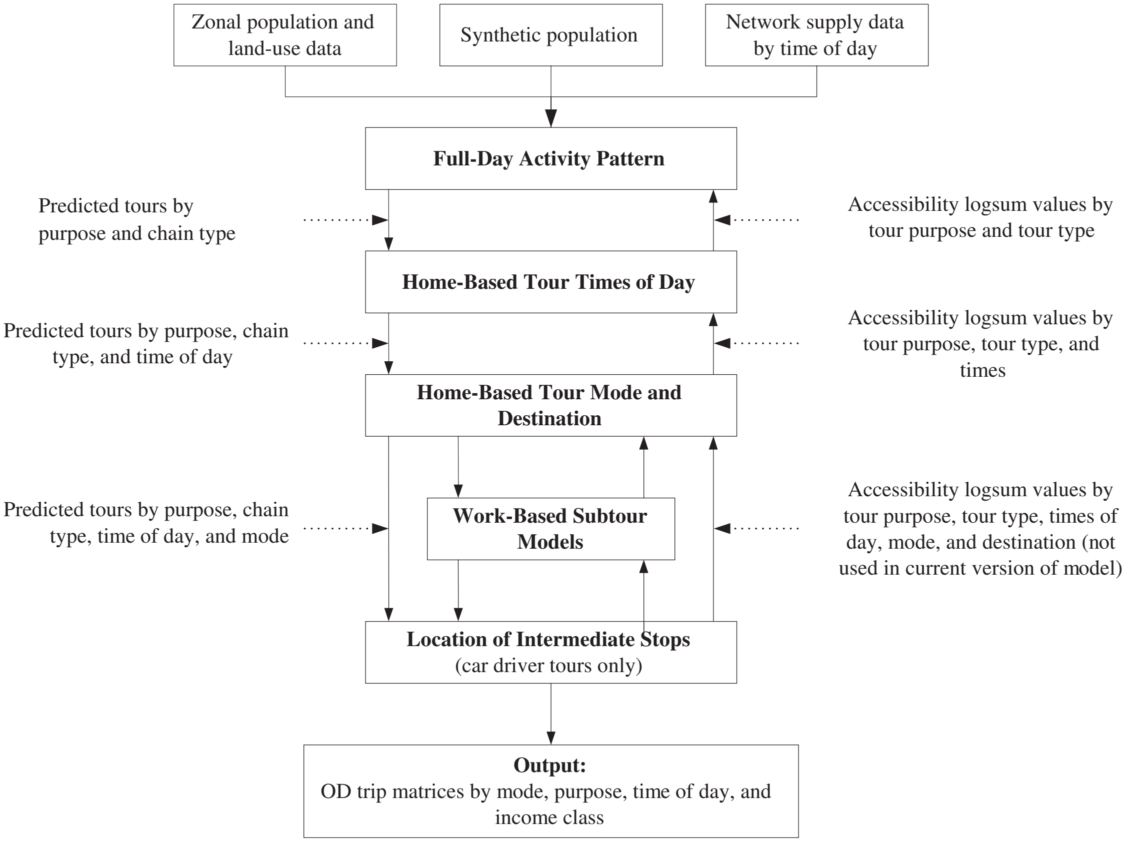


Figure 20. Information flows in Portland Tour-Based Model.

ment Procedures, 2nd ed., rev. and expanded, New York: Wiley, 1986.) The model implementation for this study carries out repeated sampling of the population dynamically as the program is running.

- The Portland model kept track of all combinations of choice probabilities for a given individual in the synthetic population and aggregated the results by all of these combinations. The model implementation for this study uses the choice probabilities from the different nests in the model to provide a discrete estimate of the combination of primary activity, times of day, mode, and primary destination for each individual in the synthetic sample.
- A number of refinements were made to increase execution efficiency and reduce the running time of the model software.

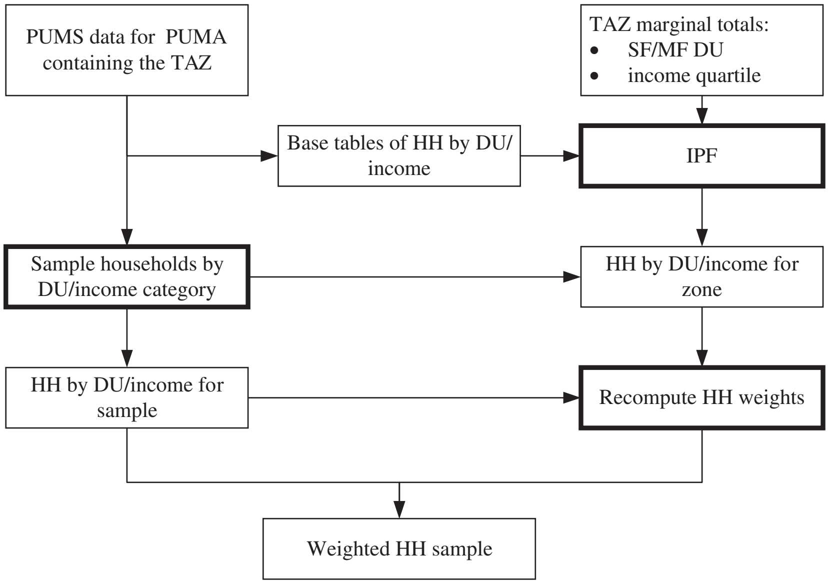
13.2.2 Model Components

13.2.2.1 Population Synthesis

The population synthesis component of the model is intended to generate a sample population that, on average, replicates the regional population for the forecast year. The population synthesis procedure is illustrated in Figure 21. Basically, the procedure consists of drawing repeated samples of households from the 1990 U.S. Census Public Use Microsample (PUMS) data for the Seattle region.

The population synthesis procedure follows the following steps:

1. For the given zone, determine the PUMS area (PUMA) that contains the zone.
2. For PUMS households in the PUMA, generate a weighted cross-classification table of households by dwelling unit type (single-/multifamily) and income quartile.
3. Using the Puget Sound Regional Council (PSRC) forecast marginal totals of households by single-/multifamily and income quartile, adjust the table using iterative proportional fit (IPF). (IPF is a maximum-likelihood procedure used to fit multidimensional tables to fixed marginal totals. In the transportation literature, it is often referred to as a Furness or Fratar procedure. Some statisticians also refer to this as Johnson's method. See Yvonne M. M. Bishop, Stephen E. Fienberg, and Paul W. Holland, *Discrete Multivariate Analysis: Theory and Practice*, Cambridge, Mass., MIT Press, 1975.)



DU = dwelling unit.
HH = household.
SF = single family.
MF = multifamily.
IPF = iterative proportional fit.
PUMS = Public Use Microsample.
PUMA = Public Use Microsample Area.
TAZ = traffic analysis zone.

Figure 21. Population synthesis procedure.

4. For each dwelling unit type/income quartile cell, sample with replacement a fixed number of households from PUMS.
5. Compute a weighted cross-classification table by dwelling unit type/income quartile for PUMS households in the sample.
6. Using the adjusted table developed in Step 3, readjust individual household weights so that the weighted total number of households in each cell of the sample equals the forecast number of households in each cell for the zone.
7. Provide the sample households to the travel modeling procedure.

13.2.2.2 Primary Activity Model

The primary activity model, illustrated in Figure 22, estimates the main activity of the day for the following primary activities:

- Work (includes school) on tour,
- Maintenance (e.g., shopping and personal business) on tour,
- Discretionary (e.g., social and recreational) on tour,
- Work at home,
- Maintenance at home, and
- Discretionary at home.

The first three primary activities involve travel; the remaining three are for a person who does not make a trip that day. Inputs to the primary activity model include characteristics of the user and logsums from the Mode/Destination and Time-of-Day Modules.

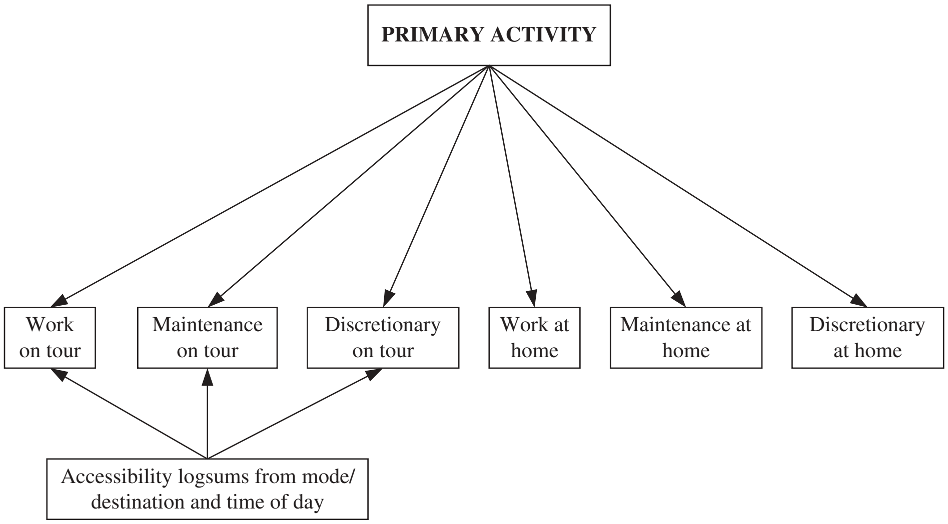
13.2.2.3 Time-of-Day Module

The Time-of-Day Module predicts time of day for leaving home and for the return trip. Five times of day are defined; the model ignores trips that extend overnight. The resulting possible combinations of times for leaving and returning home are summarized in Figure 23.

The Time-of-Day Module is illustrated in Figure 24. There are separate Time-of-Day Modules for each primary tour type. Inputs to the Time-of-Day Modules include tour type, socioeconomic characteristics of the traveler, and logsums from the mode/destination choice models.

13.2.2.4 Mode/Destination Choice

The mode/destination choice models predict simultaneous choice of mode and destination. A separate model was



Source: Mark Bradley, *A System of Activity-Based Models for Portland, Oregon,* Federal Highway Administration, U.S. Department of Transportation, FHWA-PD-99-003, 1998, p. 13.

Figure 22. Primary activity model.

developed for each primary tour type. Each model is a multinomial logit model with 147 choices, representing a combination of 21 zones by 7 travel modes. The model forms are illustrated in Figure 25.

Inputs to the mode destination models include tour type, times of day, mode characteristics (mainly time and cost), and socioeconomic characteristics of the traveler.

One significant difference between this implementation and the Portland model is that the model for this study includes only seven modes:

- Drive alone,
- Drive with passenger,
- Car passenger,
- Transit with walk access,
- Transit with auto access,
- Bicycle, and
- Walk only.

The Portland model includes two additional modes: light rail with walk access and light rail with drive access.

The mode/destination choice model is also based on a sample of destination zones. In the application for this project, the following destination zones were sampled for each application:

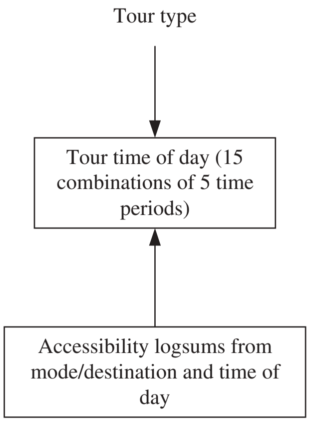
- The origin zone (zone of residence),
- Four zones from the 20th-percentile distance,
- Four zones between the 20th- and 40th-percentile distances,
- Four zones between the 40th- and 60th-percentile distance, and
- Eight zones greater than the 60th-percentile distance.

The Portland model uses a "generalized time" for motorized (i.e., car and transit) modes, equal to the total time and cost utility divided by the car drive-alone time coefficient.

Leave home	**Return home**				
	Early 0300 – 0659	**AM Peak 0700 – 0929**	**Midday 0930 – 1559**	**PM Peak 1600 – 1859**	**Late 1900 – 0259**
Early	●	●	●	●	●
AM Peak	×	●	●	●	●
Midday	×	×	●	●	●
PM Peak	×	×	×	●	●
Late	×	×	×	×	●

● = Valid combination.
× = Invalid combination.

Figure 23. Time period combinations in Portland Tour-Based Model.



Source: Mark Bradley, *A System of Activity-Based Models for Portland, Oregon,* Federal Highway Administration, U.S. Department of Transportation, FHWA-PD-99-003, 1998, p. 16.

Figure 24. Time-of-Day Module.

For each motorized mode, the generalized time utility function is a cubic function that decreases sharply at larger values of time, as shown in Figure 26.

13.2.3 Applying the Model

In the research team's original design, the model was to be applied much as it was in Portland:

1. For each zone, select a sample of households.
2. For each household, determine the appropriate weighting factor based on household type and zonal data on households by type.
3. For each person over age 16 in each sample household, compute the model choice probabilities.
4. After the choice probabilities are computed, determine the choices for the person based on a random pass through the models. This determination produces a set of choices: primary activity, subtours, time of day (outbound from home and inbound to home), primary mode/destination, and secondary destinations.
5. Decompose the tour into trips.
6. Add the trips—weighted by the household weight determined in Step 2—to the appropriate trip table(s).

13.3 DERIVATION OF ELASTICITIES

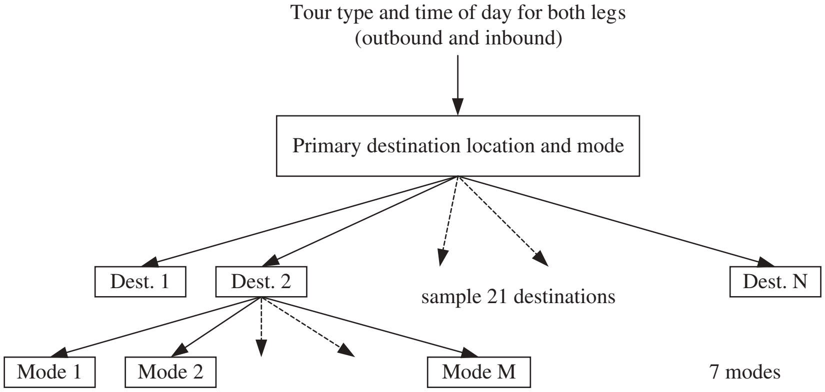
The Portland model has several drawbacks in application, chief of which is the length of time required to operate it on even a high-speed computer. Consequently, the Portland model has been used to develop a set of elasticities for predicting small changes in traveler behavior in response to individual traffic-flow improvement projects. The model was executed several times on a range of travel time saving alternatives, and the results were used to fit a set of demand/time elasticities. These elasticities were then incorporated into the NCHRP 25-21 methodology.

13.3.1 Definition of Elasticity

13.3.1.1 Economics Definitions

The elasticity of demand for travel Q with respect to its cost c is a dimensionless quantity defined as the proportionate change in demand divided by the proportionate change in the price, *all other things being equal*. Mathematically, this quantity can be expressed as follows:

$$\begin{aligned}\varepsilon_P &= \lim_{\Delta c \to 0} \frac{\Delta Q/Q}{\Delta c/c} \\ &= \frac{\partial \log Q}{\partial \log c} \qquad \text{Equation 67} \\ &= \frac{c}{Q}\frac{\partial Q}{\partial c}\end{aligned}$$



Source: Mark Bradley, *A System of Activity-Based Models for Portland, Oregon,* Federal Highway Administration, U.S. Department of Transportation, FHWA-PD-99-003, 1998, p. 18.

Figure 25. Mode/destination choice models.

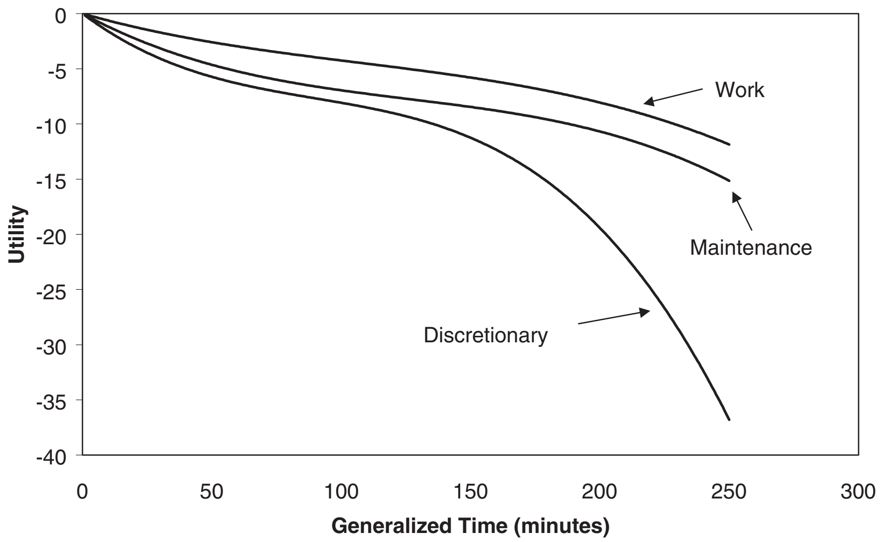


Figure 26. Generalized utilities as a function of generalized time.

In the above equation, ε_P is called the *point elasticity* because it is evaluated at a single point on the demand curve.

Other definitions of elasticity are in common use. When there are data for two points on the demand curve (indexed by 0 and 1), one can define the *arc elasticity* as follows:

$$\varepsilon_A = \frac{\log\left(Q^1/Q^0\right)}{\log\left(c^1/c^0\right)} \qquad \text{Equation 68}$$

Transit operators commonly approximate fare elasticities using the following formula:

$$\varepsilon_S = \frac{\dfrac{Q^1 - Q^0}{Q^0}}{\dfrac{c^1 - c^0}{c^0}} \qquad \text{Equation 69}$$

Where ε_S is properly called a shrinkage ratio; in this formula, the costs refer to the transit fares.

13.3.1.2 Modal Time Elasticities

The concept of elasticity can be extended to other factors that affect demand, such as travel time (which is really another form of user cost). For example, for the demand for a particular mode at a particular time (say, auto drive alone during the AM peak period), one can derive elasticities with respect to the AM peak drive-alone travel time, the AM peak travel times for competing modes, and the drive-alone travel time at other times of day. The economic term for the first of these is called an *own elasticity*: i.e., it is the elasticity of demand with respect to its own characteristics. The remaining elasticities are called *cross-elasticities* because they depend on the characteristics of other choices.

For this study, the research team adopted the following notation for deriving and applying elasticities:

$$\varepsilon^{mp}_{m'p'} = \frac{\partial \log T^{mp}_{ij}}{\partial \log t^{m'p'}_{ij}} \qquad \text{Equation 70}$$

Where:

$\varepsilon^{mp}_{m'p'}$ = elasticity of demand for travel from origin i to destination j by mode m in time period p (denoted by T^{mp}_{ij}) with respect to travel time origin i to destination j by mode m' in time period p' (denoted by $t^{m'p'}_{ij}$).

For $m' = m$ and $p' = p$, there is an own elasticity; otherwise, the quantity is a (mode or time or mode/time) cross-elasticity.

13.3.2 Deriving Elasticities from the Microsimulation Model

13.3.2.1 Method

Using the notation defined in Equation 42, one can write a constant elasticity demand model in the following form:

$$\frac{\tilde{T}^{mp}_{ij}}{T^{mp}_{ij}} = \prod_{m'p'} \left(\frac{\tilde{t}^{m'p'}_{ij}}{t^{m'p'}_{ij}} \right)^{\varepsilon^{mp}_{m'p'}} \qquad \text{Equation 71}$$

Where the quantities with tildes represent trips and travel times after some change and the other quantities represent base case trips and travel times. This can be converted to a log-log linear model:

$$Ln\left[\frac{\tilde{T}^{mp}_{ij}}{T^{mp}_{ij}}\right] = \sum_{m'p'} \varepsilon^{mp}_{m'p'} \ln\left[\frac{\tilde{t}^{m'p'}_{ij}}{t^{m'p'}_{ij}}\right] \qquad \text{Equation 72}$$

One can therefore estimate the elasticities by observing the quantities T_{ij}^{mp}, $\tilde{T}_{ij}^{mp}$, $t_{ij}^{m'p'}$, and $\tilde{t}_{ij}^{m'p'}$ and running a set of regressions.

For applying the Traveler Behavior Module, the research team defined the following modes and time periods:

- Three modes: auto drive alone, auto shared ride, and transit.
- Three time periods: AM peak, PM peak, and off peak.

Hence, 81 elasticities (own elasticities and cross-elasticities) could theoretically be considered. Practically, it does not appear desirable or feasible to estimate all possible elasticities. The research team therefore made the following assumptions:

- Only peak travel times would change for the case studies under consideration. Hence, elasticities with respect to off-peak travel times would not be estimated.
- Where both the mode and time period were different from the mode and time period under consideration, the cross-elasticities would not be estimated. In other words, the research team assumed that $\varepsilon_{m'p'}^{mp} = 0$ for both $m' \neq m$ *and* $p' \neq p$.

The result of these assumptions is illustrated diagrammatically in Table 40. The assumptions result in 30 elasticities (6 own elasticities plus 24 mode or time cross-elasticities) that need to be estimated.

13.3.2.2 Method

Given the constant elasticity model discussed above, the approach to generating the necessary data points was straightforward:

1. Define a set of *i, j* zone pairs to be sampled. These zone pairs were sampled to focus on the areas of interest. For example, given the case study area, the research team focused on movements from within King County to Seattle, from Pierce County to Seattle, and from Snohomish County to Seattle. Movements to and from Kitsap County were ignored because the research team believed that the ferry network may not be adequately represented to treat it alongside bus transit as a transit mode.
2. Pick a particular zone pair with "home" zone *i* and destination zone *j*. Randomly generate a travel time change in the AM peak period for the auto mode and run the model only for the population within zone *i*. Store the relative travel time change and the relevant changes in travel by mode and time period as a data point.
3. Repeat Step 2 for different values of change to the travel time.
4. Repeat Steps 2 and 3 for different time periods.
5. Repeat Steps 2–4 for different modes.
6. Repeat Steps 2–5 for different *i, j* zone pairs.
7. Collect the data points and run regressions on the appropriate variables.

13.3.2.3 Modifications to Original Model Implementation

The original implementation of the Portland model was designed to produce trip tables. For the elasticity analysis, the research team wanted to use the model to predict changes in trips by a given mode in a given time period for a specific OD zone pair. The research team also wanted the model to report travel times and trips by mode and time of day in a format that could be easily imported by a statistical analysis package.

TABLE 40 Elasticities to be estimated

Demand		**Travel time**					
		AM peak			**PM peak**		
		DA	**SR**	**TR**	**DA**	**SR**	**TR**
AM peak	DA	●	●	●	●	×	×
	SR	●	●	●	×	●	×
	TR	●	●	●	×	×	●
PM peak	DA	●	×	×	●	●	●
	SR	×	●	×	●	●	●
	TR	×	×	●	●	●	●
Off peak	DA	●	×	×	●	×	×
	SR	×	●	×	×	●	×
	TR	×	×	●	×	×	●

● = elasticity to be estimated.
× = elasticity assumed to be zero.
DA = drive alone.
SR = shared ride.
TR = transit.

The research team found it necessary to make the following modifications to the original Portland model implementation:

- **Change the reporting module.** The original reporting module produced trip tables. The modified design substituted a reporting module that collected travel time and trip statistics for a prespecified origin/destination zone pair.
- **Change the destination sampling method.** The Portland model uses a discrete-choice model for mode and destination choice and generates a subset of destination zones "on the fly" when the model is applied. Hence, there is no guarantee that the zone pairs of interest will be represented adequately unless the model is run for a prohibitively long time. The destination zone sampling routine was therefore changed so that the user could specify that a particular zone be made part of each destination zone sample. This change did not affect the statistical validity of the results because generated tours that did not involve the specified destination zone would be ignored.
- **Change the tour generation method.** Originally, the choice probabilities were computed once for each person, and a single tour was generated for that person. For zone pairs and modes with low selection probabilities, the model would have to run for a prohibitively long time in order to get a sufficient number of observations on that zone pair/mode/time period combination. The model was therefore modified to allow the user to specify that more than one sample tour be generated for each sample person once the choice probabilities were computed. The sample weight for each person was factored down accordingly.

13.3.3 Application of Elasticity Model

The elasticity model would be applied as follows, given a change to a single link or facility:

1. Run a SELECT LINK analysis to determine the OD pairs affected.
2. Use elasticities in combination with time changes to estimate changes in demand by OD pair, mode, and time of day.
3. Reassign the change OD demand estimates to the network.

13.3.4 Issues with the Use of an Elasticity Model

A number of issues pose potential problems with a constant elasticity model, including the following:

- There may be a large number of cross-elasticities when all modes and time periods are considered. Simplifying the problem as discussed above could ignore some important cross-elasticities. But the research team's results, discussed below, led the research team to believe that it would not have been possible to develop statistically significant estimates for cross-elasticities that were ignored.
- Using very few elasticities, the research team is trying to capture trip generation (i.e., total number of trips produced), time-of-day shifts, and mode shifts.
- Travel time changes are likely highly correlated between different motorized modes and between time periods (at least between the two peak time periods).
- It is unlikely that elasticities are constant. Not only are elasticities likely to vary by amount of time change, but they are also likely to vary with percentage time change. Longer-distance trips are likely to experience proportionally smaller changes in time than shorter-distance trips.
- The Portland model contains variables that might change over time, such as household structure, number of workers, auto ownership, and income.

Despite the above potential problems with a constant elasticity model, the research team believes that the following simplifications are reasonable:

- For small travel time changes, the constant elasticity approximation is probably good enough. It can be regarded as a first-order approximation to the demand function.
- Capacity improvements are likely to affect the peak periods only. Hence, the main mode shifts are likely to occur during the peak periods, and the research team reasonably ignored off-peak mode shifts.

13.3.5 Proposed Elasticity Model Form

The procedure employed to generate the elasticities was to randomly generate a set of travel time changes, calculate the change in demand, then estimate the elasticities using the following regression model:

$$\log\left(T_{ij}^{*mp} \middle/ T_{ij}^{mp}\right) = \sum_{m'p'} \gamma_{mp}^{m'p'} \log\left(t_{ij}^{*mp} \middle/ t_{ij}^{mp}\right) \qquad \text{Equation 73}$$

where the starred quantities indicate the changed values and the unstarred quantities indicate the base values.

To judge how well the constant elasticity assumption works, the following criteria were examined:

- Significance of the regression,
- *t*-statistics of the elasticity parameter estimates,

TABLE 41 Travel time elasticities

Demand		Travel Time					
		AM peak			PM peak		
		DA	SR	TR	DA	SR	TR
AM peak	DA	-0.225	*0.030*	0.010	-0.024	0.000	0.000
	SR	0.037	-0.303	0.032	0.000	-0.028	0.000
	TR	0.036	0.030	-0.129	0.000	0.000	-0.007
PM peak	DA	-0.124	0.000	0.000	-0.151	*0.015*	*0.005*
	SR	0.000	-0.109	0.000	*0.019*	-0.166	*0.016*
	TR	0.000	0.000	-0.051	*0.018*	*0.015*	-0.040
Off peak	DA	-0.170	0.000	0.000	-0.069	0.000	0.000
	SR	0.000	-0.189	0.000	0.000	-0.082	0.000
	TR	0.000	0.000	-0.074	0.000	0.000	-0.014

DA = drive alone.
SR = shared ride.
TR = transit.
Source: Portland Tour-Based Model Applied to PSRC data set.
Estimates (shown in italics) appear in the table when statistically significant results could not be generated from the data set. Zero values are shown for cross-elasticities that were deemed (a priori) to be insignificant.

- Residual plots (to test for heteroskedasticity, i.e., whether the elasticities might vary with the amount of time difference), and
- Overall goodness of fit.

13.4 FINAL ELASTICITIES

The final set of elasticities fitted to the Portland Tour-Based Model is shown in Table 41.

As shown in the table, a 10-percent decrease in AM peak-period travel time for drive alone would result in the following predicted demand effects:

- A 2.25-percent increase in drive alone during the AM peak,
- A 0.37-percent decrease in shared ride during the AM peak,
- A 0.36-percent decrease in transit during the AM peak,
- A 1.24-percent increase in drive alone during the PM peak, and
- A 1.70-percent increase in drive alone during the off-peak.

The table shows that travel time savings for drive alone trips in the AM peak would result in an increase in drive alone demand and a decrease in shared ride and transit during the AM peak. This change illustrates a mode shift effect within the same time period.

The table also shows that drive-alone travel time savings in the AM peak will spur increases in drive-alone demand for the other periods of the day.

The table shows that changes in PM peak travel times have generally half the effect as changes in AM peak travel times.

CHAPTER 14

DERIVATION OF GROWTH REDISTRIBUTION MODULE

The Growth Redistribution Module predicts the very long-term impacts of localized travel time changes (caused by traffic-flow improvements) on the geographic distribution of growth in a metropolitan area. There are already several sophisticated land-use models available (such as UrbanSim) that could be used for the purpose of this module. However, these models require a great deal of specialized economic data and effort to be set up for a region, and such data and effort are beyond the resources of many MPOs. Where a sophisticated land-use model exists in a region, it can be used to predict the long-term growth effects. Where a sophisticated land-use model is not available, the simplified module described here is proposed for use to approximate the long-term land-use effects of traffic-flow improvements.

14.1 MODULE DESCRIPTION

The Growth Redistribution Module requires that a baseline 20- to 25-year forecast of land-use growth (households and employment changes) be available for the metropolitan area. This baseline forecast should have been prepared either manually or with a model, taking into account accessibility changes as well as all of the other factors that commonly affect the distribution of growth within a region.

The Growth Redistribution Module consists of a simple linear regression model that is fitted to the baseline forecast. The module predicts the change in the growth rate in households and employment in each zone of the region as a function of the relative change of accessibility for each zone. Although not sophisticated enough to predict actual growth, the module should be sufficient to predict how small changes in travel time accessibility can affect the predicted baseline growth rate in specific zones of the region. The module equation is as follows:

$$LU_i^{new} = LU_i^{old} * \left[G + \mathrm{CP} * \left(\frac{A_i^{new}}{A_i^{old}} - R \right) \right] \qquad \text{Equation 74}$$

Where:

LU_i^{new} = predicted sum of the number of households and jobs in zone *i* after the traffic-flow improvement,
LU_i^{old} = sum of households and jobs in zone *i* before the traffic-flow improvement,
A_i^{new} = predicted AM peak home-based work accessibility of zone *i* after the traffic-flow improvement,
A_i^{old} = AM peak home-based work accessibility of zone *i* before the traffic-flow improvement,
CP = calibration parameter for the model determined from the linear regression (CP is the slope of the least-squared error line constrained to go through 0),
G = ratio of the total predicted number of households in the region after the traffic-flow improvement divided by the number of households in the region before the improvement, and
R = ratio of the total predicted accessibility for the region after the traffic-flow improvement divided by the total accessibility for the region before the improvement.

The module presumes that total regional growth will be unaffected by traffic-flow improvements (in other words, the module will not be sensitive to the potential effects of differing levels of regional traffic-flow improvements on the competitiveness of regions for attracting new households or jobs). The module predicts only how regional growth might be reallocated from marginally less accessible zones to more accessible zones within the region. The marginal change in zonal accessibility is obtained by subtracting the average change in regional accessibility from the zone-specific change in accessibility (this is accomplished in Equation 12 by subtracting the ratio *R* from the ratio of new to old accessibility for each zone *i*). For similar reasons, the amount of household growth that would have normally occurred in a zone (if the zone had grown at the regional average growth rate) is added to the module-predicted growth rate that is due exclusively to marginal changes in the zonal accessibility (this is accomplished in Equation 12 by adding the ratio *G*).

The effect of the above normalization is that if the ratio of the new accessibility to the old accessibility for a zone is less than the average ratio for the entire region, then the zone's growth will be less than the regional average. If the zonal accessibility ratio is greater than the average regional accessibility ratio, then the zone's growth will be greater than the regional average.

The value of *G* will normally be 1.00 unless there is a significant period of time between the "before" and "after" traffic-flow improvement dates. The ratio G allows the analyst to account for any baseline growth in the region that might have occurred between the "before" condition and the "after" condition that would have occurred with or without the traffic-flow improvement.

CP is the calibration parameter that converts a percentage change in zonal accessibility into a percentage change in zonal growth. It is the slope of the regression line fitted to local data on the correlation between the marginal change in zonal accessibility and the marginal change in zonal growth expressed as the sum of households and jobs.

The measure of zonal accessibility (A_i) is the denominator of the trip distribution gravity model for home-based work trips. The denominator is the sum of the weighted travel time impedances to each destination zone in the region. The AM peak-period accessibility for home-base work trips is used as a proxy for total daily accessibility for all trips, based on the presumption that commute accessibility has the greatest effect on housing and job location decisions.

$$A_i = \sum_j T_j * F_{ij} \qquad \text{Equation 75}$$

Where:

A_i = accessibility of zone i,
T_j = total trips generated by zone j, and
F_{ij} = AM peak travel time impedance for home-based work travel between zone i and zone j.

The impedance is a decreasing function of travel time between zones and takes whatever form was used to calibrate the regional travel demand model.

14.2 MODULE APPLICATION

The Growth Redistribution Module is calibrated for each region in which it is applied. Base and future employment and household forecasts are assembled for the region. A linear regression model of the form shown in Equation 74 is fitted to the data to obtain the value of CP. The fitted equation is then used to predict how individual zones will deviate from the regional average growth rate based upon changes in zonal accessibility from the base condition.

The following paragraphs illustrate such an application of the module to the Seattle metropolitan area. The Puget Sound Regional Council (PSRC) provided household and employment forecasts for the years 1990 and 2020. These forecasts had been produced through a combination of inventory (for 1990) and land-use modeling (using DRAM/EMPAL) with modifications made in response to local agency input.

Accessibility generally improved between the 1990 and 2020 PSRC forecasts; however, some zones experienced significant changes in accessibility between 1990 and 2020 that varied a great deal from the average (see Figure 27, which plots the percentage change in accessibility for approximately the first 790 of the PSRC zones).

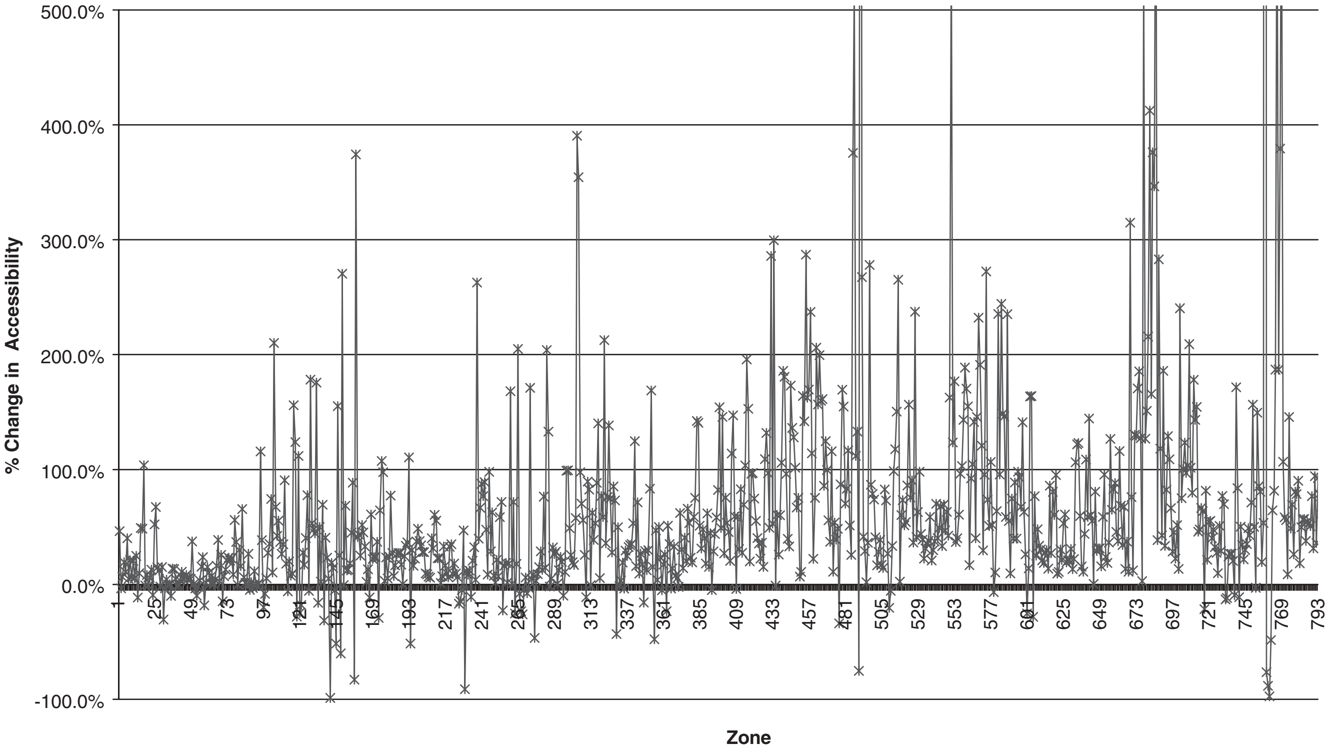


Figure 27. PSRC zonal accessibility changes between 1990 and 2020.

The zonal accessibilities for each mode of travel were reported out from the EMME2 in which the PSRC model is implemented. The reports were then imported into a spreadsheet, which was used to compute the differences between 1990 and 2020 and to fit a regression line to the data. A least-squared error regression line was fitted to the 832 zonal data points (see Figure 28). The line was forced through zero. The slope was 0.72, and the resulting correlation coefficient was 67.99 percent.

14.3 EQUILIBRATION

The initial design for the Growth Redistribution Module included an equilibration step because changes in long-term growth patterns were expected to influence travel behavior, which in turn would affect travel times, which in turn would affect long-term growth patterns. The equilibration step was implemented using the method of successive averages (MSA).

$$T_{ij}^{n+1} = \frac{1}{(n+1)} T_{ij}^{n} + \frac{n}{(n+1)} T_{ij}^{n-1} \qquad \text{Equation 76}$$

Where:

n = the current iteration number

T_{ij}^{n} = number of trips from i to j computed from the current iteration (n),

T_{ij}^{n+1} = number of trips from i to j to be used in the next iteration ($n + 1$), and

T_{ij}^{n-1} = number of trips from i to j computed from the previous iteration ($n - 1$).

However, tests with a null case (where no traffic-flow improvements were coded in the test network) demonstrated the tendency of the software implementation of the methodology to diverge from the theoretically correct result (no change in the network should cause no change in the demand). The software implementation of the model initially reproduced the theoretical "No change" result for the null case for the first few iterations of the MSA, but then diverged in succeeding iterations.

Efforts to track down the cause of this software implementation deviation from the theoretically correct "no-change" result identified two possible causes:

- In the Travel Behavior Response Module, the ratio of new travel time to old travel time is raised to a power specified by the appropriate Portland elasticity. It is possible that the mathematical algorithm used in the software to compute the value of a ratio raised to a power may have some rounding problems that cause the software to output a value slightly different than 1.00 for one raised to a power, thus resulting in nonunitary growth factors for the OD table.

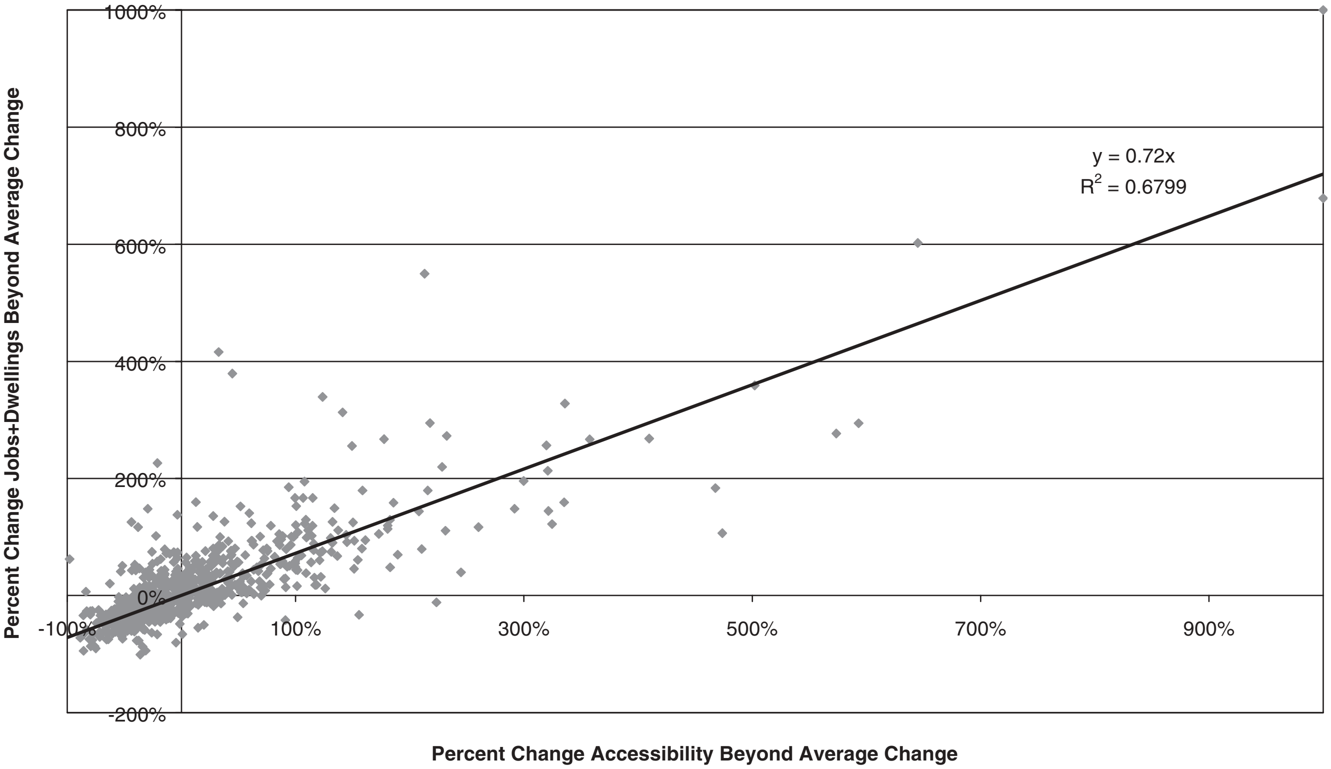


Figure 28. Calibration of long-term module to PSRC data.

- At one point in the growth redistribution algorithm, it is necessary to reallocate the trips in the baseline OD table to the zones predicted to have higher-than-average growth rates (and take away these trips from the slower growth zones). This reallocation is accomplished through a matrix-balancing routine that applies factors to each of the rows and columns of the base OD table. These factors are applied iteratively until a convergence criterion is reached. It is possible that this balancing routine left some very small changes in the table even when factors of 1.00 were applied to all of the row and column totals.

None of these possible causes could be actually observed within the precision of the results reported by the software in printed outputs. Factors of 1.00 raised to a power were reported as 1.00 within the number of significant digits provided in the output. Similarly, the reported number of trips for each cell of the OD table was found to be identical before and after the travel behavior response for each cell of the OD table. The total reported trips in the table also remained unchanged (to the nearest hundredth of a trip reported in the output). However, computing the squared error between the "before" and "after" trip tables found a squared error of one-thousandth of one trip between the two supposedly identical trip tables after two iterations. This small error was magnified in succeeding iterations until after six iterations it reached several hundred trips.

Based on the above results, it was determined that the number of iterations of the Travel Behavior Module and Growth Redistribution Module should be as limited as possible to avoid software-rounding problems. The final methodology consists of one iteration of the Travel Behavior Module to obtain medium-term results, plus one iteration of the Growth Redistribution Module and another iteration of the Travel Behavior Module to obtain the long-term results. Equilibration of iterations was dropped from the methodology.

CHAPTER 15

DERIVATION OF MODAL ACTIVITY MODULE

The purpose of the Modal Activity Module is to calculate the VHT by mode of operation (i.e., cruise, idle, and acceleration/deceleration), which is defined by speed and acceleration category. The estimates of vehicle activity are then used with modal emission factors (e.g., the University of California, Riverside/NCHRP 25-1) to produce the emission estimates.

15.1 METHODOLOGY DEVELOPMENT

The methodology for estimating modal activity is largely based on previous research conducted by the investigator under the sponsorship of CARB. (See Skabardonis. A., "A Modeling Framework for Estimating Emissions in Large Urban Areas," *Transportation Research Record 1587*, 1997; and Skabardonis A., "Feasibility and Demonstration of Network Simulation Techniques for Estimation of Emissions in a Large Urban Area," Final Report, prepared for the California Air Resources Board, DHS Inc., 1994.) This research produced a set of relationships through microscopic simulation that determine the proportion of the time spent T_{ij} on a network link i in driving mode j as a function of the link's type:

$$T_{ij} = F(\text{link type}, v/c) \qquad \text{Equation 77}$$

Where:

link type = the link classification based on the design, traffic, and control characteristics and
v/c = the volume-to-capacity ratio.

The link classification (i.e., type) was based on typical link classifications employed in planning and operational studies (e.g., facility types) and on key design/operational characteristics (e.g., number of lanes, free-flow speed, and signal spacing). Thirty-three link types were selected. The relationships were developed through processing of simulated vehicle trajectories using the INTRAS (predecessor of FRESIM) and TRAF-NETSIM microscopic simulation models.

15.1.1 Freeways

Figure 29 shows the speed distributions for freeways derived in the CARB study based on INTRAS simulations supplemented by field data from the Interstate 880 freeway floating car runs. Under undersaturated traffic conditions, most of the time was spent traveling at the free-flow speeds. Freeway connectors and weaving areas had lower speeds than basic freeway sections had. Under oversaturated traffic conditions, about 45 percent of the time was spent traveling at speeds less than 40 mph.

Recent floating car data from the Interstate 680 freeway were obtained and analyzed. The data were collected for 3 days in the AM peak period along the southbound direction of Interstate 680 freeway. The 20-mile freeway section is congested for most of the AM peak period. Figure 30 shows a typical speed contour plot from the field data. Figure 31 shows a speed-distance profile from a floating car run.

The data were analyzed to determine vehicle activity for uncongested conditions ($v/c < 1$), bottleneck locations ($v/c = 1$), and congested conditions ($v/c > 1$). Figure 32 shows three-dimensional plots of the percent time spent, speed, and acceleration for each traffic regime. Figure 33 shows the average speed and acceleration distributions for uncongested conditions.

Figure 34 shows a comparison of simulated and measured speed distributions for uncongested conditions. The simulated results agree with the field data, taking into consideration that the simulated values are based on the trajectories of all vehicles in the traffic stream and field data are from test cars traveling at the lane next to the median. This figure also shows that one can use a single distribution of time spent versus speed using the ratio of speed divided by free-flow speed. Therefore, one may account for differences in design characteristics of freeway facility types using different free-flow speed and the normalized time-spent speed/acceleration relationships.

Figure 35 shows the speed distributions for bottleneck locations and congested conditions. The data show a clearer picture of the effect of traffic conditions on the vehicle activity than the simulated values shown in Figure 29 because the simulated trajectories include data from both bottleneck locations and congested sections. Further analysis indicated no significant differences in vehicle activity in congested sections with different average travel times.

Based on the above analysis, the CARB relationships for freeway facilities were updated and replaced as follows:

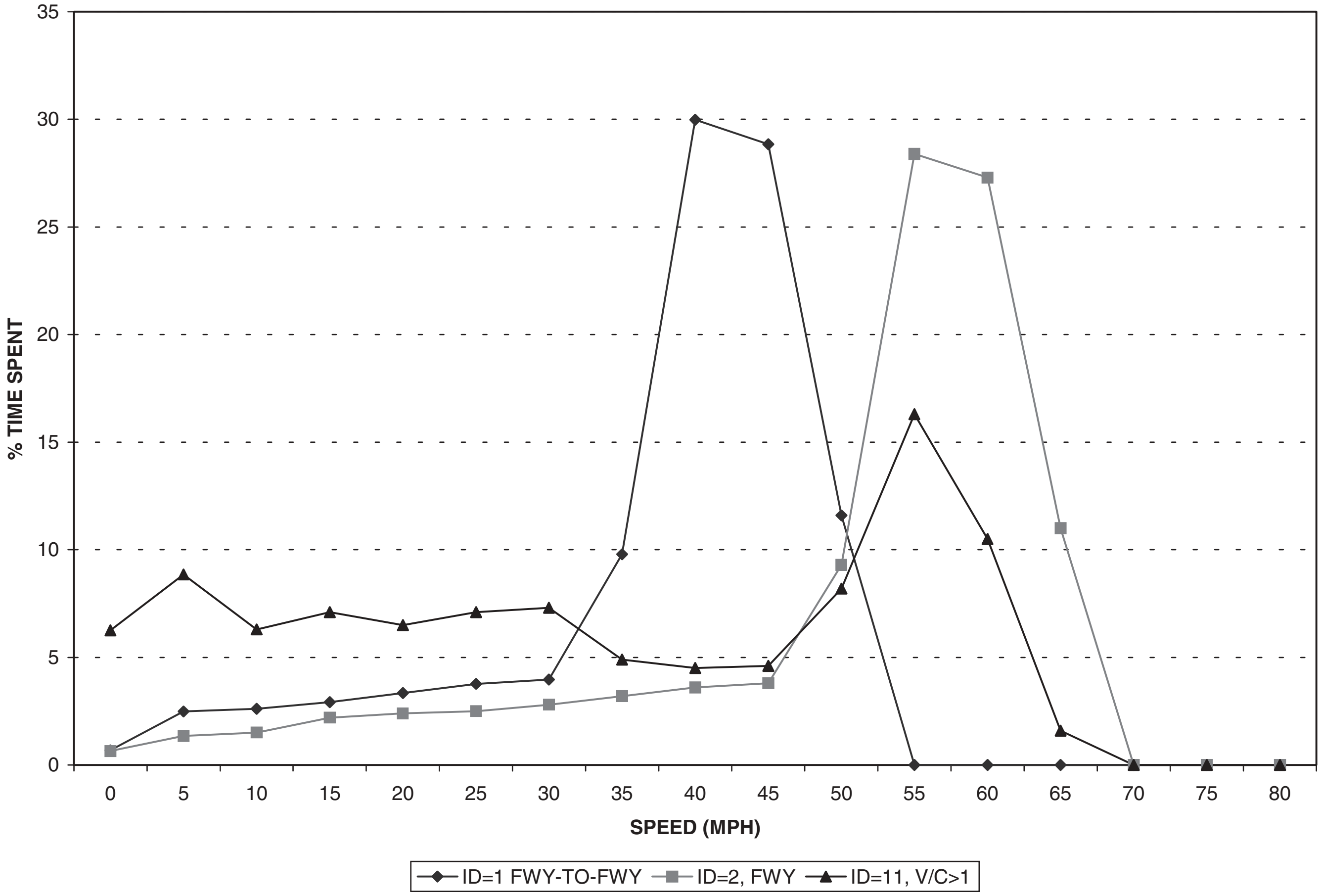
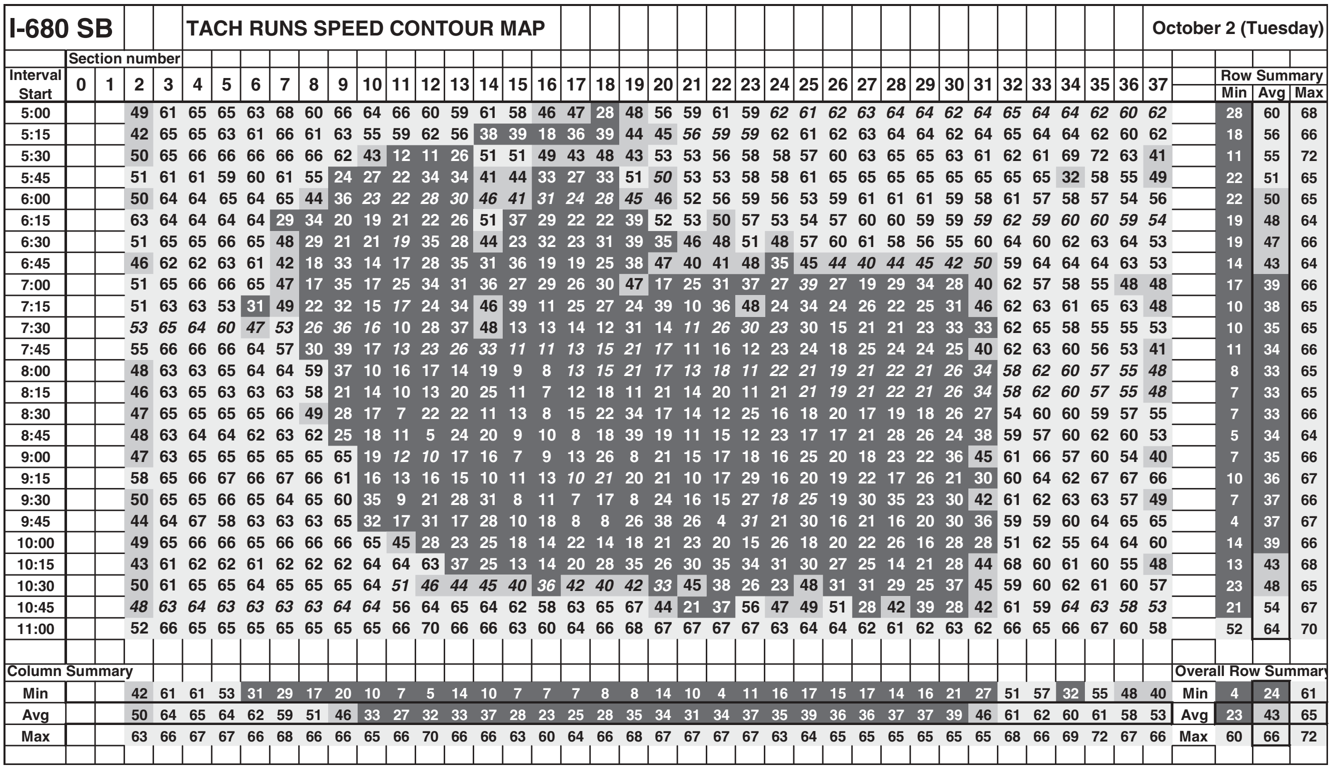


Figure 29. Speed distribution freeways—CARB simulation.



