

Feederless Traction Power Design Considerations for New Streetcar Lines

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The construction of streetcar and electric trolley bus lines in urban areas poses some unique challenges regarding the installation of overhead contact systems (OCS). These considerations range from the aesthetics of a catenary system to costs for land procurement, high voltage feeds required by a typical substation, and possible extensive buried conduit. An integrated solution of both the overhead contact system and the traction power supply substations can be used to address these issues without the need for expensive feeders along the track.

Feederless power distribution systems have been developed and implemented effectively in both Portland and Seattle using novel solutions. The systems were designed independently but have similarities, which can be used as a basis for the installation of electric traction systems in other cities. Issues which were considered include

- Restriction of the OCS to a single contact wire;
- Use of existing 480 Vac supply power systems;
- Minimizing property procurement requirements;
- Minimizing the need for underground conduit;
- Minimizing stray currents and utility relocations; and
- Providing adequate power to operate electric vehicles.

Each of these issues will be described with specific examples of the how the challenges were addressed.

INTRODUCTION

The installation of new streetcar and electric trolley bus (ETB) systems in dense urban areas poses some design challenges which are not usually seen in rapid transit or LRT systems. Streetcars and ETBs operate almost exclusively in dense urban areas, while rapid transit and light rail normally operate with long open route sections and brief forays into downtown areas. The usual strategies employed with LRT systems—namely, providing power from the fringes of the downtown area with a low impedance distribution system and relocation of all utilities in the affected streets—are difficult and very expensive to implement on an exclusively urban system. In the Northwest, the Portland (Oregon) Streetcar and Seattle (Washington) Metro ETB systems have used some innovative strategies to address these challenges.

The Portland Streetcar system design began in 1998 with an electrification system typical of a light rail line. The system was conceptualized as a 2.5-mi (4-km) line using two or three 1

MW DC traction substations and a contact wire with parallel feeders to deliver power to the vehicles and control the voltage drop in the lines. During the preliminary engineering phase the difficulty of implementing this strategy quickly became apparent. The difficulty in siting the substations, design prohibitions on using a catenary system instead of a single contact wire, and stray current levels impacting utilities over the entire alignment would prove very expensive and extremely unpopular. The task of downsizing this system without reducing capacity or performance resulted in a number of the ideas presented in this paper.

The Seattle Metro ETB system consists of 60 route-mi (96 km) of two way traffic using overhead contact wire and 37 traction power substations. The nominal system voltage is 700 V DC. The original 55-mi (88-km) system was designed and constructed between 1975 and 1981 as part of the Trolley Overhead System and Substations Rehabilitation and Expansion Project. An additional 5 mi (8 km) were added within the last 7 years. The new extensions use a feederless system consisting of 4/0 AWG copper contact wire with 500 kW substations spaced about 5,000 to 8,000 ft (1,500 to 2,400 m) apart.

Several techniques have been utilized to meet these challenges in both the Portland Streetcar and Seattle Metro Trolley Bus systems. The following six areas are discussed in this paper with examples:

- Restriction of the overhead design to a single contact wire;
- Use of existing utility power distribution systems;
- Minimization of property acquisition requirements;
- Minimization of underground conduit requirements;
- Minimization of stray currents and utility relocations; and
- Delivery of adequate power to the transit vehicles.

SINGLE CONTACT WIRE DESIGN

The single contact wire design seems to be every urban planner's overhead contact systems (OCS) preference. (That is, if they have to have a wire at all.) While it can be argued that the general public will not notice the overhead conductors, the concept of a single contact wire seems to arise in every urban area as a matter of aesthetics. From an engineering viewpoint, the single wire design is attractive for its design simplicity and lower cost.

The main concern with using only a single contact wire is the higher impedance and subsequent voltage drops which result from moving large amounts of current. Doing so through a single wire over a long period of time may also result in overheating of the wire and annealing of the copper if the sizing is not correct.

