Key Interfaces in the Design of Traction Electrification Systems for Light Rail Transit

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As does any major project, the design of a light rail transit (LRT) system requires the integration of a large number of subsystems to produce a safe, efficient operating facility at an economical cost. Failure to identify essential points of interface among the various subsystems and to evaluate the mutual effects of different design features of each subsystem on the others can result in unnecessarily high overall costs. Often the designer of one subsystem will attempt to optimize his design without recognizing the cost effects of his design decisions on other project elements.

Examples abound, and although some interrelationships are obvious--for example selection of overbridge clearances sufficient for the vehicle to pass beneath--many others are not so apparent; for example, careful selection of track maintenance tolerances to reduce the number of overhead contact system poles.

Ideally, all subsystem interface points should be identified before the design commences so full coordination and joint evaluation of mutual impacts can be performed during the design process.

One project element that has a particularly large number of interfaces with a wide variety of other elements is the traction electrification system (TES). The purpose of this paper is to identify the principal interfaces of the TES with other subsystems and to present a number of analyses of the effects on the TES design of several key design decisions in these other subsystems. Examples of TES designs from several recent light rail transit projects are presented to demonstrate these interrelationships. The discussion is concerned with traction electrification systems that use overhead contact not third rail.

IDENTIFICATION OF INTERFACES

The design of the traction electrification system, including both the power supply system (substations, feeders, switchgear, etc.) and the overhead contact system, affects and is affected by the design of the following other LRT project elements:

* Vehicles,
* Operations,
* Utilities,
* Trackwork,
* Civil works,
* Signaling and train control,
* Vehicle maintenance facility, and
* Architectural and urban design.

As a convenience in identifying potential TES interfaces, a detailed list has been prepared (see Appendix) of potential points of interface within each of these project elements. This list can assist LRT designers in identifying at the outset of the design process all areas in which mutual design impacts are likely to occur and where design decisions should be jointly made.

To demonstrate the effects of several of the more significant impacts on the TES design, the following sections include examples of analyses required to arrive at optimum mutual design decisions.

EFFECT OF VEHICLE OPERATIONS ON DIMENSIONS OF TRACTION POWER EQUIPMENT

One of the most fundamental interfaces in the design of the traction power system is designation of the vehicle loads to be imposed on the electrical system. These loads affect both the sizes and the spacing of the traction substations, as well as the sizes of the overhead contact system (OCS) conductors and feeders.

Vehicle loads are fundamentally derived from projected passenger traffic demand, but the translation of this demand into electrical loads involves designation of vehicle consists, frequencies, speeds, acceleration rates, and auxiliary loading requirements. All of these parameters can be varied within certain limits to produce the same traffic flow but generate different loads on the traction electrification system. Typically, the consists and schedules, as well as contingency operating requirements, are given to the traction power system designer as a fixed parameter, yet a broader systemwide optimization may indicate some overall benefit in varying these values. In determining the dimensions of the traction power system other variable inputs, including the selection of traction voltage level, need to be considered as well. Normally LRT systems employ 600- to 750-volt DC, and the choice affects equipment sizes and locations.

Thus, even with the vehicle loadings given, the power system studies required to determine optimum dimensions of the traction electrification system are necessarily complex; however, they are made much more manageable by use of computerized vehicle performance simulators and traction system network analyzers (1). In this process the selection of substation equipment and overhead system conductor sizes is iterative with the load flow study, which is based on the individual vehicle performance simulation combined with the overall operating schedule. The effects of voltage drop and conductor resistance are taken into account to arrive at an optimum combination of conductor sizes and substation sizes and spacings. This process, when computerized, can easily be repeated for various alternative vehicle consists and schedules, traction voltage levels, traction substation locations, and other key parameters to ultimately optimize the combination of these system components.

Two recent examples of LRT system designs, which clearly show the effects of different operating requirements on the traction electrification design, are the Sacramento and Guadalupe (San Jose) LRT systems, both in California. Both systems are approximately the same length and layout, although the Sacramento project has extensive lengths of single-track line whereas Guadalupe is predominantly double track. Both use a 750-volt DC traction power supply.