I-680 SB **TACH RUNS SPEED CONTOUR MAP** **October 2 (Tuesday)**

Interval Start	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37		Row Summary Min	Row Summary Avg	Row Summary Max
	Section number																																									
5:00			49	61	65	65	63	68	60	66	64	66	60	59	61	58	46	47	28	48	56	59	61	59	62	61	62	63	64	64	62	64	65	64	64	62	60	62		28	60	68
5:15			42	65	65	63	61	66	61	63	55	59	62	56	38	39	18	36	39	44	45	56	59	59	62	61	62	63	64	64	62	64	65	64	64	62	60	62		18	56	66
5:30			50	65	66	66	66	66	66	62	43	12	11	26	51	51	49	43	48	43	53	53	56	58	58	57	60	63	65	65	63	61	62	61	69	72	63	41		11	55	72
5:45			51	61	61	59	60	61	55	24	27	22	34	34	41	44	33	27	33	51	50	53	53	58	58	61	65	65	65	65	65	65	65	65	32	58	55	49		22	51	65
6:00			50	64	64	65	64	65	44	36	23	22	28	30	46	41	31	24	28	45	46	52	56	59	56	53	59	61	61	61	59	58	61	57	58	57	54	56		22	50	65
6:15			63	64	64	64	64	29	34	20	19	21	22	26	51	37	29	22	22	39	52	53	50	57	53	54	57	60	60	59	59	59	62	59	60	60	59	54		19	48	64
6:30			51	65	65	66	65	48	29	21	21	19	35	28	44	23	32	23	31	39	35	46	48	51	48	57	60	61	58	56	55	60	64	60	62	63	64	53		19	47	66
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9:30			50	65	65	66	65	64	65	60	35	9	21	28	31	8	11	7	17	8	24	16	15	27	18	25	19	30	35	23	30	42	61	62	63	63	57	49		7	37	66
9:45			44	64	67	58	63	63	63	65	32	17	31	17	28	10	18	8	8	26	38	26	4	31	21	30	16	21	16	20	30	36	59	59	60	64	65	65		4	37	67
10:00			49	65	66	66	65	66	66	66	65	45	28	23	25	18	14	22	14	18	21	23	20	15	26	18	20	22	26	16	28	28	51	62	55	64	64	60		14	39	66
10:15			43	61	62	62	61	62	62	62	64	64	63	37	25	13	14	20	28	35	26	30	35	34	31	30	27	25	14	21	28	44	68	60	61	60	55	48		13	43	68
10:30			50	61	65	65	64	65	65	65	64	51	46	44	45	40	36	42	40	42	33	45	38	26	23	48	31	31	29	25	37	45	59	60	62	61	60	57		23	48	65
10:45			48	63	64	63	63	63	63	64	64	56	64	65	64	62	58	63	65	67	44	21	37	56	47	49	51	28	42	39	28	42	61	59	64	63	58	53		21	54	67
11:00			52	66	65	65	65	65	65	65	65	66	70	66	66	63	60	64	66	68	67	67	67	67	63	64	64	62	61	62	63	62	66	65	66	67	60	58		52	64	70
Column Summary																																							Overall Row Summary			
Min			42	61	61	53	31	29	17	20	10	7	5	14	10	7	7	7	8	8	14	10	4	11	16	17	15	17	14	16	21	27	51	57	32	55	48	40	Min	4	24	61
Avg			50	64	65	64	62	59	51	46	33	27	32	33	37	28	23	25	28	35	34	31	34	37	35	39	36	36	37	37	39	46	61	62	60	61	58	53	Avg	23	43	65
Max			63	66	67	67	66	68	66	66	65	66	70	66	66	63	60	64	66	68	67	67	67	67	63	64	65	65	65	65	65	65	68	66	69	72	67	66	Max	60	66	72

Figure 30. Interstate 680 speed contour map.

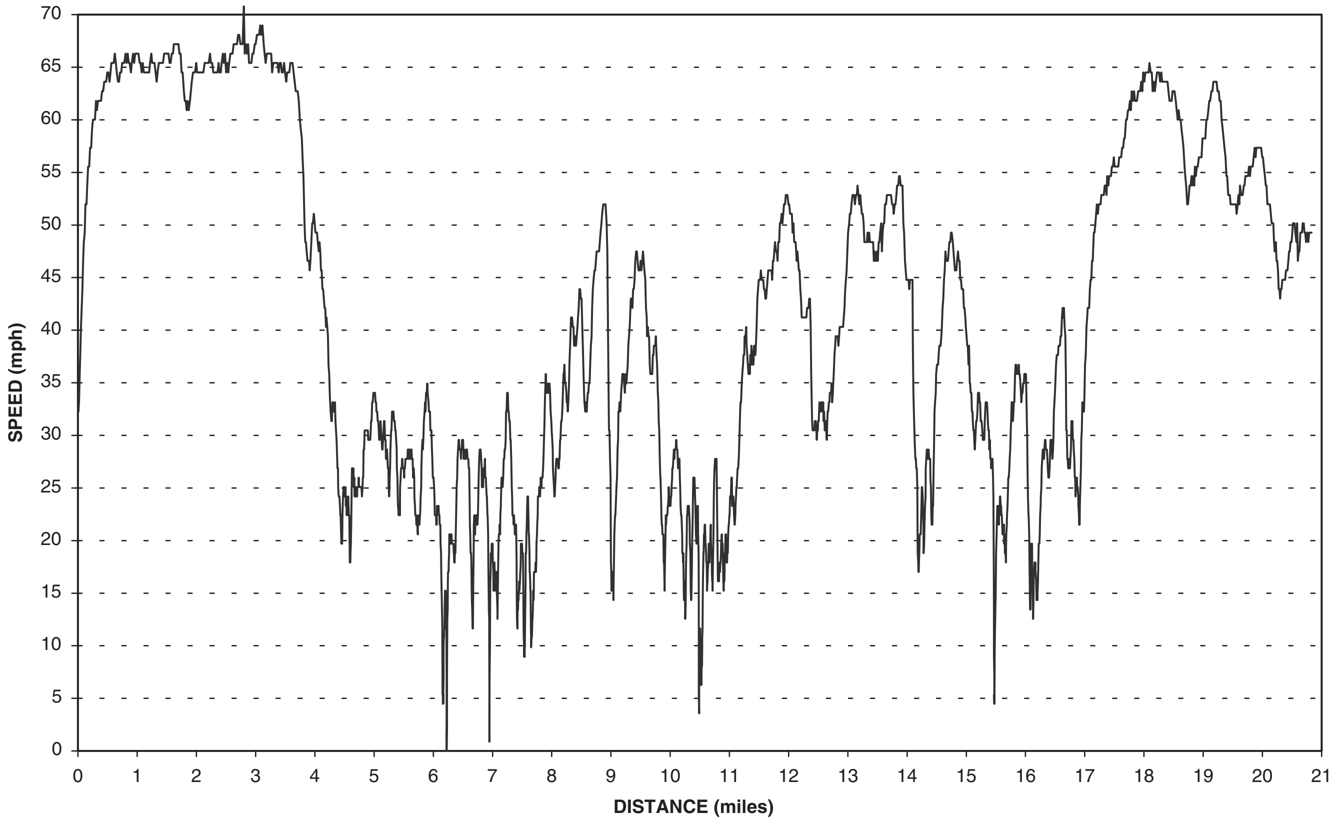


Figure 31. Speed-distance profile—floating car run Interstate 680.

- $v/c < 1$: time spent/speed/acceleration based on simulation normalized by speed divided by the free-flow speed.
- $v/c = 1$: time spent/speed/acceleration based on the field data.
- $v/c > 1$: time spent/speed/acceleration based on the field data.

15.1.2 Freeway Ramps

The same process was used to develop relationships as in basic freeway sections. Field data were analyzed and compared with the CARB simulated values. For volumes less than capacity, the simulated values agree closely with field data when one normalizes using the free-flow speed.

There were no field data available for oversaturated traffic conditions and for metered ramps. The existing CARB relationships may be used, but they need to be verified as appropriate through field data and additional simulations.

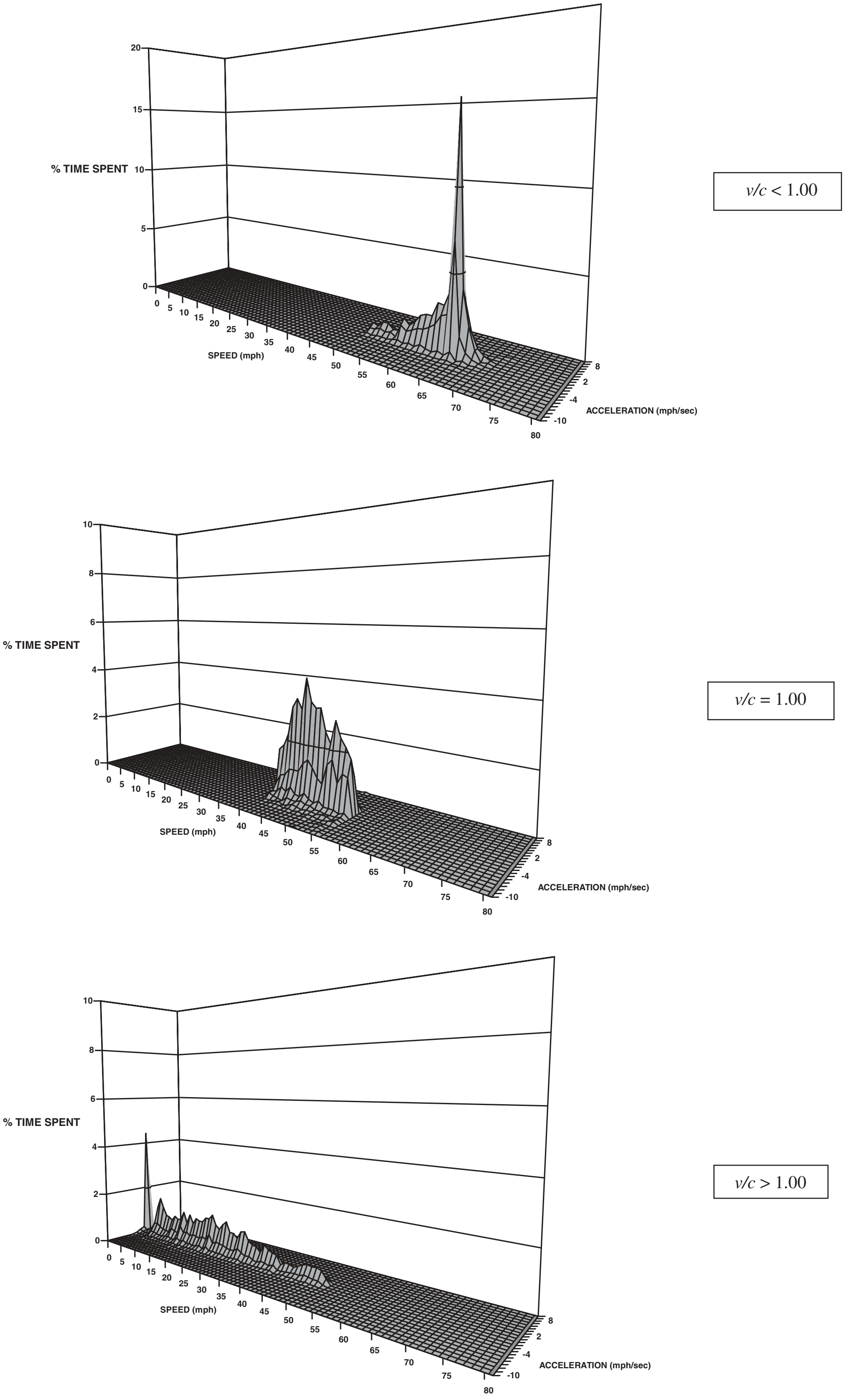
15.1.3 Arterials

The CARB relationships for uncongested conditions were evaluated and updated using the same approach as in freeway facilities, but normalized for free-flow speed. No changes were made for oversaturated traffic conditions. These relationships are based on g/C ratios typical for arterial streets. The relationships were developed based on simulated optimal timing plans (favorable signal progression), but they explicitly account for the quality of progression.

15.2 MODAL OPERATIONS TABLES

Tables of proportion of VHT spent by operating mode have been developed for the Modal Operations Module (see Tables 42 through 45). The tables are applied as follows:

1. Identify facility type and whether the volume-to-capacity ratio exceeds 1.00.
2. Select the appropriate table.
3. Multiply row-heading (leftmost column) percentages of free-flow speed by facility free-flow speed to obtain speeds that will be predicted by the table.
4. Multiply VHT by proportions in the table to obtain the number of vehicle-hours spent in each mode of operation for the facility.

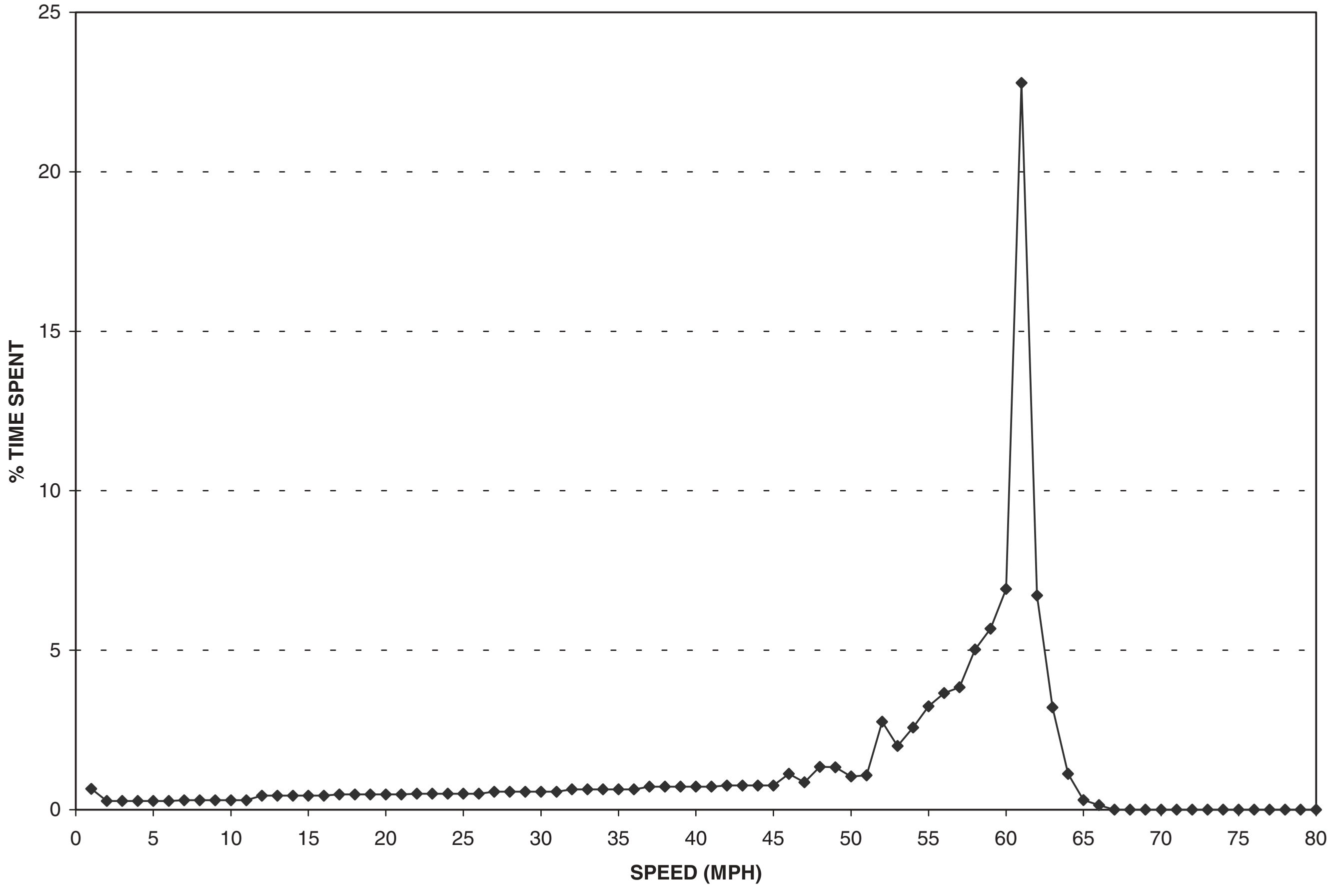


v/c < 1.00

v/c = 1.00

v/c > 1.00

Figure 32. Measured (Interstate 680) percent time spent speed acceleration.



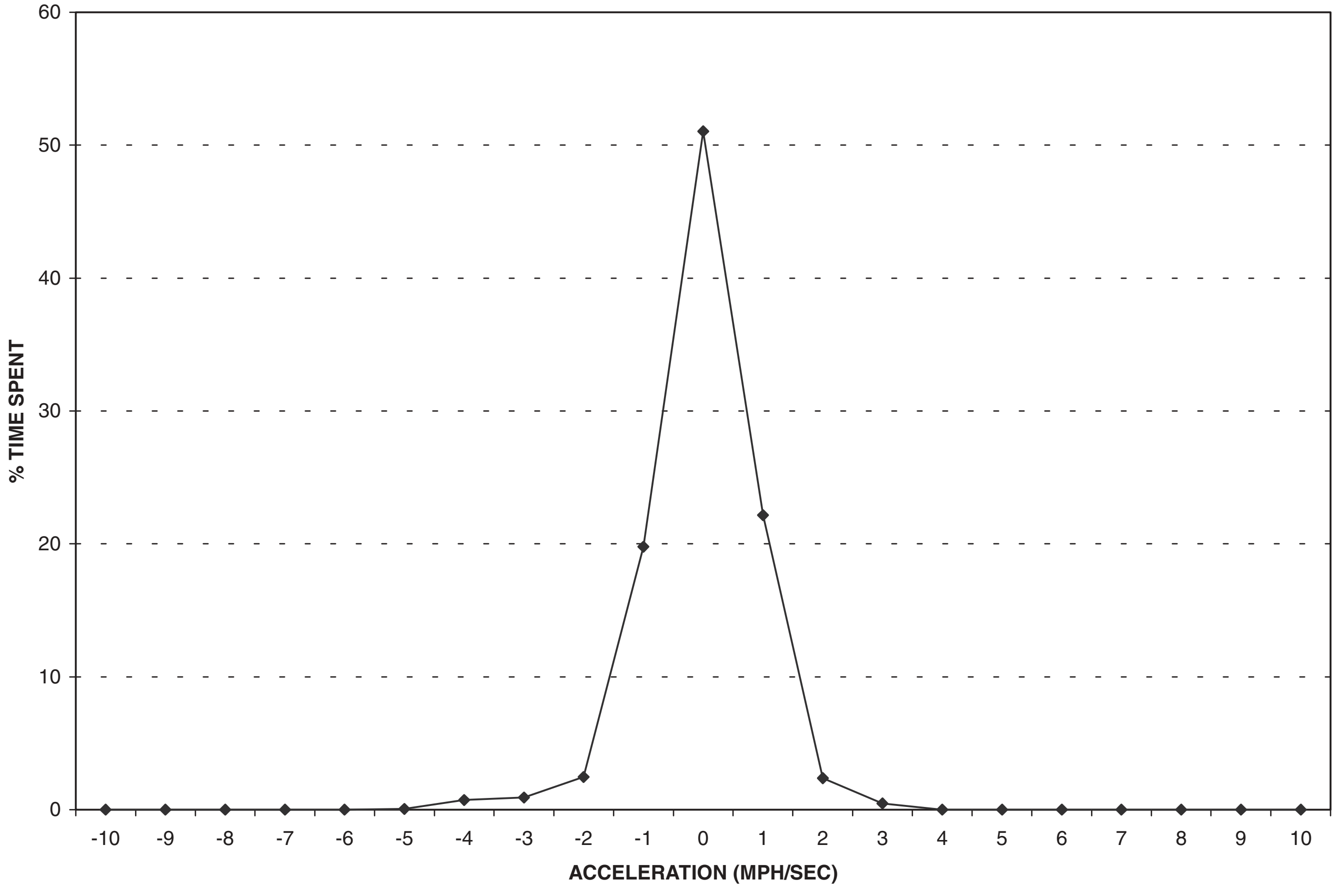


Figure 33. Field-measured speed and acceleration distributions—uncongested freeways.

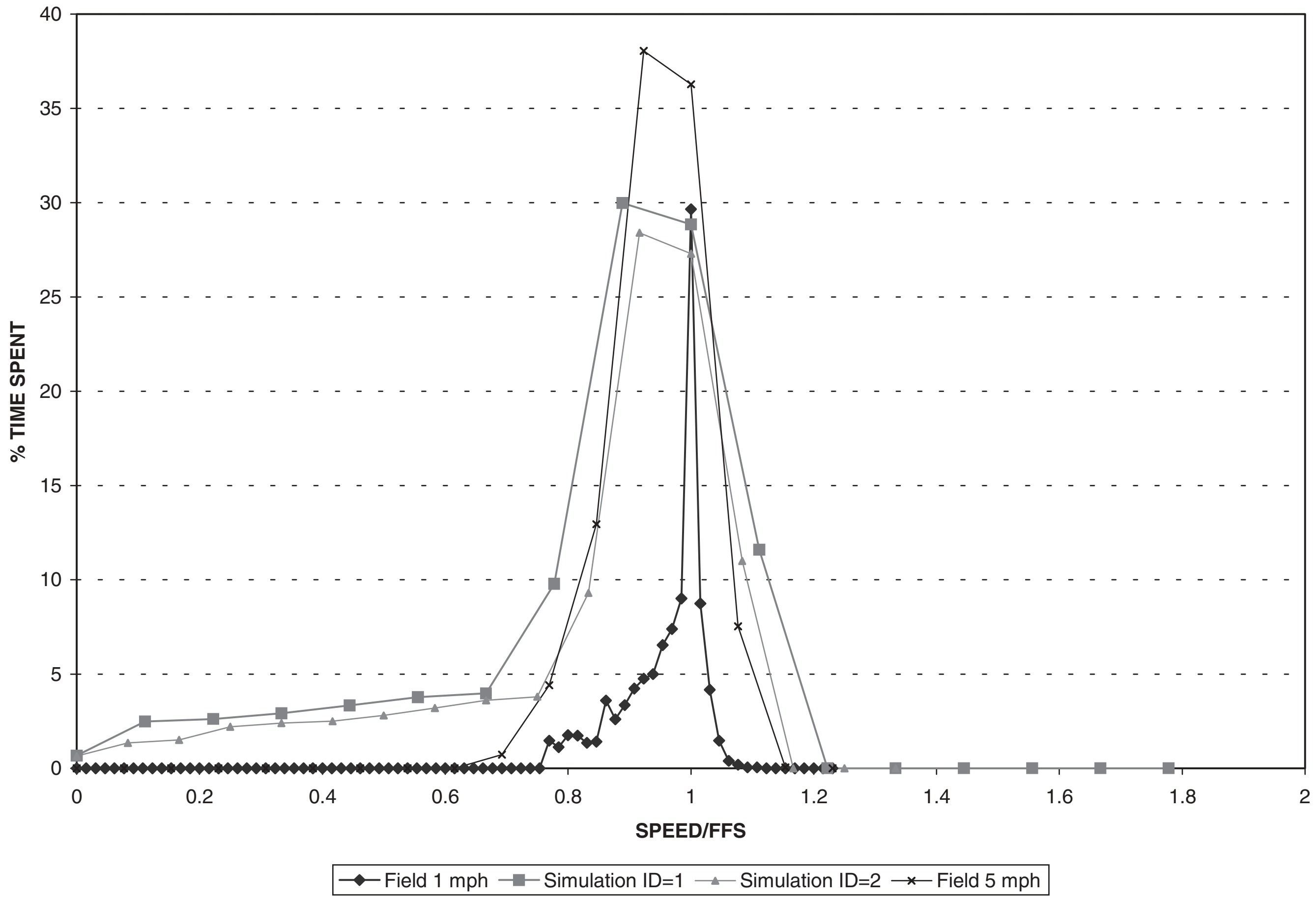
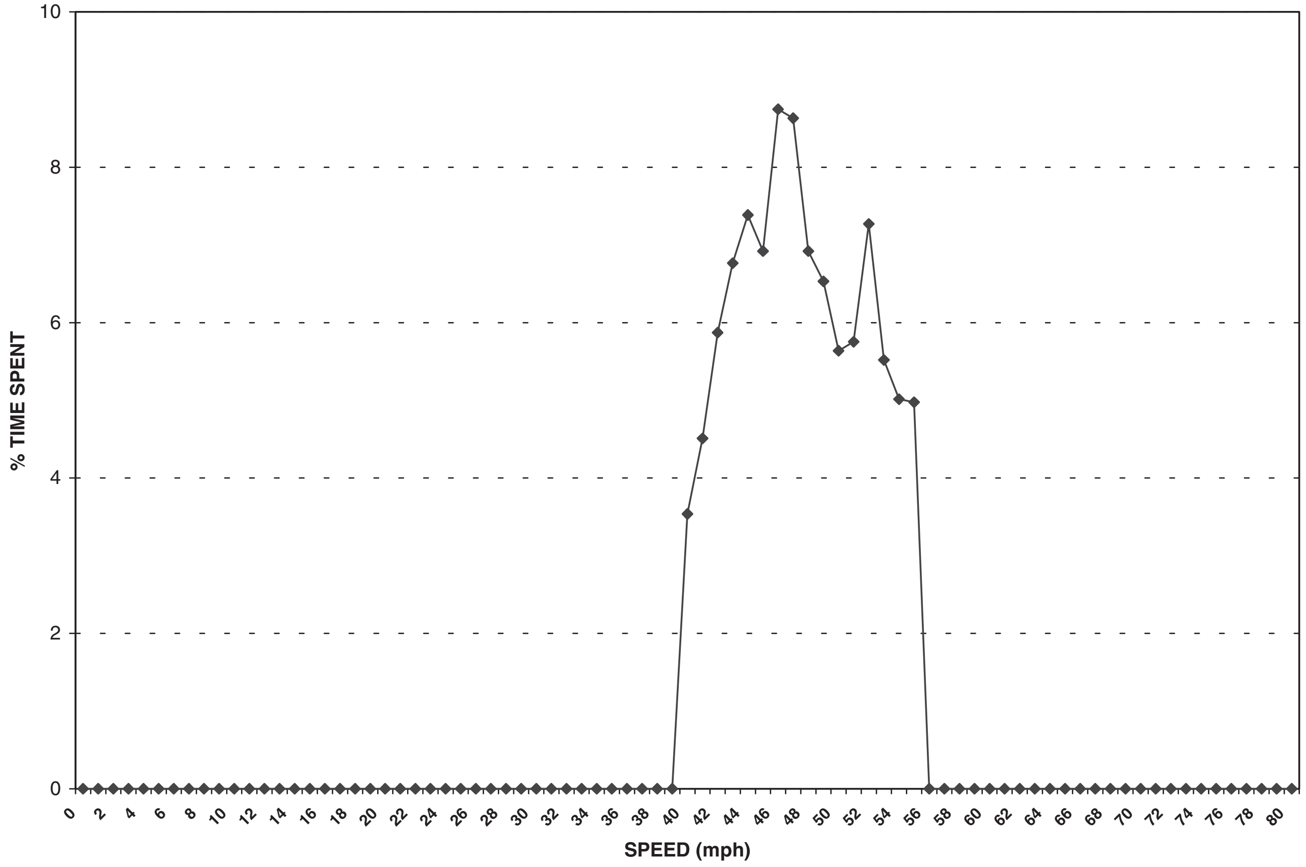


Figure 34. Comparison of measured and simulated speed distributions—uncongested freeways.



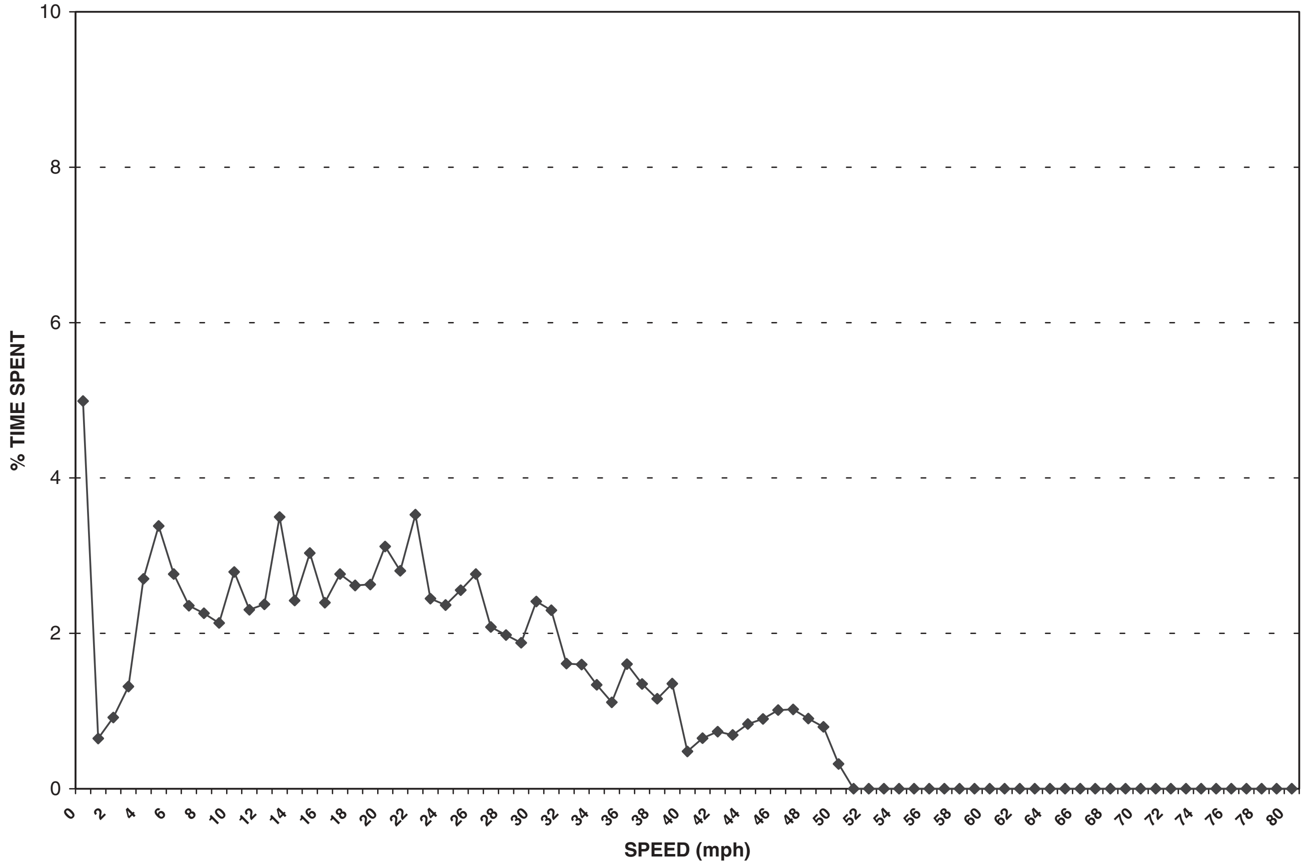


Figure 35. Speed distributions—bottleneck locations and congested freeways.

TABLE 42 Vehicle modal activity table for uncongested freeways

	ACCELERATION (mph/sec)																				
Spd/FreSpd	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
-	-	-	-	-	-	-	-	-	-	-	0.0065	-	-	-	-	-	-	-	-	-	-
0.0167	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0333	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0500	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0667	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0833	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.1000	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1167	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1333	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1500	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1667	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.3667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.3833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.5000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.5167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.6000	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6167	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6333	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6500	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6667	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7500	-	-	-	-	-	-	0.0003	0.0003	0.0006	0.0030	0.0035	0.0033	0.0003	-	-	-	-	-	-	-	-
0.7667	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0021	0.0038	0.0021	0.0002	-	-	-	-	-	-	-	-
0.7833	-	-	-	-	-	-	0.0001	0.0001	0.0003	0.0033	0.0059	0.0033	0.0003	-	-	-	-	-	-	-	-
0.8000	-	-	-	-	-	-	0.0001	0.0001	0.0003	0.0033	0.0059	0.0033	0.0003	-	-	-	-	-	-	-	-
0.8167	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0026	0.0046	0.0026	0.0002	-	-	-	-	-	-	-	-
0.8333	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0027	0.0048	0.0027	0.0002	-	-	-	-	-	-	-	-
0.8500	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0055	0.0156	0.0055	0.0003	-	-	-	-	-	-	-	-
0.8667	-	-	-	-	-	0.0001	0.0001	0.0001	0.0002	0.0040	0.0113	0.0040	0.0002	-	-	-	-	-	-	-	-
0.8833	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0052	0.0146	0.0052	0.0003	-	-	-	-	-	-	-	-
0.9000	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0065	0.0184	0.0065	0.0003	-	-	-	-	-	-	-	-
0.9167	-	-	-	-	-	0.0001	0.0001	0.0001	0.0004	0.0073	0.0207	0.0073	0.0004	-	-	-	-	-	-	-	-
0.9333	-	-	-	-	-	-	-	-	0.0003	0.0070	0.0225	0.0080	0.0004	0.0001	-	-	-	-	-	-	-
0.9500	-	-	-	-	-	-	-	-	0.0004	0.0092	0.0294	0.0105	0.0006	0.0002	-	-	-	-	-	-	-
0.9667	-	-	-	-	-	-	-	-	0.0004	0.0104	0.0333	0.0119	0.0006	0.0002	-	-	-	-	-	-	-
0.9833	-	-	-	-	-	-	-	-	0.0005	0.0127	0.0406	0.0145	0.0008	0.0003	-	-	-	-	-	-	-
1.0000	-	-	-	-	-	-	-	-	0.0017	0.0417	0.1339	0.0476	0.0025	0.0008	-	-	-	-	-	-	-
1.0167	-	-	-	-	-	-	-	-	0.0006	0.0116	0.0385	0.0153	0.0006	0.0006	-	-	-	-	-	-	-
1.0333	-	-	-	-	-	-	-	-	0.0003	0.0055	0.0184	0.0073	0.0003	0.0003	-	-	-	-	-	-	-
1.0500	-	-	-	-	-	-	-	-	0.0001	0.0019	0.0064	0.0026	0.0001	0.0001	-	-	-	-	-	-	-
1.0667	-	-	-	-	-	-	-	-	-	0.0005	0.0018	0.0007	-	-	-	-	-	-	-	-	-
1.0833	-	-	-	-	-	-	-	-	-	0.0002	0.0008	0.0003	-	-	-	-	-	-	-	-	-
1.1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are proportion of total vehicle-hours on link that fall in each speed/acceleration category.
Columns are acceleration rate category in units of miles per hour per second. Rows are speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 43 Vehicle modal activity table for congested freeway sections

	ACCELERATION (mph/sec)																			
Spd/FreSpd	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.0000	-	-	-	-	-	0.0002	0.0004	0.0008	0.0017	0.0025	0.0443	-	-	-	-	-	-	-	-	-
0.0167	-	-	-	-	-	0.0001	0.0001	0.0005	0.0010	0.0015	0.0013	0.0019	-	-	-	-	-	-	-	-
0.0333	-	-	-	-	-	-	0.0002	0.0006	0.0008	0.0023	0.0025	0.0010	0.0017	-	-	-	-	-	-	-
0.0500	-	-	-	-	-	0.0001	0.0002	0.0003	0.0011	0.0030	0.0049	0.0016	0.0010	0.0010	-	-	-	-	-	-
0.0667	-	-	-	-	-	0.0001	0.0006	0.0006	0.0023	0.0054	0.0122	0.0033	0.0013	0.0005	0.0007	-	-	-	-	-
0.0833	-	-	-	-	-	0.0002	0.0004	0.0005	0.0022	0.0057	0.0163	0.0056	0.0020	0.0006	0.0003	0.0002	-	-	-	-
0.1000	-	-	-	-	-	0.0001	0.0002	0.0010	0.0018	0.0044	0.0126	0.0053	0.0013	0.0006	0.0003	0.0001	-	-	-	-
0.1167	-	-	-	-	-	-	0.0003	0.0007	0.0015	0.0039	0.0095	0.0052	0.0017	0.0005	0.0002	0.0001	-	-	-	-
0.1333	-	-	-	-	-	0.0001	0.0003	0.0006	0.0017	0.0038	0.0091	0.0049	0.0015	0.0006	0.0002	-	-	-	-	-
0.1500	-	-	-	-	-	0.0001	0.0004	0.0007	0.0018	0.0039	0.0080	0.0042	0.0018	0.0006	0.0003	-	-	-	-	-
0.1667	-	-	-	-	-	0.0001	0.0003	0.0009	0.0022	0.0051	0.0100	0.0061	0.0023	0.0007	0.0002	0.0001	-	-	-	-
0.1833	-	-	-	-	-	-	0.0003	0.0007	0.0014	0.0044	0.0090	0.0046	0.0017	0.0006	0.0002	-	-	-	-	-
0.2000	-	-	-	-	-	0.0001	0.0003	0.0007	0.0016	0.0040	0.0094	0.0047	0.0021	0.0006	0.0001	-	-	-	-	-
0.2167	-	-	-	-	-	0.0002	0.0006	0.0009	0.0026	0.0071	0.0126	0.0068	0.0031	0.0008	0.0002	-	-	-	-	-
0.2333	-	-	-	-	-	-	0.0004	0.0005	0.0016	0.0047	0.0085	0.0056	0.0023	0.0006	0.0001	-	-	-	-	-
0.2500	-	-	-	-	-	0.0001	0.0003	0.0009	0.0024	0.0054	0.0122	0.0054	0.0027	0.0006	0.0002	-	-	-	-	-
0.2667	-	-	-	-	-	0.0001	0.0002	0.0005	0.0016	0.0043	0.0089	0.0053	0.0022	0.0007	0.0001	0.0001	-	-	-	-
0.2833	-	-	-	-	-	0.0001	0.0003	0.0008	0.0018	0.0050	0.0113	0.0052	0.0022	0.0008	0.0001	-	-	-	-	-
0.3000	-	-	-	-	0.0001	-	0.0002	0.0007	0.0015	0.0048	0.0106	0.0057	0.0021	0.0004	0.0001	-	-	-	-	-
0.3167	-	-	-	-	0.0001	-	0.0003	0.0008	0.0017	0.0044	0.0107	0.0056	0.0020	0.0006	0.0001	-	-	-	-	-
0.3333	-	-	-	-	-	-	0.0003	0.0007	0.0021	0.0053	0.0125	0.0066	0.0026	0.0008	0.0001	-	-	-	-	-
0.3500	-	-	-	-	-	0.0001	0.0004	0.0005	0.0013	0.0045	0.0125	0.0059	0.0024	0.0004	-	-	-	-	-	-
0.3667	-	-	-	-	0.0001	0.0001	0.0002	0.0004	0.0025	0.0069	0.0144	0.0075	0.0025	0.0008	-	-	-	-	-	-
0.3833	-	-	-	-	-	0.0001	0.0002	0.0004	0.0012	0.0038	0.0107	0.0056	0.0020	0.0004	0.0001	-	-	-	-	-
0.4000	-	-	-	-	-	-	0.0003	0.0004	0.0015	0.0047	0.0093	0.0050	0.0020	0.0003	0.0001	-	-	-	-	-
0.4167	-	-	-	-	-	-	0.0001	0.0002	0.0012	0.0043	0.0115	0.0059	0.0018	0.0003	0.0001	-	-	-	-	-
0.4333	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0042	0.0130	0.0066	0.0014	0.0003	0.0001	-	-	-	-	-
0.4500	-	-	-	-	-	-	0.0002	0.0003	0.0012	0.0034	0.0092	0.0045	0.0017	0.0003	-	-	-	-	-	-
0.4667	-	-	-	-	-	-	0.0002	0.0004	0.0009	0.0033	0.0091	0.0046	0.0011	0.0002	-	-	-	-	-	-
0.4833	-	-	-	-	-	0.0001	0.0002	0.0004	0.0010	0.0033	0.0076	0.0045	0.0014	0.0003	-	-	-	-	-	-
0.5000	-	-	-	-	0.0001	0.0001	0.0002	0.0003	0.0012	0.0045	0.0105	0.0055	0.0014	0.0003	0.0001	-	-	-	-	-
0.5167	-	-	-	-	-	0.0001	0.0002	0.0004	0.0013	0.0034	0.0109	0.0051	0.0013	0.0003	-	-	-	-	-	-
0.5333	-	-	-	-	-	-	0.0001	0.0002	0.0005	0.0025	0.0077	0.0038	0.0008	0.0002	0.0001	-	-	-	-	-
0.5500	-	-	-	-	-	-	0.0002	0.0003	0.0007	0.0028	0.0067	0.0039	0.0012	0.0002	-	-	-	-	-	-
0.5667	-	-	-	-	-	0.0001	0.0001	0.0004	0.0006	0.0019	0.0063	0.0032	0.0007	0.0001	-	-	-	-	-	-
0.5833	-	-	-	-	-	0.0001	-	0.0003	0.0006	0.0015	0.0047	0.0029	0.0009	0.0001	-	-	-	-	-	-
0.6000	-	-	-	-	-	0.0001	0.0002	0.0002	0.0006	0.0023	0.0080	0.0037	0.0009	0.0001	-	-	-	-	-	-
0.6167	-	-	-	-	-	-	0.0002	0.0003	0.0006	0.0020	0.0064	0.0033	0.0005	0.0001	-	-	-	-	-	-
0.6333	-	-	-	-	-	-	0.0001	0.0001	0.0006	0.0015	0.0057	0.0026	0.0008	0.0001	-	-	-	-	-	-
0.6500	-	-	-	-	-	-	-	0.0002	0.0009	0.0022	0.0054	0.0036	0.0011	0.0002	-	-	-	-	-	-
0.6667	-	-	-	-	-	-	-	0.0002	0.0001	0.0007	0.0022	0.0012	0.0003	0.0001	-	-	-	-	-	-
0.6833	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0009	0.0035	0.0014	0.0003	-	-	-	-	-	-	-
0.7000	-	-	-	-	-	-	-	0.0001	0.0006	0.0011	0.0033	0.0017	0.0006	0.0001	-	-	-	-	-	-
0.7167	-	-	-	-	-	-	0.0001	0.0001	0.0004	0.0013	0.0027	0.0018	0.0004	0.0001	-	-	-	-	-	-
0.7333	-	-	-	-	-	-	-	0.0001	0.0005	0.0015	0.0035	0.0019	0.0006	-	-	-	-	-	-	-
0.7500	-	-	-	-	-	-	0.0001	0.0002	0.0003	0.0013	0.0044	0.0023	0.0004	-	-	-	-	-	-	-
0.7667	-	-	-	-	-	0.0001	0.0001	0.0002	0.0002	0.0020	0.0050	0.0021	0.0003	0.0001	-	-	-	-	-	-
0.7833	-	-	-	-	-	-	0.0001	0.0002	0.0006	0.0016	0.0046	0.0023	0.0007	0.0001	-	-	-	-	-	-
0.8000	-	-	-	-	-	-	-	0.0002	0.0002	0.0014	0.0048	0.0017	0.0006	-	-	-	-	-	-	-
0.8167	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0013	0.0043	0.0017	0.0003	0.0001	-	-	-	-	-	-
0.8333	-	-	-	-	-	-	-	0.0001	-	0.0004	0.0019	0.0006	0.0001	-	-	-	-	-	-	-
0.8500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.8667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.8833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9333	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0333	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are proportion of total vehicle-hours on link that fall in each speed/acceleration category.
Columns are acceleration rate category in units of miles per hour per second. Rows are speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 44 Vehicle modal activity table for uncongested arterials

	ACCELERATION (mph/sec)																			
Spd/FreSpd	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.000	-	-	-	-	-	-	-	-	-	-	0.2006	-	-	-	-	-	-	-	-	-
0.0286	-	-	-	-	-	0.0001	-	-	0.0008	0.0005	0.0009	0.0005	0.0001	0.0002	0.0001	0.0005	-	-	-	-
0.0571	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.0857	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1143	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1429	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1714	-	-	-	-	-	0.0002	0.0001	0.0003	0.0012	0.0009	0.0020	0.0012	0.0005	0.0006	0.0006	0.0005	0.0002	-	-	-
0.2000	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2286	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2571	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2857	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.3143	-	-	-	-	-	0.0002	0.0004	0.0004	0.0013	0.0010	0.0016	0.0010	0.0004	0.0011	0.0011	0.0004	0.0003	-	-	-
0.3429	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.3714	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4000	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4286	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4571	-	-	-	-	-	0.0002	0.0005	0.0003	0.0012	0.0009	0.0018	0.0011	0.0005	0.0028	0.0002	-	0.0003	-	-	-
0.4857	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5143	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5429	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5714	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.6000	-	-	-	-	-	0.0001	0.0004	0.0004	0.0011	0.0009	0.0020	0.0022	0.0019	0.0025	-	-	-	-	-	-
0.6286	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.6571	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.6857	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.7143	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.7429	-	-	-	-	-	0.0001	0.0005	0.0003	0.0010	0.0009	0.0043	0.0065	0.0025	0.0006	-	-	-	-	-	-
0.7714	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8000	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8286	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8571	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8857	-	-	-	-	-	0.0001	0.0003	0.0002	0.0010	0.0020	0.0209	0.0175	0.0010	-	-	-	-	-	-	-
0.9143	-	-	-	-	-	0.0001	0.0003	0.0002	0.0012	0.0023	0.0253	0.0198	0.0011	-	-	-	-	-	-	-
0.9429	-	-	-	-	-	0.0002	0.0005	0.0004	0.0019	0.0039	0.0395	0.0330	0.0018	0.0001	-	-	-	-	-	-
0.9714	-	-	-	-	-	0.0001	0.0004	0.0003	0.0015	0.0031	0.0316	0.0264	0.0015	0.0001	-	-	-	-	-	-
1.0000	-	-	-	-	-	0.0001	0.0004	0.0003	0.0015	0.0031	0.0316	0.0264	0.0015	0.0001	-	-	-	-	-	-
1.0286	-	-	-	-	-	0.0001	0.0003	0.0003	0.0011	0.0016	0.0214	0.0172	0.0002	-	-	-	-	-	-	-
1.0571	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.0857	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1143	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1429	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1714	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0002	0.0073	0.0038	-	-	-	-	-	-	-	-
1.2000	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2286	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2571	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2857	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.3143	-	-	-	-	-	-	-	-	-	0.0001	0.0015	0.0011	-	-	-	-	-	-	-	-
1.3429	-	-	-	-	-	-	-	-	-	0.0001	0.0008	0.0006	-	-	-	-	-	-	-	-
1.3714	-	-	-	-	-	-	-	-	-	0.0001	0.0008	0.0006	-	-	-	-	-	-	-	-
1.4000	-	-	-	-	-	-	-	-	-	-	0.0006	0.0005	-	-	-	-	-	-	-	-
1.4286	-	-	-	-	-	-	-	-	-	-	0.0006	0.0005	-	-	-	-	-	-	-	-
1.4571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are proportion of total vehicle-hours on link that fall in each speed/acceleration category.
Columns are acceleration rate category in units of miles per hour per second. Rows are speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 45 Vehicle modal activity table for congested arterials

Spd/FreSpd	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
0.0000	-	-	-	-	-	-	-	-	-	-	0.5317	-	-	-	-	-	-	-
0.0286	-	-	-	-	-	0.0001	-	-	0.0013	0.0006	0.0007	0.0002	0.0001	0.0003	0.0001	0.0009	-	-
0.0571	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.0857	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1143	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1429	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1714	-	-	-	-	-	0.0001	0.0001	0.0007	0.0017	0.0008	0.0018	0.0012	0.0005	0.0009	0.0010	0.0004	0.0002	-
0.2000	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2286	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2571	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2857	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.3143	-	-	-	-	-	0.0002	0.0009	0.0007	0.0013	0.0007	0.0012	0.0008	0.0002	0.0017	0.0014	0.0003	0.0004	-
0.3429	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.3714	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4000	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4286	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4571	-	-	-	-	-	0.0002	0.0010	0.0005	0.0012	0.0006	0.0007	0.0008	0.0008	0.0040	0.0002	0.0001	0.0003	-
0.4857	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5143	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5429	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5714	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.6000	-	-	-	-	-	0.0002	0.0009	0.0003	0.0012	0.0005	0.0010	0.0035	0.0027	0.0019	-	-	0.0001	-
0.6286	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.6571	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.6857	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.7143	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.7429	-	-	-	-	-	0.0001	0.0006	0.0003	0.0005	0.0007	0.0082	0.0075	0.0019	0.0001	-	-	-	-
0.7714	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8000	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8286	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8571	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8857	-	-	-	-	-	0.0001	0.0004	0.0002	0.0009	0.0005	0.0069	0.0094	0.0005	-	-	-	-	-
0.9143	-	-	-	-	-	-	0.0002	0.0001	0.0004	0.0002	0.0031	0.0042	0.0002	-	-	-	-	-
0.9429	-	-	-	-	-	0.0001	0.0003	0.0002	0.0007	0.0004	0.0051	0.0070	0.0004	-	-	-	-	-
0.9714	-	-	-	-	-	0.0001	0.0002	0.0001	0.0006	0.0003	0.0041	0.0056	0.0003	-	-	-	-	-
1.0000	-	-	-	-	-	0.0001	0.0002	0.0001	0.0006	0.0003	0.0041	0.0056	0.0003	-	-	-	-	-
1.0286	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0003	0.0029	0.0033	-	-	-	-	-	-
1.0571	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.0857	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1143	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1429	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1714	-	-	-	-	-	-	-	-	-	0.0001	0.0004	0.0009	-	-	-	-	-	-
1.2000	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2286	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2571	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2857	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.3143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.3429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.3714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.9143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.9429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are proportion of total vehicle-hours on link that fall in each speed/acceleration category.
Columns are acceleration rate category in units of miles per hour per second. Rows are speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

CHAPTER 16

DERIVATION OF VEHICLE EMISSION MODULE

This chapter describes the recommended method by which the emission effects of traffic-flow improvements will be estimated. There are several central concepts that guide the selection of the specific methods described. These concepts relate to both (1) the effect of traffic-flow improvement projects on vehicle activity and (2) the state of knowledge and available modeling tools for emission estimation. An outline of the emission analysis methodology is then presented, followed by specific descriptions of the specific models and data requirements for the various emission processes.