LRT systems constructed with a single contact wire generally use along-track underground feeder cables typically sized from 500 to 750 kcmil. The other option is a full catenary, often with a reduced system height referred to as a low profile catenary. The difference in line resistance is significant. With a full catenary system (300 kcmil contact wire and a 500 kcmil messenger) the resulting resistance is 0.071 ohm per mi (0.044 ohm per km). The underground feeder systems (300 kcmil contact wire with a parallel underground 750 kcmil feeder) result in a resistance of 0.054 ohm per mi (0.034 ohm per km). By contrast, a single 300 kcmil contact wire yields a resistance of 0.188 ohm per mi (0.117 ohm per km), or three times the line resistance of a typical LRT system.

On the Portland Streetcar alignment this challenge was met by shrinking the distance between substations to 0.5 mi (0.8 km) instead of a typical LRT spacing of 1 mi (1.6 km). This effectively reduces the maximum distance from a substation to one half that seen on an LRT system, approximately 1320 ft (400 m), and consequently reduces the line resistance by half. Additionally, for the anticipated single-car operation the required current flow in the overhead line is also reduced compared to a typical LRT two-car consist. The operational voltages on the line are discussed further in a subsequent section.

In Seattle, 4/0 AWG overhead contact wire without parallel feeders in outlying area results in an impedance of 0.266 ohm per mi (0.162 ohm per km), almost one and a half times the impedance of the Portland Streetcar system. The lighter ETBs with a maximum current draw of 500 amps allow the system to be operated with a substation spacing of 5,000 to 8,000 ft (1,500 to 2,400 m).

The key to designing for a single contact wire is knowing what the loads are going to be and designing a system that will serve these loads within the limits of the wire.

MINIMIZING UNDERGROUND CONDUIT

Using the single wire concept instead of a parallel feeder system also greatly reduces the need for an underground conduit system to contain the feeder system. Generally, two 4-in. (100 mm) conduits are installed for along-track feeders with a manhole placed every 300 ft (90 m) and a lateral feeder run to a pole base and up to the contact wire on every block.

Underground conduit can also be required for transfer tripping substations as a back-up to the primary overcurrent protection. These wires require an additional 2-in. (50 mm) conduit. On both Portland Streetcar and Seattle Metro ETB systems the di/dt protection with reclosure relays is relied on to ensure an adjacent substation trips in the event of higher impedance faults where the primary overcurrent protection does not see the fault.

The cost of installing underground conduits for the power distribution feeders and transfer trip cables can be grossly estimated at \$90/ft (\$295/m), including the cost of manholes and lateral feeders at approximately 300 ft (100 m) intervals. With the tracks separated by a block on the Portland Streetcar system there are 5 linear track miles (8 km) to cover both tracks. The cost of the total underground distribution system can be estimated at about \$2.5 million.

An additional benefit to eliminating an underground traction power conduit system is the avoidance of the problems that arise from trying to fit it into a street which is already crowded with the underground services of several local utilities. Relocating utilities is a task which is wise to avoid.

EXISTING UTILITY DISTRIBUTION SYSTEMS

Another challenge in urban areas is the supply of primary 60 Hz power to the traction power substations. Typical LRT substations are fed from dedicated medium voltage (12 to 25 kV) feeders run from the nearest utility substation. In dense urban areas these feeds can be very long, and the installation under existing streets can be very difficult and costly. The Portland Streetcar system was faced with an average cost of \$25,000 per substation for the local utility to supply 13 kV power, with one location that may have approached \$50,000. On the other hand, a 480 V distribution grid was easily accessible at all locations.

Low voltage service drops, such as 480 Vac, are not normally used for traction power substations because of the high power demands normally encountered. Typical LRT systems use 1 to 1.5 MW substations, while electrical utilities in general will not usually provide for loads above 500 kVA without installing a medium or high voltage feed. The ampacity requirements are too large.

It was Portland Streetcar's decision to keep the substations below 500 kVA to make use of the local 480 Vac distribution system. The power rating chosen was 300 kW at the output. All substations except for one are fed with a 480 Vac supply. The exception is a substation located in a City of Portland parking garage where the existing 208 Vac supply had sufficient capacity to handle the substation load.