For the Sacramento project, the vehicles are articulated, six-axle units with a maximum starting power of 500 kW and a maximum speed of 55 mph. The peak-hour loading was specified as comprising four-car consists traveling in opposite directions at 15-min headways. In addition, allowance was made in the design for the possibility of two four-car consists accelerating simultaneously adjacent to a substation. In case of a substation out of service, adjacent substations must provide sufficient power for one four-car consist to accelerate in the disabled substation section while other trains in the section continue operation at normal cruising speed.

On the basis of the traction power studies performed for these conditions, the following TES design dimensions were selected:

- Substation spacing: approximately 1.5 mi average.
- Substation rating: 1 MW (continuous).
- Catenary conductors: contact wire, 300-kcmil, solid hard-drawn copper; messenger wire, 500-kcmil, stranded hard-drawn copper.
- Single contact wire conductors: contact wire, 300-kcmil, solid hard-drawn copper; parallel feeder (per track), two 500-kcmil, copper cables, 2-kV insulation.

For the Guadalupe LRT project, the vehicles are also articulated, six-axle units that weigh approximately the same as the Sacramento vehicles but with a maximum starting power of approximately 800 kW. Maximum operating speed is 55 mph. For the TES design, the peak-hour loading comprises three-car consists at 5-min headways in each direction. With one substation out of service, one three-car consist must be able to accelerate in the disabled substation section while other vehicles in the section continue at normal cruising speed.

On the basis of these criteria, the TES design dimensions were

- Substation spacing: approximately 1.5 mi average.
- Substation rating: 1.5 MW (continuous).
- Catenary conductors: contact wire, 300-kcmil, solid hard-drawn copper; messenger wire, two 350-kcmil, stranded hard-drawn copper.
- Single contact wire conductors: contact wire, 300-kcmil, solid hard-drawn copper; parallel feeder (per track), two 750-kcmil, copper cables, 2-kV insulation.

Comparing the Sacramento and Guadalupe LRT systems, the vehicle loading on Guadalupe is seen to be more demanding than on Sacramento. Although Guadalupe uses smaller trains (three car versus four car), the headway is much less (5 min versus 15 min) and accelerating capability is greater, which results in a heavier loading on the traction electrification system. As a consequence substation sizes on Guadalupe are 1.5 MW (compared to 1.0 MW on Sacramento), and a twin messenger wire is required to provide the necessary ampacity and voltage drop capability for the same 1.5-mi substation spacing. This additional design capacity was required in spite of the double-track configuration in Guadalupe that permitted electrical paralleling of the two catenaries.

EFFECT OF TRACK TOLERANCES ON OCS POLE SPACING

Turning to another element of the TES design, the cost of the TES is dependent on the spacing of overhead contact system support poles. The poles, foundations, and crossarms typically represent 50 to 60 percent of the total overhead system cost, so significant savings can be realized by the use of longer spans where possible (2). These savings occur during both construction and maintenance. In addition, the use of longer spans improves the aesthetic appearance of the overhead contact system.

Among the most critical factors affecting the OCS pole spacing are track maintenance tolerances and pantograph width. Pole spacing is determined by a series of calculations generally grouped under the term "pantograph security analysis." The purpose of this analysis is to confirm that the contact wire will remain on the pantograph under all conditions of wind loading and vehicle operation. The pantograph security analysis includes the calculation of the lateral displacement of the contact wire with respect to the pantograph centerline for a given OCS span length. A sample analysis, based on a span length of 220 ft, is given in Table 1 and shown in Figure 1. In addition to the span length, other factors that affect the calculation are

- Track condition,
- Vehicle characteristics,
- OCS parameters, and
- Wind loading (during vehicle operation).

As seen in the sample analysis in Table 1, the effect of track tolerances on pantograph security is significant, and the values should be carefully selected in conjunction with the OCS design.