16.1 OVERVIEW OF EMISSION ESTIMATION METHODOLOGY

The underlying concept for traditional on-road emission inventory development using composite emission factors expressed in grams per mile can be thought of as "traffic on roads." That is, the fundamental processes affecting emissions can be decomposed to roadway segments and characterized by the nature of traffic occurring on them. The emission effects of traffic-flow improvement projects arise from a variety of factors that go beyond segment-based analysis. Although second-by-second vehicle operations are important, route choice and trip-making behavior also influence total emissions. For this reason, the research team recommends that the emission estimation methodology be based on a "vehicles making trips" concept. Under this approach, traffic-flow improvement projects will be evaluated by identifying the number of vehicles whose activity is influenced by the project and by characterizing the effect of the project on the vehicle's trip characteristics.

Currently, no single model addresses the range of specific emission processes in sufficient detail to capture the effects of traffic-flow improvement projects. At the present time, the CMEM (NCHRP 25-11) model provides the most detailed and best tested estimates of hot-stabilized vehicle exhaust emissions at different speeds and accelerations. Similarly, EMFAC2000 (Version 2.02) provides the most detailed estimates of process-specific evaporative emissions and excess start emissions. The methodology proposed here relies on emission rate estimates from these two models. As described previously, no currently available models address either heavy-duty vehicle emissions or PM emissions at the same level of detail as CMEM.

MOBILE6 includes comparable detail to that of EMFAC-2000 (Version 2.02) and may be used in its place. MOBILE6 closely follows EMFAC2000 in its treatment of start and evaporative emissions, relying in some cases on the same databases and statistical models.

The primary effects of traffic-flow improvement projects relate to speeds and delay along specific corridors. The direct emissions effects include

- Running exhaust emissions (due to changes in vehicle speed and acceleration profiles, as well as changes in VMT due to route choice),
- Running evaporative emissions (due to changes in total travel time), and
- Refueling and CO_2 emissions (due to changes in fuel efficiency).

The CMEM (NCHRP 25-11) model can produce running exhaust emission and fuel consumption rates for user-specified speed and acceleration frequency distributions (SAFDs). These SAFDs, expressed in the number of vehicle-seconds of operation falling within specified ranges of speeds and accelerations, can be generated in a number of ways. For urban areas, a set of driving cycles were developed for MOBILE6 that were intended to characterize facility-class–specific driving patterns on local roads, on-ramps, arterials, and freeways. Different cycles were developed for different levels of service (LOSs) on arterials and freeways. These cycles can be used to provide a nominal estimate of urban SAFDs from available VMT and LOS data.

To evaluate traffic-flow improvement project effects, a two-step process is needed. First, the base case vehicle activity affected by the project (expressed as the vehicle-seconds in each category of the SAFD) is identified and removed from the regional SAFD. Second, a new SAFD for the affected traffic is developed. Running exhaust emissions and fuel consumption estimates are calculated directly using CMEM. Running evaporative emission rates are produced not by CMEM, but by EMFAC2000 (Version 2.02) on a gram/hour basis. These rates can be directly applied to the total vehicle-seconds of operation for base case and traffic-flow improvement project case SAFDs to evaluate running-loss VOC emission effects.

Traffic-flow improvement projects (particularly ramp metering) can potentially cause enrichment events. CMEM was designed to directly address such events, but requires more detailed inputs for emission calculation. If the nature of traffic-flow improvement effects are expected to include increases in sustained accelerations, second-by-second vehicle trajectories (i.e., distance traveled at each second while within the corridor) are needed for emission analysis. Microscale simulation can provide vehicle trajectories at this level of detail, but questions exist regarding the representativeness of second-by-second acceleration results. For specific projects, empirical vehicle trajectory inputs may provide more accurate emission estimates. In either case, emissions for each vehicle (or for each of several "representative" vehicles) moving along a corridor can be modeled with CMEM and aggregated to obtain total project effects. If sustained accelerations do not occur, the emissions calculated using detailed time-series inputs are effectively identical to those calculated using combined SAFDs as model inputs.

There are two secondary effects of traffic-flow improvement projects that influence emissions. First, to the extent that traffic-flow improvement projects reduce total travel time, there may be some increase in the number of trips made, resulting in additional start emissions. Second, both reduced travel time and increased numbers of trips alter the number and timing of hot soak, diurnal, and resting loss periods for the vehicle. Given that the number of vehicles within a region is not affected by traffic-flow improvement projects, and that the average time each vehicle spends parked each day remains relatively constant, it is the potential increase in start and hot soak emissions that will be most important. EMFAC2000 (Version 2.02) produces start emissions on a grams-per-start basis for soak times of 10 through 1,440 minutes. It also produces hot soak emissions on a grams-per-1-hour-soak basis. Inputs required to estimate base case emissions are the number of starts and the distribution of soak times through the day for the region of interest. Traffic-flow improvement project effects require the explicit identification of new trips and of additional intermediate destinations (i.e., trip chaining). Duration of soak times will be particularly important for the destinations of new trips or intermediate destinations. The research team anticipates that these soak times may be shorter than average, as the new destinations are likely to be brief errands, rather than major new activities. Assumptions may be needed regarding the timing of new trips as they affect soak time distributions for diurnal and resting evaporative emissions.

The following notation is used to describe the specific calculation approach for estimating total emissions and emission changes resulting from traffic-flow improvement projects:

Q_X = total emissions for process X in grams;
q_X = emission rate (typically g/s) for process X (arguments, such as $q_X(m)$, indicate dependence on a factor such as speed or soak time, where m is the index value for that factor);
$v(ij)$ = vehicle speed and acceleration frequency distribution (cumulative vehicle-seconds) for the ith speed category and jth acceleration category; and
$s(k)$ = number of vehicle starts following a park of duration within the kth soak time range.

Process indicators are as follows:

S = starts,
R = running exhaust,
E = running losses (evaporative),
K = hot soak,
L = diurnal,
G = resting loss, and
F = fuel-related (refueling and CO_2 exhaust).

Virtually all rates depend on ambient temperature, and this dependence is not shown. In practice, an average summer day temperature profile will be used (or average winter day for CO analyses), resulting in an implicit dependence of each equation on time of day (from the fact that rates for hour h will be calculated based on the assumed ambient temperature for hour h). Start and running exhaust emissions have separate rates for VOC, NO_X, and CO. Fuel-related emissions have separate rates for VOC and CO_2. All other rates are VOC only. Start and running exhaust PM and running road dust and tire and brake wear PM emissions also have separate rates.

16.2 ESTIMATION OF START EXHAUST EMISSIONS

Start emission rates $q_S(k)$ vary with soak time. Thus,

$$E_S = \sum_k q_S(k) * s(k) \qquad \text{Equation 78}$$

Where:

E_S = the start exhaust emissions and
q_S = the emission rate in grams per start for starts following a soak time of the kth duration, as provided by EMFAC2000 (Version 2.02).

A nominal soak time distribution can be assumed for regional travel totals, but the traffic-flow improvement project effects on new starts and the soak time distributions for new starts must be explicitly estimated. For example, new starts arising from an additional shopping destination on a return HBW trip will likely have a distribution of soak times in the 10-, 20-, or 30-minute range, rather than the regional average, which is likely to be longer than 4 hours.

The start exhaust emission rates provided by the EMFAC-2000 and MOBILE6 models presume a regional average distribution of soak times. This macroscopic assumption is not compatible with the microscopic emissions analysis proposed for this project using CMEM.

Additional research would be required to develop a model of the microscopic vehicle soak time impacts of traffic-flow improvements so that CMEM rates for cold starts could be applied as adjustments to the CMEM running exhaust emissions. Consequently, this methodology currently neglects the differences in the cold-start emissions between build and no-build cases for a traffic-flow improvement project.

16.3 ESTIMATION OF RUNNING EXHAUST EMISSIONS

Vehicle speed- and acceleration-indexed running exhaust emission rates $q_R(i,j)$ can be produced by the CMEM model in units of grams per second. Thus,

$$E_R = \sum_{ij} q_R(i,j) \cdot v(i,j) \qquad \text{Equation 79}$$

Where E_R equals running exhaust emissions and the identification of the joint speed-acceleration frequency distribution v can represent regional totals or the specific vehicle activity affected by the traffic-flow improvement projects. CMEM calculates emission rates for feasible values of vehicle speeds and accelerations based on vehicle weight and engine power output. The development of SAFDs in the Traffic Module must be constrained to these feasible values. Otherwise, emissions will be underestimated, as vehicles will be assumed to travel at higher-than-achievable speeds (and for shorter time periods) than would actually be the case.

Heavy-duty vehicle running exhaust emissions will not be treated in this methodology for several reasons. Only limited preliminary data are available from NCHRP Project 25-14 on speed and acceleration effects on heavy-duty NO_X emissions, and even fewer data are available for other pollutants. Also, the Traffic Module will not be able to produce reliable estimates of the changes in SAFDs for heavy-duty vehicle activity, and such changes may well be negligible for many traffic-flow improvement projects. Consequently, the methodology will neglect the differences in the heavy-duty vehicle activity between build and no-build cases for a traffic-flow improvement project.

Similarly, no modeling tools are currently available that accurately characterize acceleration effects on PM emissions (except as embodied in driving cycle–based rate measurements for different average speeds). Consequently, the methodology will neglect the differences in the heavy-duty vehicle activity between build and no-build cases for a traffic-flow improvement project.

16.4 ESTIMATION OF OFF-CYCLE EMISSIONS

If traffic-flow improvement projects influence the frequency of sustained hard accelerations, such as metering traffic on freeway on-ramps, second-by-second vehicle trajectory data are needed as inputs to CMEM for running exhaust emissions. These are distance vector inputs of form $d = (d(1), d(2), \ldots, d(n))$ for an n-second trajectory of length $d(n)$. CMEM directly produces total trajectory emissions:

$$E_R = Q_R(d) \qquad \text{Equation 80}$$

Where:

Q_r = the function (as implemented in CMEM) that calculates E_r based on the distance vector and the vehicle characteristics (weight, engine displacement, etc.).

Emissions over multiple trajectories and vehicle types must be summed for the subset of vehicle activity of interest. Representative trajectories can be used, but individual vehicle emissions must be calculated and aggregated to obtain fleet-average effects. Initial CMEM runs were conducted using both time-series and speed- and acceleration-indexed emission calculations to determine if enrichment effects are significant. It was found that while there were significant effects, speed- and acceleration-indexed emission rates would satisfactorily capture most of the impacts of traffic-flow improvement projects.

16.5 ESTIMATION OF RUNNING EVAPORATIVE EMISSIONS

Running evaporative emission rates (q_E) are calculated internally in EMFAC2000 (Version 2.02) for different trip durations, but are currently only output on a gram-per-vehicle-hour basis. Traffic-flow improvement projects are unlikely to significantly alter the average duration of trips, and the functional form of trip-duration dependence of running evaporative emissions is not highly sensitive to trip duration. Therefore, running evaporative emissions (E_E) can be calculated as

$$E_E = q_E * \sum_{ij} v(ij) \qquad \text{Equation 81}$$

However, because CMEM does not include running evaporative emissions, the impact of traffic-flow improvements on running evaporative emissions is currently not included in the NCHRP Project 25-21 methodology.

16.6 ESTIMATION OF HOT SOAK, DIURNAL, AND RESTING EVAPORATIVE EMISSIONS

The so-called "trip-end" evaporative emissions depend primarily on ambient temperatures. Each trip end generates a hot soak, and park times longer than 1 hour produce diurnal or resting evaporative emissions depending on whether ambient temperatures are rising, constant, or falling. The change in total vehicle operating time $\sum_{i,j} v(i,j)$ between scenarios results directly in an increase or decrease in resting loss or diurnal emission times, since the total number of vehicles within a region is assumed to be constant. For purposes of evaluating traffic-flow improvement project effects, one can focus on the change in vehicle operating time, multiplying this difference by the appropriate diurnal or resting loss rate, q_L or q_G.

Hot soak emissions require additional information because they are specifically associated with new trips or trip chaining. Base case hot soak emissions are calculated based on an assumed distribution of soak times by hour of day:

$$E_K = \sum_k q_K(k)s(k) \qquad \text{Equation 82}$$

Where:

E_K = hot soak, diurnal, and resting evaporative emissions,
$s(k)$ = the number of trips ending that will have a soak time of duration index k, and
$q_K(k)$ = the fraction of a 1-hour hot soak emission that is associated with a soak time of duration index k (constant for soak times longer than 1 hour).

If a significant fraction of soak times for added trips are less than 1 hour, then the nonlinear nature of $q_K(k)$ for short soak times should be explicitly treated.

The available data do not provide information on how the number of starts will be impacted by traffic-flow improvement projects. Especially difficult would be finding data on how traffic-flow improvement projects influence soak times. Consequently this methodology will neglect the differences in the number of starts and soak times between build and no-build cases for a traffic-flow improvement project.

16.7 ESTIMATION OF FUEL-DEPENDENT EMISSIONS

CMEM directly calculates fuel consumption from engine load for (1) both speed- and acceleration-indexed vehicle activity inputs or (2) time-series vehicle activity inputs. Thus, the evaporative emissions associated with fuel use can be directly calculated from the grams-per-second fuel consumption rates as

$$E_F = C * \sum_{ij} q_F(i,j) * v(i,j) \qquad \text{Equation 83}$$

Where:

E_F = fuel-dependent emissions,
$q_F(i,j)$ = rate of fuel-dependent emissions, and
C = a factor derived from EPA AP-42 (or other refueling emission factors) and any unit conversion factors needed for fuel density and vapor pressure.

The same equation can be used for CO_2 emissions if C is derived from the carbon mass fraction of fuel and conversion factors for CO_2 molecular weight.

Because the necessary activity data are lacking, evaporative emissions will be neglected in this methodology.

16.8 ESTIMATION OF PM10 EMISSIONS

PM10 emissions could be estimated using EMFAC2000 rates per VMT for each speed category by functional road class. However, because CMEM, upon which the NCHRP 25-21 methodology is based, does not include PM10 emissions, the impact of traffic-flow improvements on PM10 emissions is currently not included in the NCHRP 25-21 methodology.

16.9 ESTIMATION OF HEAVY-DUTY VEHICLE EMISSIONS

Changes in heavy-duty vehicle emissions due to traffic-flow improvements are not explicitly included in the methodology for two reasons. One, modal emission rate data were not available for heavy-duty vehicles at the time of the NCHRP 25-21 project. Two, the majority of urban area travel demand models do not explicitly model heavy-duty vehicle activity separately from light-duty vehicles. The proposed methodology consequently focuses on modeling light-duty vehicle emission changes.

The primary heavy-duty vehicle emissions of interest are NO_X. These are currently estimated using rates keyed to the mean speed and vehicle type. As such, a weighted-average emission rate can be used for light- and heavy-duty vehicles combined and applied to total VMT based on an estimated percentage of heavy-duty vehicles in the vehicle fleet. However, results from NCHRP Project 25-14, "Heavy-Duty Emission Factors," were not ready in time for this research.

16.10 FINAL VHT-BASED EMISSION RATES

Two sets of emission rates tables are included in the methodology. The first table, taken from EMFAC2000, is based on average trip speeds. The second set of rates is based on time spent by light-duty vehicles at specific acceleration/deceleration rates and speeds during a trip. The tables convert VHT into appropriate emissions in grams.

16.11 TREATMENT OF EMISSION RATE UPDATES

Revised CMEM modal emission rates reflecting new emission control technology and new fuel standards can be substituted into the methodology if and when they become available. The analyst simply substitutes the new rates by modal activity category for Tables 46 through 49.

TABLE 46 EMFAC2000 light-duty vehicle emission rates (grams/hour)

Speed (mph)	THC	CO	NOx	Speed (mph)	THC	CO	NOx
1	14.67607	159.5444	11.61292	41	24.80151	528.7634	58.42341
2	14.67607	159.5444	11.61292	42	25.15197	539.0394	60.04349
3	14.67607	159.5444	11.61292	43	25.50243	549.3153	61.66357
4	14.67607	159.5444	11.61292	44	25.85289	559.5912	63.28365
5	14.67607	159.5444	11.61292	45	26.20335	569.8672	64.90373
6	15.84475	179.0649	13.29768	46	26.75994	583.4598	66.83860
7	17.01342	198.5855	14.98243	47	27.31652	597.0524	68.77347
8	18.18209	218.1060	16.66719	48	27.87311	610.6450	70.70834
9	19.35076	237.6266	18.35195	49	28.42970	624.2376	72.64321
10	20.51943	257.1471	20.03670	50	28.98628	637.8302	74.57808
11	20.91987	270.0474	21.37240	51	29.82726	656.7163	76.93856
12	21.32031	282.9476	22.70810	52	30.66824	675.6025	79.29904
13	21.72074	295.8479	24.04379	53	31.50923	694.4886	81.65952
14	22.12118	308.7481	25.37949	54	32.35021	713.3747	84.02000
15	22.52162	321.6484	26.71519	55	33.19119	732.2609	86.38048
16	22.61334	331.0057	27.87704	56	34.43988	759.6495	89.32167
17	22.70507	340.3631	29.03890	57	35.68856	787.0381	92.26286
18	22.79679	349.7205	30.20075	58	36.93725	814.4268	95.20406
19	22.88851	359.0779	31.36260	59	38.18594	841.8154	98.14525
20	22.98024	368.4353	32.52446	60	39.43462	869.2041	101.08640
21	22.97946	376.0226	33.62934	61	41.28965	910.5624	104.83420
22	22.97869	383.6099	34.73422	62	43.14467	951.9207	108.58200
23	22.97791	391.1972	35.83910	63	44.99969	993.2791	112.32980
24	22.97714	398.7845	36.94398	64	46.85472	1034.6370	116.07750
25	22.97636	406.3718	38.04887	65	48.70974	1075.9960	119.82530
26	22.98913	413.3314	39.18121	66	48.70974	1075.9960	119.82530
27	23.00189	420.2911	40.31356	67	48.70974	1075.9960	119.82530
28	23.01466	427.2508	41.44591	68	48.70974	1075.9960	119.82530
29	23.02742	434.2105	42.57826	69	48.70974	1075.9960	119.82530
30	23.04018	441.1702	43.71061	70	48.70974	1075.9960	119.82530
31	23.12495	448.3715	44.93947	71	48.70974	1075.9960	119.82530
32	23.20971	455.5729	46.16833	72	48.70974	1075.9960	119.82530
33	23.29448	462.7743	47.39719	73	48.70974	1075.9960	119.82530
34	23.37924	469.9757	48.62605	74	48.70974	1075.9960	119.82530
35	23.46400	477.1770	49.85491	75	48.70974	1075.9960	119.82530
36	23.66141	485.4391	51.24460	76	48.70974	1075.9960	119.82530
37	23.85882	493.7012	52.63428	77	48.70974	1075.9960	119.82530
38	24.05623	501.9633	54.02396	78	48.70974	1075.9960	119.82530
39	24.25364	510.2254	55.41365	79	48.70974	1075.9960	119.82530
40	24.45105	518.4875	56.80333	80	48.70974	1075.9960	119.82530

THC = total hydrocarbons.
CO = carbon monoxide.
NO_X = oxides of nitrogen.

TABLE 47 CMEM light-duty vehicle hyrocarbon emission rates (grams/hour)

Speed	Acceleration (mph/sec)																
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.002658	0.002696	0.002734	0.00277	0.002815	0.00287	0.002936	0.002973	0.003021	0.003079	0.003148	0.003227	0.00319	0.003152	0.003114	0.003076
1		0.002677	0.002718	0.002758	0.002797	0.002846	0.002905	0.002976	0.003017	0.00307	0.002965	0.003611	0.004525	0.005438	0.006488	0.007662	0.008949
2		0.002696	0.002739	0.002782	0.002824	0.002876	0.00294	0.003016	0.003061	0.003118	0.002851	0.004073	0.005822	0.007686	0.009823	0.01221	0.014822
3		0.002715	0.002761	0.002807	0.002851	0.002907	0.002975	0.003057	0.003106	0.003168	0.002912	0.004172	0.005968	0.007879	0.010071	0.01252	0.015199
4		0.002734	0.002782	0.002831	0.002877	0.002937	0.00301	0.003097	0.00315	0.003217	0.002974	0.00427	0.006113	0.008071	0.010319	0.012829	0.015577
5		0.002753	0.002804	0.002855	0.002904	0.002968	0.003046	0.003138	0.003195	0.003267	0.003036	0.004372	0.006267	0.008271	0.010584	0.013162	0.015984
6		0.002772	0.002826	0.00288	0.002931	0.002998	0.003081	0.003179	0.00324	0.003318	0.003099	0.004473	0.006421	0.00847	0.010849	0.013495	0.01639
7		0.002791	0.002847	0.002904	0.002958	0.003029	0.003116	0.003221	0.003286	0.003369	0.003199	0.004639	0.006647	0.008797	0.011255	0.013995	0.016985
8		0.002809	0.002869	0.002928	0.002985	0.00306	0.003152	0.003262	0.003332	0.003421	0.003299	0.004805	0.006874	0.009123	0.011661	0.014495	0.017579
9		0.002828	0.00289	0.002952	0.003012	0.003091	0.003188	0.003304	0.003379	0.003473	0.003454	0.005077	0.007247	0.009612	0.012262	0.016072	0.019497
10		0.002847	0.002912	0.002977	0.003039	0.003121	0.003224	0.003346	0.003425	0.003526	0.003609	0.005349	0.00762	0.0101	0.012864	0.017649	0.021414
11		0.002866	0.002933	0.003001	0.003066	0.003152	0.00326	0.003389	0.003473	0.00358	0.003831	0.005681	0.008066	0.010651	0.013562	0.018357	0.022567
12		0.002885	0.002955	0.003025	0.003093	0.003183	0.003296	0.003432	0.003521	0.003634	0.004053	0.006013	0.008512	0.011202	0.01426	0.019065	0.02372
13		0.002885	0.002955	0.003025	0.003094	0.003185	0.0033	0.00344	0.003534	0.003654	0.004294	0.006375	0.009001	0.011812	0.015005	0.020031	0.026457
14		0.002885	0.002955	0.003025	0.003094	0.003186	0.003304	0.003448	0.003548	0.003675	0.004536	0.006738	0.009489	0.012423	0.01575	0.020998	0.029195
15		0.002885	0.002955	0.003025	0.003094	0.003188	0.003307	0.003454	0.003557	0.003687	0.004175	0.006286	0.009011	0.012397	0.016558	0.021999	0.032044
16		0.002885	0.002955	0.003025	0.003094	0.003189	0.003311	0.003459	0.003565	0.003699	0.003815	0.005835	0.008534	0.012372	0.017365	0.023001	0.034894
17		0.002885	0.002955	0.003025	0.003095	0.00319	0.003314	0.003465	0.003575	0.003714	0.003918	0.006039	0.008855	0.012567	0.018326	0.024525	0.037048
18		0.002885	0.002955	0.003025	0.003095	0.003192	0.003318	0.003472	0.003585	0.003728	0.00402	0.006243	0.009176	0.012761	0.019287	0.026049	0.039203
19		0.002885	0.002955	0.003025	0.003096	0.003194	0.003322	0.00348	0.003599	0.003747	0.00415	0.006484	0.009548	0.013303	0.02048	0.028191	0.041716
20		0.002885	0.002955	0.003025	0.003096	0.003195	0.003326	0.003488	0.003613	0.003766	0.00428	0.006725	0.009921	0.013844	0.021672	0.030333	0.04423
21		0.002885	0.002955	0.003025	0.003097	0.003198	0.003331	0.003498	0.003629	0.003787	0.00444	0.00701	0.010353	0.014466	0.023047	0.032765	0.047201
22		0.002885	0.002955	0.003025	0.003097	0.0032	0.003336	0.003508	0.003645	0.003808	0.0046	0.007294	0.010786	0.015089	0.024421	0.035196	0.050173
23		0.002885	0.002955	0.003025	0.003098	0.003202	0.003341	0.00352	0.003663	0.003831	0.004781	0.007615	0.011274	0.015786	0.02489	0.038191	0.053409
24		0.002885	0.002955	0.003025	0.003098	0.003205	0.003347	0.003532	0.00368	0.003853	0.004962	0.007936	0.011762	0.016483	0.025359	0.041187	0.056644
25		0.002885	0.002955	0.003025	0.003099	0.003208	0.003353	0.003545	0.003699	0.003877	0.004673	0.007614	0.011577	0.01727	0.027457	0.044686	0.060157
26		0.002885	0.002955	0.003025	0.0031	0.003211	0.003359	0.003558	0.003718	0.0039	0.004384	0.007292	0.011392	0.018056	0.029554	0.048185	0.063669
27		0.002885	0.002955	0.003025	0.003101	0.003214	0.003366	0.003571	0.003737	0.003924	0.004506	0.007568	0.011896	0.018792	0.031874	0.052215	0.067293
28		0.002885	0.002955	0.003025	0.003101	0.003217	0.003373	0.003585	0.003756	0.003948	0.004628	0.007845	0.012399	0.019527	0.034194	0.056244	0.070917
29		0.002885	0.002955	0.003025	0.003102	0.00322	0.003381	0.003599	0.003776	0.003972	0.004768	0.008165	0.012974	0.020779	0.037172	0.059341	0.073925
30		0.002885	0.002955	0.003025	0.003103	0.003224	0.003389	0.003613	0.003796	0.003996	0.004908	0.008485	0.013549	0.022031	0.040151	0.062437	0.076934
31		0.002885	0.002955	0.003025	0.003104	0.003228	0.003397	0.003628	0.003816	0.004021	0.005069	0.008846	0.014246	0.026044	0.055502	0.083352	0.09644
32		0.002885	0.002955	0.003025	0.003105	0.003231	0.003406	0.003643	0.003836	0.004045	0.005231	0.009208	0.014942	0.030058	0.070853	0.104266	0.115947
33		0.002885	0.002955	0.003025	0.003106	0.003235	0.003415	0.003659	0.003857	0.00407	0.005415	0.0096	0.015646	0.034014	0.075459	0.10678	0.116582
34		0.002885	0.002955	0.003025	0.003107	0.00324	0.003425	0.003675	0.003878	0.004095	0.005598	0.009993	0.016351	0.03797	0.080066	0.109294	0.117217
35		0.002885	0.002955	0.003025	0.003108	0.003244	0.003435	0.003691	0.0039	0.00412	0.0058	0.010414	0.017107	0.042012	0.085436	0.111487	0.117473
36		0.002885	0.002955	0.003025	0.003109	0.003248	0.003446	0.003708	0.003921	0.004146	0.006003	0.010836	0.017863	0.046054	0.090806	0.113679	0.117729
37		0.002885	0.002955	0.003025	0.003111	0.003252	0.003456	0.003724	0.003942	0.00417	0.006221	0.011284	0.019046	0.050309	0.094876	0.115585	0.117879
38		0.002885	0.002955	0.003025	0.003112	0.003256	0.003467	0.003741	0.003963	0.004195	0.00644	0.011732	0.020228	0.054563	0.098945	0.117491	0.11803
39		0.002885	0.002955	0.003025	0.003113	0.003262	0.003479	0.003759	0.003986	0.00422	0.006678	0.012211	0.021496	0.05862	0.102344	0.117605	0.118131
40		0.002885	0.002955	0.003025	0.003115	0.003267	0.003491	0.003777	0.004008	0.004245	0.006916	0.01269	0.022763	0.062677	0.105743	0.117719	0.118233
41		0.002885	0.002955	0.003025	0.003116	0.003272	0.003503	0.003794	0.00403	0.00427	0.007158	0.013193	0.024449	0.066554	0.107877	0.117829	0.118409
42		0.002885	0.002955	0.003025	0.003118	0.003278	0.003516	0.003812	0.004051	0.004294	0.0074	0.013696	0.026134	0.07043	0.11001	0.117938	0.118585
43		0.002885	0.002955	0.003025	0.003119	0.003283	0.003528	0.00383	0.004072	0.004317	0.007675	0.014233	0.028355	0.074045	0.111712	0.118044	0.118629
44		0.002885	0.002955	0.003025	0.003121	0.003289	0.00354	0.003847	0.004094	0.00434	0.007951	0.01477	0.030575	0.07766	0.113413	0.11815	0.118674
45		0.002885	0.002955	0.003025	0.003123	0.003296	0.003553	0.003864	0.004111	0.004358	0.007571	0.014581	0.033722	0.08189	0.115578	0.118223	0.118712
46		0.002885	0.002955	0.003025	0.003125	0.003302	0.003566	0.00388	0.004128	0.004377	0.00719	0.014392	0.036869	0.086119	0.117744	0.118296	0.118751
47		0.002885	0.002955	0.003025	0.003127	0.003309	0.003582	0.003902	0.004156	0.004381	0.007407	0.014936	0.040112	0.091233	0.117894	0.118592	0.118837
48		0.002885	0.002955	0.003025	0.003129	0.003315	0.003598	0.003925	0.004183	0.004386	0.007624	0.01548	0.043356	0.096347	0.118044	0.118887	0.118924
49		0.002885	0.002955	0.003025	0.003131	0.003322	0.003614	0.003946	0.004209	0.00436	0.007874	0.016025	0.046748	0.098776	0.118163	0.118963	0.118996
50		0.002885	0.002955	0.003025	0.003134	0.003329	0.00363	0.003967	0.004235	0.004335	0.008124	0.016569	0.05014	0.101206	0.118282	0.119039	0.119068
51		0.002885	0.002955	0.003025	0.003136	0.003335	0.003646	0.003988	0.004225	0.004315	0.008402	0.017218	0.053512	0.104209	0.118369	0.119097	0.119122
52		0.002885	0.002955	0.003024	0.003138	0.003342	0.003661	0.004008	0.004216	0.004294	0.00868	0.017866	0.056883	0.107212	0.118456	0.119154	0.119177
53		0.002885	0.002955	0.003024	0.003141	0.003349	0.003676	0.004027	0.0042	0.004278	0.008991	0.018885	0.061015	0.109287	0.118535	0.119205	0.119225
54		0.002885	0.002955	0.003024	0.003143	0.003356	0.003692	0.004047	0.004185	0.004262	0.009303	0.019905	0.065148	0.111362	0.118613	0.119256	0.119274
55		0.002885	0.002955	0.003024	0.003146	0.003364	0.003707	0.004067	0.004173	0.00425	0.009647	0.02097	0.068089	0.112713	0.118971	0.119301	0.119318
56		0.002885	0.002955	0.003024	0.003149	0.003372	0.003722	0.004087	0.00416	0.004237	0.009991	0.022035	0.07103	0.114065	0.119329	0.119347	0.119361
57		0.002885	0.002955	0.003024	0.003152	0.00338	0.003738	0.004091	0.00415	0.004227	0.010388	0.023019	0.073712	0.116439	0.119372	0.119388	0.119401
58		0.002885	0.002955	0.003024	0.003155	0.003388	0.003753	0.004096	0.00414	0.004216	0.010785	0.024003	0.076395	0.118812	0.119415	0.11943	0.119441
59		0.002885	0.002955	0.003025	0.003159	0.003397	0.003768	0.004087	0.004132	0.004208	0.011203	0.025289	0.080088	0.119213	0.119789	0.119825	0.119854
60		0.002885	0.002955	0.003025	0.003163	0.003405	0.003783	0.004079	0.004124	0.0042	0.011621	0.026575	0.083781	0.119614	0.120164	0.12022	0.120267
61		0.002885	0.002955	0.003026	0.003167	0.003415	0.003798	0.004072	0.004117	0.004193	0.012076	0.028303	0.08672	0.11971	0.120203	0.120256	0.120301
62		0.002885	0.002955	0.003026	0.003171	0.003424	0.003813	0.004065	0.00411	0.004186	0.012531	0.03003	0.089659	0.119807	0.120242	0.120293	0.120335
63		0.002885	0.002955	0.003027	0.003175	0.003435	0.003828	0.004059	0.004105	0.004393	0.013026	0.032123	0.092225	0.119899	0.120276	0.120325	0.120365
64		0.002885	0.002955	0.003028	0.00318	0.003445	0.003844	0.004054	0.0041	0.0046	0.013521	0.034216	0.094791	0.119991	0.12031	0.120357	0.120396
65		0.002885	0.002955	0.003029	0.003185	0.003459	0.003862	0.004047	0.004094	0.004742	0.014057	0.037802	0.09815	0.120064	0.120344	0.120388	0.120425

TABLE 48 CMEM light-duty vehicle CO emission rates (grams/hour)

Speed	Acceleration (mph/sec)																
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.028047	0.028482	0.028916	0.029297	0.029973	0.030957	0.032259	0.033447	0.034957	0.03679	0.038944	0.041419	0.040984	0.04055	0.040116	0.039681
1		0.028264	0.02873	0.029195	0.029604	0.030337	0.031408	0.032827	0.034132	0.03579	0.034819	0.046809	0.069906	0.08806	0.106167	0.125502	0.145875
2		0.028482	0.028978	0.029474	0.029912	0.030701	0.031859	0.033395	0.034817	0.036623	0.032847	0.054673	0.098394	0.135136	0.171784	0.210888	0.252068
3		0.028699	0.029226	0.029753	0.03022	0.031068	0.032316	0.033975	0.03552	0.037481	0.03399	0.056689	0.101211	0.138787	0.176257	0.216237	0.258334
4		0.028916	0.029474	0.030033	0.030529	0.031436	0.032774	0.034554	0.036223	0.038339	0.035134	0.058704	0.104028	0.142439	0.18073	0.221585	0.264599
5		0.029133	0.029722	0.030312	0.030838	0.031806	0.033238	0.035146	0.036945	0.039226	0.036318	0.060684	0.10697	0.143501	0.185463	0.227265	0.271271
6		0.02935	0.029971	0.030591	0.031147	0.032176	0.033702	0.035738	0.037667	0.040113	0.037501	0.062664	0.109912	0.144563	0.190196	0.232945	0.277942
7		0.029567	0.030219	0.03087	0.031457	0.03255	0.034175	0.036344	0.038412	0.041031	0.039142	0.064794	0.110489	0.15009	0.19462	0.24136	0.287548
8		0.029784	0.030467	0.031149	0.031767	0.032924	0.034648	0.036951	0.039157	0.041949	0.040783	0.066923	0.111066	0.155617	0.199045	0.249774	0.297153
9		0.030002	0.030715	0.031428	0.032078	0.033303	0.035129	0.037573	0.039926	0.042903	0.043185	0.070557	0.11468	0.162242	0.206266	0.348428	0.41193
10		0.030219	0.030963	0.031707	0.03239	0.033681	0.035611	0.038196	0.040696	0.043857	0.045588	0.07419	0.118295	0.168867	0.213487	0.447081	0.526707
11		0.030436	0.031211	0.031987	0.032702	0.034064	0.036104	0.038838	0.041495	0.044853	0.048782	0.078812	0.123638	0.173964	0.224166	0.440598	0.564039
12		0.030653	0.031459	0.032266	0.033015	0.034446	0.036597	0.03948	0.042295	0.045849	0.051976	0.083433	0.128981	0.179062	0.234845	0.434115	0.601371
13		0.030653	0.031459	0.032266	0.033019	0.034493	0.03673	0.039742	0.042727	0.046493	0.055636	0.088675	0.135375	0.185885	0.243104	0.449627	0.730662
14		0.030653	0.031459	0.032266	0.033023	0.03454	0.036864	0.040005	0.04316	0.047138	0.059297	0.093917	0.141769	0.192708	0.251363	0.46514	0.859953
15		0.030653	0.031459	0.032266	0.033034	0.034582	0.036962	0.040179	0.043431	0.047524	0.055207	0.090169	0.142488	0.201027	0.25945	0.476636	1.057539
16		0.030653	0.031459	0.032266	0.033045	0.034624	0.03706	0.040353	0.043701	0.047911	0.051117	0.086422	0.143206	0.209345	0.267537	0.488132	1.255126
17		0.030653	0.031459	0.032266	0.033057	0.034672	0.037172	0.040551	0.044008	0.048348	0.052658	0.08933	0.147124	0.213806	0.281838	0.521418	1.396491
18		0.030653	0.031459	0.032266	0.03307	0.034719	0.037283	0.04075	0.044315	0.048785	0.054199	0.092238	0.151042	0.218266	0.296139	0.554704	1.537856
19		0.030653	0.031459	0.032266	0.033085	0.034773	0.037412	0.041009	0.044756	0.049381	0.056202	0.095788	0.155977	0.226882	0.323353	0.617387	1.704427
20		0.030653	0.031459	0.032266	0.0331	0.034827	0.037541	0.041269	0.045197	0.049977	0.058206	0.099339	0.160912	0.235498	0.350567	0.680069	1.870999
21		0.030653	0.031459	0.032266	0.033117	0.034898	0.037698	0.041582	0.045689	0.050621	0.060715	0.103593	0.166882	0.244733	0.381279	0.763732	2.111163
22		0.030653	0.031459	0.032266	0.033134	0.03497	0.037854	0.041895	0.046182	0.051265	0.063224	0.107846	0.172851	0.253969	0.411991	0.847395	2.351327
23		0.030653	0.031459	0.032266	0.033153	0.03505	0.038031	0.042259	0.046722	0.051953	0.066021	0.112615	0.17967	0.26321	0.47856	1.006917	2.601943
24		0.030653	0.031459	0.032266	0.033172	0.035131	0.038208	0.042623	0.047261	0.052641	0.068819	0.117384	0.18649	0.272451	0.545129	1.166439	2.852558
25		0.030653	0.031459	0.032266	0.033194	0.03522	0.038405	0.043023	0.047835	0.053358	0.065894	0.117043	0.193401	0.283011	0.617672	1.388613	3.105985
26		0.030653	0.031459	0.032266	0.033215	0.03531	0.038603	0.043423	0.048408	0.054075	0.062969	0.116703	0.200311	0.29357	0.690215	1.610787	3.359413
27		0.030653	0.031459	0.032266	0.03324	0.03541	0.038822	0.043843	0.048997	0.054803	0.064945	0.121222	0.20854	0.316367	0.772146	1.927233	3.558146
28		0.030653	0.031459	0.032266	0.033264	0.035509	0.039042	0.044263	0.049587	0.055531	0.066921	0.125741	0.216768	0.339165	0.854078	2.243678	3.756879
29		0.030653	0.031459	0.032266	0.033291	0.035618	0.039285	0.044703	0.050192	0.05627	0.069154	0.130954	0.225943	0.377428	1.04598	2.4849	3.824236
30		0.030653	0.031459	0.032266	0.033318	0.035728	0.039528	0.045143	0.050798	0.057008	0.071388	0.136167	0.235117	0.415691	1.237882	2.726122	3.891593
31		0.030653	0.031459	0.032266	0.033348	0.035847	0.039795	0.045605	0.05142	0.057758	0.073924	0.14199	0.245964	0.55502	2.441528	4.409657	5.124772
32		0.030653	0.031459	0.032266	0.033378	0.035966	0.040063	0.046067	0.052043	0.058507	0.076459	0.147813	0.25681	0.69435	3.645173	6.093192	6.357952
33		0.030653	0.031459	0.032266	0.033411	0.036096	0.040356	0.046551	0.052681	0.059265	0.079425	0.154055	0.267552	0.917787	3.920339	6.170853	6.394732
34		0.030653	0.031459	0.032266	0.033444	0.036226	0.040649	0.047034	0.05332	0.060023	0.08239	0.160298	0.278295	1.141225	4.195504	6.248513	6.431511
35		0.030653	0.031459	0.032266	0.033481	0.036366	0.04097	0.047541	0.053976	0.06079	0.085646	0.16688	0.289615	1.491987	4.572735	6.285364	6.445984
36		0.030653	0.031459	0.032266	0.033517	0.036506	0.041291	0.048048	0.054631	0.061557	0.088901	0.173462	0.300935	1.842749	4.949966	6.322216	6.460458
37		0.030653	0.031459	0.032266	0.033557	0.036631	0.041615	0.048552	0.055276	0.062304	0.092351	0.180323	0.350712	2.329718	5.301288	6.382241	6.468102
38		0.030653	0.031459	0.032266	0.033597	0.036756	0.041939	0.049057	0.055921	0.06305	0.0958	0.187183	0.400489	2.816687	5.652609	6.442266	6.475747
39		0.030653	0.031459	0.032266	0.03364	0.036917	0.042314	0.049604	0.056598	0.063816	0.099501	0.194386	0.448877	3.001184	5.854157	6.446879	6.479942
40		0.030653	0.031459	0.032266	0.033684	0.037078	0.042689	0.050151	0.057276	0.064582	0.103202	0.201589	0.497264	3.185683	6.055706	6.451492	6.484138
41		0.030653	0.031459	0.032266	0.033731	0.03725	0.043068	0.050692	0.057936	0.065317	0.106758	0.209033	0.531855	3.277467	6.168096	6.456062	6.5064
42		0.030653	0.031459	0.032266	0.033778	0.037422	0.043447	0.051234	0.058596	0.066052	0.110314	0.216476	0.566446	3.369252	6.280485	6.460631	6.528662
43		0.030653	0.031459	0.032266	0.033829	0.037604	0.043829	0.051767	0.059235	0.066748	0.114437	0.224304	0.639643	3.484976	6.303052	6.465085	6.530388
44		0.030653	0.031459	0.032266	0.033879	0.037787	0.04421	0.052301	0.059873	0.067445	0.118559	0.232131	0.71284	3.6007	6.32562	6.469538	6.532115
45		0.030653	0.031459	0.032266	0.033943	0.037988	0.044601	0.0528	0.060402	0.068005	0.115489	0.240296	0.876628	3.844832	6.384479	6.470284	6.533744
46		0.030653	0.031459	0.032266	0.034006	0.03819	0.044992	0.053298	0.060931	0.068565	0.112419	0.24846	1.040417	4.088964	6.443338	6.47103	6.535373
47		0.030653	0.031459	0.032266	0.034075	0.038392	0.046587	0.056188	0.065067	0.073945	0.122485	0.263922	1.289181	4.703476	6.455601	6.513739	6.545506
48		0.030653	0.031459	0.032266	0.034144	0.038594	0.048182	0.059078	0.069202	0.079326	0.132551	0.279383	1.537945	5.317988	6.467863	6.556447	6.55564
49		0.030653	0.031459	0.032266	0.034218	0.038804	0.049771	0.061928	0.073295	0.084662	0.141913	0.292048	1.799182	5.468068	6.479035	6.567725	6.567054
50		0.030653	0.031459	0.032266	0.034292	0.039013	0.051361	0.064778	0.077388	0.089998	0.151274	0.304713	2.060419	5.618147	6.490208	6.579003	6.578468
51		0.030653	0.031459	0.032256	0.034361	0.039222	0.052934	0.067592	0.081443	0.089294	0.152942	0.315395	2.416013	5.763675	6.494328	6.585236	6.584744
52		0.030653	0.031459	0.032246	0.034431	0.03943	0.054507	0.070406	0.085498	0.088589	0.15461	0.326077	2.771608	5.909202	6.498448	6.591469	6.59102
53		0.030653	0.031459	0.03224	0.034511	0.039651	0.056077	0.073215	0.083953	0.086315	0.158401	0.371649	2.840733	6.106389	6.499936	6.595277	6.594852
54		0.030653	0.031459	0.032234	0.03459	0.039872	0.057648	0.076024	0.082408	0.084041	0.162192	0.417221	2.909858	6.303576	6.501425	6.599084	6.598685
55		0.030653	0.031459	0.032234	0.034681	0.040108	0.059216	0.077493	0.081054	0.082756	0.167163	0.461675	3.125623	6.320415	6.553251	6.601884	6.601498
56		0.030653	0.031459	0.032233	0.034771	0.040343	0.060784	0.078962	0.079699	0.08147	0.172135	0.506128	3.341387	6.337254	6.605077	6.604683	6.604311
57		0.030653	0.031459	0.032237	0.034873	0.040594	0.062349	0.078017	0.078853	0.080713	0.178873	0.536202	3.48152	6.447301	6.607379	6.606992	6.606624
58		0.030653	0.031459	0.032242	0.034975	0.040845	0.063914	0.077072	0.078006	0.079955	0.185611	0.566276	3.621652	6.557348	6.609681	6.609301	6.608937
59		0.030653	0.031459	0.032253	0.03509	0.041113	0.065475	0.076429	0.077463	0.079516	0.192368	0.5896	4.071856	6.706609	6.756441	6.756442	6.756446
60		0.030653	0.031459	0.032264	0.035204	0.04138	0.067037	0.075786	0.076921	0.079077	0.199126	0.612923	4.522059	6.85587	6.903201	6.903583	6.903955
61		0.030653	0.031459	0.032281	0.035331	0.041665	0.068594	0.075337	0.076575	0.078848	0.206551	0.67175	4.718489	6.865068	6.909377	6.909732	6.910086
62		0.030653	0.031459	0.032298	0.035459	0.041951	0.070151	0.074888	0.07623	0.078618	0.213977	0.730576	4.914918	6.874267	6.915552	6.915882	6.916216
63		0.030653	0.031459	0.032323	0.0356	0.042277	0.071724	0.074587	0.076034	0.079409	0.222057	0.810598	4.965501	6.882252	6.920411	6.920721	6.921045
64		0.030653	0.031459	0.032347	0.035741	0.042604	0.073298	0.074285	0.075838	0.0802	0.230138	0.890619	5.016084	6.890237	6.925269	6.925561	6.925874
65		0.030653	0.031459	0.03238	0.035896	0.044123	0.073073	0.073884	0.07565	0.08228	0.238931	1.066209	5.396034	6.896957	6.929721	6.929997	6.930302

TABLE 49 CMEM light-duty vehicle NO_X emission rates (grams/hour)