An additional positive consequence of the low voltage supplies is the ability to use a standard industrial switchboard for the power supply instead of an incoming AC cubicle and a 15 kV AC breaker. This reduces the price of the primary power equipment by a factor of three and, of course, the footprint of the substation building is also reduced.

MINIMIZING PROPERTY ACQUISITION

The acquisition of real estate for the siting of traction power substations in central business districts is also a major cost element in the design of urban transit. The typical 1MW substation with a medium voltage primary will occupy a minimum of 650 sq ft (57 sq m), with a buried ground mat of 1,250 sq ft (116 sq m). Typical dimensions of the property acquisition are 60 ft by 30 ft (18.3 by 9.2 m).

By contrast, the smaller low voltage, low power substations used on the Portland Streetcar alignment require only 400 sq ft (37.2 sq m) of property for a stand-alone substation with a perimeter ground. The use of low voltage, 480 and 208 Vac, eliminates the need for large clearances in the AC incoming cubicle. These factors allow for much greater flexibility in the siting of the units.

Portland Streetcar took full advantage of this flexibility. Of the six substations on the line, two are stand-alone prefabricated package units, two are installed in vaults placed under the sidewalks, one is installed in a city parking garage, and one is installed in an unused basement extension under the sidewalk. One of the package units is installed on the maintenance facility property which is leased from the state of Oregon and located under a freeway overpass. The two units installed in vaults under the sidewalks are in the city of Portland right of way. The parking garage unit was constructed with the loss of only two parking spaces to the city of Portland. The location in the building basement extension was donated by the building owner and only required the installation of a fireproof door to the main basement and a personnel access door in the sidewalk. The final substation was located in the backyard of property owned by a major stakeholder and only required a credit on the local improvement district assessment. A route map showing the substation locations is included as [Figure 1](#).

Seattle Metro has also been flexible in accommodating any available area for their substations. The majority of their 37 substations are located on properties which Seattle City Light (SCL), the local power utility, has granted easements. Only three substations are located on

private, purchased properties. Three of the four newest substations were installed in Washington Department of Transportation right of way under Interstate 5 structures. The fourth substation was installed on SCL property. A route map showing the substation locations is included as [Figure 2](#).

One of the major differences is in the grounding of the substations. As mentioned above, the Portland Streetcar substations use a perimeter ground instead of a full ground mat. A perimeter ground consists of four 15-ft (5-m) ground rods installed 3 ft (1 m) from each side of the substation at the four corners and electrically tied together. The ground rods are driven, without excavation, and tested to ensure a maximum resistance of five ohms-to-earth. The utility neutral is tied to the substation structure and the perimeter ground. This results in a considerable cost savings over the excavation and installation of a full ground mat under a substation serviced by medium or high voltage.

STRAY CURRENT CONTROL

The primary impact of stray current control on the construction of a transit system is the need to move underground utilities away from the track bed. Direct current stray, or leakage, currents will tend to corrode both underground metallic services and structures along the right-of-way. Thus there is the requirement to relocate all metallic elements where the level of stray currents may cause a reduced life. Needless to say, the relocation of underground utilities is an expensive proposition.

While it is not practical to totally prevent the leakage of current from the return rails to the earth, it is practical to control the currents to a level of about 50 mA per 1,000 ft (305 m) or less. A detailed metal loss analysis indicated this would not impact underground services located greater than 18 in. (457 mm) from the tracks. This is about one third of the level normally tolerated in LRT projects. To achieve these levels three major design strategies were used:

1. The distance between substations was kept as short as economically feasible,
2. The resistance from the rails-to-earth was maximized, and
3. The magnitudes of the vehicle currents were minimized.

As described in previous sections, a substation spacing of approximately 2,500 ft (760 m) was used. This spacing limits the maximum distance for return currents in the rails to approximately 1,250 ft (380 m) and results in maximum rail-to-earth potentials of 5.5 V under normal operating conditions and 8.7 V with a substation out of service. These low potentials translated to a maximum short-term leakage current of 50 mA per 1,000 ft (305 m) of track with soil resistivities found on the right-of-way and the rail-to-earth resistances described below.