Track condition is defined by the Federal Railroad Administration (FRA) in terms of allowable track maintenance tolerances for a given maximum operating speed and class of track. This is shown as (3)

FRA Track Class	Maximum Operating Speed (mph) Freight Train	Passenger Train	Track Tolerances (in.) Alignment	Cross-Level
1	10	15	5	3
2	25	30	3	2
3	40	60	1 3/4	1 3/4
4	60	80	1 1/2	1 1/4
5	80	90	3/4	1
6	110	110	1/2	1/2

Most LRT projects have a maximum operating speed around 55 mph and therefore the minimum track quality

TABLE 1 Sample Pantograph Security Analysis—Tangent Track

	Displacement (in.)
Track tolerances	
Alignment 1½ in.	1.5
Cross-level 1¼ in. x (19 ft 6 in. height/4 ft 8½ in. gauge)	5.2
Pantograph sway/vehicle roll[a] into wind = 3.2 in. + 1°00' above 1.3 ft	7.0
Crossarm swing effect	2.4
Blow-off (220-ft maximum span)	10.0
Stagger effect (8-in. alternating staggers)	1.6
Pole deflection due to wind	2.0
Erection tolerance	2.0
Design allowance	1.0
Total allowances	32.7
Margin of safety (by difference)	6.3
Half pantograph width	39.0

Note: Lateral displacement of contact wire with respect to pantograph centerline at midspan for track Class 4, 19 ft 6 in. contact wire height, 6 ft 6 in. pantograph, and 220-ft span.
[a]Normal maximum = 3.2 in. + 1°30' above 1.3 ft.

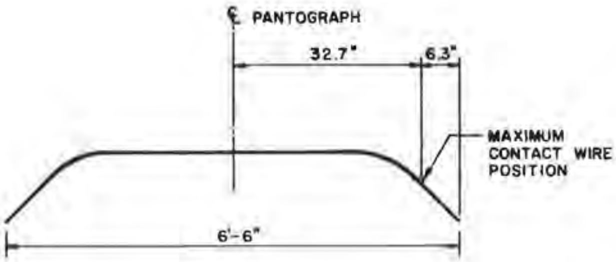

FIGURE 1 Sample analysis.

required is FRA Class 3. The two parameters that are of importance to the overhead contact system design are the alignment tolerance and the cross-level tolerance. These tolerances are tabulated in the preceding table for each class of track.

The impact of the cross-level tolerance on pantograph security is compounded by the contact wire height. To illustrate, the lateral displacement of the pantograph due to the effects of the various track tolerance standards are shown in the following table for the three contact wire heights commonly used on LRT projects: 15 ft in exclusive LRT right-of-way, 19 ft in shared right-of-way (with street traffic), and 22 ft over other operating railroads:

FRA Track Class	Lateral Displacement (in.) 15-ft Wire Height	19-ft Wire Height	22-ft Wire Height
1	14.6	17.1	19.0
2	9.4	11.1	12.3
3	7.3	8.8	9.9
4	5.5	6.5	7.3
5	3.9	4.8	5.4
6	2.1	2.5	2.8

It is seen that track quality is a significant contributor to pantograph security and that reducing track tolerances will have the effect of permitting longer spans without sacrificing pantograph security.

For the Sacramento LRT project the costs of the overhead contact system were estimated for both FRA Class 3 and Class 4 track. The analysis employed a computer program that calculates the maximum span length for a given catenary configuration and the resulting OCS cost per single-track mile. The effect of improving the class of track (for tangent track, 19 ft 6 in. contact wire height, and 6 ft 6 in. pantograph width) is

	Class 3	Class 4
Maximum span length (ft)	215	233
Calculated cost per single-track mile ($)	153,000	147,000
Savings (%)		4

Although the calculated costs should be used for comparative purposes only, and not in absolute terms, the savings expected by shifting from Class 3 to Class 4 represent approximately 4 percent of the total OCS costs. In the overall systemwide evaluation, this savings should be compared with the incremental cost of maintaining the track to the higher standards.