Speed	Acceleration (mph/sec)																
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.00071	0.000712	0.000715	0.000716	0.000734	0.000782	0.000868	0.000982	0.001126	0.001299	0.001501	0.001732	0.001729	0.001726	0.001724	0.001721
1		0.000711	0.000714	0.000717	0.000718	0.000738	0.000791	0.000886	0.001011	0.001168	0.001117	0.002465	0.004046	0.005485	0.007039	0.008712	0.010503
2		0.000712	0.000716	0.000719	0.000719	0.000742	0.0008	0.000903	0.00104	0.001211	0.000935	0.00343	0.00636	0.00924	0.012351	0.015699	0.019285
3		0.000714	0.000717	0.000721	0.000721	0.000746	0.000809	0.000922	0.00107	0.001256	0.001004	0.003575	0.006584	0.009528	0.012711	0.016141	0.019816
4		0.000715	0.000719	0.000722	0.000723	0.00075	0.000819	0.00094	0.0011	0.001301	0.001073	0.00372	0.006808	0.009816	0.013072	0.016582	0.020346
5		0.000717	0.00072	0.000724	0.000725	0.000754	0.000829	0.00096	0.001132	0.001348	0.001147	0.003875	0.007046	0.010133	0.013458	0.017057	0.020919
6		0.000718	0.000722	0.000726	0.000727	0.000759	0.00084	0.00098	0.001164	0.001396	0.001222	0.004029	0.007285	0.01045	0.013845	0.017532	0.021493
7		0.000719	0.000724	0.000728	0.000729	0.000763	0.000851	0.001001	0.001199	0.001446	0.001345	0.004261	0.007614	0.010857	0.014367	0.018152	0.022229
8		0.000721	0.000725	0.000729	0.000731	0.000768	0.000862	0.001022	0.001233	0.001497	0.001468	0.004493	0.007942	0.011264	0.014889	0.018771	0.022966
9		0.000722	0.000727	0.000731	0.000733	0.000773	0.000874	0.001045	0.00127	0.001551	0.001753	0.004925	0.0085	0.011939	0.015685	0.020202	0.024612
10		0.000724	0.000728	0.000733	0.000735	0.000778	0.000886	0.001068	0.001306	0.001605	0.002038	0.005357	0.009058	0.012613	0.016481	0.021632	0.026258
11		0.000725	0.00073	0.000735	0.000737	0.000783	0.0009	0.001093	0.001346	0.001663	0.002408	0.005864	0.009707	0.01339	0.017407	0.02251	0.027521
12		0.000726	0.000731	0.000737	0.000739	0.000788	0.000913	0.001117	0.001385	0.001721	0.002778	0.006371	0.010355	0.014167	0.018334	0.023388	0.028784
13		0.000726	0.000731	0.000737	0.000739	0.000792	0.000925	0.001142	0.001426	0.001781	0.003201	0.006941	0.01108	0.015037	0.019366	0.024615	0.03061
14		0.000726	0.000731	0.000737	0.00074	0.000796	0.000937	0.001166	0.001466	0.001841	0.003623	0.007511	0.011805	0.015907	0.020397	0.025841	0.032436
15		0.000726	0.000731	0.000737	0.00074	0.000799	0.000946	0.001183	0.001492	0.001877	0.003016	0.00689	0.0112	0.01647	0.021469	0.027123	0.036146
16		0.000726	0.000731	0.000737	0.000741	0.000803	0.000956	0.001199	0.001517	0.001913	0.002408	0.006269	0.010596	0.017033	0.022542	0.028404	0.039856
17		0.000726	0.000731	0.000737	0.000741	0.000807	0.000967	0.001219	0.001546	0.001954	0.002631	0.006621	0.0111	0.017074	0.023872	0.029932	0.043863
18		0.000726	0.000731	0.000737	0.000742	0.000811	0.000978	0.001238	0.001575	0.001995	0.002853	0.006973	0.011604	0.017114	0.025202	0.03146	0.04787
19		0.000726	0.000731	0.000737	0.000743	0.000815	0.00099	0.001262	0.001616	0.00205	0.003115	0.007374	0.012176	0.017578	0.02657	0.033189	0.050153
20		0.000726	0.000731	0.000737	0.000744	0.00082	0.001003	0.001287	0.001657	0.002106	0.003377	0.007776	0.012748	0.018042	0.027939	0.034917	0.052437
21		0.000726	0.000731	0.000737	0.000745	0.000827	0.001018	0.001317	0.001704	0.002166	0.003674	0.008225	0.013388	0.018837	0.029514	0.037043	0.0548
22		0.000726	0.000731	0.000737	0.000745	0.000834	0.001034	0.001346	0.00175	0.002226	0.00397	0.008675	0.014027	0.019633	0.031089	0.039168	0.057164
23		0.000726	0.000731	0.000737	0.000747	0.000842	0.001051	0.001381	0.0018	0.00229	0.004291	0.009167	0.014732	0.020586	0.032628	0.046087	0.059711
24		0.000726	0.000731	0.000737	0.000748	0.000849	0.001069	0.001415	0.001851	0.002354	0.004612	0.009658	0.015437	0.02154	0.034167	0.053007	0.062259
25		0.000726	0.000731	0.000737	0.000749	0.000858	0.001088	0.001453	0.001905	0.002421	0.00417	0.009259	0.015249	0.022603	0.034959	0.054569	0.065133
26		0.000726	0.000731	0.000737	0.000751	0.000867	0.001107	0.001491	0.001958	0.002488	0.003729	0.00886	0.01506	0.023666	0.03575	0.056131	0.068007
27		0.000726	0.000731	0.000737	0.000752	0.000876	0.001128	0.00153	0.002013	0.002555	0.003986	0.009312	0.015788	0.024719	0.037164	0.060508	0.071253
28		0.000726	0.000731	0.000737	0.000754	0.000886	0.001149	0.00157	0.002068	0.002623	0.004244	0.009763	0.016515	0.025771	0.038578	0.064885	0.0745
29		0.000726	0.000731	0.000737	0.000756	0.000896	0.001172	0.001611	0.002124	0.002691	0.004528	0.010271	0.017333	0.027154	0.04665	0.068097	0.079059
30		0.000726	0.000731	0.000737	0.000757	0.000906	0.001195	0.001652	0.002181	0.00276	0.004812	0.010779	0.018151	0.028537	0.054721	0.07131	0.083618
31		0.000726	0.000731	0.000737	0.000759	0.000918	0.001221	0.001695	0.002238	0.002829	0.005121	0.011334	0.019389	0.032247	0.069823	0.090544	0.09832
32		0.000726	0.000731	0.000737	0.000762	0.000929	0.001246	0.001738	0.002296	0.002899	0.005431	0.011888	0.020628	0.035958	0.084926	0.109778	0.113022
33		0.000726	0.000731	0.000737	0.000764	0.000941	0.001273	0.001783	0.002355	0.002969	0.005795	0.012474	0.021645	0.043996	0.089076	0.111044	0.113725
34		0.000726	0.000731	0.000737	0.000766	0.000954	0.001301	0.001828	0.002414	0.003039	0.006159	0.01306	0.022661	0.052035	0.093227	0.112309	0.114429
35		0.000726	0.000731	0.000737	0.000769	0.000967	0.001331	0.001875	0.002475	0.00311	0.006513	0.013675	0.02375	0.053835	0.099019	0.113086	0.114694
36		0.000726	0.000731	0.000737	0.000772	0.00098	0.001361	0.001922	0.002535	0.00318	0.006867	0.01429	0.024839	0.055635	0.104812	0.113862	0.114959
37		0.000726	0.000731	0.000737	0.000775	0.000992	0.001391	0.001968	0.002595	0.003249	0.007237	0.014933	0.0262	0.059043	0.106868	0.114481	0.115094
38		0.000726	0.000731	0.000737	0.000779	0.001004	0.001421	0.002015	0.002654	0.003318	0.007608	0.015575	0.02756	0.062452	0.108925	0.1151	0.115228
39		0.000726	0.000731	0.000737	0.000782	0.00102	0.001456	0.002066	0.002717	0.003389	0.008	0.016252	0.028914	0.068435	0.110739	0.115208	0.115334
40		0.000726	0.000731	0.000737	0.000786	0.001035	0.001491	0.002116	0.00278	0.00346	0.008393	0.016928	0.030267	0.074417	0.112553	0.115316	0.11544
41		0.000726	0.000731	0.000737	0.00079	0.001051	0.001526	0.002167	0.002841	0.003528	0.00874	0.017624	0.032984	0.079901	0.112976	0.11542	0.115564
42		0.000726	0.000731	0.000737	0.000794	0.001068	0.001562	0.002217	0.002902	0.003596	0.009087	0.01832	0.035701	0.085384	0.113399	0.115524	0.115688
43		0.000726	0.000731	0.000737	0.000799	0.001085	0.001597	0.002267	0.002962	0.003661	0.009512	0.019061	0.0371	0.090015	0.113918	0.115623	0.115771
44		0.000726	0.000731	0.000737	0.000804	0.001103	0.001633	0.002316	0.003021	0.003726	0.009937	0.019802	0.038499	0.094646	0.114437	0.115723	0.115853
45		0.000726	0.000731	0.000737	0.00081	0.001123	0.00167	0.002363	0.003071	0.003778	0.009502	0.019581	0.045323	0.099275	0.115095	0.115804	0.115925
46		0.000726	0.000731	0.000737	0.000817	0.001143	0.001708	0.002411	0.003121	0.003831	0.009067	0.01936	0.052146	0.103905	0.115754	0.115885	0.115996
47		0.000726	0.000731	0.000737	0.000824	0.001162	0.001783	0.002533	0.003285	0.004038	0.009658	0.020316	0.055965	0.106478	0.116131	0.11631	0.116366
48		0.000726	0.000731	0.000737	0.000831	0.001181	0.001858	0.002655	0.00345	0.004245	0.010249	0.021272	0.059784	0.109052	0.116508	0.116734	0.116736
49		0.000726	0.000731	0.000737	0.000839	0.001201	0.001933	0.002773	0.003611	0.004261	0.010497	0.022051	0.062572	0.11115	0.117239	0.117453	0.117454
50		0.000726	0.000731	0.000737	0.000847	0.001221	0.002007	0.002892	0.003772	0.004276	0.010744	0.022829	0.065361	0.113248	0.11797	0.118173	0.118173
51		0.000726	0.000731	0.000736	0.000855	0.001242	0.002081	0.003008	0.003733	0.004076	0.011035	0.023839	0.068341	0.115	0.118388	0.118583	0.118582
52		0.000726	0.000731	0.000736	0.000863	0.001262	0.002156	0.003124	0.003695	0.003876	0.011326	0.024849	0.071321	0.116751	0.118806	0.118993	0.118992
53		0.000726	0.000731	0.000736	0.000871	0.001284	0.002229	0.003239	0.003576	0.00375	0.011728	0.026264	0.07117	0.117085	0.119093	0.119273	0.119272
54		0.000726	0.000731	0.000736	0.00088	0.001305	0.002302	0.003355	0.003457	0.003624	0.01213	0.02768	0.071018	0.11742	0.11938	0.119553	0.119551
55		0.000726	0.000731	0.000736	0.000889	0.001328	0.002375	0.003286	0.003375	0.003539	0.012611	0.028856	0.074127	0.117975	0.119679	0.119764	0.119763
56		0.000726	0.000731	0.000736	0.000899	0.001351	0.002448	0.003217	0.003294	0.003455	0.013093	0.030033	0.077235	0.11853	0.119978	0.119976	0.119975
57		0.000726	0.000731	0.000736	0.000909	0.001374	0.002521	0.003158	0.003235	0.003395	0.01376	0.031211	0.08091	0.119344	0.12015	0.120149	0.120147
58		0.000726	0.000731	0.000736	0.000919	0.001398	0.002594	0.003099	0.003177	0.003336	0.014427	0.032389	0.084586	0.120157	0.120323	0.120321	0.12032
59		0.000726	0.000731	0.000737	0.00093	0.001423	0.002666	0.003055	0.003134	0.003294	0.015032	0.034573	0.096071	0.12467	0.124824	0.124825	0.124826
60		0.000726	0.000731	0.000738	0.000941	0.001449	0.002738	0.003011	0.003092	0.003252	0.015637	0.036756	0.107557	0.129183	0.129325	0.129328	0.129333
61		0.000726	0.000731	0.000739	0.000953	0.001475	0.002809	0.002977	0.00306	0.003222	0.016295	0.037851	0.110544	0.129464	0.12959	0.129594	0.129598
62		0.000726	0.000731	0.00074	0.000966	0.001502	0.002881	0.002944	0.003028	0.003192	0.016953	0.038946	0.11353	0.129745	0.129856	0.129859	0.129864
63		0.000726	0.000731	0.000741	0.000979	0.001532	0.002931	0.002919	0.003005	0.003491	0.017665	0.042293	0.115898	0.129976	0.130071	0.130074	0.130079
64		0.000726	0.000731	0.000743	0.000992	0.001562	0.002981	0.002894	0.002982	0.00379	0.018377	0.045641	0.118266	0.130208	0.130286	0.130289	0.130295
65		0.000726	0.000731	0.000745	0.001007	0.00163	0.002923	0.002858	0.002955	0.003955	0.019146	0.050374	0.121041	0.130421	0.130488	0.130491	0.130497

CHAPTER 17

VALIDATION OF METHODOLOGY

This chapter presents the results of various examinations of the validity of the recommended methodology.

17.1 VALIDATION OBJECTIVES

The objective of validation is to verify the results predicted by the methodology against field measurements of the impacts of traffic-flow improvements on air quality. This objective is very difficult to achieve because of the subtlety and pervasiveness of the impacts of traffic-flow improvements. As described previously, a traffic-flow improvement impacts more than just the traffic on the facility itself. It impacts traffic flows and speeds on numerous nearby facilities and impacts trip making and mode choice. It is therefore very difficult to identify a bounded domain for conducting "before and after" measurements of the traffic impacts of the traffic-flow improvements. In addition, the desire to capture the full long-term effects of a traffic-flow improvement requires a very long time frame (30 years or so) for measuring the "after" effects.

A confounding problem for measuring the validity of the methodology is the research team's inability to "control" for the impacts of factors extraneous to the methodology that the research team is trying to validate. Other unrecorded traffic-flow improvements in the area, demographic changes, and economic changes are all factors that can impact the measured results in the field, cannot be controlled by the investigator, and are external to the methodology.

Finally, since this methodology is new, previous efforts to measure the impacts of traffic-flow improvements on air quality did not gather the necessary data for this new methodology and did not control for the factors external to this methodology.

Thus, hard numeric validation of this new methodology against numeric results in the field is not feasible without launching a new data collection effort specifically tailored to the features of this new methodology. A new data collection effort will also require extensive resources since the methodology is designed to track the "regional" air quality impacts of a specific traffic-flow improvement.

What can be done is to review the performance of the methodology on a series of case studies and compare the results to expectations about the direction and magnitude of the impacts based upon theory. Thus, if the methodology predicts a net travel time reduction for the facility and a consequent increase in usage of the facility, the methodology is following the research team's expectations that reductions in travel costs (in this case time) result in increases in demand for the facility.

While theory quite clearly guides the research team on the likely impacts of traffic-flow improvements on facility usage, theory is less clear about systemwide impacts (since there are many counteracting behavioral mechanisms). Increases in usage of a single facility may be partially or completely counteracted by decreases in parallel facilities.

The predictions of the methodology for the systemic impacts of traffic-flow improvements can be compared with the results of previous studies of the systemwide impacts of traffic-flow improvements. The recommended methodology can be exercised on a set of case studies and the resulting predicting of travel behavior converted into equivalent elasticities. The elasticities output by the methodology can then be compared with the ranges of elasticities produced by various previous studies of the impacts of capacity improvements on VMT.

However, the previous studies (since they used simpler methodologies) did not collect and document the "before and after" values of the many factors required by the proposed methodology. Consequently, the comparison of elasticities can be only on an "order of magnitude" basis, and even when there are large differences, there may be legitimate undocumented reasons for the differences.

17.2 EVALUATION AGAINST EXPECTATIONS FOR FACILITY-SPECIFIC IMPACTS

The recommended methodology was exercised on 12 case studies (see Table 50). These case studies were selected specifically to illustrate the application of the recommended methodology to a wide range of traffic-flow improvement projects (many of which have not previously been considered) and to show how the impacts of an improvement project can vary widely depending on the base conditions prior to the improvement.

The PSRC 2020 travel model database for the Seattle-Tacoma metropolitan area was selected as the test-bench for the case studies. The methodology was applied to each case study. More information about the specifics of the application

TABLE 50 Description of case studies

Case #	Case Study Title	Description
0	Null (No Change)	This is the “base” network for all of the other case studies. The “Null Case” was created from a duplicate of the base network for the purpose of verifying the accuracy of the software implementation of the methodology. No change in network should result in no change in behavior.
1	Add Fwy Lane Rural (uncongested)	This case involves the addition of one continuous through lane in each direction to 7.6 miles of freeway located in a rural mountainous area. The freeway was uncongested in the base case; thus, this capacity increase had no impact on freeway operating speeds. It was included to demonstrate the impacts of capacity improvements that result in no performance improvements for the facility.
2	Add Fwy Lane Urban (modest congestion)	This case is the addition of one continuous through lane in each direction to 6.6 miles of two-lane (in each direction) freeway in an urban location. The improvement reduced the peak-period, peak-direction volume/capacity ratio from 94% to 78%, thus improving travel speeds.
3a	Add Fwy HOV Lane (uncongested)	This case added a pair of median HOV lanes (one lane in each direction) to 2.05 miles of urban freeway. The freeway was generally uncongested (volume/capacity < 89%) before the addition of the HOV lanes. The HOV lanes in this case consequently had no effect on freeway operating speeds.
3b	Add Fwy HOV Lane (congested)	This case added a pair of median HOV lanes (one lane in each direction) to 2.00 miles of congested urban freeway. Peak-period, peak-direction volume/capacity ratios ranged between 94% and 96% before the addition of the HOV lanes. The HOV lanes in this case increased freeway operating speeds.
4	Add Arterial Lane	This case added one through lane in each direction to 10.1 miles of a suburban/rural highway.
5	Access Management	This case involved conversion of a 10.1-mile stretch of rural highway with uncontrolled driveway access into an urban expressway with access consolidated at signalized intersections.
6	Intersection Channelization Improvement	This case added left-turn and right-turn lanes to each of four approaches of an uncongested urban signalized intersection.
7	Signal Coordination	This case coordinated six traffic signals on a 0.54-mile stretch of urban arterial. Free-flow speeds were improved 10%.
8	Transit Improvement	This case doubled the frequency of service for a 23.55-mile radial bus route serving a central business district. Headways were improved from 30 minutes to 15 minutes.
9	Park-and-Ride Lot	This case added a park-and-ride lot 5 miles outside of the central business district on a major freeway serving downtown with a dedicated HOV lane with existing express bus service.
10	30 Years of Improvements	This case added 1,683 lane-miles of highway capacity improvements, plus many bus and ferry transit improvements contained in a typical 20-year regional transportation plan, plus those improvements completed 10 years prior to adoption of the regional transportation plan. The intent of this case is to show the impacts of 30 years’ worth of traffic-flow and transit improvements.

of the methodology to each case study can be found in the user’s guide, which is published as the second part of this report. The AM peak-period, peak-direction travel times and volumes predicted by the methodology were compared with the base case (i.e., no change) travel times and volumes and divided by the base times and volumes to obtain the percentage change for each case. The percentage volume change was divided by the percentage time change to obtain the equivalent demand/travel time elasticity predicted by the methodology for each case. The results are shown in Table 51.

As can be seen in Table 51, five case studies resulted in predicted travel time savings on the facility, as expected. Three of the case studies had no predicted travel time savings, also as expected. The null case had no change in the network, so there should be no time savings. Case 1, the rural freeway lane addition case, had no congestion prior to the lane addition, so the addition of a lane would be expected to have no travel time impacts. Case 3a, the addition of an HOV lane to an uncongested freeway, also resulted in no predicted travel time savings. Again, this result was expected, because the original freeway had plenty of excess capacity. The addition of more excess capacity to a preexisting excess capacity situation results in no improvement in freeway operating speeds.

For the five case studies where facility-specific travel time savings were reported, various increases in peak-direction, peak-period traffic volumes were also predicted by the methodology. Again, the results were as expected. Travel time savings in all cases resulted in predicted increases in facility

TABLE 51 Facility-specific case study results

Case Studies		Project Length (mi)	Capacity Change (lane-mi)	Facility-Specific Time and Volume Changes AM Peak Period Only, Peak Direction		
				Time Change	Volume Change	Elasticity
0	Null (No Change)	0.0	0	0%	0%	n/a
1	Add Fwy Lane Rural	7.6	15.1	0%	0%	n/a
2	Add Fwy Lane Urban	6.6	13.2	-30.00%	19.00%	-0.64
3a	Add Fwy HOV Lane	2.1	4.1	0%	3.00%	infinite
3b	Add Fwy HOV Lane	2.0	4.5	-6.00%	14.00%	-2.49
4	Add Arterial Lane	10.1	20.1	-6.00%	21.00%	-3.49
5	Access Management	10.1	0	-12.00%	78.00%	-6.62
6	Intersection Channelization Improvement	0.0	0	n/a	n/a	n/a
7	Signal Coordination	0.5	0	-9.00%	70.00%	-7.70
8	Transit Improvement	n/a	0	n/a	n/a	n/a
9	Park-and-Ride Lot	n/a	0.1	n/a	n/a	n/a
10	30 Years of Improvements	n/a	1686.3	n/a	n/a	n/a

n/a = not applicable.

usage. In several cases, the volume/travel time elasticity exceeded 100 percent. The elasticities of demand with respect to travel time were all negative and quite large, as expected.

In one case, Case 3a, no change in facility travel time still resulted in a modest 3-percent increase in facility usage. The mere provision of an additional facility in the freeway for HOVs resulted in more traffic being attracted to the freeway, a result found in prior studies of the effects of HOV lanes on demand. (See Dowling, R. G., J. Billheimer, V. Alexidis, and A. D. May, *Predicting High Occupancy Vehicle Lane Demand, Final Report*, Federal Highway Administration, report FHWA-SA-96-073, August 1996.)

The definition of a meaningful highway facility for the other case studies (6, 8, 9, and 10) was not feasible; consequently, no facility-specific results are reported for these four case studies. Only systemwide results are reported.

17.3 EVALUATION AGAINST PRIOR STUDIES OF SYSTEMWIDE ELASTICITIES

This section compares the systemwide VMT elasticities output by the recommended methodology for the case studies against the systemwide VMT elasticities reported in the literature.

17.3.1 Systemwide Elasticities Reported in the Literature

Chapter 2 identified and reviewed the results of numerous studies of the systemwide travel behavior impacts of facility-specific traffic-flow improvements. These studies looked at how VMT changes are correlated to lane-mile changes, average highway speed changes, and travel time changes. Those studies correlating daily per-capita VMT increases to increases in lane-miles per capita have reported short-run elasticities of 0.30 to 0.60 and long-run elasticities of 0.70 to 1.00. It should be noted that the changes in VMT and lane-miles considered in these correlation studies considered only a subset of the regional transportation system (often just the state highways where the best data are available). The definitions of "short run" and "long run" are unclear in many of the reports, although a few reports are quite clear on the distinction.

TRB Special Report 245: Expanding Metropolitan Highways: Implications for Air Quality and Energy Use (1995) reports elasticities in the range of 0.58 to 1.76 for daily VMT with respect to changes in the average highway speed based upon a review of the literature.

Barr reports elasticities in the range of –0.30 to –0.50 for daily household VMT with respect to changes in trip travel time based on a cross-sectional analysis of a national household travel behavior survey. (See Barr, Lawrence, "Testing the Significance of Induced Highway Travel Demand in Metropolitan Areas," Pre-Print CD, paper 00812, Transportation Research Board Annual Meeting, Washington, D.C., 2000.)

17.3.2 Case Study Elasticity Results

The systemwide impacts of the various case study traffic-flow improvements are shown in Tables 52 and 53. Table 52 shows the VHT, VMT, and elasticity results for the short term (behavioral response only, no redistribution of growth). Table 53 shows the results for the long term (both behavioral and redistribution of land-use impacts).

The short-term results are generally quite consistent in terms of systemwide VHT impacts. All of the case studies result in net reductions in total time spent traveling in a vehicle for the region. With the exception of the 30-year improvement program, the impacts are miniscule (on the order of 0.1 to 0.01 percent). This finding is reasonable given that the case

TABLE 52 Case study systemwide results—short term

Case Studies		Project Length (mi)	Lane-Mile Capacity Change	Short-Term Regional Impacts		
				VHT Change	VMT Change	VMT/Lane-mi Elasticity
0	Null (No Change)	0.0	0.00%	0.00%	0.00%	n/a
1	Add Fwy Lane Rural	7.6	0.09%	0.00%	0.00%	0.00
2	Add Fwy Lane Urban	6.6	0.08%	-0.21%	0.00%	-0.04
3a	Add Fwy HOV Lane	2.1	0.02%	0.00%	-0.02%	-0.78
3b	Add Fwy HOV Lane	2.0	0.03%	-0.02%	**0.01%**	**0.23**
4	Add Arterial Lane	10.1	0.12%	-0.04%	-0.01%	-0.06
5	Access Management	10.1	0.00%	-0.01%	**0.02%**	n/a
6	Intersection Channelization Improvement	0.0	0.00%	0.00%	0.00%	n/a
7	Signal Coordination	0.5	0.00%	-0.12%	0.00%	n/a
8	Transit Improvement	n/a	0.00%	0.00%	0.00%	n/a
9	Park-and-Ride Lot	n/a	0.00%	-0.19%	-0.15%	n/a
10	30 Years of Improvements	n/a	9.70%	-8.11%	-0.31%	-0.03

n/a = not applicable.
Positive values shown in bold.
"Short term" includes travel behavior response, but not land-use redistribution impacts.
The elasticities are computed using full precision results for VMT changes rather than the three significant digit results shown in the table. Thus, some apparent zero-change results have non-zero elasticities.

studies themselves generally increase the number of lane-miles of capacity in the region by less than 0.1 percent.

Contrary to the facility-specific results, which showed significant volume increases on specific facilities, the systemwide impacts on VMT are (with a few exceptions) quite miniscule (on the order of a few hundredths of 1 percent) and generally negative. The peak-period, peak-direction volume increases on the specific facility where the improvement occurs are cancelled out by volume decreases elsewhere in the system.

Case 3b (HOV lane addition to congested freeway), and Case 5 (Access Management) show positive increases in system VMT due to traffic-flow improvement. The effect, however, is on the order of 0.01 percent.

Noting the wide range in results predicted by the methodology for the addition of an HOV lane (Cases 3a and 3b result in –0.78 and 0.23 VMT elasticities, respectively), it becomes apparent that the specifics of each case study have a profound effect on the predicted impacts on systemwide VMT. Case 3a adds an HOV lane to an uncongested urban ring freeway. Case 3b adds an HOV lane to a congested urban radial freeway serving the central business district.

The Case 3b result of 0.23 VMT elasticity is on the low side of the 0.3 to 0.6 range reported in the literature. The elas-

TABLE 53 Case study systemwide results—long term

Case Studies		Project Length (mi)	Lane-Mile Capacity Change	Long-Term Regional Impacts		
				VHT Change	VMT Change	VMT/Lane-mi Elasticity
0	Null (No Change)	0.0	0.00%	0.00%	0.00%	n/a
1	Add Fwy Lane Rural	7.6	0.09%	0.00%	0.00%	0.00
2	Add Fwy Lane Urban	6.6	0.08%	-0.06%	0.00%	-0.01
3a	Add Fwy HOV Lane	2.1	0.02%	0.00%	-0.02%	-0.69
3b	Add Fwy HOV Lane	2.0	0.03%	**0.03%**	**0.02%**	**0.74**
4	Add Arterial Lane	10.1	0.12%	**0.01%**	0.00%	**0.01**
5	Access Management	10.1	0.00%	-0.07%	0.00%	n/a
6	Intersection Channelization Improvement	0.0	0.00%	0.00%	0.00%	n/a
7	Signal Coordination	0.5	0.00%	-0.16%	-0.01%	n/a
8	Transit Improvement	n/a	0.00%	0.00%	0.00%	n/a
9	Park-and-Ride Lot	n/a	0.00%	-0.12%	-0.14%	n/a
10	30 Years of Improvements	n/a	9.70%	-10.17%	-0.70%	-0.07

n/a = not applicable.
Positive values shown in bold.
"Long term" includes both travel behavior response and land-use redistribution impacts.

ticities reported in the literature, however, are for the addition of a full lane available to all traffic and not just HOVs.

Cases 1 and 2, addition of freeway lane, are most comparable to the results in the literature; however, they show elasticities of 0 to –0.04, while the literature reports a range of 0.3 to 0.6. The Case 1 results are to be expected of a capacity improvement made at a location that does not need a capacity improvement. The literature generally considered real projects that state highway departments planned and built in response to actual or anticipated traffic growth. The two freeway case studies, however, were selected for illustrative purposes and were not vetted through the usual DOT planning process to determine where the most cost-effective improvements should be made to the freeway system. Thus, while the research reported in the literature considered capacity improvement projects that actually address severe congestion problems, the two case studies looked at projects at less congested or totally uncongested locations.

The freeway capacity improvements considered in the literature were generally more effective at reducing congestion than the projects selected for the two case studies. Thus, the research reported in the literature found a greater effect on VMT than the NCHRP 25-21 methodology found for the two freeway case studies.

The nonfreeway case studies considered here are generally incomparable to the projects evaluated in the literature; thus, the elasticities reported above for many of the case studies cannot be compared to the 0.3 to 0.6 range found in the literature.

The long-term VHT results for the case studies show that total system travel time actually increases for a couple of the case studies (Case 3b, Add HOV Lane; and Case 4, Add Arterial Lane). All other case studies resulted in predicted net reductions in the time spent traveling in vehicles (see Table 53).

The long-term VMT elasticities with respect to lane-miles predicted by the methodology are a mix of positive and negative depending on the specifics of the case study. Case 3a (Add HOV Lane) has an elasticity of –0.69, while Case 3b (also Add HOV Lane) has an elasticity of 0.74. This latter result falls right within the long-term range of 0.7 to 1.0 reported in the literature (but given the wide variation in results predicted by the NCHRP 25-21 methodology for the same action, Add HOV Lane, this latter result is as much due to coincidence as anything else).

The incorporation of the growth redistribution effects in the long-term analysis causes the predicted VMT impacts of the case studies to increase for some cases (Cases 3b, 4, and 9) and decrease for others (Cases 5, 7, and 10) and has no impact on the rest (Cases 0, 1, 2, 3a, 6, and 8) as compared to consideration of just the travel behavior impacts in the short-term analysis.

The systemwide VMT elasticities with respect to average highway speed were also computed for the short- and long-term case study results for the purpose of comparing them with the reported TRB elasticity results of 0.58 to 1.76 (see Table 54).

The short-term results for Case 3a (Add HOV Lane) and Case 5 (Access Management) fall within the TRB-estimated elasticity range. The short-term elasticity results are positive but below the TRB range for Cases 3b and 4. The remainder of the short-term elasticity results are negative, contrary to the TRB range. The wide range in results reported by the NCHRP 25-21 methodology for identical actions taken in different situations (Cases 3a and 3b, for example) suggests that the specifics of the situation in which an improvement is made are better predictors of the VMT impacts than the change in the average highway speed is.

The long-term elasticity results show a similar range in positive and negative elasticities. One case study has a positive

TABLE 54 Case study results: Elasticity with respect to mean speed

Case Studies		Short-Term Regional Impacts			Long-Term Regional Impacts		
		Speed Change	VMT Change	VMT/Time Elasticity	Speed Change	VMT Change	VMT/Time Elasticity
0	Null (No Change)	0.00%	0.00%	#DIV/0!	0.00%	0.00%	#DIV/0!
1	Add Fwy Lane Rural	0.00%	0.00%	#DIV/0!	0.00%	0.00%	#DIV/0!
2	Add Fwy Lane Urban	0.21%	0.00%	-0.01	0.06%	0.00%	-0.01
3a	Add Fwy HOV Lane	-0.01%	-0.02%	1.25	-0.02%	-0.02%	0.78
3b	Add Fwy HOV Lane	0.03%	0.01%	0.22	-0.01%	0.02%	-1.70
4	Add Arterial Lane	-0.04%	-0.01%	0.20	0.01%	0.00%	0.18
5	Access Management	0.03%	0.02%	0.62	0.07%	0.00%	0.03
6	Intersection Channelization Improvement	0.00%	0.00%	#DIV/0!	0.00%	0.00%	#DIV/0!
7	Signal Coordination	0.12%	0.00%	-0.02	0.15%	-0.01%	-0.09
8	Transit Improvement	0.00%	0.00%	#DIV/0!	0.00%	0.00%	#DIV/0!
9	Park-and-Ride Lot	0.03%	-0.15%	-4.73	-0.03%	-0.14%	5.24
10	30 Years of Improvements	7.22%	-0.31%	-0.04	8.59%	-0.70%	-0.08

#DIV/0! = divide by zero error.

TABLE 55 Predicted percent change in emissions for case studies

Case Study	CMEM			EMFAC2000 (Ver. 2.02)		
	THC	CO	NOx	THC	CO	NOx
	Predicted Percent Change in Emissions					
0 Null (No Change)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1 Add Fwy Lane Rural	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2 Add Fwy Lane Urban	0.19%	0.28%	0.37%	0.03%	0.25%	0.40%
3a Add Fwy HOV Lane	0.02%	0.04%	0.03%	0.01%	0.01%	0.02%
3b Add Fwy HOV Lane	0.06%	0.08%	0.08%	0.05%	0.08%	0.10%
4 Add Arterial Lane	0.00%	0.00%	0.00%	0.00%	0.00%	-0.01%
5 Access Management	-0.04%	-0.03%	-0.02%	-0.06%	-0.04%	-0.03%
6 Intersection Channelization Improvement	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7 Signal Coordination	-0.04%	-0.03%	-0.02%	-0.06%	-0.04%	-0.03%
8 Transit Improvement	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9 Park-and-Ride Lot	-0.09%	-0.09%	-0.08%	-0.10%	-0.09%	-0.08%
10 30 Years of Improvements	-7.30%	-6.61%	-6.45%	-7.66%	-6.37%	-5.55%

THC = total hydrocarbons.
CO = carbon monoxide.
NO_X = oxides of nitrogen.

elasticity consistent with the TRB range. Other case studies show lower or negative elasticities.

The TRB-reported range of systemwide VMT elasticities with respect to average highway speed was developed by a consensus of experts rather than a statistical analysis of specific research results. Thus, it is hard to identify specific causes for differences between the case study results and the TRB elasticity range.

Table 55 shows the predicted percent change in emissions for the various case studies. Validation data are not available for evaluating the accuracy of the emission results.

17.4 CONCLUSIONS

The evaluation showed that at a facility-specific level, the NCHRP 25-21 predicts percentage-wise large increases in peak-direction, peak-period traffic flows for case studies. These increases result in peak-direction, peak-period increases in travel speeds. This result is consistent with theory and is expected.

It is not easy, however, to make a clear statement regarding the consistency of the NCHRP 25-21 methodology with observed real-world results at a system level because of the difficulty of obtaining reliable “before and after” system travel results at the level of detail and with the degree of control required to accurately verify the validity of the methodology.

Order-of-magnitude comparisons of the specific case study results and published results in the literature for more general traffic-flow improvements show that the NCHRP 25-21 methodology can produce results consistent with the literature. However, the case studies show that a traffic-flow improvement can result in a wide range of impacts on VMT (either positive or negative) for the same action, depending upon the specific environment in which the improvement is made. The location of a traffic-flow improvement (on a radial or peripheral freeway, for example) and the conditions present on the facility prior to improvement (degree of congestion, for example) have profound impacts on the ultimate systemwide impacts of the project.

CHAPTER 18

CONCLUSIONS AND RECOMMENDATIONS

NCHRP Project 25-21 has identified and investigated almost every conceivable significant impact of traffic-flow improvements on travel behavior and air quality suspected or known at this point in time. The impacts of traffic-flow improvements on household trip making, destination choice, time-of-day choice, mode choice, and route choice have been considered and included in a recommended comprehensive methodology for predicting the air quality impacts of traffic-flow improvements. The long-term impacts on the redistribution of future economic activity from less accessible areas of the region to more accessible areas have also been considered and incorporated into the methodology.

18.1 OVERVIEW OF THE NCHRP 25-21 METHODOLOGY

A review of the state of the art identified disaggregate demand modeling and microsimulation of traffic operations (such as those employed in the STEP model, the Portland Tour-Based Model, and the TRANSIMS model) as the approaches best able to achieve the objectives of this research project.

The recommended methodology is a blended macroscopic-microscopic approach composed of the following five modules:

- The HCM Assignment Module predicts the highway travel times based upon traffic operations analysis speed-flow curves contained in the 2000 HCM.
- The Traveler Behavior Response Module uses elasticities derived from the Portland Tour-Based Model to predict the impact of travel time changes on trip making by peak period and by mode of travel.
- The Growth Redistribution Module predicts the impacts of traffic-flow improvements on growth patterns within the region. Subareas within the region that have better-than-average accessibility improvements will have greater-than-average growth rates in the region.
- The Modal Activity Module translates the mean speeds and volumes predicted by the previous modules into a distribution VHT by speed category and acceleration/deceleration rate category.
- The Air Quality Module translates the modal activity data into estimates of vehicle emissions.

The proposed methodology predicts the change in demand and vehicle emissions caused by traffic-flow improvements in the short term (5 to 10 years) and long term (25+ years).

The NCHRP 25-21 methodology employs state-of-the-art techniques for disaggregate modeling of individual household trip making and microscopic simulation of vehicle operating modes. However, rather than create another TRANSIMS, the NCHRP 25-21 methodology employs proxies of other, more detailed techniques, and these proxies mimic the more detailed techniques in an expeditious manner. Specifically, the following proxies are employed:

- Rather than a dynamic microsimulation process such as the one employed in TRANSIMS, the HCM-based speed-flow equations are used in the traffic assignment (i.e., route choice) process.
- Rather than the full Portland model itself, demand elasticities by mode and time period that have been fitted to the Portland Tour-Based Model are used to predict changes in demand.
- Rather than a full-scale dynamic land-use simulation model such as UrbanSim, a linear model of the change in zonal growth rates as a function of changes in zonal accessibility is used to redistribute growth from less accessible zones to more accessible zones. The linear model is fitted to available forecasts that were developed from more sophisticated models like UrbanSim or DRAM/EMPAL.
- Rather than a full-traffic microsimulation model, tables of vehicle mode of operation derived from CORSIM are used to predict modal operation data.
- Rather than the full CMEM, categorized emission rates by speed and acceleration category derived from CMEM are used to predict emissions.

18.2 EXCLUSIONS FROM THE NCHRP 25-21 METHODOLOGY

Only two identified impacts of traffic-flow improvements on air quality have been intentionally excluded from the NCHRP 25-21 methodology:

- The potential impact on the overall growth of a metropolitan region of significantly different levels of investment in traffic-flow improvements between regions and
- The potential indirect impact of traffic-flow improvements on actual or perceived accessibility (via nonmotorized modes) for transit, pedestrian, and bicycle modes.

The potential impacts of major deviations in infrastructure investment levels on interregional competitiveness have been excluded because of the added data requirements of modeling variations in growth between the metropolitan regions of the United States.

The potential indirect impacts of traffic-flow improvements on nonmotorized modes have been excluded because of a lack of data on these effects and project resource limitations.

The emission estimates are limited to running exhaust emissions because of the limitations of the modal emission model upon which the NCHRP 25-21 methodology is based (CMEM).

18.3 ACCOMPLISHMENT OF NCHRP 25-21 METHODOLOGY OBJECTIVES

The accomplishment of the NCHRP 25-21 methodology objectives by the proposed methodology is outlined in Table 56.

18.4 VALIDATION OF THE NCHRP 25-21 METHODOLOGY

The NCHRP 25-21 methodology was applied to a series of case studies, and the results were compared with more general results reported in the literature.

TABLE 56 Accomplishment of NCHRP 25-21 methodology objectives

NCHRP 25-21 Methodology Objectives	Accomplishment by Proposed Methodology
Predict short- and long-term effects	The methodology predicts traveler behavior response for the short term and growth redistribution impacts for the long term.
Be accurate	Available data sets do not generally support determination of the accuracy of the methodology. The methodology employs generally advanced techniques, which are expected to be more accurate than less sophisticated and more aggregate approaches.
Cover a wide geographic scale of impacts	The methodology covers highway segment, corridor, and regional impacts.
Predict the duration of impacts	The methodology does not directly predict duration, but duration can be inferred from the short-term and long-term “snapshots” provided by the methodology.
Be suitable for small and large MPOs	The methodology requires a regional transportation network (with transit) and a regional OD table. As such, the methodology can best be employed by medium to large MPOs.
Cover a range of projects	The methodology is best suited to projects that change capacity or speed.
Include land-use effects	Land-use effects are included in the Long-Term Response Module, but no explicit land-use model is included.
Include pedestrian/bicycle/transit access/safety effects	The impacts of traffic-flow improvements on nonmotorized use are not currently included in the methodology because of a lack of data on the subject. Because of the same lack of data, the methodology does not incorporate perceived or actual safety effects.
Use commonly available data	All of the required data (regional highway network and regional OD table) are routinely gathered by large MPOs in the region. The required data exceed the capabilities of small MPOs.
Be implementable in commonly used software	The methodology can be implemented in commonly used software for travel demand modeling.
Be compatible with modal emission model	The methodology is specifically designed to use a light-duty vehicle modal emission model.
Include heavy-duty vehicle emissions	Because of a lack of data on modal emissions for heavy-duty vehicles, the methodology does not include a specific heavy-duty vehicle demand response model, modal activity, or emission model.
Include PM emissions	The methodology does not address PM emissions because of a lack of emission rate data compatible with the CMEM methodology.

The facility-specific results showed travel time and volume changes for the specific facility that were quite consistent with theory and expectation. It was difficult, though, to validate the methodology's predictions for system level (regionwide) performance. Some of the results fell within the broad range of results that have been reported in the literature. Other results fell outside the range of results reported in the literature.

Indeed, application of the methodology to the same traffic improvement to different locations in the region showed a wide range of predicted system impacts. An HOV lane was added at two locations. In both cases, the HOV lane caused net increases in traffic volumes on the facility. However, at one location, the systemwide result was a net decrease in VMT for the region, while the other location caused a net increase in regional VMT.

The validation was limited because of the data requirements of the new methodology and the lack of the necessary data in available "before and after" studies of traffic-flow improvements. More work could and should be done to validate the methodology in other regions of the United States and against datasets gathered specifically for the purpose of validating the NCHRPH 25-21 methodology.

18.5 CASE STUDY RESULTS

The NCHRP 25-21 methodology was applied to 10 case studies. The impacts of individual traffic-flow improvement projects on regional daily VMT were on the order of a few hundredths of 1 percent. A 30-year improvement program impacted VMT by less than 1 percent. The impacts varied from a reduction in VMT to an increase in VMT, depending upon the specifics of each case study. The variation in the predicted VMT impacts for the same traffic-flow improvement (HOV lanes) applied at different locations was greater than the magnitude of the predicted impact itself.

The case study results suggest that more applications of each traffic-flow improvement type on different facility types (i.e., radial and peripheral facilities), in different area types (i.e., urban, suburban, and rural), and at different congestion levels are needed to better understand the conditions under which traffic-flow improvements contribute to an overall net increase or decrease in vehicle emissions.

18.6 IMPLEMENTATION PLAN

The NCHRP 25-21 research makes a critical contribution to current practice, providing a model of how to analyze the long- and short-term air pollutant emission impacts of corridor-level transportation projects. The methodology is implementable within a stand-alone software product or can be incorporated as a postprocessor (or preprocessor) for current transportation network analysis and air quality analysis software. Application of the methodology to the study of the impacts of traffic-flow improvements will contribute to the accomplishment of national air quality goals.

This section presents the recommended implementation plan for disseminating the results of this research project to the community of practitioners.

18.6.1 Research Product

The research product is a comprehensive methodology to predict the short-term and long-term effects of corridor-level, traffic-flow improvement projects on CO, VOCs, and NO_X). (PM is not estimated because of a lack of data.) The methodology can be used to evaluate the magnitude, scale (such as regionwide, corridor, or local), and duration of the effects for a variety of representative urbanized areas. The methodology is documented in this final research report and user's guide.

18.6.2 Expected Audience and Market for the Research Product

The target audience for the new methodology is all agencies currently performing air quality conformity analyses and project-level environmental impact analyses. These agencies are primarily the 350 MPOs and 50 state DOTs in the United States, plus cities, counties, and private consultants.

18.6.3 Possible Impediments to Successful Implementation

Most MPOs and state DOTs already have a significant investment in existing transportation and air quality analysis methodologies and software. This fact represents a significant amount of institutional inertia, but the inertia can be overcome by training and dissemination of the NCHRP air quality analysis methodology to public agencies. Further validation information is necessary to demonstrate the superior accuracy of the methodology over current conventional methods.

Another likely impediment to general application of the NCHRP 25-21 methodology is that the methodology is likely to estimate more adverse air quality impacts than current simplistic methods. If this happens, then there may be significant institutional resistance to adoption of a more accurate methodology that results in more conformity problems. This resistance can be overcome by FHWA and EPA adopting the NCHRP 25-21 methodology as one of the methods that constitute the state of the practice for evaluating the air quality impacts of highway projects.

18.6.4 Likely Institutional Leaders in Application

The FHWA and EPA, by specifying acceptable methodologies for use in conformity analyses, will be the institutional leaders in promoting the application of the recommended methodology. These two agencies are already promoting the TRANSIMS research package of programs as the ultimate replacement for the old UTPS package, upon which most of today's software and transportation models are based. TRANSIMS, however, still has a few more years of pilot testing and refinement before it will be ready for general distribution.

It will be necessary to demonstrate to the EPA and FHWA that the NCHRP 25-21 methodology will play a valuable role as a medium between the detailed data and analytical requirements of TRANSIMS and the simplistic approaches contained in many available sketch-planning methods. The NCHRP 25-21 methodology will also be available to the planning community in a usable form much sooner than TRANSIMS will, and it will be applicable by the large number of small and medium-size MPOs that may not have the resources or analytical needs for a more sophisticated package like TRANSIMS.

18.6.5 Recommended Follow-On Activities for Successful Implementation

The following follow-on activities are recommended for successful implementation of the NCHRP 25-21 methodology:

- Demonstrate, through more cases studies and validation data sets in other regions of the United States, that the NCHRP 25-21 methodology gives more reliable results than currently available methods do. This demonstration would involve data collection tailored to the needs of the NCHRP 25-21 methodology to validate its results for different areas of the country.
- Publish the research results and user's guide as an official NCHRP research report.
- Present the NCHRP 25-21 methodology at the TRB Annual Meeting.
- Present a 1-day training course on the NCHRP 25-21 methodology and software for FHWA, TRANSIMS, and EPA personnel, perhaps offered in Washington D.C., in coordination with the TRB Annual Meeting and opened to other professionals as well.
- Include a regular training course on the NCHRP 25-21 methodology and software in the FHWA's National Highway Institute course list.

18.6.6 Indicators of Progress and Success

Adoption of the NCHRP 25-21 methodology by the EPA and FHWA as a state-of-the-practice methodology for performing conformity analyses would be an immediate and complete indicator of the success of the research project in developing a methodology for use in general practice. Another indicator of success would be adaptation of various modules of the NCHRP 25-21 methodology by MPOs and software developers to various existing transportation planning models and software packages.

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GLOSSARY OF ACRONYMS

ABAG = Association of Bay Area Governments
AirQ = Air Quality
API = application program interface
BART = Bay Area Rapid Transit
BEA = Bureau of Economic Affairs
BPR = Bureau of Public Roads
BTS = Bureau of Transportation Statistics
CARB = California Air Resources Board
CATS = Chicago Area Transportation Study
CMEM = Comprehensive Modal Emission Model
CMSA = Consolidated Metropolitan Statistical Area
CO = carbon monoxide
CORSIM = Corridor Simulation
CTA = Chicago Transit Authority
CUF = California Urban Futures
DoT = U.K. Department of Transport
DRAM/ EMPAL = Disaggregate Residential Allocation Model/Employment Allocation Model
DVRPC = Delaware Valley Regional Planning Commission
E/I/E = external/internal/external
EMFAC = Emission Factor
EMME/2 = Equilibre Multimodal, Multimodal Equilibrium
EPA = Environmental Protection Agency
FORTRAN = Formula Translation
FREESIM = Freeway Simulation Model
FTP = Federal Test Procedure
GIS = geographic information systems
GUI = graphical user interface
HC = hydrocarbons
HCM = *Highway Capacity Manual*
HERS = Highway Economic Requirements System
HLFM II+ = Highway Land Use Forecasting Model
HOV = high-occupancy vehicle
HPMS = Highway Performance Monitoring System
HYROAD = Hybrid Roadway Intersection Model
IDAS = ITS Deployment Analysis System
ICC = Interstate Commerce Commission
I/I = internal/internal
ILUTE = Integrated Land Use, Transportation, Environment
INTRAS = Integrated Traffic Simulator
IO = input output
IPF = iterative proportional fit
ISTEA = Intermodal Surface Transportation Efficiency Act of 1991
ITLUP = Integrated Transportation and Land Use Package
ITS = intelligent transportation systems
LANL = University of California Los Alamos National Laboratory
LEV = low-emission vehicle
LOS = level of service
LRTP = long-range transportation plan
LUTRAQ = Land Use Transportation Air Quality
LUTRIM = Land Use Transportation Interaction Model
MEASURE = Mobile Emission Assessment System for Urban and Regional Evaluation
MEPLAN = Marcial Echenique Plan
METROPILUS = Metropolitan Integrated Land Use System
MOBILE = EPA vehicle emission factor model
MOVES = Motor Vehicle Emission Simulator
MPO = metropolitan planning organization
MSA = method of successive averages
MTC = San Francisco Metropolitan Transportation Commission
MWCOG = Metropolitan Washington Council of Governments
NCTCOG = North Central Texas Council of Governments
NEMA = National Electrical Manufacturers Association
NETSIM = Network Simulation
NO_X = oxides of nitrogen
NYMTC-LUM = New York Metropolitan Transportation Council Land Use Model
OD = origin-destination
OMSI = Oregon Museum of Science and Industry
ORNL = Oak Ridge National Laboratory
PART5 = Particulate Emission Factor Model
PCE = passenger car equivalent
PM = particulate matter
POLIS = Projective Optimization Land Use Information System
PSRC = Puget Sound Regional Council
PUMA = Public Use Microdata Area
PUMS = Public Use Microdata Sample
QRS = Quick Response System
RTP = regional transportation plan
SACMET = Sacramento Metropolitan Travel Demand Model
SACOG = Sacramento Area Council of Governments
SACTRA = Standing Advisory Committee on Trunk Road Assessment
SAFD = speed and acceleration frequency distribution
SCAG = Southern California Association of Governments
SIC = Standard Industrial Classification
SMD = strategic model database
SMITE = Spreadsheet Model for Induced Travel Estimation
SOV = single-occupancy vehicle
SP = stated preference
SPASM = Sketch Planning Analysis Spreadsheet Model

STEAM = Surface Transportation Efficiency Analysis Model
STEP = Short-Range Transportation Evaluation Program
SUE = static user equilibrium
TCM = transportation control measure
TDM = transportation demand management
TEAPAC = Traffic Engineering Application Package
TEA-21 = Transportation Equity Act for the 21st Century
THC = total hydrocarbons
TIP = Transportation Improvement Program
TLUMIP = Transportation and Land Use Model Integration Project
TMIP = Travel Model Improvement Program
TRAF-NETSIM = Traffic Network Simulation
TRANSIMS = Transportation Analysis Simulation System
TRANSYT-7F = Traffic Network Study Tool, Release #7
TRANUS = an integrated land-use and transportation model developed by Dr. Tomas de la Barra (formerly known as "Transporte y Uso del Suelo," or "Transportation and Land Use")
Tranplan = Transportation Planning
TSM = transportation system management
TTI = Texas Transportation Institute
UTPS = Urban Transportation Planning System
VDF = volume-delay function
VHT = vehicle-hours traveled
VMT = vehicle-miles traveled
VOC = volatile organic compound
WTP = willingness to pay

User’s Guide

CHAPTER 1

INTRODUCTION

This user's guide describes the recommended NCHRP 25-21 methodology for predicting the long- and short-term mobile source emission impacts of traffic-flow improvement projects. The application of the methodology is illustrated through example problems consisting of case studies of various traffic-flow improvements.

1.1 OBJECTIVES OF THE NCHRP 25-21 METHODOLOGY

The objective of the NCHRP 25-21 research project was to develop and demonstrate, in case study applications, a methodology to predict the short-term and long-term effects of corridor-level, traffic-flow improvement projects on carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO_X), and particulate emissions (PM).

The methodology is designed to evaluate the magnitude, scale (such as regionwide, corridor, or local), and duration of the effects for a variety of representative urbanized areas. It is designed to be implementable in a broad range of existing software used for travel demand modeling.

The methodology is not designed to predict pollutant concentrations or ozone formation resulting from traffic-flow improvement projects. Rather, the methodology uses the best available emission factors and vehicle operations and activity data to estimate net changes in emissions of ozone precursors, CO, and particulates.

1.2 ORGANIZATION OF USER'S GUIDE

Chapter 2 provides an overview of the NCHRP 25-21 methodology. The next five chapters describe the various modules of the methodology in more detail.

Chapters 8 through 19 illustrate the application of the methodology to a series of case studies:

- Case 1: Addition of a Freeway Lane in a Rural Area,
- Case 2: Removal of a Freeway Lane in an Urban Area,
- Case 3a: Removal of Freeway HOV lane from an uncongested freeway,
- Case 3b: Removal of Freeway HOV lane from a congested freeway,
- Case 4: Narrowing a Street,
- Case 5: Access Management,
- Case 6: Intersection Channelization Improvement,
- Case 7: Signal Coordination,
- Case 8: Transit Improvement,
- Case 9: Removal of a Freeway Express Bus Park-and-Ride Lot, and
- Case 10: Construction of a 30-Year Transportation Improvement Program.

The case studies reported here in the user's guide are identical to the case studies described in the final report. Readers may note, however, that Case Studies 2, 3a, 3b, 4, and 9 here involve the effects of removing lanes or a park-and-ride lot rather than those of adding lanes and a park-and-ride lot, as described in the final report. This is because it is mechanically easier to remove an HOV lane or a park-and-ride lot from coded highway and transit networks than it is to add one. When adding facilities (such as an HOV lane or a park-and-ride lot) to a model, the modeler must also code the supporting link structure and must be careful to follow the network coding conventions used in the network. When deleting a facility, the modeler need not be concerned about the coding conventions.

The user's guide consequently describes the case studies and their results as they were actually performed in the Puget Sound Regional Council (PSRC) travel demand model. The results from Case Studies 2, 3a, 3b, 4, and 9 were then reported in the final report as their mirror image. For example, a lane closure in the user's guide for Case Study 2 is reported as a lane addition in the final report. The "before" result for Case Study 2 in the user's guide became the "after" result in the final report. The "after" result in the user's guide became the "before" result in the final report.

CHAPTER 2

THE METHODOLOGY

The NCHRP 25-21 methodology is designed to answer one fundamental question, "Will a specified traffic-flow improvement contribute to improved or worsened air quality locally and at the regional level, in the short term and in the long term?" Repeated exercise of the methodology on various case studies will answer the question, "Under what conditions will a specified traffic-flow improvement contribute to improved or worsened air quality?"