The required rail-to-earth resistances were established by simulating the actual operation of the network. Initially five resistance levels were used; 25, 50, 100, 200, and 500 ohms per 1,000 ft (305 m). The lower ranges approximate rails directly embedded in concrete or asphalt and the upper values reflect rails electrically isolated from the track bed and the track bed electrically isolated from earth. The required value developed from the simulations was a minimum of 108 ohms per 1,000 ft (305 m) of track. This level of isolation was obtained using a high density polymer rail boot that completely encapsulated the rail. [Figure 3](#) shows a section of the rail with the boot installed.

The magnitude of the vehicle current was constrained with the 66-ft (20-m) vehicles

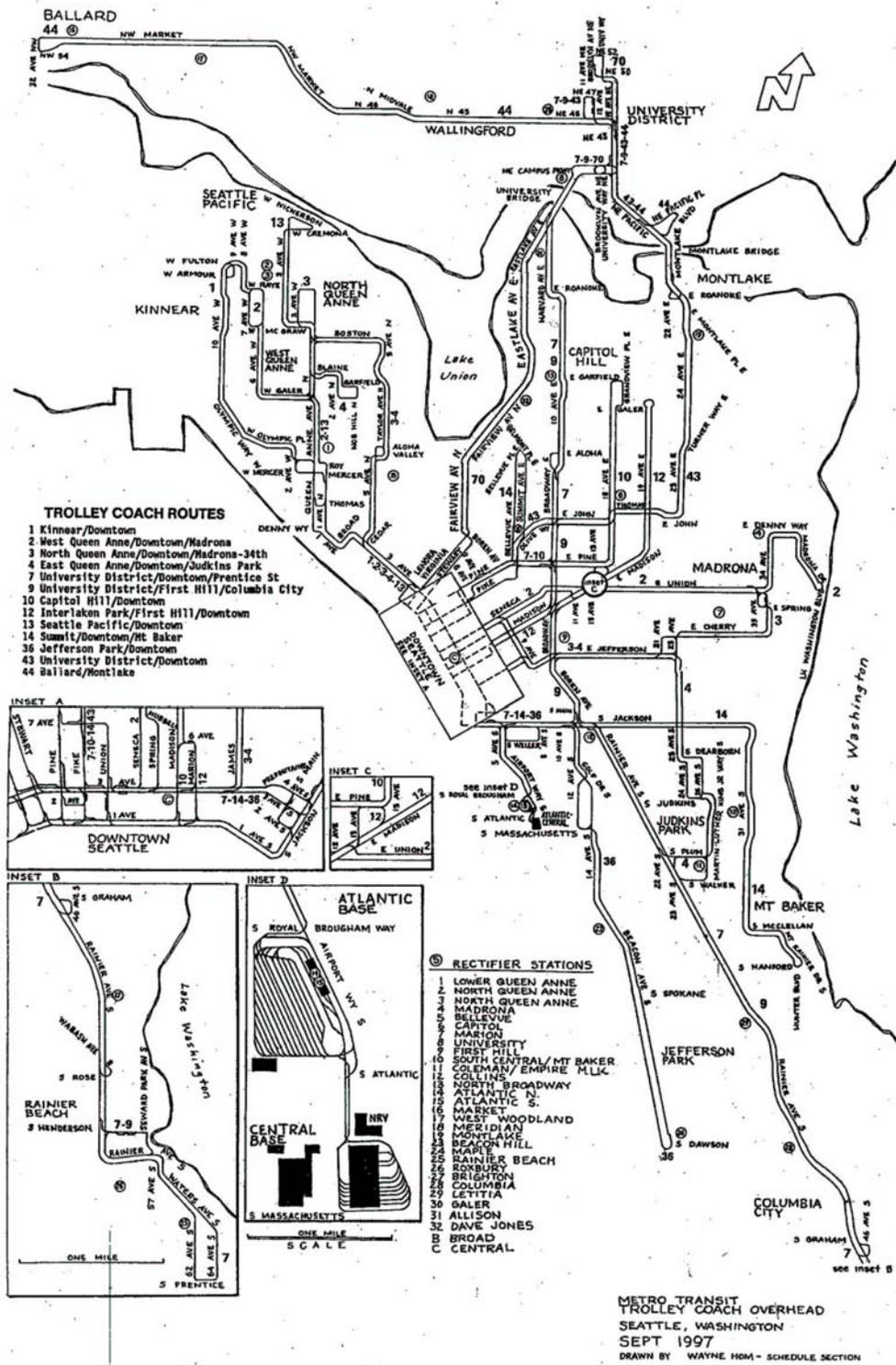


FIGURE 2 Seattle METRO substation locations.

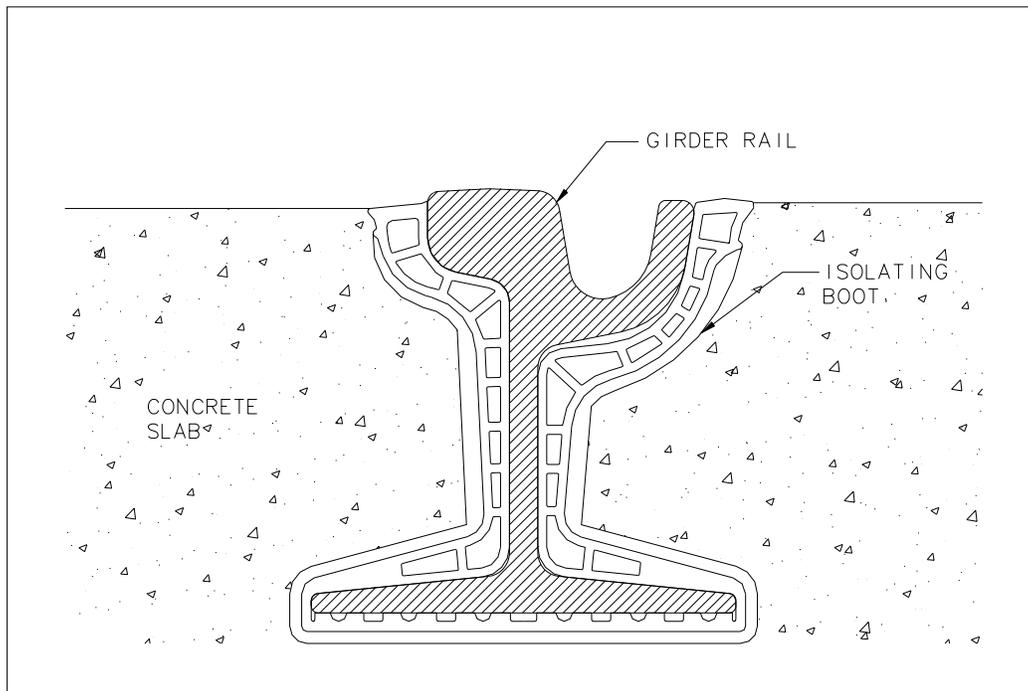


FIGURE 3 Cross section of rail with isolating boot.

operating only as single units. Typical acceleration currents are less than 1,000 amps. In contrast, a two-car light rail vehicle consist will draw over twice this level of current.

While not all three of these methods can be implemented on every transit system, the use of the applicable strategies described above can reduce stray current levels and limit the amount of utility relocation that needs to be undertaken. The fewer relocations, the lower the cost.

ADEQUATE POWER TO VEHICLES

The last point is also the most important. The DC supply and distribution system must be capable of supplying adequate power at an acceptable voltage to the transit vehicles at all times.

Substation sizing, spacing, and the cross-sectional area of the distribution system all have a direct impact on the ability to operate transit vehicles, especially when operation needs to be assured even with a substation out of service. The verification of this capacity is performed using computer programs which model the performance of the vehicles and the power demand on the distribution system.