EFFECT OF PANTOGRAPH WIDTH ON TES POLE SPACING

Increasing the overall width of the pantograph will also permit longer spans by increasing the allowance for wind blow-off on tangent and for contact wire stagger on curves. For the Sacramento LRT project the cost of simple catenary was estimated for pantograph widths of 6 ft 0 in. and 6 ft 6 in., resulting in the following comparison (for tangent track, 19 ft 6 in. contact wire height, and Class 4 track):

	6 ft 0 in. Pantograph	6 ft 6 in. Pantograph
Maximum span length (ft)	207	233
Calculated cost per single-track mile ($)	156,000	147,000
Savings (%)		6

The combined effect of adopting track Class 4 and a panotgraph 6 ft 6 in. wide instead of track Class 3 and a pantograph 6 ft 0 in. wide was as follows:

	6 ft 0 in. Pantograph and Track Class 3	6 ft 6 in. Pantograph and Track Class 4
Maximum span length (ft)	182	233
Calculated cost per single-track mile	168,000	147,000
Savings (%)		13

On the basis of these analyses, the 6 ft 6 in. pantoograph and FRA track Class 4 were adopted for the Sacramento LRT project. A maximum span of 220 ft was selected for the 19 ft 6 in. contact wire height, which allows a small additional margin for uncertainty in the vehicle roll characteristics.

A similar analysis was performed for the Guadalupe LRT project, which also resulted in selection of the 6 ft 6 in. pantograph, Class 4 track, and a maximum span of 200 ft. The difference in span lengths between the two projects is due to the differences in conductor configurations and vehicle roll characteristics.

AESTHETIC CONSIDERATIONS

A particularly important interface with the overhead contact system is the aesthetic design of the LRT system. Several measures are commonly employed to minimize the visual impact of the overhead system, especially in sensitive urban environments. These include the use of parallel underground feeders to reduce the number of aerial conductors, judicious placement of trees and other features to "shield" the overhead, joint use of support poles for street lighting and other functions, and special architectural design of poles and bracket arms.

Another measure that has been applied in some recent designs is the use of synthetic rope for cross-spans and intersection guying to support the contact wire. In conventional overhead support designs in which single contact wire is used, cross-spans of galvanized stranded steel guy wire are used to suspend the contact wire approximately every 100 feet along city streets. These wires are fastened to poles on opposite sides of the street and generally require installation of two insulators along the span between each pole and the contact wire. The resulting spans are often considered unsightly and are particularly so at intersection turnings of the rail line where complex overhead guying networks are required to support and register the contact wires.

Synthetic rope can be used in place of the stranded steel wire to provide a more aesthetic appearance, in most cases at a significantly lower cost. Synthetic rope consists of multiple aramid fibers encased in a nylon jacket and is produced by a number of manufacturers. Two common products are Parafil, manufactured by ICI Fibres of England, and Phillystran, manufactured by Philadelphia Resins Corporation. Comparative physical properties of these synthetic ropes and equivalent stranded steel guy wire are

	Diameter (in.)	Breaking Strength (lb)	Weight (lb/ft)
Parafil type A	0.43	4,400	0.057
	0.67	11,000	0.140
Phillystran SB-060GZ	0.34	6,000	0.041
Phillystran SB-110GZ	0.48	11,000	0.077
Stranded steel (3/8 in. common grade)	0.375	4,250	0.273
Stranded steel (1/2 in. Siemens-Martin grade)	0.500	12,100	0.517

For the same tension load, synthetic rope of a similar or smaller diameter and lighter weight can be used, and, because the rope itself is an insulator, there is no need to install additional insulators in the span guy. Thus, in addition to improving aesthetics, the lighter weight and absence of insulators considerably simplify installation of the guys, thus contributing to cost reduction.

Synthetic rope has been used in numerous transit systems in such countries as Italy, Australia, and France, but its application in the United States so far is limited. Although it is aesthetically pleasing, there have been concerns expressed about the use of synthetic rope on LRT systems. These concerns are primarily about the security of the termination connections and the long-term resistance to the effects of ultraviolet (UV) radiation. Various types of termination hardware are available, some of which are based on external clamping of the rope, which may result in damage to the jacket if not carefully designed and installed. This concern may be alleviated by requiring full-load testing of the proposed termination assemblies before installation.

Little is known about long-term resistance to ultraviolet effects, although some synthetic rope installed as antenna guying has reportedly been in place for more than 20 years with no apparent deterioration. The synthetic trolley support spans in Melbourne, Australia, have been in use since 1977, with no adverse ultraviolet effects, even though UV radiation levels are known to be approximately 25 percent greater in the southern hemisphere. Black colored jackets are more resistant to UV effects than are gray jackets, and improved jacket materials, such as the Zytel ST 801 jacket now available for Phillystran rope, are also being developed

One of the few major installations of synthetic rope in the United States is in San Francisco on the recently installed No. 24 Divisadero trolleybus line electrification. Approximately 7 route-miles have been installed on this project and have been in use since October 1983. The only significant problem experienced so far on this installation is damage to the span guys caused by dewirements of the trolleybus collector poles. This problem would not occur, of course, with LRV pantograph operation.