2.1 THEORETICAL FOUNDATION

The NCHRP 25-21 methodology proceeds from the fundamental theoretical foundation that "nobody travels for the fun of it." People travel in order to participate in activities or to obtain goods that are superior to what they could have done or obtained at their original location. Even sightseers use the transportation to experience a vista they could not see at home. They may say they enjoy the drive, but what they really enjoy is what they can see out of the window. The research team will exclude from this blanket statement individuals who test their vehicles or are hired to drive a vehicle.

Travel demand is, therefore, not vehicle-miles traveled (VMT). Travel demand is the schedule of activities, by location, that travelers would like to pursue that day. In modeling parlance, it is the origin-destination (OD) table of person trips for that day by time of day. However, VMT is the most cost-effective measure (from the traveler's point of view) for measuring that demand.

Thus, traffic-flow improvements by reducing average travel times can affect both the total demand for travel and the traveler's choice of the most cost-effective means for satisfying that demand.

In addition, some traffic-flow improvements do not change the average travel time but reduce the variance in travel speeds by smoothing out the traffic flow. Thus, it is possible for a traffic-flow improvement to have no effect on demand or on how that demand is satisfied on the street system and yet still have an effect on air quality by smoothing out the "stop-and-go" nature of the trip itself.

Finally, a series of traffic-flow improvements can make one portion of the metropolitan area more attractive to growth and new development than older, more established parts of the region. The shifting of growth from centrally located developed areas to undeveloped fringe areas can affect both demand and how it is satisfied on the transportation system. This effect is very long term. (Extensive transportation capacity investments in one metropolitan area can also increase the net in-migration to the region, but this effect will not be considered in this research.)

Thus, the NCHRP 25-21 methodology addresses four basic mechanisms by which traffic-flow improvements can influence mobile source emissions:

- Operational improvements that smooth out traffic flow and thus reduce acceleration/deceleration events,
- Travel time savings and losses on particular routes and modes of travel that influence the traveler's choice of the most cost-effective means for satisfying their demand to travel,
- Travel time savings that increase the total demand for travel, and
- Travel time savings that increase the relative attractiveness and therefore the growth rate of subareas in the region.

The first mechanism, operational improvements, will be called the "operations" effect. Traffic flow improvements may increase the average speed on the facility, and/or they may increase the capacity of the facility prior to affecting travel behavior. Operational improvements will also affect vehicle mode of operation activity by reducing acceleration and deceleration events. The operations effect occurs on the first day that an improvement is opened for traffic. Travelers have not yet had an opportunity to change their demand schedule in response to the travel time savings provided by the improvement.

The second and third effects of traffic-flow improvements will be combined into a single "traveler behavior" effect. This effect comes in the months following opening day. As travelers become aware of the improvements, they change route, mode of travel, and departure time to take advantage of them. After the improvement has been in place for sufficient time for travelers to change their demand schedule (e.g., the OD table), they will take advantage of the reduced travel costs brought about by the improvement. Traveler behavior effects include changes in destination choice and trip generation (extra trips or stops along the way of a preexisting trip). The result of the behavior effects will be to partially counteract the opening day travel time improvements. It is assumed that the traveler behavior effects cannot completely eliminate the "opening day" travel time improvements; otherwise, there is no longer a stimulus to cause the traveler behavior effects.

The fourth effect of traffic-flow improvements is a redistribution of growth (i.e., new homes and jobs) within the region to areas that benefit from the travel time savings attributable to a traffic-flow improvement. This effect will be called the "growth redistribution" effect. It is possible that the traffic-flow improvement might also enhance the relative competitiveness of the entire metropolitan region for new jobs and new homes, thus influencing overall growth of the region. However, this global effect is beyond the scope of this research project and methodology. It would require a full-blown socioeconomic forecasting model plus some kind of assumption regarding the pace of traffic-flow improvements in other competing metropolitan areas of the United States, Mexico, and Canada.

The research team assumes for the sake of this research project that all competing metropolitan areas have similar policies for implementing traffic-flow improvements. Thus, a specific set of traffic-flow improvements would likely also be implemented in all metro regions. Thus, the relative competitiveness of the metro regions would be unaffected. The methodology will focus on redistribution impacts within a region, not total growth impacts for the entire region.

The foundation of the NCHRP 25-21 methodology is that traveler behavior response and growth redistribution occur *only* if the traffic-flow improvement results in a net change in trip *travel time*. Thus, travel behavior responses and growth redistribution can never drive travel time savings to zero.

This research will not account for possible effects of a traffic-flow improvement that do not relate to travel time, such as operating cost improvements. Vehicle operating cost (which can also affect travel demand) is correlated with travel time and is not treated separately here, since the research team is not considering toll changes. The marginal effects of reduced acceleration/deceleration events on vehicle wear and tear (and thus vehicle operating costs) also will be unaccounted for.

2.2 OUTLINE OF THE METHODOLOGY

The recommended methodology is a blended macroscopic-microscopic approach composed of five modules:

- The HCM Assignment Module predicts the highway travel times based upon traffic operations analysis speed-flow equations contained in the 2000 *Highway Capacity Manual* (HCM).
- The Traveler Behavior Response Module uses elasticities derived from the Portland Tour-Based Model to predict the impact of travel time changes on trip making by peak period and by mode of travel.
- The Growth Redistribution Module predicts the impacts of traffic-flow improvements on growth patterns within the region. Subareas within the region that have better-than-average accessibility improvements will have greater-than-average growth rates in the region.
- The Modal Activity Module translates the mean speeds and volumes predicted by the previous modules into a distribution vehicle-hours of travel (VHT) by speed category and acceleration/deceleration rate category.
- The Air Quality Module translates the modal activity data into estimates of vehicle emissions.

The methodology employs macroscopic approximations of microscopic behavior throughout each of the modules. The intent is to obtain a practical methodology that can be employed by a wide range of agencies while retaining as much as possible the behavioral accuracy of a microscopic analytical approach.

The proposed methodology predicts the change in demand and vehicle emissions caused by traffic-flow improvements at two points in time: short term (5 to 10 years) and long term (25+ years). Figure 1 provides a flow chart overview of the methodology.

The methodology requires as input

- A set of baseline travel demand tables (OD tables) for AM, PM, and off-peak periods;
- A set of baseline highway and transit networks for the AM, PM, and off-peak periods; and
- The proposed traffic-flow improvement characterized in terms of its impact on mean free-flow speeds and capacities in the baseline networks.

The first round of analysis (i.e., the base) assigns the baseline OD tables (by mode of travel and time period) to the baseline (i.e., no improvement) transportation networks for each time period and mode. The methodology then computes the mean speed and flow for each highway link. This link information is fed to the Vehicle Modal Activity Module, which outputs tables of vehicle activity (VHT) by speed and acceleration/deceleration category. The modal activity information is fed to the Vehicle Emissions Module (VOC, CO, NO_X, and PM), which computes the vehicular emissions.

The second round of analysis (short term) adds the traffic-flow improvement to the baseline network and computes new vehicle trip travel times for the improved network. The new travel times are compared with the baseline travel times to determine the changes in travel times. The changed travel times are entered into the Traveler Behavior Response Module, which modifies the baseline OD tables to produce revised OD tables. The revised OD tables are assigned to the highway network to produce mean speed and flow for each highway link. The information is then fed to the Vehicle Modal Activity and Vehicle Emissions Modules to obtain emissions for the short term.

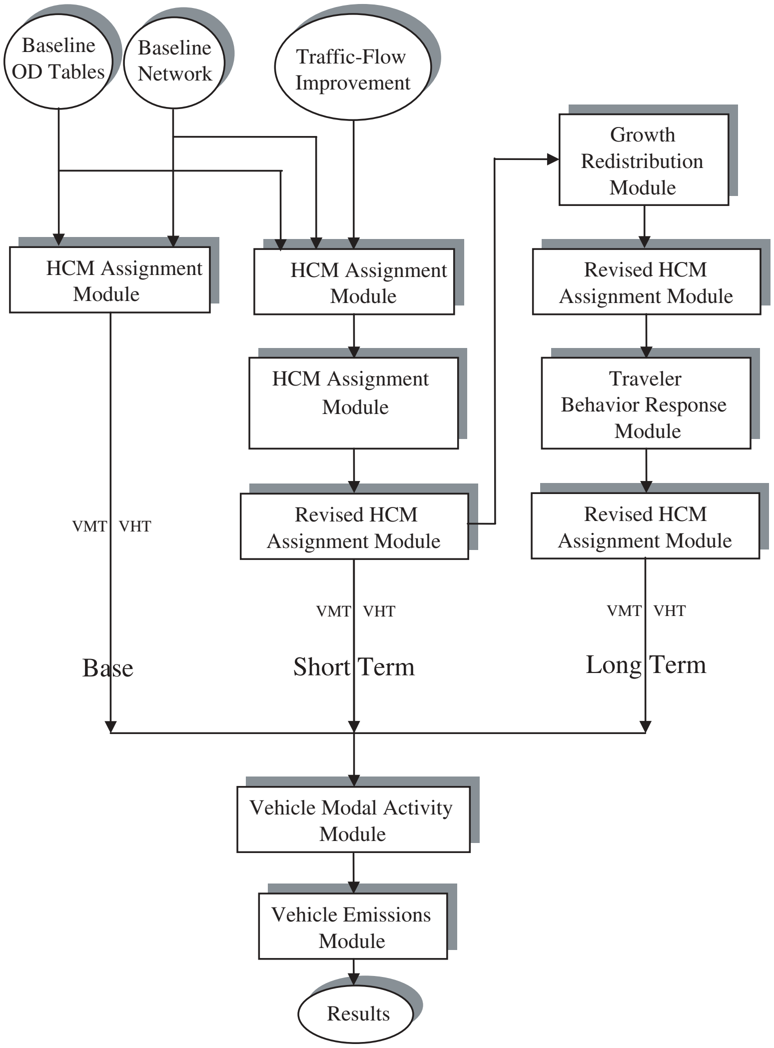


Figure 1. The NCHRP 25-21 methodology.

The third round of analysis (long term) feeds the short-term results into the Growth Redistribution Module, which computes the impacts of the traffic-flow improvements on the relative growth rates of zones within the region. The revised growth rates are used to redistribute the origins and destinations of the trips in the short-term OD tables. The revised OD tables are then fed back through the Traveler Behavior Response Module one more time to obtain mean speed and flow for each highway link. The information is then fed to the Vehicle Modal Activity and Vehicle Emissions Modules to obtain emissions for the long term.

The methodology generally follows the recommendations of NCHRP Project 8-33. The methodology is designed to predict the changes due to the traffic-flow improvement projects. It does not predict baseline conditions. Baseline conditions (the baseline OD tables) must be input to the methodology.

The methodology does not separately model the demand response of heavy-duty vehicles to traffic-flow improvements. Modeling truck demand response would require a completely separate methodology with separate data requirements. Trucks are presumed to be a fixed percent of current and future traffic demands in this methodology.

The methodology does not forecast socioeconomic changes, traffic condition changes, or emission changes that are due to factors other than traffic-flow improvements. The proposed methodology, therefore, must be used in conjunction with some other model for predicting future baseline conditions, usually a conventional travel demand model.

2.3 HCM ASSIGNMENT MODULE

On the opening day, drivers will experience the maximum travel time savings provided by an improvement project. The improved road section will have higher operating speeds and fewer and milder acceleration/deceleration events. If the improvement also increases peak capacity, then more vehicles will be able to pass through the improved segment during the peak hour, and this increase in peak capacity may impact downstream capacity bottlenecks.

The HCM Assignment Module predicts the highway vehicle travel time effects of the traffic-flow improvement for a fixed level of demand. Inputting the base demand to the module is equivalent to predicting travel times for the day that a traffic-flow improvement is first opened to traffic. Travelers have not had time to adjust to the travel time savings, so, at this stage in time, there is no demand response. If future demands are input to the module, then the module will predict future travel times and delays for that level of demand. This module has multiple uses in the methodology, being applied to the base case, short-term, and long-term analyses.

The required inputs for the HCM Module are vehicle OD tables (by mode and time period), the baseline geometric characteristics of the regional highway network (facility type, free-flow speeds, capacity characteristics, and segment lengths), and similar geometric information for the traffic-flow improvement. The module computes the highway link operating characteristics: volume/capacity and mean speed.

The module uses the 2000 HCM Chapter 30 speed-flow equations (sometimes called the Akcelik equations in the literature) and capacities to estimate the mean speed of traffic on each link of the highway network. A standard static users equilibrium (SUE) assignment of the OD table is performed in this module using the HCM equations for each period of the day (typically AM, PM, and off-peak).

It should be noted that the travel time savings on the improved segment may be partially compensated by increased delays at downstream bottlenecks. This "downstream" effect of traffic-flow improvements are neglected by this module. (Tests with the PSRC model show that this effect is not significant for the conditions of the PSRC model. See Chapter 12 of the final report for more details.)

The module computes only highway travel times for mixed-flow and high-occupancy vehicle (HOV) lanes. Transit, bicycle, and pedestrian travel times (if needed) must be computed using some standard travel demand modeling procedure consistent with the procedure used to estimate the baseline OD tables by time period for each of these nonauto modes of travel.

2.4 TRAVELER BEHAVIOR RESPONSE MODULE

Travelers will adjust their demand schedule for travel in response to changes in the travel time required to reach their daily activity locations. Demand responses may include changes in trip lengths (i.e., trip distribution), number of trips (i.e., trip generation), time of day (i.e., peaking), and mode of travel (i.e., mode choice). The Traveler Behavior Response Module predicts how travel demand will react to the travel time savings created by traffic-flow improvements.

The module computes estimated changes in demand for each entry in the OD table for each mode of travel and each period of the day based on the estimated changes in travel times by mode and by time period. The module employs direct elasticities and cross-elasticities derived from the Portland Tour-Based Model. An example of a direct elasticity is the percentage change in HOV demand during the AM peak for each percentage change in HOV travel time during the AM peak. An example of a cross-elasticity is the percentage change in HOV demand during the AM peak for each percentage change in single-occupancy vehicle (SOV) travel time during the AM peak. Cross-elasticities are also used to account for shifting of travel between peak and off peak for each mode of travel.

Heavy-duty vehicles (e.g., trucks) are presumed to respond in the same manner as light-duty SOVs to travel changes in this module. They are not modeled separately.

If a metropolitan planning organization already has a tour-based model in place that can predict the impacts of travel time and cost changes on out-of-home trip making, time of day, and mode choice, then that model can be used in place of the simpler Traveler Behavior Response Module described here.

2.5 GROWTH REDISTRIBUTION MODULE

Significant improvements in transportation infrastructure in one part of the urban region will impact the geographic distribution of housing and job growth in the region over the very long term (25+ years). Significant infrastructure investments may also affect the total growth rate for the region by changing the attractiveness of the region to migrants from other regions. This latter effect, however, requires a model at the national level to properly account for migration between regions. Therefore, this overall affect on total regional growth will be excluded from the methodology.

The Growth Redistribution Module will predict the very long-term impacts of localized travel time changes (caused by traffic-flow improvements) on the geographic distribution of growth in a metropolitan area. There are already several sophisticated land-use models available (such as UrbanSim) that could be used for the purpose of this module. However, these models require a great deal of specialized economic data and effort to set up for a region (which may be beyond the resources of many metropolitan planning organizations). When a sophisticated land-use model exists in a region, it can be used to predict the long-term effects. When such a model is not available, the simple Growth Redistribution Module is proposed for use to approximate the long-range land-use effects of traffic-flow improvements.

The Growth Redistribution Module requires that a baseline 20- to 25-year forecast of land-use growth (households and employment changes) be available for the metropolitan area. This baseline forecast should have been prepared either manually or with a model taking into account accessibility changes as well as all of the other factors that commonly affect the distribution of growth within a region. A simple linear regression model is fitted to the baseline land-use forecast.

The regression model predicts the change in the growth rate in households and employment in each zone of the region as a function of the relative change of accessibility for each zone. Although not sophisticated enough to predict actual growth, the model should be sufficient to predict how small changes in travel time accessibility can affect the predicted baseline growth rate in specific zones of the region.

The module presumes that total regional growth will be unaffected by traffic-flow improvements (in other words, the module will not be sensitive to the potential effects of differing levels of regional traffic-flow improvements on the competitiveness of regions for attracting new households or jobs). The module predicts only how regional growth might be reallocated from marginally less accessible zones to more accessible zones within the region.

2.6 VEHICLE MODAL ACTIVITY MODULE

The Vehicle Modal Activity Module converts the macroscopic vehicle activity data produced by the previous modules (VHT and VMT by link, mode, and time period) to microscopic modal activity data (VHT by speed and acceleration category). Four tables (Uncongested Freeway, Congested Freeway, Uncongested Arterial, Congested Arterial) containing percentages are used to determine the proportion of total vehicles-hours on each street and freeway segment that are spent in each speed/acceleration category. These tables were derived from microsimulation of vehicle activity on example real-world sections of freeways and arterial streets using the Federal Highway Administration Corridor Simulation (CORSIM) model.

Additional tables for other facility types and varying intelligent transportation systems (ITS) and traffic management options can be created using the FHWA CORSIM program. The creation of such tables was beyond the resources of this research project and was consequently deferred to future research.

2.7 VEHICLE EMISSION MODULE

The Vehicle Emission Module converts the passenger car modal activity data into estimates of vehicular emissions. The potential impacts of traffic-flow improvements on heavy-duty vehicle and transit vehicle emissions are neglected. (The necessary information on heavy-duty vehicle emission rates by mode of operation was not available at the time of this research.) Modal emission factors from the University of California, Riverside, NCHRP 25-11 Comprehensive Modal Emission Model (CMEM) and Emission Factor 2000 (EMFAC2000) are used to produce the emission estimates.

The primary effects of traffic-flow improvement projects relate to speeds and delay along specific corridors. The direct emission effects include

- Running exhaust emissions (due to changes in vehicle speed and acceleration profiles, as well as changes in VMT due to route choice),
- Running loss emissions (due to changes in total travel time), and
- Refueling and CO_2 emissions (due to changes in fuel efficiency).

CMEM was used to produce running exhaust emission rates for the specified speed and acceleration frequency distributions (SAFDs) contained in the modal activity data.

The impacts of traffic-flow improvements on running loss emissions and refueling/CO_2 emissions are currently not included in the NCHRP 25-21 methodology. This is because the NCHRP 25-21 methodology is based on CMEM, which does not include these emissions.

There are two secondary effects of traffic-flow improvement projects that influence emissions. First, to the extent that traffic-flow improvement projects reduce total travel time, there may be some increase in the number of trips made, resulting in additional start emissions. Second, both reduced travel time and increased numbers of trips alter the number and timing of hot soak, diurnal, and resting loss periods for the vehicle. Neither of these effects is included in CMEM, and, consequently, neither is included in the current version of the NCHRP 25-21 methodology.

Virtually all emission rates depend on ambient temperature. The NCHRP 25-21 methodology uses an average summer day temperature profile for VOC and NO_X, and an average winter day for CO analyses.

CHAPTER 3

THE HCM ASSIGNMENT MODULE

The purpose of the HCM Assignment Module is to improve current methods for estimating the travel delay effects of traffic congestion. The approach taken was to replace the conventional Bureau of Public Roads (BPR) equation method still used in many travel demand models with more up-to-date traffic operations research results contained in the 2000 HCM. The module substitutes the following HCM-based information into the SUE traffic assignment step of the travel demand model process:

- Free-flow speeds by facility type and area type;
- Link capacities by facility type, area type, and other characteristics of facility; and
- HCM-based Akcelik set of speed-flow equations.

3.1 FREE-FLOW SPEEDS

The free-flow speed is the mean speed of traffic when demand is so low that changes in demand do not affect the mean speed of traffic on the segment. For freeways and multilane highways, free flow is the mean speed observed when volumes are under 1,300 vehicles per hour per lane. For signalized streets, the free-flow speed is the maximum mean speed of traffic obtained at any point between signalized intersections for low-volume conditions.

The mean speed is computed as the sum of the travel times to traverse the length of the segment, divided into the length of the segment times the number of vehicles in the sample. The following linear equations from *NCHRP Report 387* can be used to estimate free-flow speed based on the posted speed limit for arterials, freeways, and highways.

For posted speed limits of 50 mph or greater,

$$\text{FFS} = 0.88 * \text{PSL} + 14 \qquad \text{Equation 1}$$

For posted speed limits of less than 50 mph,

$$\text{FFS} = 0.79 * \text{PSL} + 12 \qquad \text{Equation 2}$$

Where:

FFS = free-flow speed (mph) and
PSL = posted speed limit (mph).

3.2 CAPACITIES

Highway link capacities are estimated using the procedures contained in the 2000 HCM. The following subsections summarize the information contained in Chapter 30 of the HCM.

3.2.1 Freeways, Multilane Highways, and Two-Lane Highways

The following equation is used to compute the capacity of a freeway or highway link at its critical point. The critical point is the point on the link with the lowest throughput capacity.

$$c = Q * N * F_{hv} * F_p * F_g * \text{PHF} \qquad \text{Equation 3}$$

Where:

c = capacity (vph),
Q = the passenger car equivalent (p.c.e.) capacity per hour per lane,
N = number of through lanes (ignore auxiliary and "exit only" lanes),
F_{hv} = heavy-vehicle adjustment factor,
F_p = driver population adjustment factor,
F_g = grade adjustment factor, and
PHF = peak-hour factor.

Table 1 provides the HCM-recommended passenger car equivalent capacities per lane (Q). See the HCM for appropriate values for the adjustment factors.

3.2.2 Arterials

The capacity of an arterial is determined by examining the through movement capacity at each signal-controlled intersection on the arterial link. The intersection with the lowest through capacity determines the overall capacity of the arterial link. The following equation is used to compute the one-direction through capacity at each signal.

$$c = S_0 * N * f_w * f_{hv} * F_g * f_p * f_{bb} * f_a * f_{LU} * f_{LT} * f_{RT} * F_{Lpb} * f_{Rpb} * \text{PHF} * g/C \qquad \text{Equation 4}$$

TABLE 1 Passenger car equivalent (PCE) capacities for freeways and highways

Free-Flow Speed	PCE Capacity (passenger cars per hour per lane)		
	Freeways	Multilane Hwys	Two-Lane Hwys
75 mph (112 km/h)	2400		
70 mph (104 km/h)	2350		
65 mph (96 km/h)	2300	2200	1700
60 mph (88 km/h)	2250	2100	1700
55 mph (80 km/h)		2000	1700
50 mph (70 km/h)		1900	1700

Where:

c = capacity (vph),
s_0 = ideal saturation flow rate = 1,900 vehicles per hour of green per lane,
N = number of lanes,
f_w = lane-width adjustment factor,
f_{hv} = heavy-vehicle adjustment factor,
F_g = grade adjustment factor,
f_p = on-street parking crossing adjustment factor,
f_{bb} = local bus adjustment factor,
f_a = central business district adjustment factor,
f_{LU} = lane use adjustment factor,
f_{LT} = left-turn adjustment factor,
f_{RT} = right-turn adjustment factor,
f_{Lpb} = pedestrian/bicycle blockage of left-turn factor,
f_{Rpb} = pedestrian/bicycle blockage of right-turn factor,
PHF = peak-hour factor, and
g/C = ratio of effective green time per cycle.

See the HCM for appropriate values for the adjustment factors.

3.3 HCM/AKCELIK SPEED-FLOW EQUATION

The mean speed for each segment during the peak period is estimated using the following equations taken from the 2000 HCM. The mean vehicle speed for the link is computed by dividing the link length by the link traversal time. The link traversal time (R) is computed according to the following modified Akcelik equation from the HCM:

$$R = R_0 + D_0 + D_L + 0.25N * T\left[(x-1) + \sqrt{(x-1)^2 + \frac{16J * L^2 * x}{N^2T^2}}\right] \qquad \text{Equation 5}$$

Where:

R = segment traversal time (hours),
R_0 = segment traversal time at free-flow speed (hours),
D_0 = zero-flow control delay at signals (equals zero if no signals) (hours),
D_L = segment delay between signals (equals zero if no signals) (hours),
N = number of signals on the segment (equals one if no signals),
T = expected duration of the demand (length of analysis period) (hours),
x = segment demand/capacity ratio,
L = segment length (miles), and
J = calibration parameter.

The segment traversal time at free-flow conditions is computed from the free-flow speed:

$$R_0 = {}^{L}\!/\!_{S_0} \qquad \text{Equation 6}$$

Where:

R_0 = free-flow traversal time (hours),
L = length (miles), and
S_0 = the segment free-flow speed (mph).

The computation of the signal delay terms (D_0, D_L) is explained in the following section.

The number of signals (N) on the facility segment excludes the signal at the start of the street segment (if present), because this signal should already have been counted in the upstream segment. (Streets are often split into segments (links) starting and ending at signalized intersections. The counting convention suggested here avoids double-counting of the signals located at the start and end points of each segment.)

When there are no signals on the facility, N is still set equal to one. This is because N is really the number of "delay-causing elements" on the facility. Each delay-causing element on the facility adds to the overall segment delay when demand starts to approach and/or exceed capacity at that element or point. Because demand in excess of capacity must wait its turn to enter the facility segment, there is always at least one "delay-causing element" (the segment itself) on a facility even when there are no signals. The more signals there are on a facility, the more points there are where traffic is delayed along the way. This means that a bottleneck section of the facility should be coded as a single link and not arbitrarily split into sublinks. The HCM/Akcelik equation (and the standard BPR equation as well) treats each link as a potential delay-causing bottleneck on the network. Splitting one real-world bottleneck into three hypothetical links, each with the same demand, would triple the estimated delay at the bottleneck.

The duration of demand (T) is set equal to the length of the analysis period.

The segment demand/capacity ratio (x) is the ratio of the total demand for the analysis period divided by the total capacity for the period.

The calibration parameter J is selected so that the traversal time equation will predict the mean speed of traffic (averaged over the length L of the link) when demand is equal to capacity. It is computed according to the following equation:

$$J = \frac{(R_c - R_0 - D_0 - D_L)^2}{L^2} \qquad \text{Equation 7}$$

Where:

J = calibration parameter,
R_c = link traversal time when demand equals capacity (hours),
R_0 = free-flow speed traversal time (hours),
D_0 = zero-flow control delay (hours), and
D_L = segment delay (hours).

The values for J, shown in Tables 2 and 3, reproduce the mean segment speeds at capacity predicted by the analysis

TABLE 2 Recommended calibration parameters *J* for freeways and highways

SI Units

Facility Type	Signals Per Km	Free-Flow Speed (km/h)	Speed at Capacity (km/h)	J
Freeway	n/a	120.0	85.7	1.11E-05
Freeway	n/a	110.0	83.9	8.00E-06
Freeway	n/a	100.0	82.1	4.75E-06
Freeway	n/a	90.0	80.4	1.76E-06
Multilane Hwy	n/a	100.0	88.0	1.86E-06
Multilane Hwy	n/a	90.0	80.8	1.60E-06
Multilane Hwy	n/a	80.0	74.1	9.91E-07
Multilane Hwy	n/a	70.0	67.9	1.95E-07
Two-Lane Hwy	n/a	110.0	70.0	2.70E-05
Two-Lane Hwy	n/a	100.0	60.0	4.44E-05
Two-Lane Hwy	n/a	90.0	50.0	7.90E-05
Two-Lane Hwy	n/a	80.0	40.0	1.56E-04
Two-Lane Hwy	n/a	70.0	30.0	3.63E-04

Customary Units

Facility Type	Signals Per Mile	Free-Flow Speed (mph)	Speed at Capacity (mph)	J
Freeway	n/a	75.0	53.3	2.947E-05
Freeway	n/a	70.0	53.3	2.003E-05
Freeway	n/a	65.0	52.2	1.423E-05
Freeway	n/a	60.0	51.1	8.426E-06
Freeway	n/a	55.0	50.0	3.306E-06
Multilane Hwy	n/a	60.0	55.0	2.296E-06
Multilane Hwy	n/a	55.0	51.2	1.821E-06
Multilane Hwy	n/a	50.0	47.5	1.108E-06
Multilane Hwy	n/a	45.0	42.2	2.174E-06
Two-Lane Hwy	n/a	65.0	40.2	9.043E-05
Two-Lane Hwy	n/a	60.0	35.2	0.0001385
Two-Lane Hwy	n/a	55.0	30.2	0.0002239
Two-Lane Hwy	n/a	50.0	25.2	0.0003893
Two-Lane Hwy	n/a	45.0	20.2	0.0007484

TABLE 3 Recommended calibration parameters *J* for signalized streets

SI Units

Facility Type	Signals Per Km	Free-Flow Speed (km/h)	Speed at Capacity (km/h)	J
Arterial Class I	0.333	80	53	2.21E-05
Arterial Class I	1.000	80	31	2.04E-04
Arterial Class I	2.500	80	15	1.25E-03
Arterial Class II	0.500	64	40	4.99E-05
Arterial Class II	1.000	64	28	2.00E-04
Arterial Class II	2.000	64	18	7.91E-04
Arterial Class III	2.000	56	17	8.02E-04
Arterial Class III	3.000	56	13	1.78E-03
Arterial Class III	4.000	56	10	3.18E-03
Arterial Class IV	4.000	48	10	3.17E-03
Arterial Class IV	5.000	48	8	4.99E-03
Arterial Class IV	6.000	48	7	7.11E-03

Customary Units

Facility Type	Signals Per Mile	Free-Flow Speed (mph)	Speed at Capacity (mph)	J
Arterial Class I	1	50	33.1	2.21E-05
Arterial Class I	2	50	19.3	2.04E-04
Arterial Class I	4	50	9.6	1.25E-03
Arterial Class II	1	40	24.8	4.99E-05
Arterial Class II	2	40	17.8	2.00E-04
Arterial Class II	3	40	11.2	7.91E-04
Arterial Class III	3	35	10.9	8.02E-04
Arterial Class III	5	35	7.9	1.78E-03
Arterial Class III	6	35	6.3	3.18E-03
Arterial Class IV	6	30	6.1	3.17E-03
Arterial Class IV	8	30	5.0	4.99E-03
Arterial Class IV	10	30	4.3	7.11E-03

procedures contained in the 2000 HCM. These two tables use the following HCM definitions of facility types:

- **Freeway—**A multilane, divided highway with a minimum of two lanes for the exclusive use of traffic in each direction and full control of access without traffic interruption.
- **Multilane highway—**A highway with at least two lanes in each direction for the exclusive use of traffic, with no control or partial control of access, but that may have periodic interruptions to flow at signalized intersections no closer than 2 miles apart.
- **Two-lane highway—**A highway with only one lane in each direction (with or without occasional passing lanes) for the exclusive use of traffic, with no control or partial control of access, but that may have periodic interruptions to flow at signalized intersections no closer than 2 miles apart.
- **Arterial—**A signalized street that primarily serves through traffic and that secondarily provides access to abutting properties, with signals spaced 2 miles or less apart. Arterials are divided into classes according to the posted speed limit and signal density criteria shown in Table 4.

3.4 SIGNAL DATA REQUIRED BY HCM/AKCELIK

The zero-flow control delay and the between-signal delay are required to estimate speeds for signalized arterial streets. The zero-flow control delay (D_o) is computed as follows:

$$D_0 = \frac{N}{3{,}600} * \mathrm{DF} * \frac{C}{2}\left(1 - {}^{g}\!/\!{}_{C}\right)^2 \qquad \text{Equation 8}$$

Where:

D_0 = the zero-flow control delay at the signal (hours);
N = maximum of one, or the number of signals on the segment;
3,600 = conversion from seconds to hours;
g/C = average effective green time per cycle for signals on segment;

TABLE 4 HCM arterial class criteria

Arterial Class	SI Units		Customary Units	
	Posted Speed Limit	Signal Density	Posted Speed Limit	Signal Density
Class I	70-90 km/h	0.3-2.5 signals/km	45-55 mph	0.5-4 signals/mi.
Class II	55-70	0.3-3.1	35-45	0.5-5
Class III	50-55	2.5-6.3	30-35	4-10
Class IV	40-50	2.5-12.5	25-35	4-20

Source: Chapter 15, Urban Streets, HCM.

Note: There may be instances of overlaps in arterial class definitions. The analyst should consult Chapter 15 of the HCM for additional information on the identification of a specific arterial class.

C = average cycle length for all signals on the segment (seconds); and
DF = delay factor,
= 0.9 for uncoordinated traffic-actuated signals,
= 1.0 for uncoordinated fixed-time signals,
= 1.2 for coordinated signals with unfavorable progression,
= 0.9 for coordinated signals with favorable progression, and
= 0.6 for coordinated signals with highly favorable progression.

If the ratio of green time per cycle for the arterial through movement is not known, a default value of 0.44 can be used. Similarly, if the signal cycle length is not known, then a default value of 120 seconds can be used. A survey of local average signal cycle lengths by area type (e.g., downtown, suburban, and rural) may be desirable to establish appropriate local default values.

The segment delay between signals (D_L) is estimated as follows:

$$D_L = L * \frac{d_L}{60} \qquad \text{Equation 9}$$

Where:

L = the length of the segment and
d_L = the delay per mile, given in Table 5.

TABLE 5 Segment delay between signals

secs/mile

Arterial Class: Free-Flow Speed (mph)	I 55	I 50	I 45	II 45	II 40	II 35	III 35	III 30	IV 35	IV 30
signal spacing (miles)										
0.05										107
0.10							42	35	62	60
0.15							32	21	37	30
0.20				29	25	22	25	14	27	20
0.25	32	28	24	24	20	16	17	7	19	12
0.30	27	23	19	19	12	7				
0.40	17	14	14	14	6	2				
0.50	8	6	8	8	3	0				
1.00	0	0	0	0	0	0				

secs/km

Arterial Class: Free-Flow Speed (km/h)	I 88	I 80	I 72	II 72	II 64	II 56	III 56	III 48	IV 56	IV 48
signal spacing (km)										
0.08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	66.9
0.16	n/a	n/a	n/a	n/a	n/a	n/a	26.3	21.9	38.8	37.5
0.24	n/a	n/a	n/a	n/a	n/a	n/a	20.1	13.1	23.2	18.8
0.32	n/a	n/a	n/a	18.1	15.6	13.8	15.7	8.8	17.0	12.5
0.40	19.7	17.5	15.0	15.0	12.5	10.1	10.7	4.4	12.0	7.5
0.48	16.6	14.4	11.9	11.9	7.5	4.5	n/a	n/a	n/a	n/a
0.64	10.3	8.8	8.8	8.8	3.8	1.3	n/a	n/a	n/a	n/a
0.80	4.7	3.8	5.0	5.0	1.9	0.0	n/a	n/a	n/a	n/a
1.60	0.0	0.0	0.0	0.0	0.0	0.0	n/a	n/a	n/a	n/a

Source: 2000 HCM, Exhibit 15-3, Segment Running Time Per Mile. Table computed by subtracting running time if traveling at free-flow speed from running time shown in exhibit.

CHAPTER 4

THE TRAVEL BEHAVIOR RESPONSE MODULE

The Portland Tour-Based Model was selected as the basis for the Travel Behavior Response Module because of its ability to predict both modal and temporal shifts in travel behavior as well as predict the impact on overall out-of-the-home trip making. The Portland Tour-Based Model is complex, so it is implemented in NCHRP Project 25-21 as a set of elasticities rather than as the full model.

4.1 OVERVIEW OF THE PORTLAND TOUR-BASED MODEL

The Portland Tour-Based Model was originally developed as part of a project to analyze road pricing policy alternatives in Portland. An overview of the Portland model in a larger context is shown in Figure 2; the tour-based model proper consists of the blocks within the large rectangle. (A full description of the Portland Tour-Based Model is given in Mark Bradley Research and Consulting, A System of Activity-Based Models for Portland, Oregon, Washington, D.C.: Travel Model Improvement Program, U.S. Dept. of Transportation, Report No.: DOT-T-99-02, U.S. Environmental Protection Agency, 1998. Consult this reference for details on model structure and coefficients.)

A more detailed look at the Portland model is given in Figure 3, which shows information flows between the different submodels. The model system is designed to predict the following:

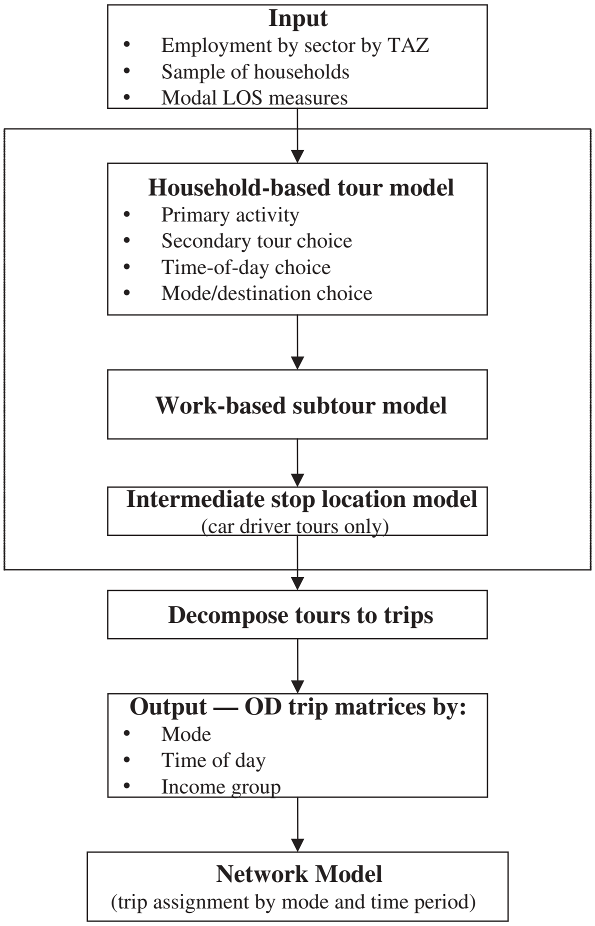
- A full-day activity pattern (primary activity and, for tour activities, subtour pattern),
- Time of day (outbound, inbound) for home-based tours,
- Primary mode and destination,
- Work-based subtours, and
- Location of intermediate stops.

The Portland model is a conceptual descendant of Greig Harvey's Short-Range Transportation Evaluation Program (STEP) model, with considerable additional detail. A description of the STEP model and the theory behind the model is presented in Elizabeth Deakin and Greig Harvey's *Transportation Pricing Strategies for California: An Assessment of Congestion, Emissions, Energy and Equity Impacts: Final Report*, prepared for the California Air Resources Board, 1996. The model has several features that distinguish it from traditional four-step travel models:

- Simultaneous modeling of trip generation, time of day, mode choice, and destination choice. Utilities of lower-level choices (e.g., mode and destination choice) are incorporated in the utilities of higher-level choices (e.g., time of day and primary activity pattern).
- Application of the model to individual travelers. This approach, known as *sample enumeration* when applied to travel survey data, and more generally as *microsimulation*, is considered to be at the forefront of the current state of the art in travel modeling. Microsimulation allows the incorporation of detailed household and person characteristics that can significantly affect travel behavior, such as presence of children in the household and competition for available cars in the household for different trip purposes.
- Use of a *synthetic sample* to develop the base population to which the model is applied. This approach provides the model with a sufficiently large population so that complete trip tables can be produced. Sample enumeration approaches based only on travel surveys generally produce results at a much larger scale, such as superdistrict-to-superdistrict trip movements. The synthetic sampling approach has been used for over 25 years. One early application was to the development of a database for research on discrete-choice models. See Gerald Duguay, Woo Jung, and Daniel McFadden, "SYNSAM: A Methodology for Synthesizing Household Transportation Survey Data," Berkeley: Urban Travel Demand Forecasting Project, Working paper no. 7618, September 1976. Synthetic sampling is currently used in the TRANSIMS model and in the current version of the STEP model. An additional advantage of the synthetic sampling approach is that it enables disaggregation of benefit and cost estimates by socioeconomic category, which is often a significant issue in transportation policy analysis.

4.2 DERIVATION OF ELASTICITIES

The Portland model has several drawbacks in application, chief of which is the length of time required to operate it on



TAZ = traffic analysis zone.
LOS = level of service.
OD = origin-destination.

Figure 2. Portland Tour-Based Model flow chart.

even a high-speed computer. Consequently, it was decided to use the Portland model to develop a set of elasticities for predicting small changes in traveler behavior in response to individual traffic-flow improvement projects. The model was executed several times on a range of travel time saving alternatives, and the results were used to fit a set of demand/time elasticities. These elasticities were then incorporated into the NCHRP 25-21 methodology.

A constant elasticity demand model in the following form was fitted to the Portland model:

$$\frac{\tilde{T}_{ij}^{mp}}{T_{ij}^{mp}} = \prod_{m'p'} \left(\frac{\tilde{t}_{ij}^{m'p'}}{t_{ij}^{m'p'}} \right)^{\varepsilon_{m'p'}^{mp}} \qquad \text{Equation 10}$$

Where:

$\varepsilon_{m'p'}^{mp}$ = the elasticity of demand for travel from origin i to destination j by mode m in time period p (denoted by T_{ij}^{mp}) with respect to travel time origin i to destination j by mode m' in time period p' (denoted by $t_{ij}^{m'p'}$).

For $m' = m$ and $p' = p$, there is an own elasticity; otherwise, the quantity is a (mode or time or mode/time) cross-elasticity.

The quantities with tildes represent trips and travel times after some change, and the other quantities represent base case trips and travel times.

The equation can be converted to a log-log linear model:

$$\ln\left[\frac{\tilde{T}_{ij}^{mp}}{T_{ij}^{mp}} \right] = \sum_{m'p'} \varepsilon_{m'p'}^{mp} \ln\left[\frac{\tilde{t}_{ij}^{m'p'}}{t_{ij}^{m'p'}} \right] \qquad \text{Equation 11}$$

Therefore, the elasticities can be estimated by observing the quantities T_{ij}^{mp}, $\tilde{T}_{ij}^{mp}$, $t_{ij}^{m'p'}$, and $\tilde{t}_{ij}^{m'p'}$ predicted by the Portland model and running a set of regressions against these results. The approach to generating the necessary data points was straightforward:

1. Define a set of *i, j* zone pairs to be sampled. These zone pairs were sampled to focus on the areas of interest. For example, given the case study area, the research team focused on movements from within King County to Seattle, from Pierce County to Seattle, and from Snohomish County to Seattle. Movements to and from Kitsap County were ignored because the research team believes that the ferry network may not be adequately represented to treat this movement alongside bus transit as a transit mode.
2. Pick a particular zone pair with home zone *i* and destination zone *j*. Randomly generate a travel time change in the AM peak period for the auto mode, and run the model only for the population within zone *i*. Store the relative change in travel time and the relevant changes in travel by mode and time period as a data point.
3. Repeat Step 2 for different values of change to the travel time.
4. Repeat Steps 2 and 3 for different time periods.
5. Repeat Steps 2–4 for different modes.
6. Repeat Steps 2–5 for different *i, j* zone pairs.
7. Collect the data points and run regressions on the appropriate variables.

The research team believes that the following simplifications were reasonable:

- For small travel time changes, the constant elasticity approximation is probably good enough. It can be regarded as a first-order approximation to the demand function.
- Capacity improvements are likely to affect the peak periods only. Hence, the main mode shifts are likely to occur

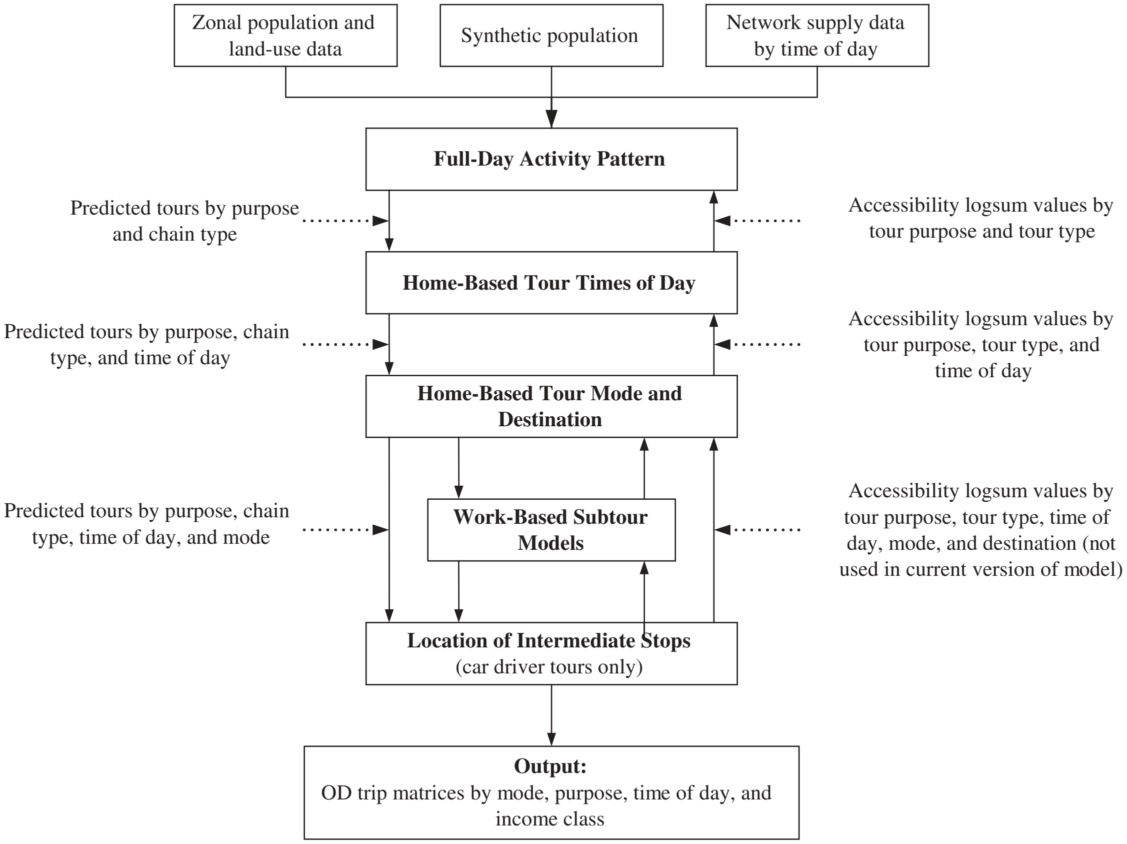


Figure 3. Information flows in the Portland Tour-Based Model.

during the peak periods, and the research team reasonably ignores off-peak mode shifts.

4.3 ELASTICITIES

The final set of elasticities fitted to the Portland Tour-Based Model is shown in Table 6. As shown in the table, a 10-percent decrease in AM peak-period travel time for drive alone would result in the following predicted demand effects:

- A 2.25-percent increase in drive alone during the AM peak,
- A 0.37-percent decrease in shared ride during the AM peak,
- A 0.36-percent decrease in transit riders during the AM peak,
- A 1.24-percent increase in drive alone during the PM peak, and
- A 1.70-percent increase in drive alone during the off peak.

4.4 ALTERNATE METHODS FOR DERIVING ELASTICITIES

Most users of the NCHRP 25-21 methodology can probably use the elasticities provided in Table 6 without having to repeat the application of the Portland model to the Seattle test bed. However, tour-based models like Portland are a recent development. Little is known about the robustness of their parameters when applied to other areas. Consequently, researchers cannot state with assurance that a particular tour-based model can be applied to similar or dissimilar urban regions.

Analysts with greater resources can apply the Portland model or another tour-based model to their own urban region as described in the above sections to see how elasticities derived from application of the tour-based model to their own region vary from those shown in Table 6. Locally derived elasticities would presumably be more reliable than ones borrowed from another region, but, again, there is little or no practical experience to back up this conjecture.

TABLE 6 Travel time elasticities

Demand		Travel Time					
		AM peak			PM peak		
		DA	SR	TR	DA	SR	TR
AM peak	DA	-0.225	*0.030*	0.010	-0.024	0.000	0.000
	SR	0.037	-0.303	0.032	0.000	-0.028	0.000
	TR	0.036	0.030	-0.129	0.000	0.000	-0.007
PM peak	DA	-0.124	0.000	0.000	-0.151	*0.015*	*0.005*
	SR	0.000	-0.109	0.000	*0.019*	-0.166	*0.016*
	TR	0.000	0.000	-0.051	*0.018*	*0.015*	-0.040
Off peak	DA	-0.170	0.000	0.000	-0.069	0.000	0.000
	SR	0.000	-0.189	0.000	0.000	-0.082	0.000
	TR	0.000	0.000	-0.074	0.000	0.000	-0.014

Note: DA = drive alone, SR = shared ride, TR = transit.
Source: Portland Tour-Based Model Applied to PSRC data set.
Estimates (shown in italics) appear in the table when statistically significant results could not be estimated from the data set. Zero values are shown for cross-elasticities that were deemed (a priori) to be insignificant.

CHAPTER 5

THE GROWTH REDISTRIBUTION MODULE

The Growth Redistribution Module predicts the very long-term impacts of localized travel time changes (caused by traffic-flow improvements) on the geographic distribution of growth in a metropolitan area. There are already several sophisticated land-use models available (such as UrbanSim) that could be used for the purpose of this module. However, these models require a great deal of specialized economic data and effort (which are beyond the resources of many MPOs) to set up for a region. When a sophisticated land-use model exists in a region, it can be used to predict the long-term growth effects. When such a model is not available, the simplified model described here is proposed for use to approximate the long-term land-use effects of traffic-flow improvements.

5.1 MODULE DESCRIPTION

The Growth Redistribution Module requires that a baseline 20- to 25-year forecast of land-use growth (i.e., households and employment changes) be available for the metropolitan area. This baseline forecast should have been prepared either manually or with a model, taking into account accessibility changes as well as all of the other factors that commonly affect the distribution of growth within a region.

The Growth Redistribution Module consists of a simple linear regression model that is fitted to the baseline forecast. The regression model predicts the change in the growth rate in households and employment in each zone of the region as a function of the relative change of accessibility for each zone. Although not sophisticated enough to predict actual growth, the module should be sufficient to predict how small changes in travel time accessibility can affect the predicted baseline growth rate in specific zones of the region. The module is as follows:

$$LU_i^{new} = LU_i^{old} * \left[G + \text{CP} * \left(\frac{A_i^{new}}{A_i^{old}} - R \right) \right] \qquad \text{Equation 12}$$

Where:

LU_i^{new} = predicted sum of the number of households and jobs in zone *i* after traffic-flow improvement,
LU_i^{old} = sum of households and jobs in zone *i* before traffic-flow improvement,
A_i^{new} = predicted AM peak home-based work accessibility of zone *i* after traffic-flow improvement,
A_i^{old} = AM peak home-based work accessibility of zone *i* before traffic-flow improvement,
CP = calibration parameter for model determined from linear regression (CP is the slope of the least-squared error line constrained to go through zero),
G = ratio of the total predicted number of households in the region after the traffic-flow improvement divided by the number of households in the region before the improvement, and
R = ratio of the total predicted accessibility in the region after the traffic-flow improvement divided by the total accessibility in the region before the improvement.

The module presumes that total regional growth will be unaffected by traffic-flow improvements (in other words, the model will not be sensitive to the potential effects of differing levels of regional traffic-flow improvements on the competitiveness of regions for attracting new households or jobs). The module predicts only how regional growth might be reallocated from marginally less accessible zones to more accessible zones within the region. The marginal change in zonal accessibility is obtained by subtracting the average change in regional accessibility from the zone-specific change in accessibility (this is accomplished in Equation 12 by subtracting the ratio *R* from the ratio of new to old accessibility for each zone *i*). For similar reasons, the amount of household growth that would have normally occurred in a zone (if the zone had grown at the regional average growth rate) is added to the model-predicted growth rate that is due exclusively to marginal changes in the zonal accessibility (this is accomplished in Equation 12 by adding the ratio *G*).