The simulations focused on three elements which were judged to be controlling factors in the design—the voltage supplied at the vehicle’s pantograph, the power required from the substations, and the heating effects of the rms currents on the copper conductors. These elements were evaluated during a simulated operation of the vehicles at 10-min headways, 20-s station dwell times, and a load weight of AW2. The vehicle accelerations and decelerations were set to

the maximum rate and regeneration during braking was disabled to produce worst case conditions. All simulations were run with the Carnegie Mellon Energy Management Model (EMM) program.

The voltages at the pantograph were recorded during simulated runs in both directions while maintaining the required headways. The criteria for the voltage was to keep the voltage at the vehicle above a minimum 525 Vdc—the level at which the propulsion and auxiliary inverters on the vehicles would shutdown. Sample plots of the line voltages with all substations operational and with one substation (Legacy) off line are included as Figures 4 and 5. Since the streetcar system is a starter system that may be significantly expanded in the future and also has the maintenance facility on the route, a large margin was desired for future headways decreasing to 5 min or less.

The RMS power delivered by the substation was also simulated with the EMM program. Figures 6 and 7 show the RMS power demands on each substation for revenue operation. The substation power demand is far below the sustainable levels for a 300 kW substation, and no short-term overloads were observed. However, no significant cost savings could be anticipated by lowering the capacity, and room for future growth of the system capacity is assured.

Heating of the copper conductors was also calculated with a 10-min headway. The highest temperature found was 50°C including a 40°C ambient and a wind speed of only 0.5 ft/s (0.15 m/s). The annealing temperature for the copper wire is 75°C. Room for future growth is again assured.

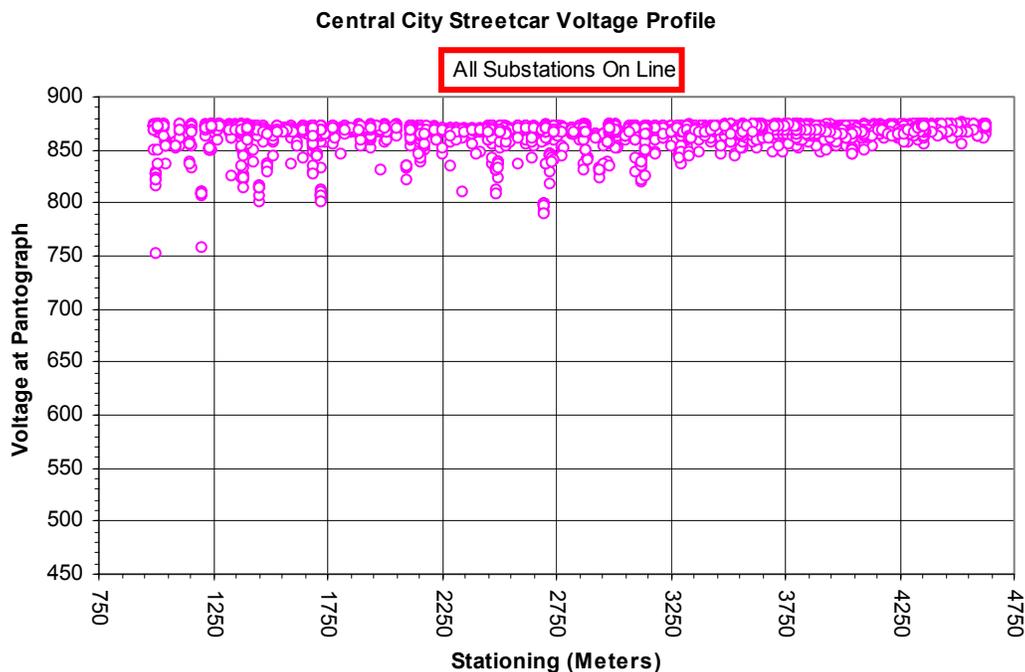


FIGURE 4 Voltage profile with all substations on line (normal operation at design capacity).