A limited number of spans have been installed in some light rail facilities, such as in San Diego and Philadelphia, for testing purposes. In the Guadalupe LRT project the use of synthetic rope has been specified for all single contact wire cross-spans, including intersection guying.

Associated with the aesthetics of using synthetic rope for span guys is the requirement to keep the guying network simple at intersection turnings. The usual "spiderweb" network of guy wires at such intersections can be unsightly, even with the use of synthetic rope instead of steel guys with insulators. The complexity of loadings and the large number of pull-off supports needed require special attention in the network design to avoid excessive visual intrusion.

Aesthetic design of intersection wiring is now being achieved by interactive computerized design techniques originally developed for the more complex requirements of trolleybuses. This process was employed on both the Sacramento and the Guadalupe LRT projects and on several other trolley overhead designs. In applying this program, from the designated location of the overhead contact wire, the designer determines the physical geometry of the guying network and the program calculates the tension in each span guy and the vertical and horizontal load on each pole and then plots the guying network. The interactive feature permits the designer to easily alter the network arrangement to achieve the most effective design with the least visual intrusion. Moreover, perspective views can be prepared from any angle to provide others with a conceptual sketch of the general appearance of the guying network. Figure 2 shows one of the major intersections on the Sacramento LRT project.

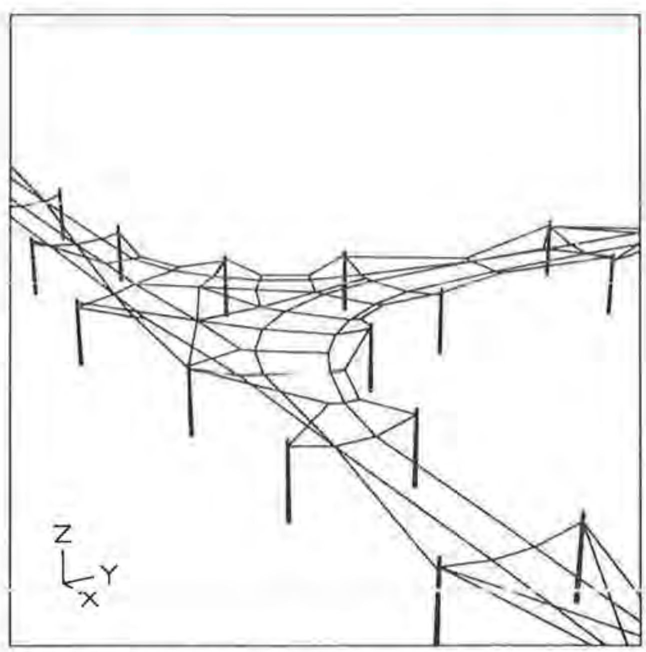

FIGURE 2 Perspective aerial view of intersection guying—12th and Whitney, Sacramento LRT.

OTHER SITE-SPECIFIC INTERFACES

The foregoing examples have systemwide application; on any project there are also numerous site-specific interfaces, which can create design problems disproportionately high for their actual constructed costs. For example, on the Guadalupe project one grade crossing of a main-line railroad required a pantograph reach of 23 ft 0 in. where 20 ft would be acceptable for normal street operation. In San Diego, where the LRT uses an existing main-line railroad, a dispensation had to be obtained from standard rules (California General Order 95) requiring 22 ft 0 in. contact wire height because of pantograph reach limitations.

Other common examples of site-specific interfaces include individual bridge attachments, use of eyebolts in private buildings to support cross-spans, possible interference with the operation of fire-fighting equipment, joint use of TES poles for lighting and traffic signals, and special foundations on sidewalks over basements.