The effect of the above normalization is that if the ratio of the new accessibility to the old accessibility for a zone is less than the average ratio for the entire region, then the zone's growth will be less than the regional average. If the zonal accessibility ratio is greater than the average regional accessibility ratio, then the zone's growth will be greater than the regional average.

The value of *G* will normally be 1.00, unless there is a significant period of time between the "before" and "after" traffic-flow improvement dates. The ratio *G* allows the analyst to account for any baseline growth in the region that might have occurred between the "before" condition and the "after" condition that would have occurred with or without the traffic-flow improvement.

CP is the calibration parameter that converts a percentage change in zonal accessibility into a percentage change in zonal growth. It is the slope of the regression line fitted to local data on the correlation between the marginal change in zonal accessibility and the marginal change in zonal growth expressed as the sum of households and jobs.

The measure of zonal accessibility (A_i) is the denominator of the trip distribution gravity model for home-based work trips. The denominator is the sum of the weighted travel time impedances to each destination zone in the region. The AM peak-period accessibility for home-based work trips is used as a proxy for total daily accessibility for all trips, based on the presumption that commute accessibility has the greatest effect on housing and job location decisions.

$$A_i = \sum_j T_j * F_{ij} \qquad \text{Equation 13}$$

Where:

A_i = accessibility of zone i,
T_j = total trips generated by zone j, and
F_{ij} = AM peak travel time impedance for home-based work travel between zone i and zone j.

The impedance is a decreasing function of travel time between zones and takes whatever form was used to calibrate the regional travel demand model.

The analyst may experiment with fitting more elaborate linear or nonlinear models to the land-use intensity forecasts. A full-scale land-use forecasting model, like UrbanSim, could be used instead of the simple linear model presented above. Application of a full-scale model like UrbanSim would double or triple the amount of time required to analyze the traffic-flow improvement project. The simple linear model was selected for the sake of efficiency, enabling more rapid computations of the impacts of various traffic-flow improvement projects.

The analyst can also adopt a more elaborate measure of accessibility than the simple gravity model denominator suggested above. Ideally, this more elaborate measure should be based upon some kind of trip distribution model for predicting the likelihood that a trip will be made to a particular destination.

5.2 MODULE APPLICATION

The Growth Redistribution Module is calibrated for each region in which it is applied. Base and future employment and household forecasts are assembled for the region. A linear regression model of the form shown in Equation 12 is fitted to the data to obtain the value of CP. The fitted equation is then used to predict how individual zones will deviate from the regional average growth rate based upon changes in zonal accessibility from the base condition.

The following paragraphs illustrate such an application of the module to the Seattle metropolitan area. The PSRC provided household and employment forecasts for the years 1990 and 2020. These forecasts had been produced through a combination of inventory (for 1990) and land-use modeling (using Disaggregate Residential Allocation Model/Employment Allocation Model [DRAM/EMPAL]) with modifications made in response to local agency input.

Accessibility generally improved between the 1990 and 2020 PSRC forecasts; however, some zones experienced significant changes in accessibility between 1990 and 2020 that varied a great deal from the average (see Figure 4, which plots the percentage change in accessibility for approximately the first 790 of the PSRC zones).

The zonal accessibilities for each mode of travel were reported out from the Equilibre Multimodal, Multimodal Equilibrium (EMME2) in which the PSRC model was implemented. The reports were then imported into a spreadsheet, which was used to compute the differences between 1990 and 2020 and fit a regression line to the data. A least-squared error regression line was fitted to the 832 zonal data points (see Figure 5). The line was forced through zero. The slope was 0.72, and the resulting correlation coefficient was 67.99 percent.

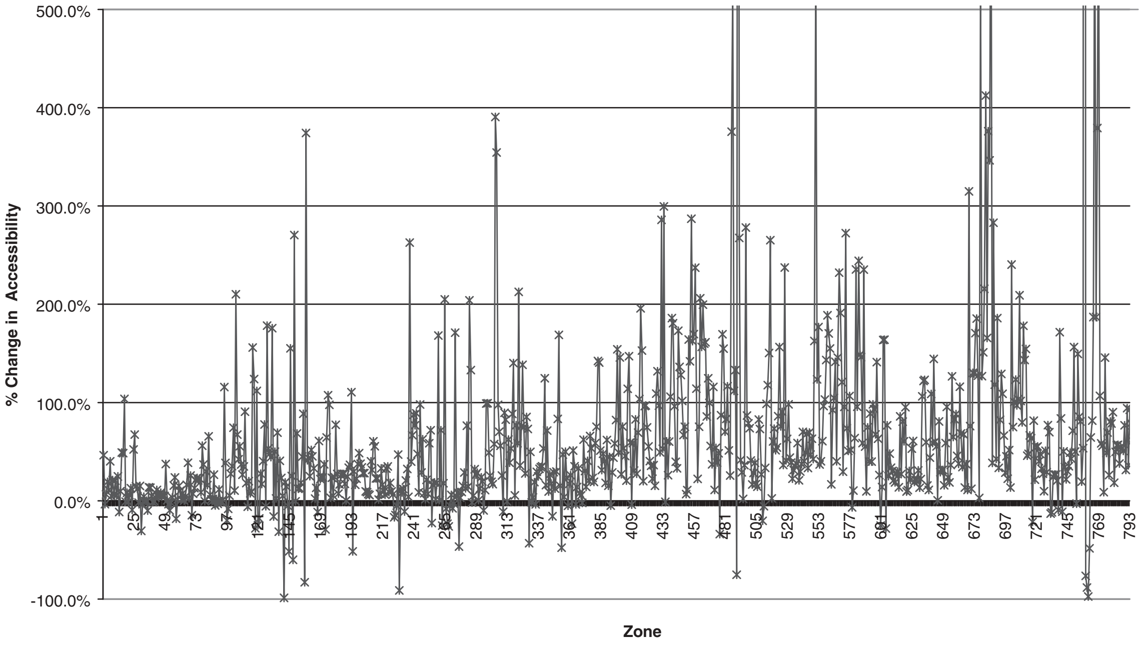


Figure 4. *PSRC zonal accessibility changes between 1990 and 2020.*

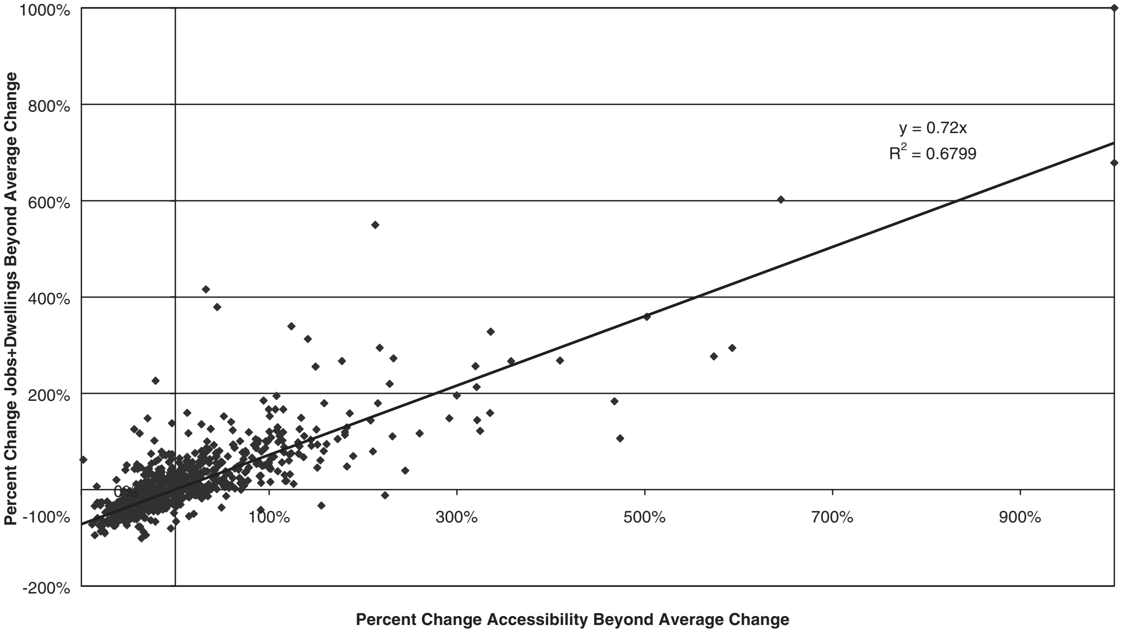


Figure 5. *Calibration of long-term module to PSRC data.*

CHAPTER 6

THE MODAL ACTIVITY MODULE

The purpose of the Modal Activity Module is to calculate the VHT by mode of operation (i.e., cruise, idle, and acceleration/deceleration), which is defined by speed and acceleration category. The estimates of vehicle activity are then used with modal emission factors (e.g., University of California, Riverside/NCHRP 25-1) to produce the emission estimates.

6.1 METHODOLOGY DEVELOPMENT

The methodology for estimating modal activity is largely based on previous research conducted by the investigator under the sponsorship of the California Air Resources Board (CARB). (See Skabardonis. A., "A Modeling Framework for Estimating Emissions in Large Urban Areas," *Transportation Research Record 1587*, Transportation Research Board, 1997; and Skabardonis, A., "Feasibility and Demonstration of Network Simulation Techniques for Estimation of Emissions in a Large Urban Area," Final Report, prepared for the California Air Resources Board, DHS Inc., 1994.) This research produced a set of relationships through microscopic simulation that determine the proportion of the time spent T_{ij} on a network link i in driving mode j as a function of the link's type and its volume/capacity ratio. The link classification (type) was based on typical link classifications employed in planning and operational studies (e.g., facility types), and key design/operational characteristics (e.g., number of lanes, free-flow speed, and signal spacing). The relationships were developed through processing of simulated vehicle trajectories using the Integrated Traffic Simulator (INTRAS; the predecessor of the Freeway Simulation Model [FRESIM]) and the Traffic Network Simulation (TRAF-NETSIM) microscopic simulation models.

Comparisons of simulated and actual field measurements for different facility types, free-flow speeds, and levels of congestion showed that a single distribution of time spent versus speed (using the ratio of speed/free-flow speed) could be used to represent many different free-flow speed conditions. Tables 7 through 10 were developed to divide up the total VHT on a link among the various speed and acceleration categories:

- Uncongested freeway (volume/capacity [v/c] < 1.00),
- Congested freeway ($v/c \geq 1.00$),
- Uncongested arterial street ($v/c < 1.00$), and
- Congested arterial street ($v/c \geq 1.00$).

6.2 METHODOLOGY APPLICATION

The methodology requires as input the facility type, the link volume/capacity ratio, and the link VHT. The total VHT on a link is multiplied by the proportions in the appropriate table to obtain the distribution of VHT by speed category and acceleration category.

TABLE 7 Vehicle modal activity for uncongested freeways

	ACCELERATION (mph/sec)																				
Spd/FreSpd	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
-	-	-	-	-	-	-	-	-	-	-	0.0065	-	-	-	-	-	-	-	-	-	-
0.0167	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0333	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0500	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0667	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.0833	-	-	-	-	-	-	-	-	0.0003	0.0007	0.0008	0.0007	0.0002	-	-	-	-	-	-	-	-
0.1000	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1167	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1333	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1500	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1667	-	-	-	-	-	-	-	0.0002	0.0004	0.0006	0.0008	0.0008	0.0002	-	-	-	-	-	-	-	-
0.1833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0008	0.0012	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.2833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0014	0.0010	0.0004	0.0002	-	-	-	-	-	-	-
0.3500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.3667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.3833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0010	0.0016	0.0012	0.0004	-	-	-	-	-	-	-	-
0.4333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.4833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.5000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0012	0.0018	0.0014	0.0004	-	-	-	-	-	-	-	-
0.5167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5500	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5667	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.5833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0022	0.0016	0.0004	-	-	-	-	-	-	-	-
0.6000	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6167	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6333	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6500	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6667	-	-	-	-	-	-	-	0.0002	0.0004	0.0020	0.0022	0.0020	0.0004	-	-	-	-	-	-	-	-
0.6833	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7000	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7167	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7333	-	-	-	-	-	-	0.0002	0.0002	0.0004	0.0020	0.0024	0.0022	0.0002	-	-	-	-	-	-	-	-
0.7500	-	-	-	-	-	-	0.0003	0.0003	0.0006	0.0030	0.0035	0.0033	0.0003	-	-	-	-	-	-	-	-
0.7667	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0021	0.0038	0.0021	0.0002	-	-	-	-	-	-	-	-
0.7833	-	-	-	-	-	-	0.0001	0.0001	0.0003	0.0033	0.0059	0.0033	0.0003	-	-	-	-	-	-	-	-
0.8000	-	-	-	-	-	-	0.0001	0.0001	0.0003	0.0033	0.0059	0.0033	0.0003	-	-	-	-	-	-	-	-
0.8167	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0026	0.0046	0.0026	0.0002	-	-	-	-	-	-	-	-
0.8333	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0027	0.0048	0.0027	0.0002	-	-	-	-	-	-	-	-
0.8500	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0055	0.0156	0.0055	0.0003	-	-	-	-	-	-	-	-
0.8667	-	-	-	-	-	0.0001	0.0001	0.0001	0.0002	0.0040	0.0113	0.0040	0.0002	-	-	-	-	-	-	-	-
0.8833	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0052	0.0146	0.0052	0.0003	-	-	-	-	-	-	-	-
0.9000	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0065	0.0184	0.0065	0.0003	-	-	-	-	-	-	-	-
0.9167	-	-	-	-	-	0.0001	0.0001	0.0001	0.0004	0.0073	0.0207	0.0073	0.0004	-	-	-	-	-	-	-	-
0.9333	-	-	-	-	-	-	-	-	0.0003	0.0070	0.0225	0.0080	0.0004	0.0001	-	-	-	-	-	-	-
0.9500	-	-	-	-	-	-	-	-	0.0004	0.0092	0.0294	0.0105	0.0006	0.0002	-	-	-	-	-	-	-
0.9667	-	-	-	-	-	-	-	-	0.0004	0.0104	0.0333	0.0119	0.0006	0.0002	-	-	-	-	-	-	-
0.9833	-	-	-	-	-	-	-	-	0.0005	0.0127	0.0406	0.0145	0.0008	0.0003	-	-	-	-	-	-	-
1.0000	-	-	-	-	-	-	-	-	0.0017	0.0417	0.1339	0.0476	0.0025	0.0008	-	-	-	-	-	-	-
1.0167	-	-	-	-	-	-	-	-	0.0006	0.0116	0.0385	0.0153	0.0006	0.0006	-	-	-	-	-	-	-
1.0333	-	-	-	-	-	-	-	-	0.0003	0.0055	0.0184	0.0073	0.0003	0.0003	-	-	-	-	-	-	-
1.0500	-	-	-	-	-	-	-	-	0.0001	0.0019	0.0064	0.0026	0.0001	0.0001	-	-	-	-	-	-	-
1.0667	-	-	-	-	-	-	-	-	-	0.0005	0.0018	0.0007	-	-	-	-	-	-	-	-	-
1.0833	-	-	-	-	-	-	-	-	-	0.0002	0.0008	0.0003	-	-	-	-	-	-	-	-	-
1.1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are the proportion of total vehicle-hours on the link that fall in each speed/acceleration category. Columns are the acceleration rate category in units of miles per hour per second. Rows are the speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 8 Vehicle modal activity for congested freeway sections

	ACCELERATION (mph/sec)																			
Spd/FreSpd	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.0000	-	-	-	-	-	0.0002	0.0004	0.0008	0.0017	0.0025	0.0443	-	-	-	-	-	-	-	-	-
0.0167	-	-	-	-	-	0.0001	0.0001	0.0005	0.0010	0.0015	0.0013	0.0019	-	-	-	-	-	-	-	-
0.0333	-	-	-	-	-	-	0.0002	0.0006	0.0008	0.0023	0.0025	0.0010	0.0017	-	-	-	-	-	-	-
0.0500	-	-	-	-	-	0.0001	0.0002	0.0003	0.0011	0.0030	0.0049	0.0016	0.0010	0.0010	-	-	-	-	-	-
0.0667	-	-	-	-	-	0.0001	0.0006	0.0006	0.0023	0.0054	0.0122	0.0033	0.0013	0.0005	0.0007	-	-	-	-	-
0.0833	-	-	-	-	-	0.0002	0.0004	0.0005	0.0022	0.0057	0.0163	0.0056	0.0020	0.0006	0.0003	0.0002	-	-	-	-
0.1000	-	-	-	-	-	0.0001	0.0002	0.0010	0.0018	0.0044	0.0126	0.0053	0.0013	0.0006	0.0003	0.0001	-	-	-	-
0.1167	-	-	-	-	-	-	0.0003	0.0007	0.0015	0.0039	0.0095	0.0052	0.0017	0.0005	0.0002	0.0001	-	-	-	-
0.1333	-	-	-	-	-	0.0001	0.0003	0.0006	0.0017	0.0038	0.0091	0.0049	0.0015	0.0006	0.0002	-	-	-	-	-
0.1500	-	-	-	-	-	0.0001	0.0004	0.0007	0.0018	0.0039	0.0080	0.0042	0.0018	0.0006	0.0003	-	-	-	-	-
0.1667	-	-	-	-	-	0.0001	0.0003	0.0009	0.0022	0.0051	0.0100	0.0061	0.0023	0.0007	0.0002	0.0001	-	-	-	-
0.1833	-	-	-	-	-	-	0.0003	0.0007	0.0014	0.0044	0.0090	0.0046	0.0017	0.0006	0.0002	-	-	-	-	-
0.2000	-	-	-	-	-	0.0001	0.0003	0.0007	0.0016	0.0040	0.0094	0.0047	0.0021	0.0006	0.0001	-	-	-	-	-
0.2167	-	-	-	-	-	0.0002	0.0006	0.0009	0.0026	0.0071	0.0126	0.0068	0.0031	0.0008	0.0002	-	-	-	-	-
0.2333	-	-	-	-	-	-	0.0004	0.0005	0.0016	0.0047	0.0085	0.0056	0.0023	0.0006	0.0001	-	-	-	-	-
0.2500	-	-	-	-	-	0.0001	0.0003	0.0009	0.0024	0.0054	0.0122	0.0054	0.0027	0.0006	0.0002	-	-	-	-	-
0.2667	-	-	-	-	-	0.0001	0.0002	0.0005	0.0016	0.0043	0.0089	0.0053	0.0022	0.0007	0.0001	0.0001	-	-	-	-
0.2833	-	-	-	-	-	0.0001	0.0003	0.0008	0.0018	0.0050	0.0113	0.0052	0.0022	0.0008	0.0001	-	-	-	-	-
0.3000	-	-	-	-	0.0001	-	0.0002	0.0007	0.0015	0.0048	0.0106	0.0057	0.0021	0.0004	0.0001	-	-	-	-	-
0.3167	-	-	-	-	0.0001	-	0.0003	0.0008	0.0017	0.0044	0.0107	0.0056	0.0020	0.0006	0.0001	-	-	-	-	-
0.3333	-	-	-	-	-	-	0.0003	0.0007	0.0021	0.0053	0.0125	0.0066	0.0026	0.0008	0.0001	-	-	-	-	-
0.3500	-	-	-	-	-	0.0001	0.0004	0.0005	0.0013	0.0045	0.0125	0.0059	0.0024	0.0004	-	-	-	-	-	-
0.3667	-	-	-	-	0.0001	0.0001	0.0002	0.0004	0.0025	0.0069	0.0144	0.0075	0.0025	0.0008	-	-	-	-	-	-
0.3833	-	-	-	-	-	0.0001	0.0002	0.0004	0.0012	0.0038	0.0107	0.0056	0.0020	0.0004	0.0001	-	-	-	-	-
0.4000	-	-	-	-	-	-	0.0003	0.0004	0.0015	0.0047	0.0093	0.0050	0.0020	0.0003	0.0001	-	-	-	-	-
0.4167	-	-	-	-	-	-	0.0001	0.0002	0.0012	0.0043	0.0115	0.0059	0.0018	0.0003	0.0001	-	-	-	-	-
0.4333	-	-	-	-	-	0.0002	0.0002	0.0004	0.0014	0.0042	0.0130	0.0066	0.0014	0.0003	0.0001	-	-	-	-	-
0.4500	-	-	-	-	-	-	0.0002	0.0003	0.0012	0.0034	0.0092	0.0045	0.0017	0.0003	-	-	-	-	-	-
0.4667	-	-	-	-	-	-	0.0002	0.0004	0.0009	0.0033	0.0091	0.0046	0.0011	0.0002	-	-	-	-	-	-
0.4833	-	-	-	-	-	0.0001	0.0002	0.0004	0.0010	0.0033	0.0076	0.0045	0.0014	0.0003	-	-	-	-	-	-
0.5000	-	-	-	-	0.0001	0.0001	0.0002	0.0003	0.0012	0.0045	0.0105	0.0055	0.0014	0.0003	0.0001	-	-	-	-	-
0.5167	-	-	-	-	-	0.0001	0.0002	0.0004	0.0013	0.0034	0.0109	0.0051	0.0013	0.0003	-	-	-	-	-	-
0.5333	-	-	-	-	-	-	0.0001	0.0002	0.0005	0.0025	0.0077	0.0038	0.0008	0.0002	0.0001	-	-	-	-	-
0.5500	-	-	-	-	-	-	0.0002	0.0003	0.0007	0.0028	0.0067	0.0039	0.0012	0.0002	-	-	-	-	-	-
0.5667	-	-	-	-	-	0.0001	0.0001	0.0004	0.0006	0.0019	0.0063	0.0032	0.0007	0.0001	-	-	-	-	-	-
0.5833	-	-	-	-	-	0.0001	-	0.0003	0.0006	0.0015	0.0047	0.0029	0.0009	0.0001	-	-	-	-	-	-
0.6000	-	-	-	-	-	0.0001	0.0002	0.0002	0.0006	0.0023	0.0080	0.0037	0.0009	0.0001	-	-	-	-	-	-
0.6167	-	-	-	-	-	-	0.0002	0.0003	0.0006	0.0020	0.0064	0.0033	0.0005	0.0001	-	-	-	-	-	-
0.6333	-	-	-	-	-	-	0.0001	0.0001	0.0006	0.0015	0.0057	0.0026	0.0008	0.0001	-	-	-	-	-	-
0.6500	-	-	-	-	-	-	-	0.0002	0.0009	0.0022	0.0054	0.0036	0.0011	0.0002	-	-	-	-	-	-
0.6667	-	-	-	-	-	-	-	0.0002	0.0001	0.0007	0.0022	0.0012	0.0003	0.0001	-	-	-	-	-	-
0.6833	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0009	0.0035	0.0014	0.0003	-	-	-	-	-	-	-
0.7000	-	-	-	-	-	-	-	0.0001	0.0006	0.0011	0.0033	0.0017	0.0006	0.0001	-	-	-	-	-	-
0.7167	-	-	-	-	-	-	0.0001	0.0001	0.0004	0.0013	0.0027	0.0018	0.0004	0.0001	-	-	-	-	-	-
0.7333	-	-	-	-	-	-	-	0.0001	0.0005	0.0015	0.0035	0.0019	0.0006	-	-	-	-	-	-	-
0.7500	-	-	-	-	-	-	0.0001	0.0002	0.0003	0.0013	0.0044	0.0023	0.0004	-	-	-	-	-	-	-
0.7667	-	-	-	-	-	0.0001	0.0001	0.0002	0.0002	0.0020	0.0050	0.0021	0.0003	0.0001	-	-	-	-	-	-
0.7833	-	-	-	-	-	-	0.0001	0.0002	0.0006	0.0016	0.0046	0.0023	0.0007	0.0001	-	-	-	-	-	-
0.8000	-	-	-	-	-	-	-	0.0002	0.0002	0.0014	0.0048	0.0017	0.0006	-	-	-	-	-	-	-
0.8167	-	-	-	-	-	-	0.0001	0.0001	0.0002	0.0013	0.0043	0.0017	0.0003	0.0001	-	-	-	-	-	-
0.8333	-	-	-	-	-	-	-	0.0001	-	0.0004	0.0019	0.0006	0.0001	-	-	-	-	-	-	-
0.8500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.8667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.8833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9333	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.9833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0333	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0667	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.0833	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are the proportion of total vehicle-hours on the link that fall in each speed/acceleration category. Columns are the acceleration rate category in units of miles per hour per second. Rows are the speed category expressed as a ratio of the link free-flow speed.
Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 9 Vehicle modal activity for uncongested arterials

	ACCELERATION (mph/sec)																			
Spd/FreSpd	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.000	-	-	-	-	-	-	-	-	-	-	0.2006	-	-	-	-	-	-	-	-	-
0.0286	-	-	-	-	-	0.0001	-	-	0.0008	0.0005	0.0009	0.0005	0.0001	0.0002	0.0001	0.0005	-	-	-	-
0.0571	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.0857	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1143	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1429	-	-	-	-	-	0.0002	-	-	0.0015	0.0010	0.0018	0.0009	0.0002	0.0004	0.0001	0.0011	-	-	-	-
0.1714	-	-	-	-	-	0.0002	0.0001	0.0003	0.0012	0.0009	0.0020	0.0012	0.0005	0.0006	0.0006	0.0005	0.0002	-	-	-
0.2000	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2286	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2571	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.2857	-	-	-	-	-	0.0002	0.0002	0.0003	0.0014	0.0011	0.0023	0.0014	0.0005	0.0007	0.0007	0.0006	0.0002	-	-	-
0.3143	-	-	-	-	-	0.0002	0.0004	0.0004	0.0013	0.0010	0.0016	0.0010	0.0004	0.0011	0.0011	0.0004	0.0003	-	-	-
0.3429	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.3714	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4000	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4286	-	-	-	-	-	0.0002	0.0004	0.0004	0.0012	0.0009	0.0015	0.0010	0.0004	0.0010	0.0011	0.0004	0.0003	-	-	-
0.4571	-	-	-	-	-	0.0002	0.0005	0.0003	0.0012	0.0009	0.0018	0.0011	0.0005	0.0028	0.0002	-	0.0003	-	-	-
0.4857	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5143	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5429	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.5714	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0010	0.0020	0.0012	0.0006	0.0031	0.0002	-	0.0003	-	-	-
0.6000	-	-	-	-	-	0.0001	0.0004	0.0004	0.0011	0.0009	0.0020	0.0022	0.0019	0.0025	-	-	-	-	-	-
0.6286	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.6571	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.6857	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.7143	-	-	-	-	-	0.0002	0.0005	0.0004	0.0012	0.0009	0.0022	0.0024	0.0020	0.0027	-	-	-	-	-	-
0.7429	-	-	-	-	-	0.0001	0.0005	0.0003	0.0010	0.0009	0.0043	0.0065	0.0025	0.0006	-	-	-	-	-	-
0.7714	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8000	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8286	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8571	-	-	-	-	-	0.0002	0.0006	0.0003	0.0013	0.0012	0.0054	0.0081	0.0031	0.0008	-	-	-	-	-	-
0.8857	-	-	-	-	-	0.0001	0.0003	0.0002	0.0010	0.0020	0.0209	0.0175	0.0010	-	-	-	-	-	-	-
0.9143	-	-	-	-	-	0.0001	0.0003	0.0002	0.0012	0.0023	0.0253	0.0198	0.0011	-	-	-	-	-	-	-
0.9429	-	-	-	-	-	0.0002	0.0005	0.0004	0.0019	0.0039	0.0395	0.0330	0.0018	0.0001	-	-	-	-	-	-
0.9714	-	-	-	-	-	0.0001	0.0004	0.0003	0.0015	0.0031	0.0316	0.0264	0.0015	0.0001	-	-	-	-	-	-
1.0000	-	-	-	-	-	0.0001	0.0004	0.0003	0.0015	0.0031	0.0316	0.0264	0.0015	0.0001	-	-	-	-	-	-
1.0286	-	-	-	-	-	0.0001	0.0003	0.0003	0.0011	0.0016	0.0214	0.0172	0.0002	-	-	-	-	-	-	-
1.0571	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.0857	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1143	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1429	-	-	-	-	-	-	0.0001	0.0001	0.0005	0.0007	0.0098	0.0079	0.0001	-	-	-	-	-	-	-
1.1714	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0002	0.0073	0.0038	-	-	-	-	-	-	-	-
1.2000	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2286	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2571	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.2857	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0027	0.0014	-	-	-	-	-	-	-	-
1.3143	-	-	-	-	-	-	-	-	-	0.0001	0.0015	0.0011	-	-	-	-	-	-	-	-
1.3429	-	-	-	-	-	-	-	-	-	0.0001	0.0008	0.0006	-	-	-	-	-	-	-	-
1.3714	-	-	-	-	-	-	-	-	-	0.0001	0.0008	0.0006	-	-	-	-	-	-	-	-
1.4000	-	-	-	-	-	-	-	-	-	-	0.0006	0.0005	-	-	-	-	-	-	-	-
1.4286	-	-	-	-	-	-	-	-	-	-	0.0006	0.0005	-	-	-	-	-	-	-	-
1.4571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are the proportion of total vehicle-hours on the link that fall in each speed/acceleration category. Columns are the acceleration rate category in units of miles per hour per second. Rows are the speed category expressed as a ratio of the link free-flow speed.

Spd/FreSpd = ratio of speed over free-flow speed.

TABLE 10 Vehicle modal activity for congested arterials

Spd/FreSpd	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
0.0000	-	-	-	-	-	-	-	-	-	-	0.5317	-	-	-	-	-	-	-
0.0286	-	-	-	-	-	0.0001	-	-	0.0013	0.0006	0.0007	0.0002	0.0001	0.0003	0.0001	0.0009	-	-
0.0571	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.0857	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1143	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1429	-	-	-	-	-	0.0003	-	-	0.0025	0.0012	0.0013	0.0003	0.0003	0.0006	0.0002	0.0017	-	-
0.1714	-	-	-	-	-	0.0001	0.0001	0.0007	0.0017	0.0008	0.0018	0.0012	0.0005	0.0009	0.0010	0.0004	0.0002	-
0.2000	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2286	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2571	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.2857	-	-	-	-	-	0.0001	0.0001	0.0008	0.0019	0.0009	0.0019	0.0013	0.0006	0.0010	0.0011	0.0005	0.0003	-
0.3143	-	-	-	-	-	0.0002	0.0009	0.0007	0.0013	0.0007	0.0012	0.0008	0.0002	0.0017	0.0014	0.0003	0.0004	-
0.3429	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.3714	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4000	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4286	-	-	-	-	-	0.0002	0.0009	0.0007	0.0012	0.0006	0.0012	0.0007	0.0002	0.0016	0.0013	0.0003	0.0004	-
0.4571	-	-	-	-	-	0.0002	0.0010	0.0005	0.0012	0.0006	0.0007	0.0008	0.0008	0.0040	0.0002	0.0001	0.0003	-
0.4857	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5143	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5429	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.5714	-	-	-	-	-	0.0002	0.0011	0.0006	0.0014	0.0007	0.0008	0.0008	0.0009	0.0045	0.0002	0.0001	0.0003	-
0.6000	-	-	-	-	-	0.0002	0.0009	0.0003	0.0012	0.0005	0.0010	0.0035	0.0027	0.0019	-	-	0.0001	-
0.6286	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.6571	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.6857	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.7143	-	-	-	-	-	0.0002	0.0010	0.0003	0.0012	0.0006	0.0011	0.0037	0.0029	0.0020	-	-	0.0001	-
0.7429	-	-	-	-	-	0.0001	0.0006	0.0003	0.0005	0.0007	0.0082	0.0075	0.0019	0.0001	-	-	-	-
0.7714	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8000	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8286	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8571	-	-	-	-	-	0.0001	0.0008	0.0004	0.0007	0.0009	0.0110	0.0101	0.0025	0.0002	-	-	-	-
0.8857	-	-	-	-	-	0.0001	0.0004	0.0002	0.0009	0.0005	0.0069	0.0094	0.0005	-	-	-	-	-
0.9143	-	-	-	-	-	-	0.0002	0.0001	0.0004	0.0002	0.0031	0.0042	0.0002	-	-	-	-	-
0.9429	-	-	-	-	-	0.0001	0.0003	0.0002	0.0007	0.0004	0.0051	0.0070	0.0004	-	-	-	-	-
0.9714	-	-	-	-	-	0.0001	0.0002	0.0001	0.0006	0.0003	0.0041	0.0056	0.0003	-	-	-	-	-
1.0000	-	-	-	-	-	0.0001	0.0002	0.0001	0.0006	0.0003	0.0041	0.0056	0.0003	-	-	-	-	-
1.0286	-	-	-	-	-	0.0001	0.0001	0.0001	0.0003	0.0003	0.0029	0.0033	-	-	-	-	-	-
1.0571	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.0857	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1143	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1429	-	-	-	-	-	-	-	-	0.0001	0.0001	0.0011	0.0012	-	-	-	-	-	-
1.1714	-	-	-	-	-	-	-	-	-	0.0001	0.0004	0.0009	-	-	-	-	-	-
1.2000	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2286	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2571	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.2857	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002	-	-	-	-	-	-
1.3143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.3429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.3714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.6857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.7714	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8571	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.8857	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.9143	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.9429	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: entries are the proportion of total vehicle-hours on the link that fall in each speed/acceleration category. Columns are the acceleration rate category in units of miles per hour per second. Rows are the speed category expressed as a ratio of the link free-flow speed.

Spd/FreSpd = ratio of speed over free-flow speed.

CHAPTER **7**

THE VEHICLE EMISSION MODULE

This chapter describes the method for estimating vehicle emissions based on VHT by speed and acceleration category.

7.1 METHODOLOGY DEVELOPMENT

The underlying concept for traditional on-road emission inventory development using composite emission factors expressed in grams per mile can be thought of as "traffic on roads." That is, the fundamental processes affecting emissions can be decomposed to roadway segments and characterized by the nature of traffic occurring on them.

Currently, no single model addresses the range of specific emission processes in sufficient detail to capture the effects of traffic-flow improvement projects. CMEM provides the most detailed and best tested estimates of hot-stabilized vehicle exhaust emissions at different speeds and accelerations. Similarly, EMFAC2000 provides the most detailed estimates of process-specific evaporative emissions and excess start emissions. The methodology described here relies on emission rate estimates from these two models. (As described previously, no currently available models address either heavy-duty vehicle emissions or PM emissions at the same level of detail as CMEM.)

The rates depend on ambient temperature, which fluctuates by time of day and season of the year. A typical afternoon peak-hour temperature for a summer day is selected for the total hydrocarbons (THC) and nitric oxides (NO_X) emission rates. A typical afternoon peak hour for an average winter day is selected for CO analyses.

The exhaust emissions for THC, NO_X, and CO are estimated using the following equation:

$$E_R = \sum_{ij} q_R(i,j) * v(i,j) \qquad \text{Equation 14}$$

Where:

E_R = emissions for pollutant R in terms of grams,
$q_R(i,j)$ = CMEM emission rate for pollutant R in terms of grams per hour for movement at speed i and acceleration j, and
$v(i,j)$ = VHT at speed i and at acceleration j.

CMEM calculates emission rates for feasible values of vehicle speeds and accelerations based on vehicle weight and engine power output. The development of speed-acceleration vehicle activity in the traffic module must be constrained to these feasible values. Otherwise, emissions will be underestimated, as vehicles will be assumed to travel at higher-than-achievable speeds (and for shorter time periods) than would actually be the case.

Because of a lack of the necessary data, the emission estimates do not take into account the following emission effects that might be potentially impacted by traffic-flow improvements:

- Starts and stops (e.g., cold starts and hot soaks),
- Heavy-duty vehicle emissions, and
- PM emissions.

7.2 METHODOLOGY APPLICATION

Three emission rate tables (hydrocarbons [HC], CO, and NO_X; see Tables 11 through 13, respectively) are used to convert estimates of vehicle activity by speed and acceleration into estimates of emissions. One simply looks up the appropriate rate for the speed and acceleration category and multiplies that rate by the VHT in the speed and acceleration category to obtain the vehicle emissions for that pollutant.

7.3 NONTECHNOLOGY UPDATES TO VEHICLE EMISSION MODULE

Emission rate models are frequently being updated. To the extent that new CMEM rates become available, the analyst will need to exercise CMEM to develop new tables of average rates for each acceleration and speed category in Tables 11 through 13.

TABLE 11 CMEM light-duty vehicle emission rates—HC (grams/hour)

Speed	Acceleration (mph/sec)																
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.002658	0.002696	0.002734	0.00277	0.002815	0.00287	0.002936	0.002973	0.003021	0.003079	0.003148	0.003227	0.00319	0.003152	0.003114	0.003076
1		0.002677	0.002718	0.002758	0.002797	0.002846	0.002905	0.002976	0.003017	0.00307	0.002965	0.003611	0.004525	0.005438	0.006488	0.007662	0.008949
2		0.002696	0.002739	0.002782	0.002824	0.002876	0.00294	0.003016	0.003061	0.003118	0.002851	0.004073	0.005822	0.007686	0.009823	0.01221	0.014822
3		0.002715	0.002761	0.002807	0.002851	0.002907	0.002975	0.003057	0.003106	0.003168	0.002912	0.004172	0.005968	0.007879	0.010071	0.01252	0.015199
4		0.002734	0.002782	0.002831	0.002877	0.002937	0.00301	0.003097	0.00315	0.003217	0.002974	0.00427	0.006113	0.008071	0.010319	0.012829	0.015577
5		0.002753	0.002804	0.002855	0.002904	0.002968	0.003046	0.003138	0.003195	0.003267	0.003036	0.004372	0.006267	0.008271	0.010584	0.013162	0.015984
6		0.002772	0.002826	0.00288	0.002931	0.002998	0.003081	0.003179	0.00324	0.003318	0.003099	0.004473	0.006421	0.00847	0.010849	0.013495	0.01639
7		0.002791	0.002847	0.002904	0.002958	0.003029	0.003116	0.003221	0.003286	0.003369	0.003199	0.004639	0.006647	0.008797	0.011255	0.013995	0.016985
8		0.002809	0.002869	0.002928	0.002985	0.00306	0.003152	0.003262	0.003332	0.003421	0.003299	0.004805	0.006874	0.009123	0.011661	0.014495	0.017579
9		0.002828	0.00289	0.002952	0.003012	0.003091	0.003188	0.003304	0.003379	0.003473	0.003454	0.005077	0.007247	0.009612	0.012262	0.016072	0.019497
10		0.002847	0.002912	0.002977	0.003039	0.003121	0.003224	0.003346	0.003425	0.003526	0.003609	0.005349	0.00762	0.0101	0.012864	0.017649	0.021414
11		0.002866	0.002933	0.003001	0.003066	0.003152	0.00326	0.003389	0.003473	0.00358	0.003831	0.005681	0.008066	0.010651	0.013562	0.018357	0.022567
12		0.002885	0.002955	0.003025	0.003093	0.003183	0.003296	0.003432	0.003521	0.003634	0.004053	0.006013	0.008512	0.011202	0.01426	0.019065	0.02372
13		0.002885	0.002955	0.003025	0.003094	0.003185	0.0033	0.00344	0.003534	0.003654	0.004294	0.006375	0.009001	0.011812	0.015005	0.020031	0.026457
14		0.002885	0.002955	0.003025	0.003094	0.003186	0.003304	0.003448	0.003548	0.003675	0.004536	0.006738	0.009489	0.012423	0.01575	0.020998	0.029195
15		0.002885	0.002955	0.003025	0.003094	0.003188	0.003307	0.003454	0.003557	0.003687	0.004175	0.006286	0.009011	0.012397	0.016558	0.021999	0.032044
16		0.002885	0.002955	0.003025	0.003094	0.003189	0.003311	0.003459	0.003565	0.003699	0.003815	0.005835	0.008534	0.012372	0.017365	0.023001	0.034894
17		0.002885	0.002955	0.003025	0.003095	0.00319	0.003314	0.003465	0.003575	0.003714	0.003918	0.006039	0.008855	0.012567	0.018326	0.024525	0.037048
18		0.002885	0.002955	0.003025	0.003095	0.003192	0.003318	0.003472	0.003585	0.003728	0.00402	0.006243	0.009176	0.012761	0.019287	0.026049	0.039203
19		0.002885	0.002955	0.003025	0.003096	0.003194	0.003322	0.00348	0.003599	0.003747	0.00415	0.006484	0.009548	0.013303	0.02048	0.028191	0.041716
20		0.002885	0.002955	0.003025	0.003096	0.003195	0.003326	0.003488	0.003613	0.003766	0.00428	0.006725	0.009921	0.013844	0.021672	0.030333	0.04423
21		0.002885	0.002955	0.003025	0.003097	0.003198	0.003331	0.003498	0.003629	0.003787	0.00444	0.00701	0.010353	0.014466	0.023047	0.032765	0.047201
22		0.002885	0.002955	0.003025	0.003097	0.0032	0.003336	0.003508	0.003645	0.003808	0.0046	0.007294	0.010786	0.015089	0.024421	0.035196	0.050173
23		0.002885	0.002955	0.003025	0.003098	0.003202	0.003341	0.00352	0.003663	0.003831	0.004781	0.007615	0.011274	0.015786	0.02489	0.038191	0.053409
24		0.002885	0.002955	0.003025	0.003098	0.003205	0.003347	0.003532	0.00368	0.003853	0.004962	0.007936	0.011762	0.016483	0.025359	0.041187	0.056644
25		0.002885	0.002955	0.003025	0.003099	0.003208	0.003353	0.003545	0.003699	0.003877	0.004673	0.007614	0.011577	0.01727	0.027457	0.044686	0.060157
26		0.002885	0.002955	0.003025	0.0031	0.003211	0.003359	0.003558	0.003718	0.0039	0.004384	0.007292	0.011392	0.018056	0.029554	0.048185	0.063669
27		0.002885	0.002955	0.003025	0.003101	0.003214	0.003366	0.003571	0.003737	0.003924	0.004506	0.007568	0.011896	0.018792	0.031874	0.052215	0.067293
28		0.002885	0.002955	0.003025	0.003101	0.003217	0.003373	0.003585	0.003756	0.003948	0.004628	0.007845	0.012399	0.019527	0.034194	0.056244	0.070917
29		0.002885	0.002955	0.003025	0.003102	0.00322	0.003381	0.003599	0.003776	0.003972	0.004768	0.008165	0.012974	0.020779	0.037172	0.059341	0.073925
30		0.002885	0.002955	0.003025	0.003103	0.003224	0.003389	0.003613	0.003796	0.003996	0.004908	0.008485	0.013549	0.022031	0.040151	0.062437	0.076934
31		0.002885	0.002955	0.003025	0.003104	0.003228	0.003397	0.003628	0.003816	0.004021	0.005069	0.008846	0.014246	0.026044	0.055502	0.083352	0.09644
32		0.002885	0.002955	0.003025	0.003105	0.003231	0.003406	0.003643	0.003836	0.004045	0.005231	0.009208	0.014942	0.030058	0.070853	0.104266	0.115947
33		0.002885	0.002955	0.003025	0.003106	0.003235	0.003415	0.003659	0.003857	0.00407	0.005415	0.0096	0.015646	0.034014	0.075459	0.10678	0.116582
34		0.002885	0.002955	0.003025	0.003107	0.00324	0.003425	0.003675	0.003878	0.004095	0.005598	0.009993	0.016351	0.03797	0.080066	0.109294	0.117217
35		0.002885	0.002955	0.003025	0.003108	0.003244	0.003435	0.003691	0.0039	0.00412	0.0058	0.010414	0.017107	0.042012	0.085436	0.111487	0.117473
36		0.002885	0.002955	0.003025	0.003109	0.003248	0.003446	0.003708	0.003921	0.004146	0.006003	0.010836	0.017863	0.046054	0.090806	0.113679	0.117729
37		0.002885	0.002955	0.003025	0.003111	0.003252	0.003456	0.003724	0.003942	0.00417	0.006221	0.011284	0.019046	0.050309	0.094876	0.115585	0.117879
38		0.002885	0.002955	0.003025	0.003112	0.003256	0.003467	0.003741	0.003963	0.004195	0.00644	0.011732	0.020228	0.054563	0.098945	0.117491	0.11803
39		0.002885	0.002955	0.003025	0.003113	0.003262	0.003479	0.003759	0.003986	0.00422	0.006678	0.012211	0.021496	0.05862	0.102344	0.117605	0.118131
40		0.002885	0.002955	0.003025	0.003115	0.003267	0.003491	0.003777	0.004008	0.004245	0.006916	0.01269	0.022763	0.062677	0.105743	0.117719	0.118233
41		0.002885	0.002955	0.003025	0.003116	0.003272	0.003503	0.003794	0.00403	0.00427	0.007158	0.013193	0.024449	0.066554	0.107877	0.117829	0.118409
42		0.002885	0.002955	0.003025	0.003118	0.003278	0.003516	0.003812	0.004051	0.004294	0.0074	0.013696	0.026134	0.07043	0.11001	0.117938	0.118585
43		0.002885	0.002955	0.003025	0.003119	0.003283	0.003528	0.00383	0.004072	0.004317	0.007675	0.014233	0.028355	0.074045	0.111712	0.118044	0.118629
44		0.002885	0.002955	0.003025	0.003121	0.003289	0.00354	0.003847	0.004094	0.00434	0.007951	0.01477	0.030575	0.07766	0.113413	0.11815	0.118674
45		0.002885	0.002955	0.003025	0.003123	0.003296	0.003553	0.003864	0.004111	0.004358	0.007571	0.014581	0.033722	0.08189	0.115578	0.118223	0.118712
46		0.002885	0.002955	0.003025	0.003125	0.003302	0.003566	0.00388	0.004128	0.004377	0.00719	0.014392	0.036869	0.086119	0.117744	0.118296	0.118751
47		0.002885	0.002955	0.003025	0.003127	0.003309	0.003582	0.003902	0.004156	0.004381	0.007407	0.014936	0.040112	0.091233	0.117894	0.118592	0.118837
48		0.002885	0.002955	0.003025	0.003129	0.003315	0.003598	0.003925	0.004183	0.004386	0.007624	0.01548	0.043356	0.096347	0.118044	0.118887	0.118924
49		0.002885	0.002955	0.003025	0.003131	0.003322	0.003614	0.003946	0.004209	0.00436	0.007874	0.016025	0.046748	0.098776	0.118163	0.118963	0.118996
50		0.002885	0.002955	0.003025	0.003134	0.003329	0.00363	0.003967	0.004235	0.004335	0.008124	0.016569	0.05014	0.101206	0.118282	0.119039	0.119068
51		0.002885	0.002955	0.003025	0.003136	0.003335	0.003646	0.003988	0.004225	0.004315	0.008402	0.017218	0.053512	0.104209	0.118369	0.119097	0.119122
52		0.002885	0.002955	0.003024	0.003138	0.003342	0.003661	0.004008	0.004216	0.004294	0.00868	0.017866	0.056883	0.107212	0.118456	0.119154	0.119177
53		0.002885	0.002955	0.003024	0.003141	0.003349	0.003676	0.004027	0.0042	0.004278	0.008991	0.018885	0.061015	0.109287	0.118535	0.119205	0.119225
54		0.002885	0.002955	0.003024	0.003143	0.003356	0.003692	0.004047	0.004185	0.004262	0.009303	0.019905	0.065148	0.111362	0.118613	0.119256	0.119274
55		0.002885	0.002955	0.003024	0.003146	0.003364	0.003707	0.004067	0.004173	0.00425	0.009647	0.02097	0.068089	0.112713	0.118971	0.119301	0.119318
56		0.002885	0.002955	0.003024	0.003149	0.003372	0.003722	0.004087	0.00416	0.004237	0.009991	0.022035	0.07103	0.114065	0.119329	0.119347	0.119361
57		0.002885	0.002955	0.003024	0.003152	0.00338	0.003738	0.004091	0.00415	0.004227	0.010388	0.023019	0.073712	0.116439	0.119372	0.119388	0.119401
58		0.002885	0.002955	0.003024	0.003155	0.003388	0.003753	0.004096	0.00414	0.004216	0.010785	0.024003	0.076395	0.118812	0.119415	0.11943	0.119441
59		0.002885	0.002955	0.003025	0.003159	0.003397	0.003768	0.004087	0.004132	0.004208	0.011203	0.025289	0.080088	0.119213	0.119789	0.119825	0.119854
60		0.002885	0.002955	0.003025	0.003163	0.003405	0.003783	0.004079	0.004124	0.0042	0.011621	0.026575	0.083781	0.119614	0.120164	0.12022	0.120267
61		0.002885	0.002955	0.003026	0.003167	0.003415	0.003798	0.004072	0.004117	0.004193	0.012076	0.028303	0.08672	0.11971	0.120203	0.120256	0.120301
62		0.002885	0.002955	0.003026	0.003171	0.003424	0.003813	0.004065	0.00411	0.004186	0.012531	0.03003	0.089659	0.119807	0.120242	0.120293	0.120335
63		0.002885	0.002955	0.003027	0.003175	0.003435	0.003828	0.004059	0.004105	0.004393	0.013026	0.032123	0.092225	0.119899	0.120276	0.120325	0.120365
64		0.002885	0.002955	0.003028	0.00318	0.003445	0.003844	0.004054	0.0041	0.0046	0.013521	0.034216	0.094791	0.119991	0.12031	0.120357	0.120396
65		0.002885	0.002955	0.003029	0.003185	0.003459	0.003862	0.004047	0.004094	0.004742	0.014057	0.037802	0.09815	0.120064	0.120344	0.120388	0.120425

7.4 TECHNOLOGY UPDATES TO VEHICLE EMISSION MODULE

The impacts of new emission control technologies, including new fuel standards, can be incorporated into the NCHRP 25-21 methodology by developing new tables of modal emission rates to replace Tables 11 through 13. The analyst would need to exercise CMEM with the new technology and fuel standards to develop new tables of running exhaust emission rates for each acceleration and speed category.

7.5 ADDITIONS TO VEHICLE EMISSION MODULE

The current NCHRP 25-21 methodology does not treat the impacts of traffic-flow improvements on running evaporative emissions, refueling emissions, cold starts, and heavy-duty vehicles. If the analyst can create modifications to the basic CMEM rate tables to account for these effects, then the modified tables can be substituted into the NCHRP 25-21 methodology.