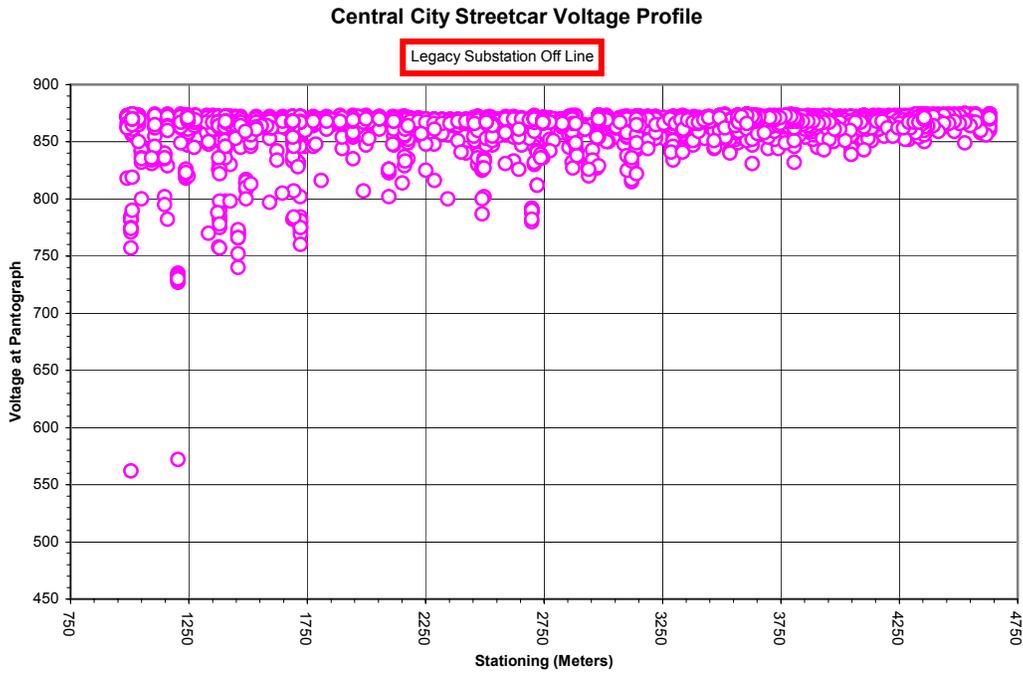


FIGURE 5 Voltage profile with Legacy substation off line (abnormal operation at design capacity).

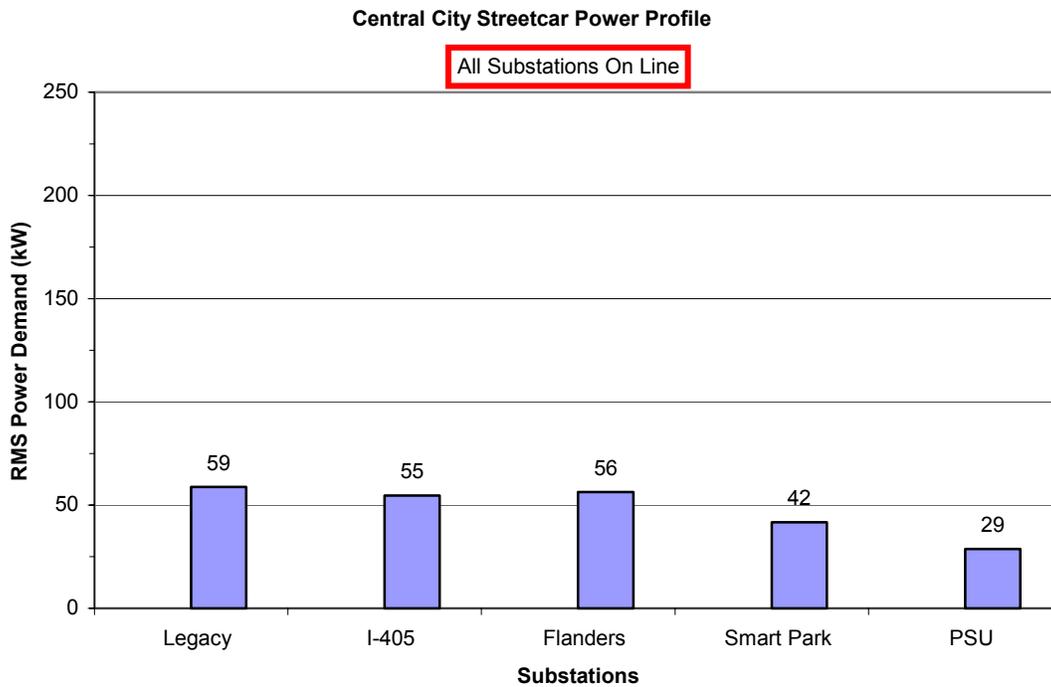


FIGURE 6 Power profile with all substations on line (normal operation at design capacity).