CONCLUSION

The examples discussed here describe only a few of the more important interfaces that occur in the design of the traction electrification system. In each case it is shown that design decisions in other elements of an LRT system can seriously affect the design, and hence the cost, of the TES. Many other similar interfaces exist, as indicated in the list in the Appendix, with similar impacts. All too often many of these design decisions are made independently and given as fixed criteria to the TES designer.

To optimize the total LRT system design, and thereby minimize the overall costs of its construction and maintenance, it is important that all such design interfaces be investigated jointly by the respective subsystem designers. Design and cost impacts on the TES of alternative design choices in other project elements, as well as the reverse effects of alternative TES design features, can be evaluated before plans are made final. This systemwide analysis is required at the preliminary engineering stage or earlier. Careful investigation of these interfaces should serve to reduce the overall costs of LRT projects now being planned and thereby contribute to the operational and commercial success of these systems.

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APPENDIX: DESIGN INTERFACES FOR TRACTION ELECTRIFICATION SYSTEM

The following list includes most of the interface items likely to be encountered in the design of the traction electrification system for a light rail transit project.

1. Light Rail Vehicles
   a. Physical dimensions and weights (empty, loaded, crush)
   b. Dynamic clearance envelope (tangent, curves)
   c. Vehicle roll, lateral shift (normal and broken suspension)
   d. Pantograph dimensions: overall width, carbon strip width, spacing between collectors, operating height range
   e. Pantograph mass and uplift pressure
   f. Limitation in contact wire gradient and gradient change
   g. Pantograph lateral sway
   h. Electrical characteristics: voltage, power
   i. Tractive and braking effort curves
   j. Acceleration and braking characteristics
   k. Auxiliary power supply (heating, lighting, air conditioning, etc.)
   l. Regenerative braking requirements.
2. Operations
   a. Train schedules, speeds, headways, dwell times, consists (peak, off-peak)
   b. Emergency operation requirements (substation outage, broken suspension, single-track running, etc.)
   c. Backup power supply requirements
   d. TES sectioning requirements (maintenance, firefighting, etc.)
   e. Maximum wind speed for vehicle operations
3. Utilities
   a. Location and voltage levels of utility supply points
   b. Utility criteria: short circuit level, harmonics, flicker, etc.
   c. System grounding philosophy and criteria
   d. Relocation of overhead utility lines in vicinity of TES
   e. Relocation of underground utilities
   f. Joint use of underground ducts for TES feeders
   g. Provisions for emergency services (fire, police, ambulances)
4. Trackwork
   a. Track dimensions, rail, ballast data
   b. Single- or double-track layouts, future track additions
   c. Track plans: alignment, profile, superelevations, clearances between tracks (especially on curves)
   d. Locations and configurations of switches, crossovers, turnouts, passing sidings, etc.
   e. Track maintenance tolerances (horizontal, cross-level)
   f. Classification of right-of-way (exclusive, shared, etc.)
   g. Locations of crossings
5. Civil works
   a. Locations, dimensions, clearances of bridges, tunnels, etc.
   b. Arrangements for TES attachments on bridges, overhead structures, and adjacent buildings
   c. Locations and arrangements of passenger stations
   d. Drainage systems--potential interference
   e. Soil characteristics for foundation design
   f. Soil resistivity
6. Signaling and train control
   a. Requirement for signal cables on TES structures

b. Electromagnetic interference between power supply and signaling
c. Joint use of TES structures for LRV and street traffic signals
d. Arrangement for intersection traffic preemption
e. Signal blocks for sectionalizing
f. Impedance bond locations

7. Vehicle maintenance facility
a. Yard and shop track layouts
b. Typical yard movements
c. Sectionalizing requirements
d. Building: clearances, power supply, door operation, ground mat, warning systems, personnel safety criteria
e. Joint use of poles for yard lighting

8. Architectural and urban design
a. Pole types, special assembly design (crossarms, counterweights, etc.)
b. Pole locations
c. Use of synthetic rope for spans and guys
d. Arrangement of TES at passenger stations (locations, overlaps, poles on platforms, etc.)
e. Locations for use of single contact wire with parallel feeders
f. Joint use of poles for street lighting, traffic signals, etc.
g. Requirements for intersection guying arrangements
h. Substation locations, architectural designs, landscaping, etc.