TABLE 12 CMEM light-duty vehicle emission rates—CO (grams/hour)

Speed	Acceleration (mph/sec)															
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.028047	0.028482	0.028916	0.029297	0.029973	0.030957	0.032259	0.033447	0.034957	0.03679	0.038944	0.041419	0.040984	0.04055	0.040116	0.039681
1		0.028264	0.02873	0.029195	0.029604	0.030337	0.031408	0.032827	0.034132	0.03579	0.034819	0.046809	0.069906	0.08806	0.106167	0.125502	0.145875
2		0.028482	0.028978	0.029474	0.029912	0.030701	0.031859	0.033395	0.034817	0.036623	0.032847	0.054673	0.098394	0.135136	0.171784	0.210888	0.252068
3		0.028699	0.029226	0.029753	0.03022	0.031068	0.032316	0.033975	0.03552	0.037481	0.03399	0.056689	0.101211	0.138787	0.176257	0.216237	0.258334
4		0.028916	0.029474	0.030033	0.030529	0.031436	0.032774	0.034554	0.036223	0.038339	0.035134	0.058704	0.104028	0.142439	0.18073	0.221585	0.264599
5		0.029133	0.029722	0.030312	0.030838	0.031806	0.033238	0.035146	0.036945	0.039226	0.036318	0.060684	0.10697	0.143501	0.185463	0.227265	0.271271
6		0.02935	0.029971	0.030591	0.031147	0.032176	0.033702	0.035738	0.037667	0.040113	0.037501	0.062664	0.109912	0.144563	0.190196	0.232945	0.277942
7		0.029567	0.030219	0.03087	0.031457	0.03255	0.034175	0.036344	0.038412	0.041031	0.039142	0.064794	0.110489	0.15009	0.19462	0.24136	0.287548
8		0.029784	0.030467	0.031149	0.031767	0.032924	0.034648	0.036951	0.039157	0.041949	0.040783	0.066923	0.111066	0.155617	0.199045	0.249774	0.297153
9		0.030002	0.030715	0.031428	0.032078	0.033303	0.035129	0.037573	0.039926	0.042903	0.043185	0.070557	0.11468	0.162242	0.206266	0.348428	0.41193
10		0.030219	0.030963	0.031707	0.03239	0.033681	0.035611	0.038196	0.040696	0.043857	0.045588	0.07419	0.118295	0.168867	0.213487	0.447081	0.526707
11		0.030436	0.031211	0.031987	0.032702	0.034064	0.036104	0.038838	0.041495	0.044853	0.048782	0.078812	0.123638	0.173964	0.224166	0.440598	0.564039
12		0.030653	0.031459	0.032266	0.033015	0.034446	0.036597	0.03948	0.042295	0.045849	0.051976	0.083433	0.128981	0.179062	0.234845	0.434115	0.601371
13		0.030653	0.031459	0.032266	0.033019	0.034493	0.03673	0.039742	0.042727	0.046493	0.055636	0.088675	0.135375	0.185885	0.243104	0.449627	0.730662
14		0.030653	0.031459	0.032266	0.033023	0.03454	0.036864	0.040005	0.04316	0.047138	0.059297	0.093917	0.141769	0.192708	0.251363	0.46514	0.859953
15		0.030653	0.031459	0.032266	0.033034	0.034582	0.036962	0.040179	0.043431	0.047524	0.055207	0.090169	0.142488	0.201027	0.25945	0.476636	1.057539
16		0.030653	0.031459	0.032266	0.033045	0.034624	0.03706	0.040353	0.043701	0.047911	0.051117	0.086422	0.143206	0.209345	0.267537	0.488132	1.255126
17		0.030653	0.031459	0.032266	0.033057	0.034672	0.037172	0.040551	0.044008	0.048348	0.052658	0.08933	0.147124	0.213806	0.281838	0.521418	1.396491
18		0.030653	0.031459	0.032266	0.03307	0.034719	0.037283	0.04075	0.044315	0.048785	0.054199	0.092238	0.151042	0.218266	0.296139	0.554704	1.537856
19		0.030653	0.031459	0.032266	0.033085	0.034773	0.037412	0.041009	0.044756	0.049381	0.056202	0.095788	0.155977	0.226882	0.323353	0.617387	1.704427
20		0.030653	0.031459	0.032266	0.0331	0.034827	0.037541	0.041269	0.045197	0.049977	0.058206	0.099339	0.160912	0.235498	0.350567	0.680069	1.870999
21		0.030653	0.031459	0.032266	0.033117	0.034898	0.037698	0.041582	0.045689	0.050621	0.060715	0.103593	0.166882	0.244733	0.381279	0.763732	2.111163
22		0.030653	0.031459	0.032266	0.033134	0.03497	0.037854	0.041895	0.046182	0.051265	0.063224	0.107846	0.172851	0.253969	0.411991	0.847395	2.351327
23		0.030653	0.031459	0.032266	0.033153	0.03505	0.038031	0.042259	0.046722	0.051953	0.066021	0.112615	0.17967	0.26321	0.47856	1.006917	2.601943
24		0.030653	0.031459	0.032266	0.033172	0.035131	0.038208	0.042623	0.047261	0.052641	0.068819	0.117384	0.18649	0.272451	0.545129	1.166439	2.852558
25		0.030653	0.031459	0.032266	0.033194	0.03522	0.038405	0.043023	0.047835	0.053358	0.065894	0.117043	0.193401	0.283011	0.617672	1.388613	3.105985
26		0.030653	0.031459	0.032266	0.033215	0.03531	0.038603	0.043423	0.048408	0.054075	0.062969	0.116703	0.200311	0.29357	0.690215	1.610787	3.359413
27		0.030653	0.031459	0.032266	0.03324	0.03541	0.038822	0.043843	0.048997	0.054803	0.064945	0.121222	0.20854	0.316367	0.772146	1.927233	3.558146
28		0.030653	0.031459	0.032266	0.033264	0.035509	0.039042	0.044263	0.049587	0.055531	0.066921	0.125741	0.216768	0.339165	0.854078	2.243678	3.756879
29		0.030653	0.031459	0.032266	0.033291	0.035618	0.039285	0.044703	0.050192	0.05627	0.069154	0.130954	0.225943	0.377428	1.04598	2.4849	3.824236
30		0.030653	0.031459	0.032266	0.033318	0.035728	0.039528	0.045143	0.050798	0.057008	0.071388	0.136167	0.235117	0.415691	1.237882	2.726122	3.891593
31		0.030653	0.031459	0.032266	0.033348	0.035847	0.039795	0.045605	0.05142	0.057758	0.073924	0.14199	0.245964	0.55502	2.441528	4.409657	5.124772
32		0.030653	0.031459	0.032266	0.033378	0.035966	0.040063	0.046067	0.052043	0.058507	0.076459	0.147813	0.25681	0.69435	3.645173	6.093192	6.357952
33		0.030653	0.031459	0.032266	0.033411	0.036096	0.040356	0.046551	0.052681	0.059265	0.079425	0.154055	0.267552	0.917787	3.920339	6.170853	6.394732
34		0.030653	0.031459	0.032266	0.033444	0.036226	0.040649	0.047034	0.05332	0.060023	0.08239	0.160298	0.278295	1.141225	4.195504	6.248513	6.431511
35		0.030653	0.031459	0.032266	0.033481	0.036366	0.04097	0.047541	0.053976	0.06079	0.085646	0.16688	0.289615	1.491987	4.572735	6.285364	6.445984
36		0.030653	0.031459	0.032266	0.033517	0.036506	0.041291	0.048048	0.054631	0.061557	0.088901	0.173462	0.300935	1.842749	4.949966	6.322216	6.460458
37		0.030653	0.031459	0.032266	0.033557	0.036631	0.041615	0.048552	0.055276	0.062304	0.092351	0.180323	0.350712	2.329718	5.301288	6.382241	6.468102
38		0.030653	0.031459	0.032266	0.033597	0.036756	0.041939	0.049057	0.055921	0.06305	0.0958	0.187183	0.400489	2.816687	5.652609	6.442266	6.475747
39		0.030653	0.031459	0.032266	0.03364	0.036917	0.042314	0.049604	0.056598	0.063816	0.099501	0.194386	0.448877	3.001184	5.854157	6.446879	6.479942
40		0.030653	0.031459	0.032266	0.033684	0.037078	0.042689	0.050151	0.057276	0.064582	0.103202	0.201589	0.497264	3.185683	6.055706	6.451492	6.484138
41		0.030653	0.031459	0.032266	0.033731	0.03725	0.043068	0.050692	0.057936	0.065317	0.106758	0.209033	0.531855	3.277467	6.168096	6.456062	6.5064
42		0.030653	0.031459	0.032266	0.033778	0.037422	0.043447	0.051234	0.058596	0.066052	0.110314	0.216476	0.566446	3.369252	6.280485	6.460631	6.528662
43		0.030653	0.031459	0.032266	0.033829	0.037604	0.043829	0.051767	0.059235	0.066748	0.114437	0.224304	0.639643	3.484976	6.303052	6.465085	6.530388
44		0.030653	0.031459	0.032266	0.033879	0.037787	0.04421	0.052301	0.059873	0.067445	0.118559	0.232131	0.71284	3.6007	6.32562	6.469538	6.532115
45		0.030653	0.031459	0.032266	0.033943	0.037988	0.044601	0.0528	0.060402	0.068005	0.115489	0.240296	0.876628	3.844832	6.384479	6.470284	6.533744
46		0.030653	0.031459	0.032266	0.034006	0.03819	0.044992	0.053298	0.060931	0.068565	0.112419	0.24846	1.040417	4.088964	6.443338	6.47103	6.535373
47		0.030653	0.031459	0.032266	0.034075	0.038392	0.046587	0.056188	0.065067	0.073945	0.122485	0.263922	1.289181	4.703476	6.455601	6.513739	6.545506
48		0.030653	0.031459	0.032266	0.034144	0.038594	0.048182	0.059078	0.069202	0.079326	0.132551	0.279383	1.537945	5.317988	6.467863	6.556447	6.55564
49		0.030653	0.031459	0.032266	0.034218	0.038804	0.049771	0.061928	0.073295	0.084662	0.141913	0.292048	1.799182	5.468068	6.479035	6.567725	6.567054
50		0.030653	0.031459	0.032266	0.034292	0.039013	0.051361	0.064778	0.077388	0.089998	0.151274	0.304713	2.060419	5.618147	6.490208	6.579003	6.578468
51		0.030653	0.031459	0.032256	0.034361	0.039222	0.052934	0.067592	0.081443	0.089294	0.152942	0.315395	2.416013	5.763675	6.494328	6.585236	6.584744
52		0.030653	0.031459	0.032246	0.034431	0.03943	0.054507	0.070406	0.085498	0.088589	0.15461	0.326077	2.771608	5.909202	6.498448	6.591469	6.59102
53		0.030653	0.031459	0.03224	0.034511	0.039651	0.056077	0.073215	0.083953	0.086315	0.158401	0.371649	2.840733	6.106389	6.499936	6.595277	6.594852
54		0.030653	0.031459	0.032234	0.03459	0.039872	0.057648	0.076024	0.082408	0.084041	0.162192	0.417221	2.909858	6.303576	6.501425	6.599084	6.598685
55		0.030653	0.031459	0.032234	0.034681	0.040108	0.059216	0.077493	0.081054	0.082756	0.167163	0.461675	3.125623	6.320415	6.553251	6.601884	6.601498
56		0.030653	0.031459	0.032233	0.034771	0.040343	0.060784	0.078962	0.079699	0.08147	0.172135	0.506128	3.341387	6.337254	6.605077	6.604683	6.604311
57		0.030653	0.031459	0.032237	0.034873	0.040594	0.062349	0.078017	0.078853	0.080713	0.178873	0.536202	3.48152	6.447301	6.607379	6.606992	6.606624
58		0.030653	0.031459	0.032242	0.034975	0.040845	0.063914	0.077072	0.078006	0.079955	0.185611	0.566276	3.621652	6.557348	6.609681	6.609301	6.608937
59		0.030653	0.031459	0.032253	0.03509	0.041113	0.065475	0.076429	0.077463	0.079516	0.192368	0.5896	4.071856	6.706609	6.756441	6.756442	6.756446
60		0.030653	0.031459	0.032264	0.035204	0.04138	0.067037	0.075786	0.076921	0.079077	0.199126	0.612923	4.522059	6.85587	6.903201	6.903583	6.903955
61		0.030653	0.031459	0.032281	0.035331	0.041665	0.068594	0.075337	0.076575	0.078848	0.206551	0.67175	4.718489	6.865068	6.909377	6.909732	6.910086
62		0.030653	0.031459	0.032298	0.035459	0.041951	0.070151	0.074888	0.07623	0.078618	0.213977	0.730576	4.914918	6.874267	6.915552	6.915882	6.916216
63		0.030653	0.031459	0.032323	0.0356	0.042277	0.071724	0.074587	0.076034	0.079409	0.222057	0.810598	4.965501	6.882252	6.920411	6.920721	6.921045
64		0.030653	0.031459	0.032347	0.035741	0.042604	0.073298	0.074285	0.075838	0.0802	0.230138	0.890619	5.016084	6.890237	6.925269	6.925561	6.925874
65		0.030653	0.031459	0.03238	0.035896	0.044123	0.073073	0.073884	0.07565	0.08228	0.238931	1.066209	5.396034	6.896957	6.929721	6.929997	6.930302

TABLE 13 CMEM light-duty vehicle emission rates—NO_X (grams/hour)

Speed	Acceleration (mph/sec)																
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
0		0.00071	0.000712	0.000715	0.000716	0.000734	0.000782	0.000868	0.000982	0.001126	0.001299	0.001501	0.001732	0.001729	0.001726	0.001724	0.001721
1		0.000711	0.000714	0.000717	0.000718	0.000738	0.000791	0.000886	0.001011	0.001168	0.001117	0.002465	0.004046	0.005485	0.007039	0.008712	0.010503
2		0.000712	0.000716	0.000719	0.000719	0.000742	0.0008	0.000903	0.00104	0.001211	0.000935	0.00343	0.00636	0.00924	0.012351	0.015699	0.019285
3		0.000714	0.000717	0.000721	0.000721	0.000746	0.000809	0.000922	0.00107	0.001256	0.001004	0.003575	0.006584	0.009528	0.012711	0.016141	0.019816
4		0.000715	0.000719	0.000722	0.000723	0.00075	0.000819	0.00094	0.0011	0.001301	0.001073	0.00372	0.006808	0.009816	0.013072	0.016582	0.020346
5		0.000717	0.00072	0.000724	0.000725	0.000754	0.000829	0.00096	0.001132	0.001348	0.001147	0.003875	0.007046	0.010133	0.013458	0.017057	0.020919
6		0.000718	0.000722	0.000726	0.000727	0.000759	0.00084	0.00098	0.001164	0.001396	0.001222	0.004029	0.007285	0.01045	0.013845	0.017532	0.021493
7		0.000719	0.000724	0.000728	0.000729	0.000763	0.000851	0.001001	0.001199	0.001446	0.001345	0.004261	0.007614	0.010857	0.014367	0.018152	0.022229
8		0.000721	0.000725	0.000729	0.000731	0.000768	0.000862	0.001022	0.001233	0.001497	0.001468	0.004493	0.007942	0.011264	0.014889	0.018771	0.022966
9		0.000722	0.000727	0.000731	0.000733	0.000773	0.000874	0.001045	0.00127	0.001551	0.001753	0.004925	0.0085	0.011939	0.015685	0.020202	0.024612
10		0.000724	0.000728	0.000733	0.000735	0.000778	0.000886	0.001068	0.001306	0.001605	0.002038	0.005357	0.009058	0.012613	0.016481	0.021632	0.026258
11		0.000725	0.00073	0.000735	0.000737	0.000783	0.0009	0.001093	0.001346	0.001663	0.002408	0.005864	0.009707	0.01339	0.017407	0.02251	0.027521
12		0.000726	0.000731	0.000737	0.000739	0.000788	0.000913	0.001117	0.001385	0.001721	0.002778	0.006371	0.010355	0.014167	0.018334	0.023388	0.028784
13		0.000726	0.000731	0.000737	0.000739	0.000792	0.000925	0.001142	0.001426	0.001781	0.003201	0.006941	0.01108	0.015037	0.019366	0.024615	0.03061
14		0.000726	0.000731	0.000737	0.00074	0.000796	0.000937	0.001166	0.001466	0.001841	0.003623	0.007511	0.011805	0.015907	0.020397	0.025841	0.032436
15		0.000726	0.000731	0.000737	0.00074	0.000799	0.000946	0.001183	0.001492	0.001877	0.003016	0.00689	0.0112	0.01647	0.021469	0.027123	0.036146
16		0.000726	0.000731	0.000737	0.000741	0.000803	0.000956	0.001199	0.001517	0.001913	0.002408	0.006269	0.010596	0.017033	0.022542	0.028404	0.039856
17		0.000726	0.000731	0.000737	0.000741	0.000807	0.000967	0.001219	0.001546	0.001954	0.002631	0.006621	0.0111	0.017074	0.023872	0.029932	0.043863
18		0.000726	0.000731	0.000737	0.000742	0.000811	0.000978	0.001238	0.001575	0.001995	0.002853	0.006973	0.011604	0.017114	0.025202	0.03146	0.04787
19		0.000726	0.000731	0.000737	0.000743	0.000815	0.00099	0.001262	0.001616	0.00205	0.003115	0.007374	0.012176	0.017578	0.02657	0.033189	0.050153
20		0.000726	0.000731	0.000737	0.000744	0.00082	0.001003	0.001287	0.001657	0.002106	0.003377	0.007776	0.012748	0.018042	0.027939	0.034917	0.052437
21		0.000726	0.000731	0.000737	0.000745	0.000827	0.001018	0.001317	0.001704	0.002166	0.003674	0.008225	0.013388	0.018837	0.029514	0.037043	0.0548
22		0.000726	0.000731	0.000737	0.000745	0.000834	0.001034	0.001346	0.00175	0.002226	0.00397	0.008675	0.014027	0.019633	0.031089	0.039168	0.057164
23		0.000726	0.000731	0.000737	0.000747	0.000842	0.001051	0.001381	0.0018	0.00229	0.004291	0.009167	0.014732	0.020586	0.032628	0.046087	0.059711
24		0.000726	0.000731	0.000737	0.000748	0.000849	0.001069	0.001415	0.001851	0.002354	0.004612	0.009658	0.015437	0.02154	0.034167	0.053007	0.062259
25		0.000726	0.000731	0.000737	0.000749	0.000858	0.001088	0.001453	0.001905	0.002421	0.00417	0.009259	0.015249	0.022603	0.034959	0.054569	0.065133
26		0.000726	0.000731	0.000737	0.000751	0.000867	0.001107	0.001491	0.001958	0.002488	0.003729	0.00886	0.01506	0.023666	0.03575	0.056131	0.068007
27		0.000726	0.000731	0.000737	0.000752	0.000876	0.001128	0.00153	0.002013	0.002555	0.003986	0.009312	0.015788	0.024719	0.037164	0.060508	0.071253
28		0.000726	0.000731	0.000737	0.000754	0.000886	0.001149	0.00157	0.002068	0.002623	0.004244	0.009763	0.016515	0.025771	0.038578	0.064885	0.0745
29		0.000726	0.000731	0.000737	0.000756	0.000896	0.001172	0.001611	0.002124	0.002691	0.004528	0.010271	0.017333	0.027154	0.04665	0.068097	0.079059
30		0.000726	0.000731	0.000737	0.000757	0.000906	0.001195	0.001652	0.002181	0.00276	0.004812	0.010779	0.018151	0.028537	0.054721	0.07131	0.083618
31		0.000726	0.000731	0.000737	0.000759	0.000918	0.001221	0.001695	0.002238	0.002829	0.005121	0.011334	0.019389	0.032247	0.069823	0.090544	0.09832
32		0.000726	0.000731	0.000737	0.000762	0.000929	0.001246	0.001738	0.002296	0.002899	0.005431	0.011888	0.020628	0.035958	0.084926	0.109778	0.113022
33		0.000726	0.000731	0.000737	0.000764	0.000941	0.001273	0.001783	0.002355	0.002969	0.005795	0.012474	0.021645	0.043996	0.089076	0.111044	0.113725
34		0.000726	0.000731	0.000737	0.000766	0.000954	0.001301	0.001828	0.002414	0.003039	0.006159	0.01306	0.022661	0.052035	0.093227	0.112309	0.114429
35		0.000726	0.000731	0.000737	0.000769	0.000967	0.001331	0.001875	0.002475	0.00311	0.006513	0.013675	0.02375	0.053835	0.099019	0.113086	0.114694
36		0.000726	0.000731	0.000737	0.000772	0.00098	0.001361	0.001922	0.002535	0.00318	0.006867	0.01429	0.024839	0.055635	0.104812	0.113862	0.114959
37		0.000726	0.000731	0.000737	0.000775	0.000992	0.001391	0.001968	0.002595	0.003249	0.007237	0.014933	0.0262	0.059043	0.106868	0.114481	0.115094
38		0.000726	0.000731	0.000737	0.000779	0.001004	0.001421	0.002015	0.002654	0.003318	0.007608	0.015575	0.02756	0.062452	0.108925	0.1151	0.115228
39		0.000726	0.000731	0.000737	0.000782	0.00102	0.001456	0.002066	0.002717	0.003389	0.008	0.016252	0.028914	0.068435	0.110739	0.115208	0.115334
40		0.000726	0.000731	0.000737	0.000786	0.001035	0.001491	0.002116	0.00278	0.00346	0.008393	0.016928	0.030267	0.074417	0.112553	0.115316	0.11544
41		0.000726	0.000731	0.000737	0.00079	0.001051	0.001526	0.002167	0.002841	0.003528	0.00874	0.017624	0.032984	0.079901	0.112976	0.11542	0.115564
42		0.000726	0.000731	0.000737	0.000794	0.001068	0.001562	0.002217	0.002902	0.003596	0.009087	0.01832	0.035701	0.085384	0.113399	0.115524	0.115688
43		0.000726	0.000731	0.000737	0.000799	0.001085	0.001597	0.002267	0.002962	0.003661	0.009512	0.019061	0.0371	0.090015	0.113918	0.115623	0.115771
44		0.000726	0.000731	0.000737	0.000804	0.001103	0.001633	0.002316	0.003021	0.003726	0.009937	0.019802	0.038499	0.094646	0.114437	0.115723	0.115853
45		0.000726	0.000731	0.000737	0.00081	0.001123	0.00167	0.002363	0.003071	0.003778	0.009502	0.019581	0.045323	0.099275	0.115095	0.115804	0.115925
46		0.000726	0.000731	0.000737	0.000817	0.001143	0.001708	0.002411	0.003121	0.003831	0.009067	0.01936	0.052146	0.103905	0.115754	0.115885	0.115996
47		0.000726	0.000731	0.000737	0.000824	0.001162	0.001783	0.002533	0.003285	0.004038	0.009658	0.020316	0.055965	0.106478	0.116131	0.11631	0.116366
48		0.000726	0.000731	0.000737	0.000831	0.001181	0.001858	0.002655	0.00345	0.004245	0.010249	0.021272	0.059784	0.109052	0.116508	0.116734	0.116736
49		0.000726	0.000731	0.000737	0.000839	0.001201	0.001933	0.002773	0.003611	0.004261	0.010497	0.022051	0.062572	0.11115	0.117239	0.117453	0.117454
50		0.000726	0.000731	0.000737	0.000847	0.001221	0.002007	0.002892	0.003772	0.004276	0.010744	0.022829	0.065361	0.113248	0.11797	0.118173	0.118173
51		0.000726	0.000731	0.000736	0.000855	0.001242	0.002081	0.003008	0.003733	0.004076	0.011035	0.023839	0.068341	0.115	0.118388	0.118583	0.118582
52		0.000726	0.000731	0.000736	0.000863	0.001262	0.002156	0.003124	0.003695	0.003876	0.011326	0.024849	0.071321	0.116751	0.118806	0.118993	0.118992
53		0.000726	0.000731	0.000736	0.000871	0.001284	0.002229	0.003239	0.003576	0.00375	0.011728	0.026264	0.07117	0.117085	0.119093	0.119273	0.119272
54		0.000726	0.000731	0.000736	0.00088	0.001305	0.002302	0.003355	0.003457	0.003624	0.01213	0.02768	0.071018	0.11742	0.11938	0.119553	0.119551
55		0.000726	0.000731	0.000736	0.000889	0.001328	0.002375	0.003286	0.003375	0.003539	0.012611	0.028856	0.074127	0.117975	0.119679	0.119764	0.119763
56		0.000726	0.000731	0.000736	0.000899	0.001351	0.002448	0.003217	0.003294	0.003455	0.013093	0.030033	0.077235	0.11853	0.119978	0.119976	0.119975
57		0.000726	0.000731	0.000736	0.000909	0.001374	0.002521	0.003158	0.003235	0.003395	0.01376	0.031211	0.08091	0.119344	0.12015	0.120149	0.120147
58		0.000726	0.000731	0.000736	0.000919	0.001398	0.002594	0.003099	0.003177	0.003336	0.014427	0.032389	0.084586	0.120157	0.120323	0.120321	0.12032
59		0.000726	0.000731	0.000737	0.00093	0.001423	0.002666	0.003055	0.003134	0.003294	0.015032	0.034573	0.096071	0.12467	0.124824	0.124825	0.124826
60		0.000726	0.000731	0.000738	0.000941	0.001449	0.002738	0.003011	0.003092	0.003252	0.015637	0.036756	0.107557	0.129183	0.129325	0.129328	0.129333
61		0.000726	0.000731	0.000739	0.000953	0.001475	0.002809	0.002977	0.00306	0.003222	0.016295	0.037851	0.110544	0.129464	0.12959	0.129594	0.129598
62		0.000726	0.000731	0.00074	0.000966	0.001502	0.002881	0.002944	0.003028	0.003192	0.016953	0.038946	0.11353	0.129745	0.129856	0.129859	0.129864
63		0.000726	0.000731	0.000741	0.000979	0.001532	0.002931	0.002919	0.003005	0.003491	0.017665	0.042293	0.115898	0.129976	0.130071	0.130074	0.130079
64		0.000726	0.000731	0.000743	0.000992	0.001562	0.002981	0.002894	0.002982	0.00379	0.018377	0.045641	0.118266	0.130208	0.130286	0.130289	0.130295
65		0.000726	0.000731	0.000745	0.001007	0.00163	0.002923	0.002858	0.002955	0.003955	0.019146	0.050374	0.121041	0.130421	0.130488	0.130491	0.130497

CHAPTER 8

BASE CASE

The PSRC travel model data set was selected for the application of the NCHRP 25-21 methodology to case studies.

The PSRC travel demand model covers four counties of the Seattle/Tacoma metropolitan area with a population of about 3 million people. (See the University of Washington and Cambridge Systematics's "Land Use and Travel Demand Forecasting Models, Model Documentation," prepared for the Puget Sound Regional Council, final report, June 30, 2001, www.psrc.org/datapubs/pubs/model_modelrequirements.pdf.) The model represents the PSRC region using 852 internal zones, about 19,000 directional road links, and 317 transit lines. The model splits travel demand between three time periods (3-hour AM peak, 3-hour PM peak, and rest of day) and three modes of travel (drive alone, carpool, and transit). An economic forecasting model and a pair of land-use allocation models (DRAM and EMPAL) are used by PSRC to generate the socioeconomic data required by the travel demand model.

8.1 INPUT

The PSRC model for the year 2020 was selected as the base case for demonstrating the application of the NCHRP 25-21 methodology. All of the other case studies using the NCHRP 25-21 were run in comparison to this base case for the year 2020.

Three key inputs are required from the PSRC model for application in the NCHRP 25-21 methodology: the highway network (Table 14), the transit network (Table 15), and the base case OD travel demand (Table 16).

The highway network contains the following data items for each directional highway link, where ul1, ul2, and ul3 are user-definable fields:

- Length (in miles),
- Modes (SOV, HOV, bus, rail, ferry, transit walk access, transit auto access),
- Number of lanes,
- Volume/delay function,
- Capacity per lane (vph) (ul1),
- Free-flow travel time (minutes) (ul2), and
- Facility type (0 = bus/walk link, 1 = freeway, 2 = expressway, 3 = urban arterial, 4 = urban one way, 5 = centroid connector, 6 = rural arterial) (ul3).

Freeway HOV lanes are coded as parallel links to the freeway with HOV/bus-only cross connectors. For each transit line, the following data are available:

- Mode,
- Vehicle type,
- Headway (minutes),
- Speed (mph),
- Length (miles), and
- Number of segments.

The projected year 2020 population is 4.3 million people, and the projected 2020 employment is 2.3 million jobs. The PSRC model estimated travel demand for 2020 is 12.4 million daily person trips in nine OD tables by mode and time period (summarized in Table 16).

8.2 APPLICATION OF THE HCM ASSIGNMENT MODULE TO THE PSRC DATA SET

The basic PSRC highway must be modified before the HCM Assignment Module can be applied to it.

8.2.1 Step 1: Code Free-Flow Speeds and Capacities

Step 1 consists of substituting HCM-based capacities and free-flow speeds for the planning values in the model. In the case of the PSRC model, the capacities and free-flow speeds are customized for individual links. Each facility type in the PSRC model is applied to a wide range of conditions. For example, ramps are sometimes coded as freeway facility types, arterial street types, or one-way arterial street types. The free-flow speeds for freeway-type links consequently range from 20 mph to 70 mph. Similar ranges occur for the other facility types. It is therefore not possible to make a blanket substitution of capacities and free-flow speeds based upon facility type and area type. The substitutions would have to be made on a link-by-link basis. Because this basis is not practical for a demonstration of the methodology, the link-specific capacities and free-flow speeds will be left unchanged.

The one change made to the current PSRC method was to replace the current link free-flow travel times (ul2) in the AM

TABLE 14 Base case 2020 highway network

Centerline-Miles	Lane-Miles	No. of Links	Capacity-Miles (VMT)	Mean Free-Flow Speed (mph)
11,388	17,390	17,711	20,194,252	19.9

TABLE 15 Base case 2020 transit network

Network	Transit Vehicles	Lines	Route-Miles
2020	1,286	542	9,716

and PM scenarios (which, in the PSRC model, are computed from congested speed output by the daily assignment) with the free-flow speeds from the daily assignment.

8.2.2 Step 2: Replace BPR Equations with HCM Equation

The BPR speed-flow equations used in the PSRC model are replaced with the HCM 2000 speed-flow equation.

The existing PSRC volume delay functions (VDFs) for the daily and off-peak scenarios were not touched. The VDFs involve 24-hour and 18-hour demand assignments and are only moderately capacity constrained (12-hour capacities for the daily assignment and 8-hour capacities for the off-peak assignment). The off-peak assignment currently uses the congested travel times from the daily assignment for its free-flow times. This use was unchanged.

The AM and PM peak-hour assignments currently use the following VDFs, where fd10, fd30, fd40, fd47, fd49, and fd59 are functions and volau is the auto volume:

- $\mathrm{fd10} = \mathrm{ul2} \ast (1 + .15 \ast (.08 \ast \mathrm{volau}/(\mathrm{lanes} \ast \mathrm{ul1})) \wedge 4)$
- $\mathrm{fd30} = \mathrm{ul2} + (((.34 \ast (\mathrm{volau}/\mathrm{ul1}) \,/\, \mathrm{lanes}) - 1)\ \mathrm{.max.}\ 0) \ast (60/\mathrm{lanes})$
- $\mathrm{fd40} = \mathrm{ul2}$
- $\mathrm{fd47} = \mathrm{ul2} \ast (1 + .15 \ast (.125 \ast \mathrm{volau}/(\mathrm{lanes} \ast \mathrm{ul1})) \wedge 4)$
- $\mathrm{fd49} = \mathrm{ul2} \ast (1 + .15 \ast (.375 \ast \mathrm{volau}/(\mathrm{lanes} \ast \mathrm{ul1})) \wedge 4)$
- $\mathrm{fd59} = \mathrm{ul2} \ast (1 + .15 \ast (.455 - .125) \ast \mathrm{volau}/(3 \ast \mathrm{lanes} \ast \mathrm{ul1}))$

Fd10 is used primarily in the daily assignment for all roads. Although 179 links appear to use fd10 in the AM peak assignment, the rationale for this use is unclear, so fd10 was replaced with fd59 for these 179 links. Fd10 is not used in the PM assignment.

Fd30 is used for 14 auto-ferry links in both the AM and PM assignments. These VDFs were retained unchanged.

Fd40 is used in both the AM and PM assignments for 404 nonauto ferry and walk links for the 1990 network. This function is also used for 1,465 links in the AM assignment and 873 links in the PM assignment for the 2020 network. In essence, the travel time for the link is fixed at whatever value was originally coded by the PSRC modeler. This VDF was not changed.

Fd47 is used for 10 freeway HOV lane links in the AM and PM peak assignments for the 2020 network (not present in the 1990 network) and was not changed.

Fd49 is used for 16 short connector links between the freeway HOV lane links and the mixed-flow lane links of the freeway for the AM and PM peak 2020 network assignments (not used in 1990 network). This VDF is also used for some rural arterial links and really short urban arterial links. This VDF was not changed.

TABLE 16 Base case 2020 person trips

Peak	Mode	Person Trips	% Mode
AM	SOV	1,720,034	79.9%
	HOV	273,841	12.7%
	Transit	160,154	7.4%
PM	SOV	2,766,570	88.9%
	HOV	345,056	11.1%
	Transit	?*	?*
Off Peak	SOV	6,732,642	96.3%
	HOV	258,595	3.7%
	Transit	?*	?*
Daily	SOV	11,219,246	90.6%
	HOV	877,492	7.1%
	Transit	287,932	2.3%
	Total	12,384,670	

*The PSRC model does not split transit trips into PM and off peak, but these trips are included in the estimated daily transit trips.

Fd59 is used for the vast majority of the road links in the AM and PM peak assignments. This VDF will be replaced with the HCM speed-flow function.

8.2.3 Step 3: Generate Additional Network Parameters Required by HCM Equation

The HCM equation requires several additional parameters not coded in the PSRC network:

- The number of signals on a link (N),
- The zero-flow signal delay (D_0),
- The segment delay between signal (D_L), and
- The calibration parameter (J).

8.2.3.1 Number of Signals

The number of signals on a link (N) is computed and stored for each link as follows:

- For freeways (ul3 = 1), centroid connectors (ul3 = 5), and rural arterials (ul3 = 6), the number of signals is zero, but because N must be at least 1, $N = 1$ for these links.
- For all other facility types, N is computed as follows:

$$N = \max[1, INT(L * S_d)] \qquad \text{Equation 15}$$

Where:

N = the number of signals on the segment,
S_d = the signal density for the link (signals/mile),
L = the length of the link (miles),
max = maximum function (outputs the maximum of two values), and
INT = integer divide function (outputs result truncated to integer value).

Note that the first signal at the start of a link is excluded from N, so if a link is 1 mile long and signals are spaced 1 mile apart, there will be two signals on the link (one at the start and one at the end), but because the first signal is excluded (to avoid double counting the signal at the end of one link and the beginning of the next link), N is equal to 1.

An integer divide is used to obtain the number of signals, since modelers usually terminate a link at a major intersection, which is likely to be signalized. So a 1.5-mile-long link with signals assumed to be spaced an average of 1 mile apart would have one signal at the start, one signal at the end, and no signals in between. Thus, the default signal density assumption is used as a rough guide for determining whether multiple signals might exist within the stretch of a model link; however, if the link length is close to a multiple of the signal density, the coded-link length is assumed to be more accurate than the assumed default signal density.

Table 17 shows the signal density (S_d). The table was created using local knowledge of typical signal densities on expressways and arterials.

8.2.3.2 Zero-Flow Signal Delay

The zero-flow delay in hours (D_0) is computed and stored for each link. The zero-flow control delay is zero for freeway, centroid, and rural facility types (ul3 = 1, 5, 6). For ul3 = 2, 3, 4, it is computed using the equation in the methodology:

$$D_0 = \frac{N}{3{,}600} * \text{DF} * \frac{C}{2}\left(1 - {}^{g}\!/_{C}\right)^2 \qquad \text{Equation 16}$$

Where:

D_0 = the zero-flow control delay at the signal (hours);
N = maximum of 1, or the number of signals on the segment;
3,600 = conversion from seconds to hours;
g/C = average effective green time per cycle for signals on segment;
C = average cycle length for all signals on the segment (seconds); and
DF = delay factor,
= 0.9 for uncoordinated traffic-actuated signals,
= 1.0 for uncoordinated fixed-time signals,

TABLE 17 Facility type, free speed, arterial class, and signal density

Free Speed	Arterial Class	Signals/Mile	
		Expressway Ul3 = 2	Urban Arterial Ul3 = 3,4
55+	I	1	2
50	I	1	2
45	I	1	2
40	II	1	2
35	III	3	5
30	IV	6	8
25-	IV	8	8

= 1.2 for coordinated signals with unfavorable progression,

= 0.9 for coordinated signals with favorable progression, and

= 0.6 for coordinated signals with highly favorable progression.

A default value of 0.44 is used for the *g*/*C* ratio. A default signal cycle length of 120 seconds is used.

8.2.3.3 Between-Signal-Segment Delay

The segment delay (D_L) is computed and stored as follows:

$$D_L = L * \frac{d_L}{60} \qquad \text{Equation 17}$$

Where:

L = the length of the segment.

The delay per mile (d_L) is given in Table 18, which was derived from the assumed signal density and Exhibit 15-3 of the HCM 2000.

8.2.3.4 The Calibration Parameter (J)

The calibration parameter *J* is stored for each link. Table 19 was created from the table provided in the methodology using the facility types and free-flow speeds coded in the PSRC model network. Centroid connectors were given a flat speed-flow equation taken from freeways (for 75+ mph free-flow speed).

Table 20 shows the final combined set of parameters for the new HCM speed-flow equations for the PSRC model. The selection criteria are used to select the default values used to compute the additional parameters for the HCM equations for each link. The standard BPR parameters (also used by the HCM equations) are already coded in the PSRC model for each link.

TABLE 18 Segment delay by facility type and free-flow speed

Free-Flow Speed	Expressway ul3 = 2	Urban Arterial ul3 = 3, 4
55+	0 secs	8 secs
50	0	8
45	0	8
40	0	8
35	0	20
30	25	45
25-	60	60

TABLE 19 *J* Parameters by facility type and free-flow speed

Free-Flow Speed	Freeway Ul3 = 1	Expressway Ul3 = 2	Urban Arterial Ul3 = 3	One-Way Arterial Ul3 = 4	Rural Arterial Ul3 = 6 Lanes > 1	Rural Arterial Ul3 = 6 Lanes = 1
75+	29.47E-06	22.1E-06	204E-06	204E-06	2.296E-06	90.43E-06
70	20.03E-06	22.1E-06	204E-06	204E-06	2.296E-06	90.43E-06
65	14.23E-06	22.1E-06	204E-06	204E-06	2.296E-06	90.43E-06
60	8.426E-06	22.1E-06	204E-06	204E-06	2.296E-06	138.5E-06
55	3.306E-06	22.1E-06	204E-06	204E-06	1.821E-06	223.9E-06
50	3.306E-06	22.1E-06	204E-06	204E-06	1.108E-06	389.3E-06
45	3.306E-06	22.1E-06	204E-06	204E-06	2.174E-06	748.4E-06
40	3.306E-06	49.9E-06	200E-06	200E-06	2.174E-06	748.4E-06
35	3.306E-06	802E-06	1780E-06	1780E-06	2.174E-06	748.4E-06
30	3.306E-06	3170E-06	4990E-06	4990E-06	2.174E-06	748.4E-06
≥25	3.306E-06	3170E-06	4990E-06	4990E-06	2.174E-06	748.4E-06

TABLE 20 Final parameters for HCM equation VDF 59

Selection Criteria				Standard BPR Parameters			Additional Parameters for HCM Equations				
Facility	ul3	@fresp	Lanes	L	R_o	X	D_o	D_L	N	T	J
Freeway	1	>70	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	2.947E-05
	1	65-70	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	2.003E-05
	1	60-65	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	1.423E-05
	1	55-60	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	8.426E-06
	1	<=55	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	3.306E-06
Expressway	2	>45	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	0	max(1,INT(len*1))	1	2.21E-05
	2	40-45	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	0	max(1,INT(len*1))	1	4.99E-05
	2	35-40	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	0	max(1,INT(len*1))	1	8.02E-04
	2	<35	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	L*25/60	max(1,INT(len*3))	1	3.17E-03
Urban Arterial	3	>45	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	L*8/60	max(1,INT(len*2))	1	2.04E-04
	3	40-45	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	L*8/60	max(1,INT(len*2))	1	2.00E-04
	3	35-40	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	L*20/60	max(1,INT(len*2))	1	1.78E-03
	3	<35	all	len	@ul21	volau/(ul1*lanes)	N*16.93/60	L*45/60	max(1,INT(len*5))	1	4.99E-03
One-Way Arterial	4	>45	all	len	@ul21	volau/(ul1*lanes)	N*6.00/60	L*8/60	max(1,INT(len*2))	1	2.04E-04
	4	40-45	all	len	@ul21	volau/(ul1*lanes)	N*6.00/60	L*8/60	max(1,INT(len*2))	1	2.00E-04
	4	35-40	all	len	@ul21	volau/(ul1*lanes)	N*6.00/60	L*20/60	max(1,INT(len*2))	1	1.78E-03
	4	<35	all	len	@ul21	volau/(ul1*lanes)	N*6.00/60	L*45/60	max(1,INT(len*5))	1	4.99E-03
Centroid Connector	5	all	all	len	@ul21	volau/(ul1*lanes)	0	0	1	1	2.947E-05
Rural Arterial	6	>60	>1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	2.296E-06
	6	55-60	>1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	1.821E-06
	6	50-55	>1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	1.108E-06
	6	<50	>1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	2.174E-06
	6	>65	1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	9.043E-05
	6	60-65	1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	0.0001385
	6	55-60	1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	0.0002239
	6	50-55	1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	0.0003893
	6	<50	1	len	@ul21	volau/(ul1*lanes)	0	0	1	1	0.0007484

ul3, ul21 = user-definable fields.
@fresp = at free-flow speed (mph).
L = segment length.
R_0 = segment traversal time at free-flow speed.
X = volume/capacity ratio.
D_0 = zero-flow control delay at the signal.
D_L = delay per mile.
N = maximum of 1, or the number of signals on the segment.
T = length of analysis period, in hours.
J = calibration parameter.
volau = auto volume.
INT = integer divide function.

CHAPTER 9

CASE STUDY 1: ADD FREEWAY LANE—RURAL

Case Study 1 adds a single through lane to each direction of a freeway in a rural mountainous area. The freeway is uncongested under the base 2020 condition; thus, adding the lane has no effect on the operating speeds of vehicles on the freeway.

The specific location for this case study is a 7.6-mile-long section of the Interstate 90 freeway between the S.E. 68th Street Interchange and the SR 202 Interchange near North Bend, Washington (see Figure 6).

9.1 APPLICATION

The 2020 base case has four lanes in the uphill direction and three in the reverse direction. The project adds one through lane in each direction over the entire length of the project. Thus, after the improvement, there are five lanes in the uphill direction, including truck-climbing lanes, and four lanes in the reverse direction. There was no change in the 70-mph free-flow speed and the 1,800-vehicles/hour/lane capacity for this freeway.

9.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 21 through 23.

This case study is an example of an unnecessary capacity improvement being placed at a location where there is already plenty of excess capacity. The extra capacity on the freeway has no effect on the speed of traffic on the freeway, which is all traveling at the free-flow speed during both the peak and off-peak periods. The result is that the capacity improvement has no effect on travel times, trip making, VMT, or emissions, as expected.

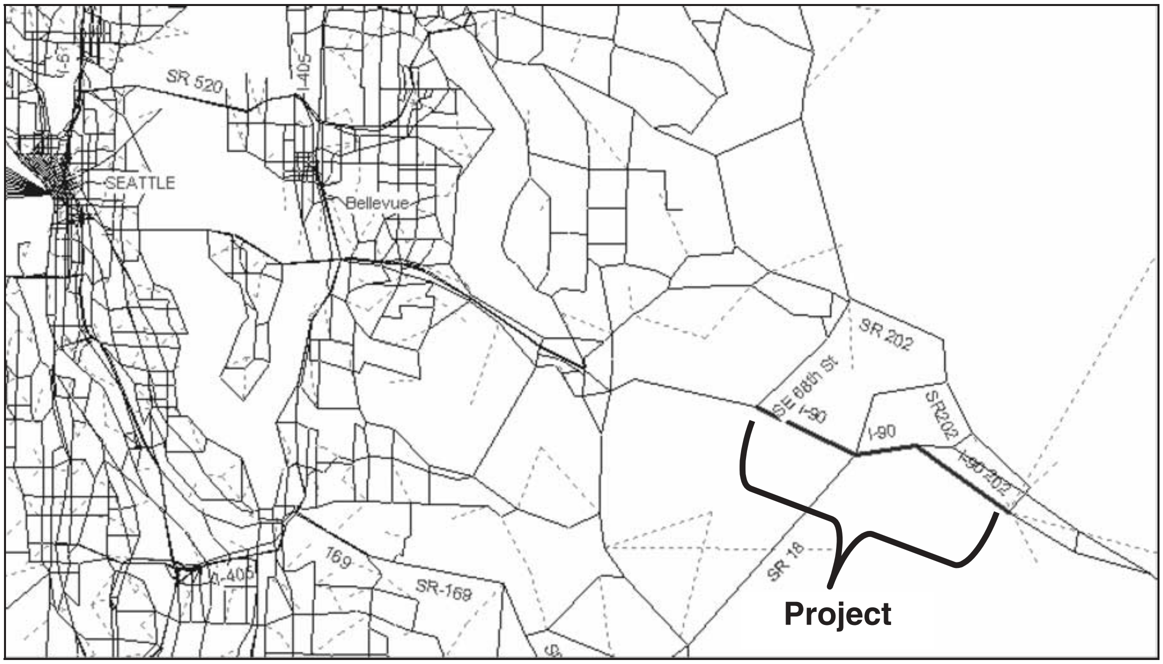


Figure 6. Case Study 1: I-90 North Bend.

TABLE 21 Case Study 1: Travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.10	69.3	6.54	0.18	69.7	6.51
	After	0.07	69.3	6.54	0.14	69.7	6.51
	Difference	-0.02	0.0	0.00	-0.04	0.0	0.00
	% Difference	-24.17%	0.00%	0.00%	-21.94%	0.00%	0.00%
PM Peak	Before	0.21	69.3	6.54	0.11	69.7	6.51
	After	0.16	69.3	6.54	0.09	69.7	6.51
	Difference	-0.05	0.0	0.00	-0.02	0.0	0.00
	% Difference	-23.77%	0.00%	0.00%	-21.44%	0.00%	0.00%
Off Peak	Before	0.08	69.3	6.54	0.06	69.7	6.51
	After	0.12	69.3	6.54	0.10	69.7	6.51
	Difference	0.04	0.0	0.00	0.04	0.0	0.00
	% Difference	51.33%	0.00%	0.00%	56.23%	0.00%	0.00%

TABLE 22 Case Study 1: Volume changes on the facility

Period	Direction	Before	After	Difference	% Difference
AM Peak	EB	1,643	1,643	0	0.00%
	WB	3,545	3,545	0	0.00%
	TOT	5,188	5,188	0	0.00%
PM Peak	EB	3,623	3,623	0	0.00%
	WB	2,299	2,299	0	0.00%
	TOT	5,922	5,922	0	0.00%
Off Peak	EB	15,830	15,830	0	0.00%
	WB	14,904	14,904	0	0.00%
	TOT	30,735	30,735	0	0.00%
Total	EB	21,096	21,096	0	0.00%
	WB	20,749	20,749	0	0.00%
	TOT	41,844	41,844	0	0.00%

TABLE 23 Case Study 1: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
Difference		0	0	0.0	0	0	0
% Difference		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

CHAPTER 10

CASE STUDY 2: CLOSE FREEWAY LANE—URBAN

Case Study 2 removes a single through lane in each direction of a freeway in an urban area. The freeway is uncongested under the base 2020 condition, but deleting the lane makes the freeway congested.

The specific location for this case study is a 6.6-mile-long section of the State Route 520 freeway (the Evergreen Point Bridge) between the I-5 and I-405 interchanges in Seattle, Washington (see Figure 7).

10.1 APPLICATION

Before the improvement, this section had three lanes in each direction. Note that this section also has a barrier-separated HOV lane in each direction. Because the links were not very congested with three lanes (peak-period volume/capacity ratio was less than 1.00), a lane was removed in each direction so as to provide a case study where the impacts of an improvement were to make conditions more congested. Thus, after the "improvement," the section has two lanes in each direction with a barrier-separated HOV lane. No change was made in the 50- to 60-mph free-flow speed and the 1,800- to 1,850-vehicles/hour/lane capacity for this freeway.

10.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 24 through 26.

This case study illustrates how removing or closing a freeway lane causes an initially uncongested freeway to become congested during the peak periods. This action reduces peak-period travel on the facility significantly, but has a very small effect on regional travel (VMT).

The mean speed on the facility is reduced significantly, and the mean travel time is increased significantly (on the order of 30 to 50 percent). Reverse commute directions are less affected. Peak-period volumes are reduced by about 15 percent, while off-peak travel is relatively unaffected. Total daily VMT is changed by less than 0.01 percent. Total emissions of THC, CO, and NO_X are reduced by 0.2 to 0.4 percent.

The net effect of closing the freeway lane is to reduce daily vehicle emissions by 0.2 to 0.4 percent.

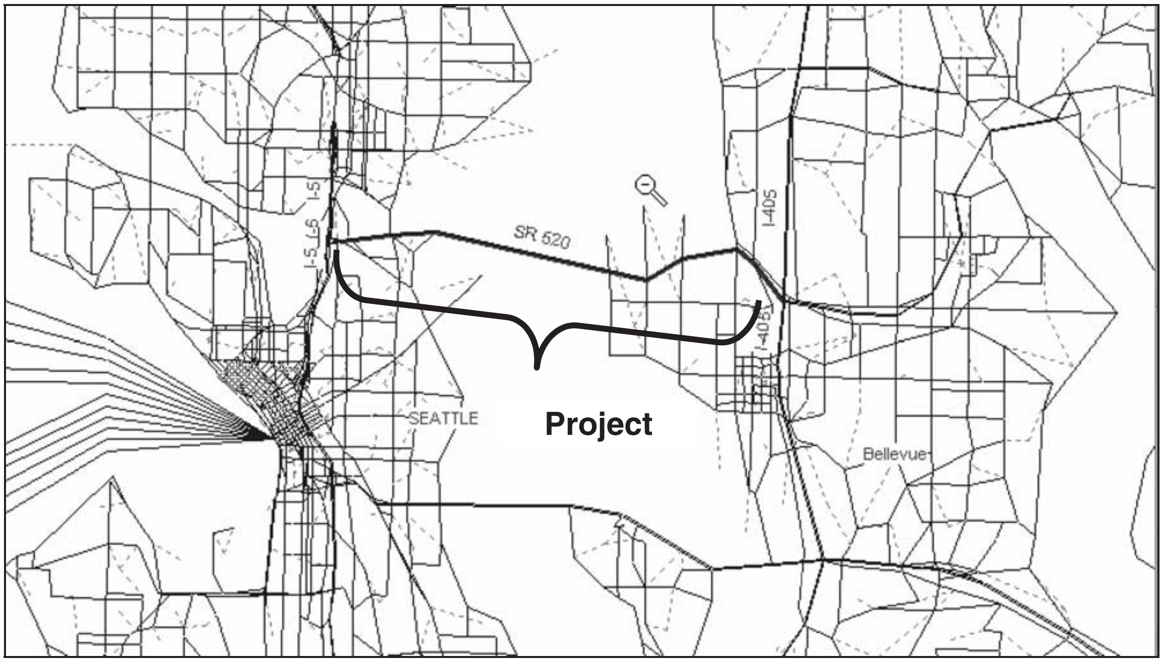


Figure 7. Case Study 2: Delete lane from SR 520 Evergreen Point Bridge.