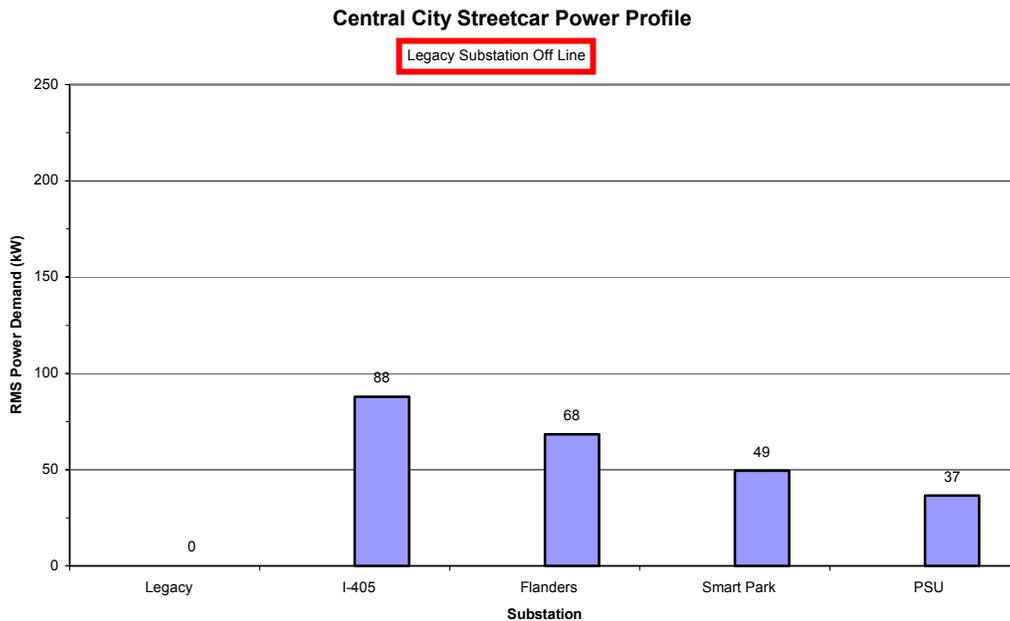


FIGURE 7 Power profile with Legacy substation off line (abnormal operation at design capacity).

Seattle Metro also used simulations to verify the operation of their 60-ft articulated and 40-ft ETBs. Similar criteria for operation with all substations operational or a single outage condition were used. The system uses a no-load voltage of 700 Vdc and both ETBs have vehicle drop-out voltage of 450 Vdc. A minimum operational ETB voltage of 500 V is used.

The other substation spacing criteria is a minimum DC fault current of 700 A or greater. This criterion insures that in case of a single outage condition a fault in the end of the line could be detected and cleared by the di/dt relay.

SUMMARY

Several techniques that can be implemented to reduce construction costs of rail transit systems in urban areas have been discussed. All or part of these can be used depending on the requirements of the transit system. Each technique needs to be evaluated independently although there is interaction between the different techniques and often two techniques can be used together for one benefit. For example, both the rail-to-earth isolation and the close spacing of substations act to reduce utility relocation costs.

Perhaps the most interesting aspect is the resiliency of the feederless systems designed. Both have sufficient capacity for the addition of more vehicles to the line in the future. Operation of two-car trains with peak currents of 1300 A per vehicle, typical of LRT lines, is feasible using the concept of smaller, low-powered, closely spaced substations, and the construction cost savings are significant.