TABLE 24 Case Study 2: Travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.45	48.5	8.55	0.78	47.9	8.62
	After	0.61	44.7	9.28	0.94	43.6	11.19
	Difference	0.16	-3.7	0.73	0.17	-4.3	2.57
	% Difference	36.05%	-7.72%	8.54%	21.48%	-8.98%	29.81%
PM Peak	Before	0.82	48.5	8.55	0.66	47.9	8.62
	After	0.92	45.1	13.22	0.93	47.3	8.72
	Difference	0.10	-3.4	4.67	0.27	-0.6	0.10
	% Difference	12.22%	-6.93%	54.62%	41.69%	-1.25%	1.16%
Off Peak	Before	0.32	48.5	8.55	0.32	47.9	8.62
	After	0.47	48.5	8.55	0.48	47.9	8.62
	Difference	0.16	0.0	0.00	0.16	0.0	0.00
	% Difference	49.73%	0.00%	0.00%	49.71%	0.00%	0.00%

TABLE 25 Case Study 2: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	EB	7,445	6,755	-691	-9.28%
	WB	12,808	10,372	-2,435	-19.02%
	TOT	20,253	17,127	-3,126	-15.43%
PM Peak	EB	13,495	10,097	-3,398	-25.18%
	WB	10,835	10,236	-600	-5.53%
	TOT	24,330	20,333	-3,998	-16.43%
Off Peak	EB	31,369	31,314	-56	-0.18%
	WB	31,526	31,465	-62	-0.20%
	TOT	62,896	62,778	-117	-0.19%
Total	EB	52,310	48,165	-4,144	-7.92%
	WB	55,170	52,073	-3,097	-5.61%
	TOT	107,479	100,238	-7,241	-6.74%

TABLE 26 Case Study 2: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO$_X$ (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,156,500	381,945	31.8			
	PM Peak	15,259,800	519,266	29.4			
	Off Peak	37,207,400	1,179,100	31.6			
	Total	64,623,700	2,080,311	31.1	44,914,702	712,081,618	46,184,899
Difference		300	1,349	0.0	-85,484	-1,983,263	-171,980
% Difference		0.00%	0.06%	-0.06%	-0.19%	-0.28%	-0.37%

CHAPTER 11

CASE STUDY 3A: REMOVE FREEWAY HOV LANE

Case Study 3a removes the freeway HOV lanes (one HOV lane in each direction) from a freeway in an urban area. The freeway is uncongested before and after the removal of the lanes.

The specific location for this case study is a 2.1-mile-long section of the I-405 freeway between the S.E. 181st and SR 169 interchanges in Renton, Washington (see Figure 8).

11.1 APPLICATION

The I-405 freeway mainline has

- Four lanes in each direction with a 45-mph free-flow speed and a 1,800-vph/lane capacity and
- An HOV lane in each direction with a 60-mph free-flow speed and a 1,500-vph/lane capacity.

In this project, the HOV lanes in both directions are removed. Thus, the section now has four lanes in each direction and no HOV lane.

11.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 27 through 29.

This case study illustrates the impacts of closing the HOV lanes on an existing, uncongested freeway. The action has no significant effect on speeds and travel times for the mixed-flow lanes, but because it closes an HOV facility, there is a significant effect on facility volumes. Peak-period volumes on the freeway increase by 12 to 20 percent. Daily volumes are increased by slightly less than 10 percent.

Total regional VMT is increased by 0.02 percent, but mobile source emissions are decreased by 0.02 to 0.04 percent. The slight speed increase appears to have overcome the slight VMT increase. This may be the result of a model coding practice that gives the HOV lane lower free-flow speeds and capacities than mixed-flow lanes on a freeway. Fewer HOVs in the HOV lanes may have slightly boosted the regional mean speed of all traffic.

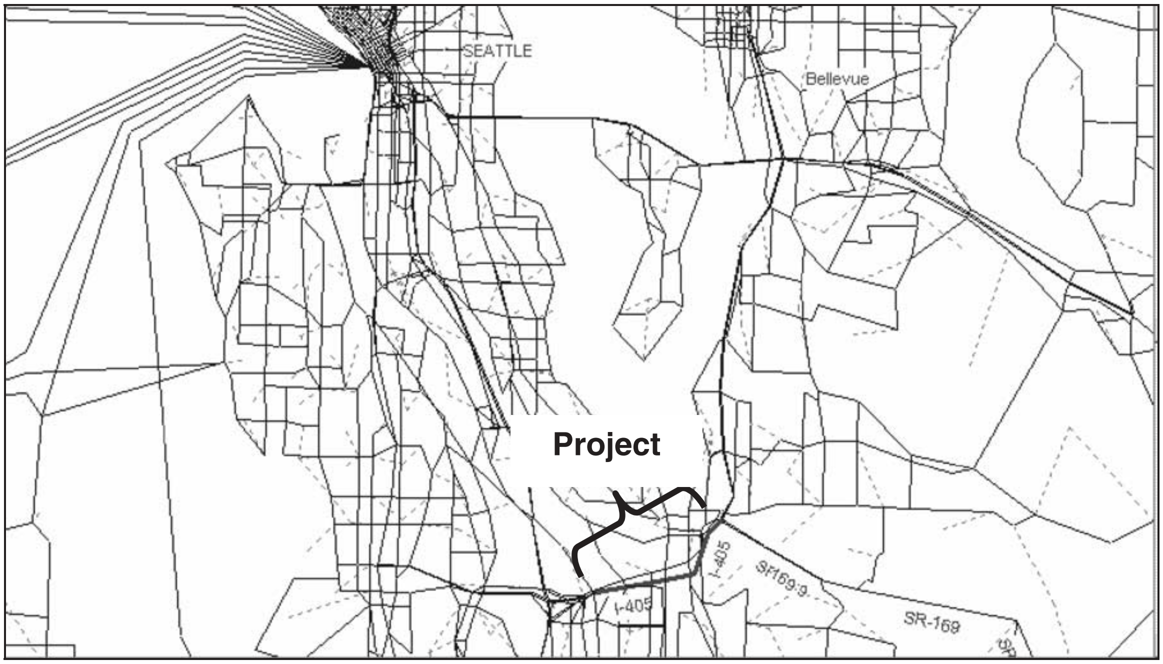


Figure 8. Case Study 3a: I-405 Renton.

TABLE 27 Case Study 3a: Travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.46	43.0	4.18	0.64	43.2	4.14
	After	0.58	43.0	4.18	0.74	43.2	4.14
	Difference	0.12	0.0	0.00	0.10	0.0	0.00
	% Difference	25.58%	0.00%	0.00%	16.43%	0.00%	0.00%
PM Peak	Before	0.81	43.0	4.18	0.75	43.2	4.14
	After	0.89	43.0	4.18	0.86	43.2	4.14
	Difference	0.08	0.0	0.00	0.10	0.0	0.00
	% Difference	10.11%	0.00%	0.00%	13.76%	0.00%	0.00%
Off Peak	Before	0.32	43.0	4.18	0.31	43.2	4.14
	After	0.34	43.0	4.18	0.32	43.2	4.14
	Difference	0.02	0.0	0.00	0.02	0.0	0.00
	% Difference	5.72%	0.00%	0.00%	5.98%	0.00%	0.00%

TABLE 28 Case Study 3a: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	EB	9,991	12,547	2,556	25.58%
	WB	13,718	15,972	2,254	16.43%
	TOT	23,709	28,519	4,810	20.29%
PM Peak	EB	17,410	19,171	1,761	10.11%
	WB	16,305	18,547	2,243	13.76%
	TOT	33,714	37,718	4,004	11.87%
Off Peak	EB	41,681	44,063	2,383	5.72%
	WB	39,612	41,980	2,369	5.98%
	TOT	81,292	86,043	4,751	5.84%
Total	EB	69,081	75,780	6,699	9.70%
	WB	69,635	76,500	6,865	9.86%
	TOT	138,716	152,280	13,564	9.78%

TABLE 29 Case Study 3a: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,157,300	381,813	31.8			
	PM Peak	15,264,100	517,755	29.5			
	Off Peak	37,212,500	1,179,300	31.6			
	Total	64,633,900	2,078,868	31.1	44,988,995	713,780,208	46,344,037
Difference		10,500	-94	0.0	-11,191	-284,673	-12,842
% Difference		0.02%	0.00%	0.02%	-0.02%	-0.04%	-0.03%

CHAPTER 12

CASE STUDY 3B: REMOVE FREEWAY HOV LANE

Case Study 3b removes the freeway HOV lanes (one HOV lane in each direction) from a freeway in an urban area. The freeway is uncongested before removal and becomes congested after the removal of the lanes.

The specific location for this case study is a 2-mile-long section of the Interstate 5 freeway feeding downtown Seattle, Washington (see Figure 9).

12.1 APPLICATION

The I-5 freeway mainline has four lanes in each direction with a 45-mph free-flow speed and 1,800-vph/lane capacity and an HOV lane in each direction with a 60-mph free-flow speed and a 1,500-vph/lane capacity. In this project, the HOV lanes in both directions are removed. Thus, the section now has four lanes in each direction and no HOV lane.

12.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 30 through 32.

This case study illustrates the impacts of closing an HOV facility on a freeway that is near capacity. The effect is to increase congestion on the freeway in the mixed-flow lanes in the peak direction of travel (reverse commute is generally unaffected).

The travel time in the peak direction is increased from 6 to 50 percent during the peak periods. Peak-period traffic (HOV plus SOV) on the facility is reduced by almost 10 percent.

The result of the HOV lane closure is a 0.02-percent reduction in regional daily VMT and a 0.06-percent reduction in mobile source emissions.

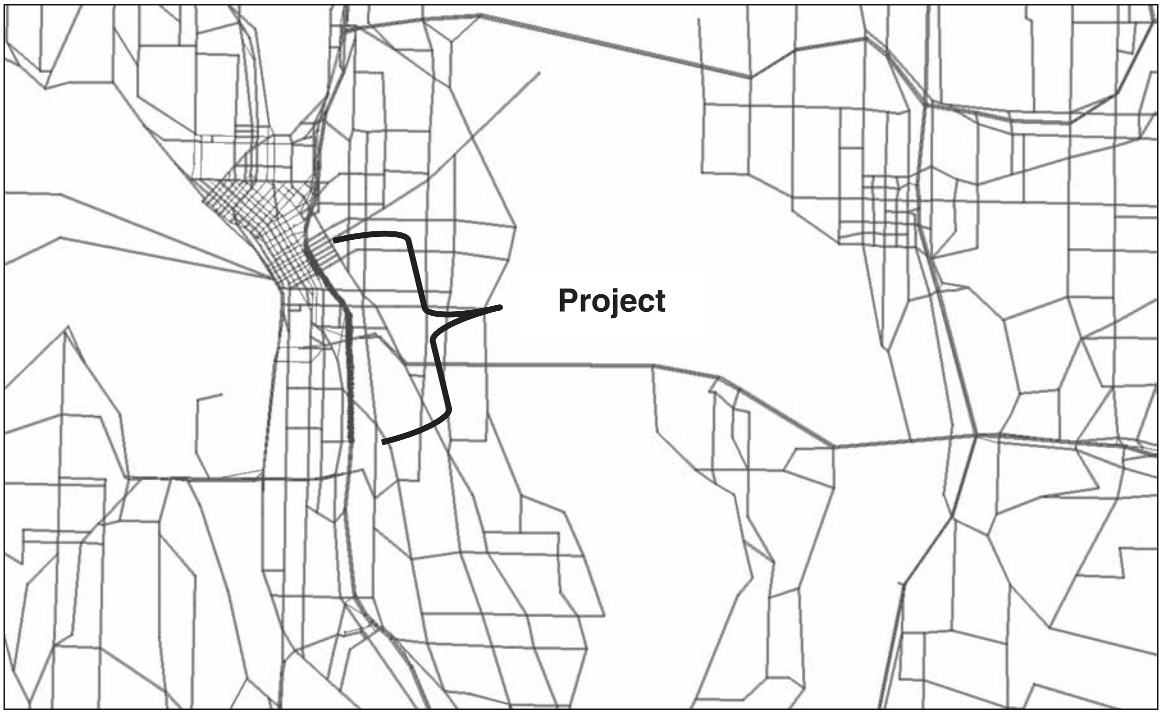


Figure 9. Case Study 3b: Remove HOV lanes from I-5.

TABLE 30 Case Study 3b: Travel time changes on the facility

Period	Scenario	NB			SB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.90	35.7	3.84	0.57	36.6	3.70
	After	0.94	35.0	4.06	0.67	36.6	3.70
	Difference	0.04	-0.7	0.22	0.10	0.0	0.00
	% Difference	4.66%	-1.84%	5.73%	18.01%	0.00%	0.00%
PM Peak	Before	0.71	37.1	3.61	0.91	36.6	3.70
	After	0.82	37.1	3.61	0.96	31.4	5.44
	Difference	0.11	0.0	0.00	0.05	-5.2	1.74
	% Difference	15.69%	0.00%	0.00%	5.32%	-14.21%	47.03%
Off Peak	Before	0.39	37.1	3.61	0.36	36.6	3.70
	After	0.46	37.1	3.61	0.42	36.6	3.70
	Difference	0.07	0.0	0.00	0.06	0.0	0.00
	% Difference	19.30%	0.00%	0.00%	17.71%	0.00%	0.00%

TABLE 31 Case Study 3b: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	NB	22,667	19,439	-3,229	-14.24%
	SB	14,256	13,809	-447	-3.14%
	TOT	36,923	33,248	-3,676	-9.96%
PM Peak	NB	17,771	16,865	-906	-5.10%
	SB	22,799	19,706	-3,093	-13.57%
	TOT	40,570	36,571	-3,999	-9.86%
Off Peak	NB	57,936	56,577	-1,359	-2.35%
	SB	54,086	52,309	-1,777	-3.29%
	TOT	112,022	108,886	-3,136	-2.80%
Total	NB	98,374	92,881	-5,493	-5.58%
	SB	91,141	85,824	-5,317	-5.83%
	TOT	189,515	178,705	-10,810	-5.70%

TABLE 32 Case Study 3b: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Period	12,151,000	381,565	31.8			
	PM Period	15,254,600	517,364	29.5			
	Off-Peak	37,205,400	1,179,400	31.5			
	Total	64,611,000	2,078,329	31.1	44,973,564	713,524,692	46,320,617
Difference		-12,400	-633	0.0	-26,622	-540,189	-36,262
% Difference		-0.02%	-0.03%	0.01%	-0.06%	-0.08%	-0.08%

CHAPTER 13

CASE STUDY 4: NARROW STREET

Case Study 4 removes a single through lane from each direction of an uncongested suburban highway. The specific location for this case study is a 10.1-mile-long section of State Route 169 between I-405 and SR 18 near Renton, Washington (see Figure 10).

13.1 APPLICATION

The project removes one mixed-flow lane in each direction to SR169, the Renton-Maple Valley Highway. Before the case study changes, SR 169 has a single-lane HOV and two lanes in each direction. Thus, the project results in the section having one mixed-flow lane and a single HOV lane in each direction.

13.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 33 through 35.

This case study illustrates the impacts of removing a mixed-flow lane in each direction from a rural highway that is near capacity. The effect is to cause modest congestion in the peak direction of travel during each peak period. Peak-period travel times increase 6 to 10 percent in the peak directions only. Total daily traffic volumes drop about 7 percent. The net effect of the lane removal on regional VMT and emissions is less than 0.01 percent.

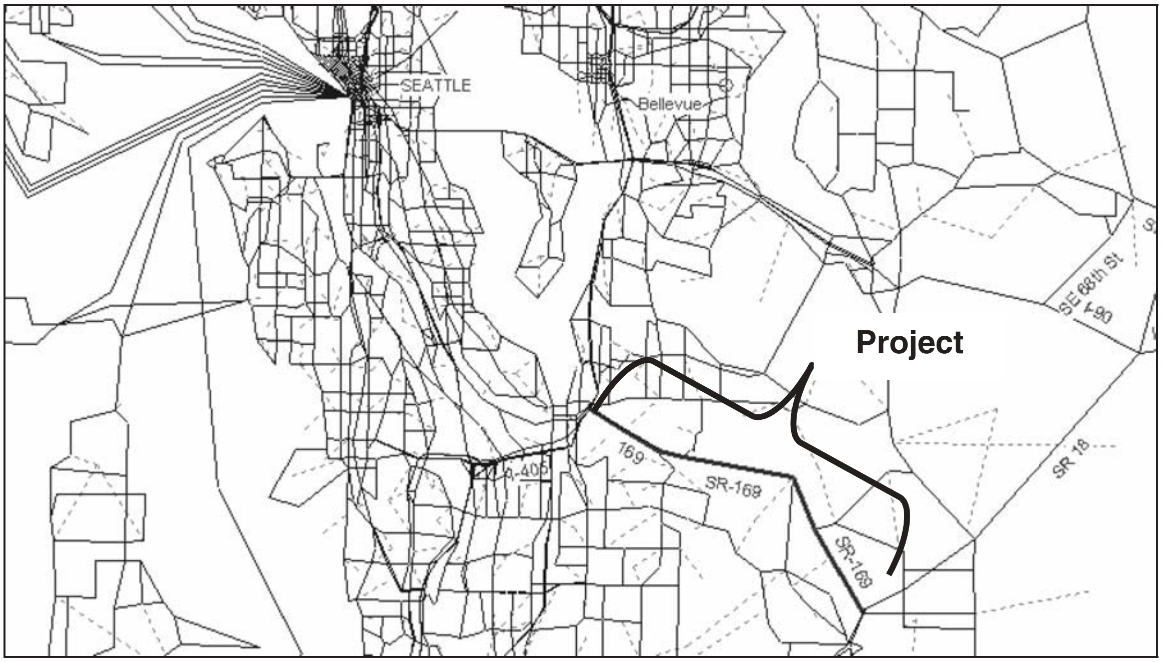


Figure 10. Case Study 4: Remove through lane from SR 169.

TABLE 33 Case Study 4: Travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.07	35.8	17.19	0.30	35.7	17.22
	After	0.13	35.8	17.19	0.47	32.8	18.25
	Difference	0.07	0.0	0.00	0.18	-2.9	1.03
	% Difference	100.22%	0.00%	0.00%	59.59%	-8.22%	5.98%
PM Peak	Before	0.29	35.8	17.19	0.13	35.7	17.22
	After	0.46	31.7	18.82	0.25	35.7	17.22
	Difference	0.18	-4.1	1.63	0.12	0.0	0.00
	% Difference	60.70%	-11.55%	9.48%	98.87%	0.00%	0.00%
Off Peak	Before	0.08	35.8	17.19	0.07	35.7	17.22
	After	0.16	35.8	17.19	0.14	35.7	17.22
	Difference	0.08	0.0	0.00	0.07	0.0	0.00
	% Difference	98.03%	0.00%	0.00%	98.00%	0.00%	0.00%

TABLE 34 Case Study 4: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	EB	568	568	0	-0.06%
	WB	2,517	2,002	-515	-20.47%
	TOT	3,085	2,569	-516	-16.71%
PM Peak	EB	2,464	1,976	-488	-19.81%
	WB	1,066	1,058	-8	-0.73%
	TOT	3,530	3,034	-496	-14.05%
Off Peak	EB	4,217	4,175	-42	-0.99%
	WB	3,728	3,690	-37	-1.00%
	TOT	7,944	7,865	-79	-0.99%
Total	EB	7,249	6,719	-530	-7.31%
	WB	7,311	6,750	-560	-7.66%
	TOT	14,559	13,469	-1,090	-7.49%

TABLE 35 Case Study 4: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,154,000	381,502	31.9			
	PM Peak	15,260,900	518,126	29.5			
	Off Peak	37,207,400	1,179,100	31.6			
	Total	64,622,300	2,078,728	31.1	44,998,481	714,063,588	46,356,164
Difference		-1,100	-234	0.0	-1,705	-1,293	-715
% Difference		0.00%	-0.01%	0.01%	0.00%	0.00%	0.00%

CHAPTER **14**

CASE STUDY 5: ACCESS MANAGEMENT

Case Study 5 tests the impacts of converting a suburban highway into a limited-access expressway. The specific location for this case study is a 10.1-mile-long section of State Route 169 between I-405 and SR 18 near Renton, Washington (see Figure 11).

14.1 APPLICATION

The stretch of SR 169 is a suburban highway with few signalized intersections and frequent driveways to access fronting land uses. The access management project includes median barriers the length of the expressway (thus enabling increased speeds) with signalized intersections at median breaks to serve fronting land uses and allow U-turns. The more frequent signalized intersections and the concentration of access at these intersections result in less green time available for through traffic on the expressway, thus reducing capacity. However, this reduced capacity is counterbalanced by increased speeds between intersections with the elimination of fronting access to the facility except at the signalized intersections.

SR 169 has two lanes in each direction. The section between I-405 and 140th Avenue SE is an urban arterial with added HOV lanes. The access management project was estimated to yield the following improvements:

- The capacity of the rural portion of the route was reduced from 1,500 vph/lane to 1,200 vph/lane to account for the effects of adding traffic signals to the rural unsignalized intersections.
- The free-flow speed for the entire length of the route was increased from 34 mph to 40 mph to account for the greater speeds possible with expressway operations.

14.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 36 through 38.

This case study illustrates the impacts of improving facility speed and capacity through access control of fronting development driveways and side streets. Unlike the earlier case studies, both peak-period and daily travel times are improved by over 10 percent. Daily traffic on the facility is increased 67 percent.

The net effect of the access control improvements is to increase regional VMT by less than 0.01 percent. However, the traffic-flow smoothing effects of the project cause a reduction in regional emissions of 0.02 to 0.04 percent.

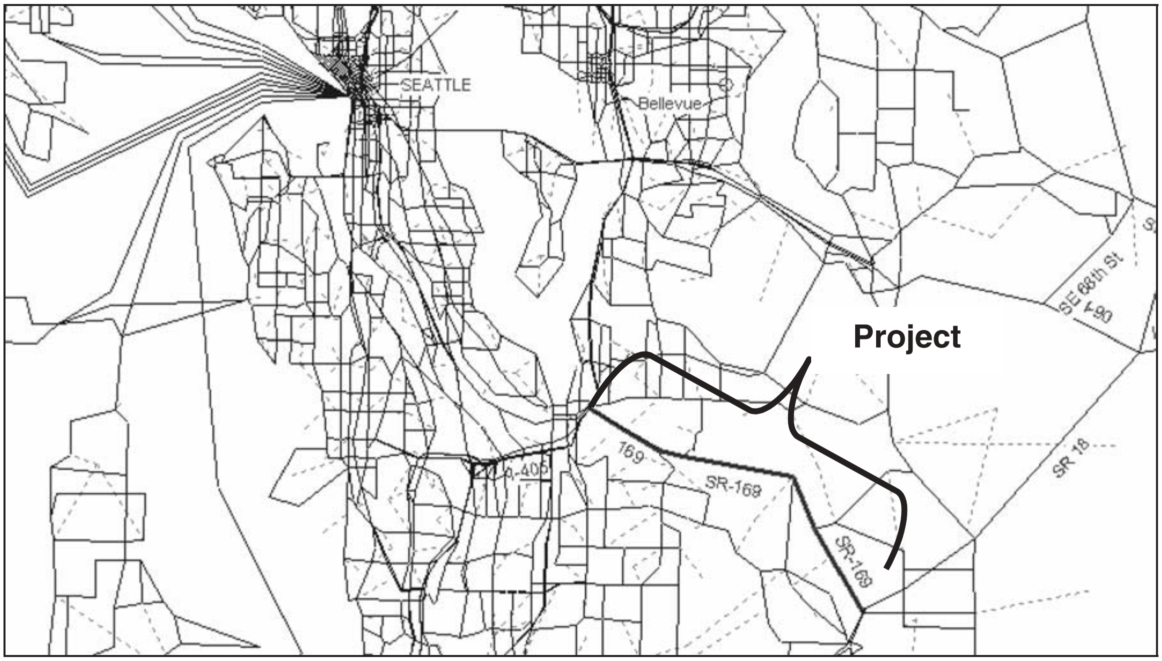


Figure 11. Case Study 5: SR-169 access management.

TABLE 36 Case Study 5: Travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.07	35.8	17.19	0.30	35.7	17.22
	After	0.12	39.8	15.15	0.62	39.7	15.18
	Difference	0.06	4.0	-2.04	0.33	4.0	-2.04
	% Difference	82.61%	11.18%	-11.87%	110.86%	11.20%	-11.85%
PM Peak	Before	0.29	35.8	17.19	0.13	35.7	17.22
	After	0.56	39.8	15.15	0.24	39.7	15.18
	Difference	0.28	4.0	-2.04	0.12	4.0	-2.04
	% Difference	95.12%	11.18%	-11.87%	94.76%	11.20%	-11.85%
Off Peak	Before	0.08	35.8	17.19	0.07	35.7	17.22
	After	0.16	39.8	15.15	0.15	39.7	15.18
	Difference	0.08	4.0	-2.04	0.07	4.0	-2.04
	% Difference	92.60%	11.18%	-11.87%	103.51%	11.20%	-11.85%

TABLE 37 Case Study 5: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	EB	568	878	310	54.64%
	WB	2,517	4,492	1,975	78.48%
	TOT	3,085	5,370	2,286	74.09%
PM Peak	EB	2,464	4,063	1,599	64.91%
	WB	1,066	1,753	687	64.45%
	TOT	3,530	5,817	2,287	64.77%
Off Peak	EB	4,217	6,794	2,578	61.13%
	WB	3,728	6,354	2,626	70.45%
	TOT	7,944	13,148	5,204	65.50%
Total	EB	7,249	11,736	4,487	61.90%
	WB	7,311	12,599	5,288	72.34%
	TOT	14,559	24,335	9,776	67.14%

TABLE 38 Case Study 5: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,152,800	381,263	31.9			
	PM Peak	15,260,400	517,202	29.5			
	Off Peak	37,211,700	1,179,000	31.6			
	Total	64,624,900	2,077,465	31.1	44,983,926	713,840,873	46,349,753
Difference		1,500	-1,497	0.0	-16,260	-224,008	-7,126
% Difference		0.00%	-0.07%	0.07%	-0.04%	-0.03%	-0.02%

CHAPTER 15

CASE STUDY 6: INTERSECTION CHANNELIZATION

Case Study 6 consists of the addition of left-turn and right-turn lanes to all four approaches of an urban intersection at Martin Luther King Jr. Way and Rainer Avenue in Seattle (see Figure 12).

15.1 APPLICATION

The addition of left-turn and right-turn lanes in the case study were coded as a 20-percent increase in the capacity on each approach. Before the improvement, all the approaches to the intersection had two lanes and a capacity of 1,300 vph other than the northbound approach, which had a capacity of 1,400 vph. After a 20-percent increase in capacity, the northbound approach has a capacity of 1,650 vph, and all the other approaches have a capacity of 1,550 vph, while the speed and number of lanes is unchanged.

15.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 39 through 43.

This case study shows the impacts of intersection channelization improvements at an uncongested intersection. The channelization improvements result in travel time improvements of below the threshold of detectability for the methodology. The result is no change in predicted traffic volumes for the intersection, no predicted changes in regional VMT, and no predicted changes in regional emissions.

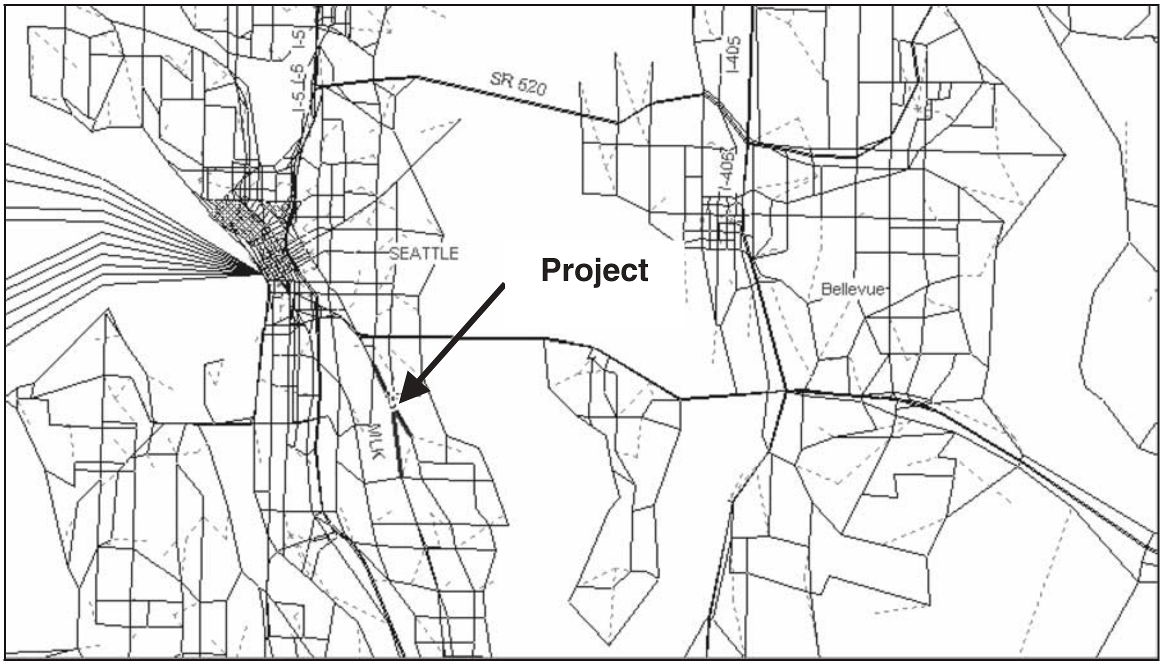


Figure 12. Case Study 6: Intersection of MLK Jr. Way and Rainer Avenue in Seattle.

TABLE 39 Case Study 6: North/south travel time changes on the facility

Period	Scenario	NB			SB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.04	31.4	2.55	0.04	31.4	2.55
	After	0.03	31.4	2.55	0.03	31.4	2.55
	Difference	0.00	0.0	0.00	0.00	0.0	0.00
	% Difference	-9.68%	0.00%	0.00%	-8.92%	0.00%	0.00%
PM Peak	Before	0.05	31.4	2.55	0.05	31.4	2.55
	After	0.05	31.4	2.55	0.04	31.4	2.55
	Difference	0.00	0.0	0.00	0.00	0.0	0.00
	% Difference	-8.59%	0.00%	0.00%	-7.07%	0.00%	0.00%
Off Peak	Before	0.02	31.4	2.55	0.02	31.4	2.55
	After	0.02	31.4	2.55	0.02	31.4	2.55
	Difference	0.00	0.0	0.00	0.00	0.0	0.00
	% Difference	-9.01%	0.00%	0.00%	-7.59%	0.00%	0.00%

TABLE 40 Case Study 6: East/west travel time changes on the facility

Period	Scenario	EB			WB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.10	31.9	2.40	0.28	32.0	2.40
	After	0.09	31.9	2.40	0.26	32.0	2.40
	Difference	-0.01	0.0	0.00	-0.02	0.0	0.00
	% Difference	-8.04%	0.00%	0.00%	-8.21%	0.00%	0.00%
PM Peak	Before	0.32	31.9	2.40	0.17	32.0	2.40
	After	0.30	31.9	2.40	0.15	32.0	2.40
	Difference	-0.02	0.0	0.00	-0.01	0.0	0.00
	% Difference	-7.66%	0.00%	0.00%	-8.31%	0.00%	0.00%
Off Peak	Before	0.10	31.9	2.40	0.09	32.0	2.40
	After	0.10	31.9	2.40	0.09	32.0	2.40
	Difference	-0.01	0.0	0.00	-0.01	0.0	0.00
	% Difference	-7.87%	0.00%	0.00%	-8.24%	0.00%	0.00%

TABLE 41 **Case Study 6: North/south volume changes on the facility**

Period	Direction	Before	After	Difference	%Difference
AM Peak	NB	302	302	0	0.00%
	SB	286	286	0	0.00%
	TOT	588	588	0	0.00%
PM Peak	NB	446	446	0	0.00%
	SB	373	373	0	0.00%
	TOT	819	819	0	0.00%
Off Peak	NB	1,153	1,153	0	0.00%
	SB	943	943	0	0.00%
	TOT	2,096	2,096	0	0.00%
Total	NB	1,901	1,901	0	0.00%
	SB	1,601	1,601	0	0.00%
	TOT	3,502	3,502	0	0.00%

TABLE 42 **Case Study 6: East/west volume changes on the facility**

Period	Direction	Before	After	Difference	%Difference
AM Peak	EB	799	799	0	0.00%
	WB	2,192	2,192	0	0.00%
	TOT	2,991	2,991	0	0.00%
PM Peak	EB	2,522	2,522	0	0.00%
	WB	1,298	1,298	0	0.00%
	TOT	3,820	3,820	0	0.00%
Off Peak	EB	4,880	4,880	0	0.00%
	WB	4,446	4,446	0	0.00%
	TOT	9,326	9,326	0	0.00%
Total	EB	8,201	8,201	0	0.00%
	WB	7,935	7,935	0	0.00%
	TOT	16,136	16,136	0	0.00%

TABLE 43 **Case Study 6: Regional results**

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
Difference		0	0	0.0	0	0	0
% Difference		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

CHAPTER 16

CASE STUDY 7: SIGNAL COORDINATION

Case Study 7 tests the impacts of a 0.5-mile-long arterial signal coordination project that increases mean speeds by 10 percent. The specific location for this case study is Montblake Boulevard, at the University of Washington in Seattle (see Figure 13). The project consists of six signals over 0.54 miles.

16.1 APPLICATION

The signal coordination project is coded as a 10-percent improvement in the free-flow speed. No capacity changes were made.

16.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Tables 44 through 46.

This case study illustrates the impacts of the optimization of signal coordination for a 0.5-mile section of urban arterial. The improvements provide a 9-percent reduction in travel times for the peak direction of the peak periods and a similar reduction for both directions during the off-peak period. Daily traffic on the facility is predicted to increase by 27 percent.

The net effect on regional travel is to reduce regional VMT by 0.01 percent and to reduce regional emissions by 0.02 to 0.04 percent.

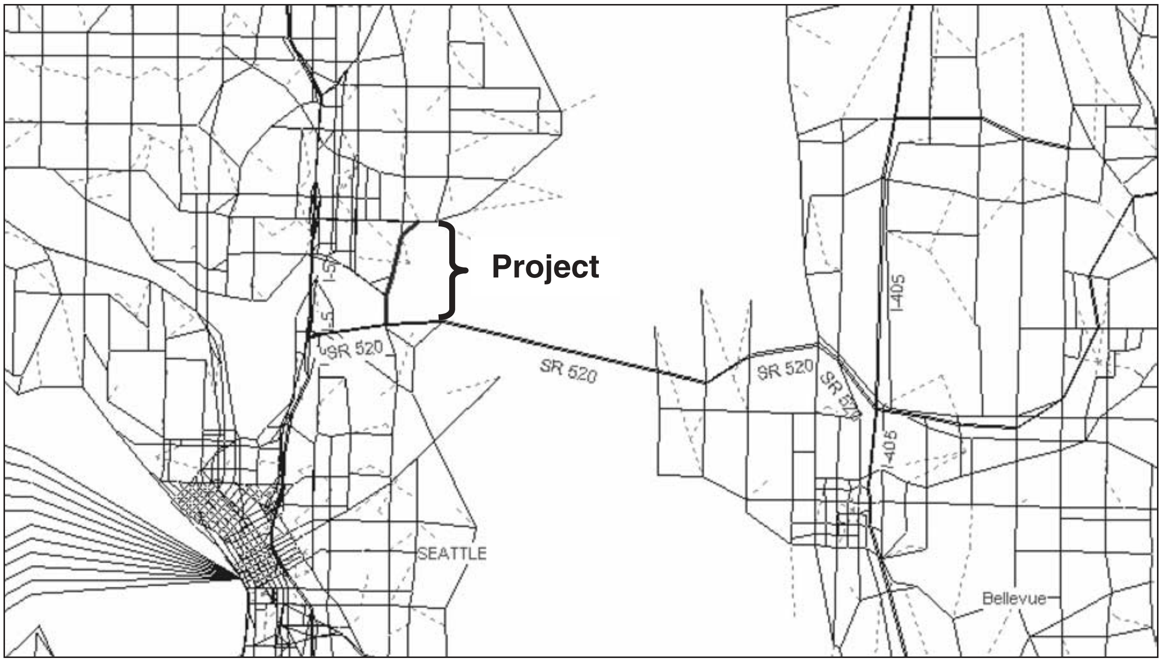


Figure 13. Case Study 7: Montblake Boulevard, Seattle.

TABLE 44 Case Study 7: Travel time changes on the facility

Period	Scenario	NB			SB		
		V/C	Speed (mph)	Time (min)	V/C	Speed (mph)	Time (min)
AM Peak	Before	0.39	17.0	5.30	0.39	18.5	4.31
	After	0.42	18.6	5.10	0.64	20.4	3.92
	Difference	0.02	1.7	-0.20	0.25	1.9	-0.39
	% Difference	6.00%	9.72%	-3.77%	63.10%	10.00%	-9.05%
PM Peak	Before	0.50	18.5	4.33	0.43	16.2	6.60
	After	0.54	20.3	3.94	0.45	17.6	6.68
	Difference	0.04	1.8	-0.39	0.02	1.4	0.08
	% Difference	8.91%	9.88%	-9.01%	5.07%	8.47%	1.21%
Off Peak	Before	0.21	18.5	4.33	0.20	18.5	4.31
	After	0.22	20.3	3.94	0.32	20.4	3.92
	Difference	0.01	1.8	-0.39	0.12	1.9	-0.39
	% Difference	5.13%	9.88%	-9.01%	58.64%	10.00%	-9.05%

TABLE 45 Case Study 7: Volume changes on the facility

Period	Direction	Before	After	Difference	%Difference
AM Peak	NB	2,167	2,297	130	6.00%
	SB	2,262	3,666	1,405	62.10%
	TOT	4,428	5,963	1,535	34.65%
PM Peak	NB	2,801	3,048	248	8.84%
	SB	2,401	2,538	137	5.68%
	TOT	5,202	5,586	384	7.38%
Off Peak	NB	7,091	7,455	364	5.13%
	SB	6,719	10,697	3,978	59.20%
	TOT	13,811	18,152	4,341	31.43%
Total	NB	12,059	12,800	741	6.15%
	SB	11,382	16,901	5,519	48.48%
	TOT	23,441	29,700	6,260	26.70%

TABLE 46 Case Study 7: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,150,900	381,266	31.9			
	PM Peak	15,259,400	517,865	29.5			
	Off Peak	37,204,700	1,176,500	31.6			
	Total	64,615,000	2,075,631	31.1	44,983,926	713,840,873	46,349,753
Difference		-8,400	-3,331	0.0	-16,260	-224,008	-7,126
% Difference		-0.01%	-0.16%	0.15%	-0.04%	-0.03%	-0.02%

CHAPTER 17

CASE STUDY 8: TRANSIT IMPROVEMENT

Case Study 8 involves doubling the frequency of bus line 7B (PSRC Model Line 4007), providing bus service on Broadway between Downtown Seattle and South Rainier Beach. This bus line extends for 23.55 route-miles (see Figure 14).

17.1 APPLICATION

Before improvement, the bus service operated at 30-minute peak-hour headways, with a mean speed of 15 mph. After improvement, the peak-hour headway was cut from 30 minutes to 15 minutes. Note that the service improvements were meant to apply to both the AM peak and PM peak hours. However, in the PSRC model, transit trips outside of the AM peak hour are not assigned to specific transit lines. Consequently, the test of the PM peak-hour service improvements could not be made with the available PSRC model database. (However, one option for overcoming this limitation of the database would have been to take the AM peak-hour impacts of the project and double them to approximate the combined AM and PM peak-hour impacts.)

17.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. Facility-specific results were not computed. The regional impacts of the transit service improvements were found to be negligible within the precision of the reported results. There were no significant differences in VMT or emissions.

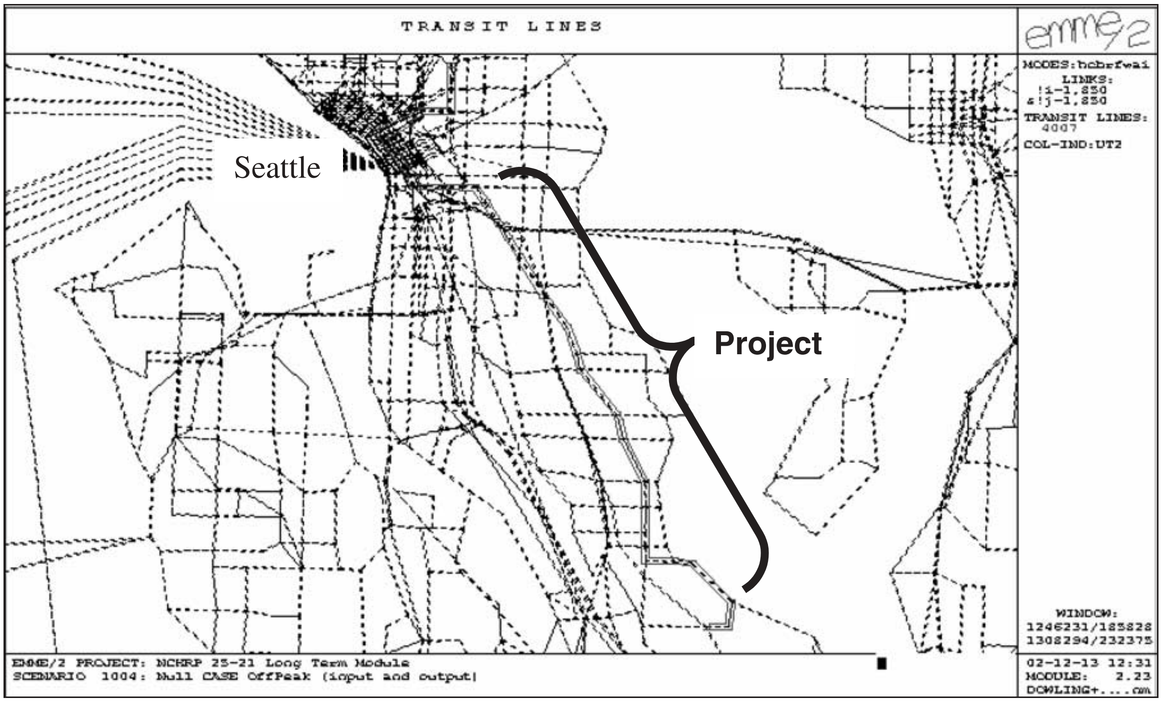


Figure 14. Case Study 8: Transit improvement.

CHAPTER 18

CASE STUDY 9: REMOVE PARK-AND-RIDE LOT

Case Study 9 looks at the impacts of removing a bus rapid transit park-and-ride lot from a critical freeway facility feeding downtown Seattle. The park-and-ride lot is located on SR 520 at Hunts Point, about 2.5 miles west of I-405 (see Figure 15).

18.1 APPLICATION

The park-and-ride lot is located at node 890 in the PSRC model. The lot is effectively removed from the model by disallowing the use of mode *i* (auxiliary auto mode) on the centroid connector from Node 890 to Node 3126.

18.2 CASE STUDY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of the traffic-flow improvement on the 2020 base case trip tables by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the improved network to determine the impact on VMT, VHT, and emissions. The results are summarized in Table 47. Facility-specific results were not tabulated.

The results show that eliminating the park-and-ride lot would increase daily VMT by 0.14 percent. Regional vehicle emissions would be increased by slightly less than 0.1 percent. These results show that in this case, construction of a park-and-ride lot at this location would result in net reductions in VMT and vehicle emissions.

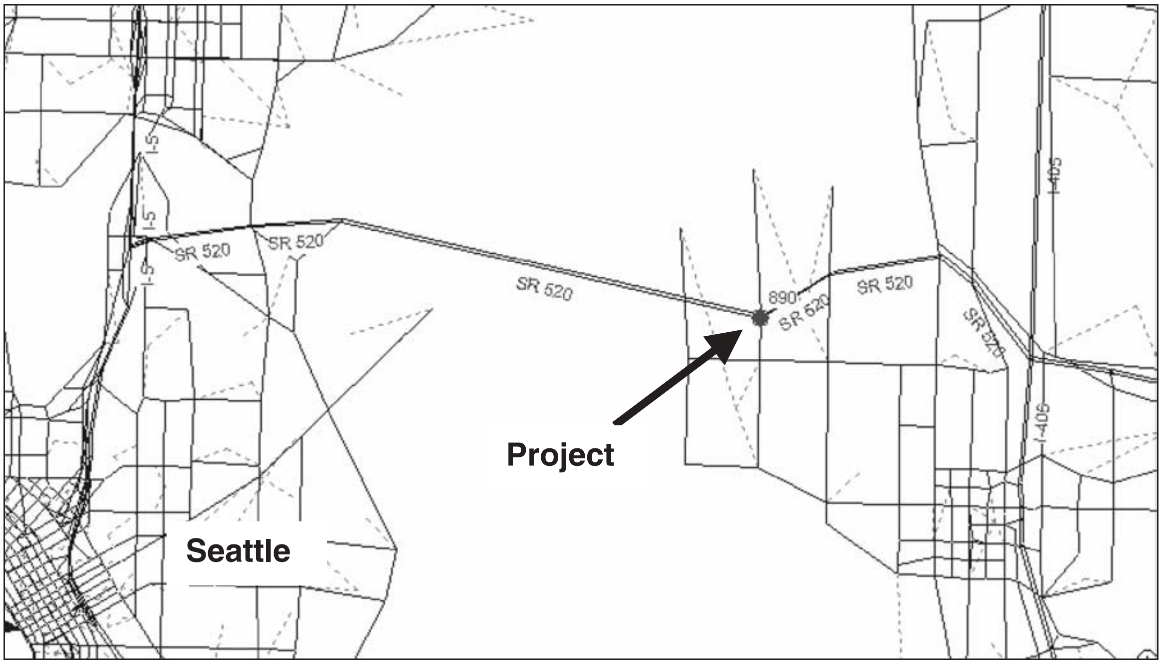


Figure 15. Case Study 9: Remove park-and-ride lot.

TABLE 47 Case Study 9: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
Before	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
After	AM Peak	12,184,800	382,704	31.8			
	PM Peak	15,288,700	518,357	29.5			
	Off Peak	37,242,100	1,180,300	31.6			
	Total	64,715,600	2,081,361	31.1	45,041,575	714,679,954	46,393,679
Difference		92,200	2,399	0.0	41,389	615,073	36,800
% Difference		0.14%	0.12%	0.03%	0.09%	0.09%	0.08%

CHAPTER 19

CASE STUDY 10: LONG-RANGE REGIONAL TRANSPORTATION PLAN

Case Study 10 involves the implementation of 30 years of transit and highway improvements in the Seattle region. The improvements include all improvements that actually occurred between 1990 and 2000, plus the planned improvements contained in the 20-year transportation plan from 2000 to 2020.

19.1 APPLICATION

Two PSRC highway networks (1990 and 2020) were compared to obtain the transportation system improvements that occurred between 1990 and 2000, plus the improvements planned between 2000 and 2020. The 2020 highway network has 11 percent more centerline-miles of road and 13 percent more capacity than the 1990 network (see Table 48).

The 2020 highway network has the following traffic-flow improvements over the 1990 network:

- New freeway HOV lanes,
- Freeway mixed-flow lane additions,
- New freeway sections,
- Urban street lane additions,
- New urban streets,
- Rural road lane additions, and
- New rural roads.

The 2020 transit network has 32 percent more transit vehicles and 21 percent more route-miles than the 1990 network (see Table 49).

The 2020 transit network has the following transit service improvements over the 1990 network:

- New transit lines,
- Frequency increases for existing service,
- Extensions of existing transit lines,
- New park-and-ride lots, and
- New stations.

19.2 RESULTS OF PSRC MODEL RUNS

The base PSRC model was run on three scenarios:

- 1990 demand loaded on 1990 network,
- 2020 demand loaded on 1990 network, and
- 2020 demand loaded on 2020 network.

The resulting VMT and VHT are shown in Table 50. The PSRC model predicted that the 2020 highway and transit network improvements would result in a 4-percent increase in daily VMT and a 9-percent reduction in daily VHT for the region.

19.3 NCHRP 25-21 METHODOLOGY RESULTS

The NCHRP 25-21 methodology was used to compute the impacts of not building the 30-year improvement program. The impacts on the 2020 base case trip tables of retaining the 1990 network were predicted by time period (AM peak, PM peak, and off peak) and by mode (SOV, HOV, and transit). The revised trip tables were then reassigned to the 1990 network to determine the impact on VMT, VHT, and emissions. The results are summarized in Table 51.

In contrast with the standard PSRC model, which predicts that the 30-year improvement program would increase VMT, the NCHRP 25-21 methodology predicts that the 30-year program of transportation improvements would decrease VMT by 0.7 percent. The NCHRP 25-21 methodology furthermore predicts that emissions would be reduced by 6 to 7 percent.

TABLE 48 Case Study 10: Highway improvements 1990 to 2020

Network	Centerline-Miles	Lane-Miles	No. of Links	Capacity-Miles	Mean Free-Flow Speed (mph)
1990	10,266	15,704	15,171	17,802,716	21.2
2020	11,388	17,390	17,711	20,194,252	19.9
Difference	1,122	1,686	2540	2391536	-1.3
% Difference	10.9%	10.7%	16.7%	13.4%	-6.1%

TABLE 49 Case Study 10: Transit service improvements 1990 to 2020

Network	Transit Vehicles	Lines	Route-Miles
1990	972	448	8,065
2020	1,286	542	9,716
Difference	314	94	1,651
% Difference	32.3%	21.0%	20.5%

TABLE 50 Comparison of baseline VMT and VHT estimates by PSRC model

Scenario	Demand	Network	Period	VMT	VHT	MPH
#902	1990	1990	AM 3hr Peak	12,049,800	384,443	31.3
#903			PM 3hr Peak	15,085,000	498,400	30.3
#904			Off Peak	37,113,300	1,175,500	31.6
			Total Day	64,248,100	2,058,343	31.2
#1002	2020	1990	AM 3hr Peak	18,459,100	696,708	26.5
#1003			PM 3hr Peak	26,472,000	1,088,500	24.3
#1004			Off Peak	56,319,200	2,081,600	27.1
			Total Day	101,250,300	3,866,808	26.2
#2002	2020	2020	AM 3hr Peak	19,363,700	630,847	30.7
#2003			PM 3hr Peak	27,670,300	977,495	28.3
#2004			Off Peak	58,668,900	1,927,400	30.4
			Total Day	105,702,900	3,535,742	29.9
Difference				4,452,600	-331,066	
% Difference				4.4%	-8.6%	

Source: base case 2020 EMME2 databank, module 6.11.

Impact of Difference = (the results for the 2020 demand loaded on the 2020 network) – (the results for the 2020 demand loaded on the 1990 network).

TABLE 51 Case Study 10: Regional results

Scenario	Period	VMT (mi)	VHT (hrs)	Speed (mph)	THC (gm)	CO (gm)	NO_X (gm)
2020 Demand On 2020 Network	AM Peak	12,152,900	381,540	31.9			
	PM Peak	15,261,700	518,222	29.5			
	Off Peak	37,208,800	1,179,200	31.6			
	Total	64,623,400	2,078,962	31.1	45,000,186	714,064,881	46,356,879
2020 Demand On 1990 Network	AM Peak	12,313,300	446,992	27.5			
	PM Peak	15,432,600	642,538	24.0			
	Off Peak	37,331,500	1,200,800	31.1			
	Total	65,077,400	2,290,330	28.4	48,285,393	761,290,211	49,348,300
Difference		-454,000	-211,368	2.7	-3,285,207	-47,225,330	-2,991,421
% Difference		-0.70%	-10.17%	8.59%	-7.30%	-6.61%	-6.45%

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation