Economic Rating and Spacing of LRT Traction Substations

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For propulsion modern light rail vehicles usually use DC power supplied by an external traction electrification system. The traction electrification system (TES) converts available medium-voltage AC power to low-voltage DC power that is then distributed to the trains. A typical TES consists of traction power substations connected to an existing utility grid and a DC distribution system. Two major types of DC distribution systems, differentiated by the final element on the power path from the substations to the vehicles, have evolved. They are the overhead contact system and the third rail, each with its own advantages and areas of application.

When a new light rail system is being designed, or an existing one extended, two major objectives become the center of attention:

1. To meet all performance, reliability, and safety criteria associated with transit operations and
2. To meet technical requirements at a minimum overall system cost.

In a broader sense, these two can be combined into one goal--to design an economically optimum TES under a set of constraints that represent performance, reliability, and safety requirements. This is a broad and far-reaching subject that is beyond the scope of a single paper. In this paper only one aspect of such an economic design objective will be addressed: the selection of substation rating and spacing, which tend to minimize the overall TES cost function.

BASIC CONCEPTS

When the LRT system operating environment becomes known, various TESs could be designed, all of which would meet the set of constraints related to performance, reliability, and safety. The operating environment consists generally of (a) vehicle data, (b) route data, (c) normal and contingency operations plan, and (d) reliability and safety requirements reflected in the TES configuration, sectionalizing, and protective relaying scheme.

The first step toward minimizing the TES cost function is the selection of the type of all major TES components: type of substations, type of poles, type of overhead contact system (OCS), and so forth. These decisions, however, are often dictated by environmental rather than economical considerations or represent a compromise between the two.

The second step toward minimizing the TES capital cost is the selection of the three major system parameters: substation rating, substation spacing, and line feeder size. For the purpose of this paper, the line feeder will be regarded as consisting of the contact wire or third rail plus any parallel reinforcing feeders such as messenger wires or underground insulated cables. Each of these three major system parameters not only affects total system cost but is also related to the other two. Their combination should render a technically sound and feasible solution, and such solutions are numerous. The traction power system load requirements, for example, could be met by using smaller substations spaced closer together and lightweight conductors or by using larger substations, spaced farther apart, in conjunction with heavier conductors.

Finding a feasible TES solution is a complex problem. The load of a typical traction power substation is highly irregular and intermittent. Random factors, such as fluctuations in headways, station dwell times, and passenger load, are also inherent in the system operations. Determination of the substation and feeder load involves consideration of a variety of factors such as vehicle propulsion system data, train size, headways, stop spacing, route horizontal profile, and vertical alignment. Practically the only way to obtain accurate results is through computer simulations using computer programs specially developed for this purpose. Because the technical aspects of TES design are not within the scope of this paper, they will not be dealt with in detail. Emphasis will be placed instead on the economic principles and relationships that can help in selecting TES parameters that result in economic design.

BASE COST FUNCTIONS

The acceptable ranges of the traction power substation rating and the line feeder size can be determined on the basis of technical feasibility, environmental or practical considerations, or a combination thereof. The unit costs of all feeder sizes and substation ratings can also be estimated and can be used to obtain corresponding curves, called base cost functions. They should include the total direct and indirect associated cost, materials, and labor.

For the substations (Figure 1), the base cost curve is defined as

$$C_1 = g_1 (P) \quad (1)$$

where

P = nominal rating (kw) and
C_1 = substation cost ($1000/substation).

The substation cost will consist of equipment, sitework (including land acquisition), and connection feeders.

For the DC distribution system, the base cost curve is defined as

$$C_2 = g_2 (A) \quad (2)$$

where

A = overall cross-sectional area in thousands of circular mils (MCM) and
C_2 = line feeder unit cost ($/ft).

In case of overhead catenary systems (Figure 2), the line feeder cost will consist of overhead conductors, crossarm assemblies, and poles. In case of third rail systems, the line feeder cost will consist of the third rail with associated accessories.

The substation rating may be increased in increments of, say, 250 kw. The line feeder cross section increases with the standard conductor size increment and the number of conductors used. The base cost functions can be obtained analytically through the least squares curve fitting method. Polynomial approximations up to second degree would give satisfactory results.

PARAMETER OPTIMIZATION

As explained before, the TES capital cost is a function of three interrelated parameters: substation rating, substation spacing, and line feeder size. For the established design criteria and permissible parameter ranges, there may exist many feasible solutions that consist of different combinations of substation ratings, spacings, and line feeder sizes. The economic solution that minimizes the overall system cost function may be obtained by the procedure outlined herein.

By selecting a certain substation rating (P) and varying the substation spacing, a series of line feeder sizes can be obtained starting from the minimum line feeder size. The greater the spacing, the larger the feeder line necessary to meet the voltage drop, ampacity, and short circuit current coordination requirements. The maximum spacing corresponding to a substation of rating P will be reached either when the substation short-term or long-term loading capabilities are exceeded or when the maximum line feeder size is reached, whichever comes first. Expressing the corresponding line feeder cost as a function of the substation spacing gives

$$f_1 (L_s) = a_0 + a_1 L_s + a_2 L_s^2 \quad (3)$$

where

f_1 = line feeder unit cost ($/ft) and
L_s = substation spacing in thousands of feet (MFT).

The unit substation cost (assuming the terminal substations are located approximately $L_s/2$ away from the end of the line) could be expressed as

$$f_2 (L_s) = g_1 (P)/L_s \quad (4)$$

Then the total system unit cost as a function of the substation spacing is given by

$$C = f_1 (L_s) + f_2 (L_s) \quad (5)$$

Assuming linear approximation for the function f_1 (which in most cases is accurate enough),

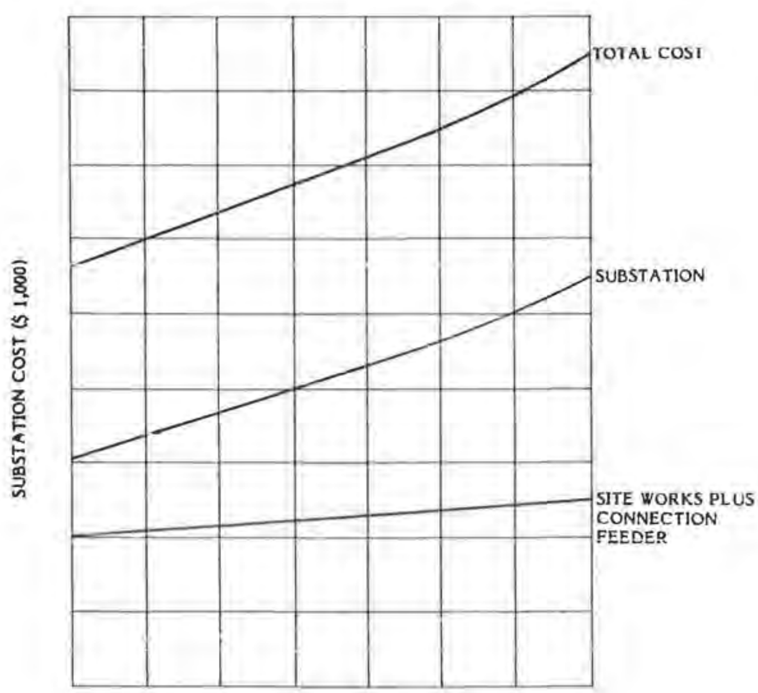

FIGURE 1 Traction substation base cost curves.

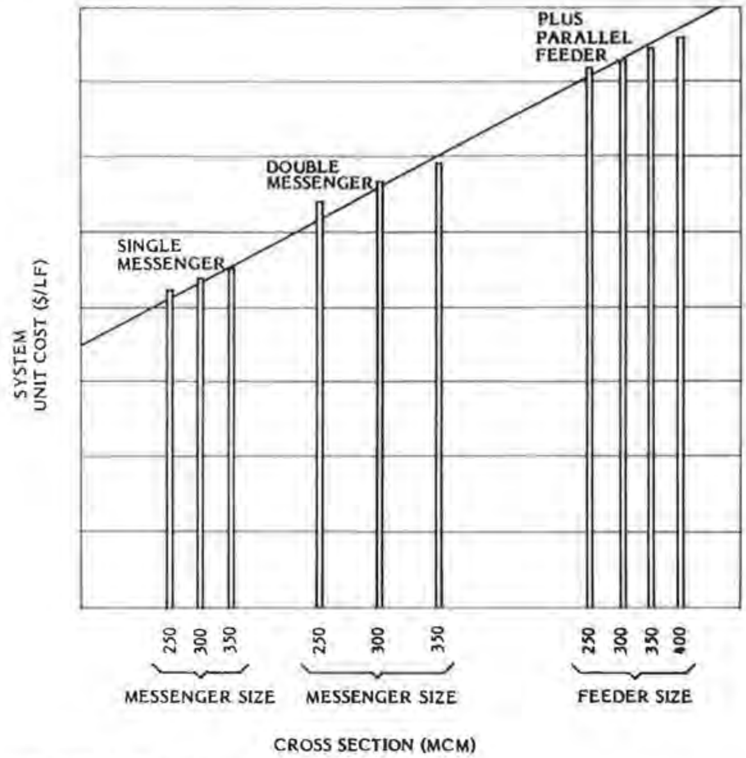

FIGURE 2 Catenary system base cost curve.

$$C = a_0 + a_1 L_s + [g_1(P)/L_s] \quad (6)$$

The minimum of this function, obtained through differentiation, is

$$L_s^{(m)} = [g_1(P)/a_1]^{1/2} \quad (7)$$

Equation 7 reveals that the economical spacing of a substation of rating P is equal to the square root of the ratio of the total substation cost to the incremental change in the line feeder unit cost. This relationship will be more complex, resulting in a cubic equation, if the line feeder unit cost is not represented by a second degree polynomial.

The substation spacing (L_s) obtained through Equation 7 can fall either within or outside the range of L_s in Equation 3. In the latter case, whichever substation spacing limit is closer to $L_s^{(m)}$ will be the most economical one.

After the set of economic substation spacings associated with each of the substation ratings has been derived, the system unit cost curves can be obtained. The first curve (X_1) represents the contribution of the substations to the overall unit cost; the second (X_2) represents a similar contribution from the DC distribution system.

Using the results from the parameteric optimization obtained so far, the following relationships can be established:

$$X_1 = X_1(P) \quad (8)$$

and

$$X_2 = X_2(P) \quad (9)$$

where

X_1 = number of substations of the system as a function of the substation rating. Each point of the curve can be obtained by dividing the total line length by the established substation spacing corresponding to the rating P.

X_2 = line feeder cross section as a function of the substation rating. Each point of the curve can be obtained by plotting the cross-sectional area corresponding to function f_1 from Equation 3. The spacing that corresponds to each substation size has already been obtained through Equation 7.

The substations unit cost function consequently can be expressed as

$$y_1(P) = \{[X_1(P) \cdot g_1(P)]/L_E\} = d_0 + d_1 \cdot P + d_2 \cdot P^2 \quad (10)$$

where

$y_1(P)$ = substation unit cost curve ($/ft),
L_E = line length (ft), and
d_0, d_1, d_2 = coefficients of the second degree polynomial presentation.

The DC distribution system cost function can be expressed as

$$y_2(P) = g_2[X_2(P)] = e_0 + e_1 \cdot P + e_2 \cdot P^2 \quad (11)$$

where

$y_2(P)$ = feeder line unit cost curve ($/ft) and
e_0, e_1, e_2 = coefficients of the second degree polynomial presentation.

Analysis of several y_1 and y_2 curves has indicated that both can be approximated to a good degree of satisfaction by a second degree polynomial (see Figure 3) using the least squares curve fitting method. Although the value of $y_1(P)$ normally decreases with the increase of the rating P, the unit

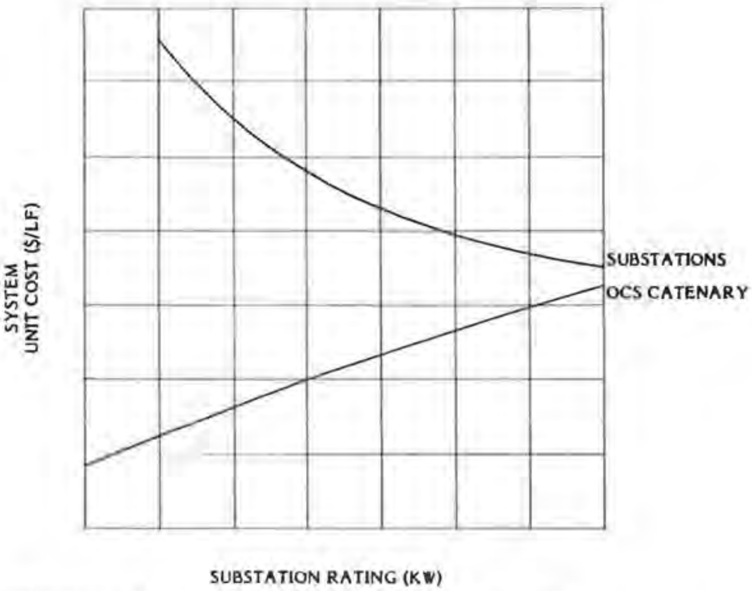

FIGURE 3 Traction electrification system unit cost curves.

line cost $y_2(P)$ on the other side exhibits an upward trend.

The total TES unit cost function then can be expressed as

$$y = y_1(P) + y_2(P) \tag{12}$$

or

$$y = d_0 + d_1 \cdot P^2 + d_2 \cdot P + e_0 + e_1 \cdot P + e_2 \cdot P^2$$

The minimum of this function with regard to P renders the economic substation rating (P_e). This minimum, obtained easily through differentiation, is

$$P_e = [(d_1 + e_1)/(2d_2 + 2e_2)] \tag{13}$$

The corresponding number of substations and the line feeder size can be found by substituting P_e in Equations 8 and 9, respectively.

SAMPLE CASE

The procedure discussed in this paper was applied to the design of the Gaudalupe Corridor LRT system in San Jose, California. The system consists of approximately 21 mi of double track and was designed in accordance with the following basic concepts:

- Substation type: transportable, preassembled, walk-in, installed on concrete pads alongside the track;
- DC distribution system type: predominantly overhead catenary system with messenger wires serving as positive feeders; and
- Catenary systems of the two tracks paralleled electrically and supported by center poles with back-to-back crossarm assemblies.

The minimum substation rating was established as 1000 kw. The equivalent line feeder size included the catenary systems of both tracks, due to their electrical connection.

Table 1 gives the estimates that were used to establish base cost curves for substations. Table 2 gives the estimates that were used to establish base cost curves for equivalent line feeder (materials and labor).

TABLE 1 Estimates for Substations

Rating (kw)	Equipment ($1,000)	Connection Feeders ($1,000)	Site ($1,000)	Total ($1,000)
1000	240	40	120	400
1500	300	60	125	485
2000	380	85	130	595

TABLE 2 Estimates for Equivalent Line Feeder (materials and labor)

Size	Conductors ($1,000/mi)	Poles ($1,000/mi)	Total ($1,000/mi)
2xA	62.6	76.36	138.96
2xB	79.5	84.92	164.42
2xC	117.5	101.5	219.00

Note: A represents one 300-MCM contact wire plus one 350-MCM messenger wire per track, B represents one 300-MCM contact wire plus two 350-MCM messenger wires per track, and C represents one 300-MCM contact wire plus two 350-MCM messengers plus one 400-MCM overhead feeder per track.

The technical aspects of the analysis, such as establishing the maximum spacing for each substation and the corresponding minimum line feeder size, were performed with the help of computer simulations. Some of the relevant results from these studies are summarized in Table 3.

The maximum incremental cost change of the line feeder was roughly estimated to be in the neighborhood of a_1 = $3-4/ft-MFT. Substituting this value in Equation 7 results in economically optimal but

TABLE 3 Relevant Results

Substation Rating (kw)	Average Spacing (ft)	Minimum Line Feeder Size per Track: Contact Wire (MCM)	Messenger Wire No.	Messenger Wire MCM	Additional Feeder No.	Additional Feeder MCM
1000	5,500	300	1	350		
1500	8,000	300	2	350		
2000	11,000	300	2	350	1	400

unconstrained substation spacing. It happens to be higher than the maximum permissible spacing obtained on the basis of technical requirements such as RMS and peak loads, ampacity, and voltage level constraints. For the 1000-kw substation, for example,

$$L_s^{(m)} = \{[g_2(P)]/a_1\}^{1/2}$$
$$= \{[425\ (\$1000)]/[4\ (\$/\text{ft-MFT})]\}^{1/2}$$
$$= 10.3\ \text{MFT}$$

In view of the load pattern, the 1000-kw substations cannot be spaced at such a distance, almost 2 mi, without overloading. Therefore the technically permissible spacing takes precedence over the economically ideal one.

The curves represented by Equations 8 and 9 need not be in analytical form. A table of discrete values related to the substation ratings (P) would be sufficient. Using the substation spacings and equivalent line feeder sizes obtained previously, these two functions can be expressed in tabular form:

P (kw)	X_1 (no.)	X_2 (MCM)
1000	20	1500
1500	14	2000
2000	10	2800

Finally, the TES unit cost curves (y_1 and y_2) can be obtained through Equations 10 and 11. In tabluar form these are

P (kw)	y_1 ($/lft)	y_2 ($/lft)
1000	72.73	26.32
1500	61.72	34.14
2000	54.10	41.48

The total line length is approximately L_E = 110 MFT, including a 1 1/2-mi branch off the main route.

The analytical expressions of these two functions, obtained through the least squares approximation method, are

$$y_1 = 104.922 - 0.03897P + 6.87 \times 10^{-6}P^2,$$
dollars per linear foot.

and

$$y_2 = 33.24 - 0.01796P + 11.04 \times 10^{-6}P^2$$
dollars per linear foot.

Equation 13 will lend the economic substation rating. Substituting, the following is obtained:

$$P_e = -\{(-0.03897 - 0.01796)/[2(6.871 \times 10^{-6} + 11.04 \times 10^{-6})]\} = 1589\ \text{kw}$$

The closest substation rating, using 250-kw increments is 1500 kw. To assess the sensitivity of the solution, the system unit cost function (Equation 12) is calculated for all substation ratings of the 1000- to 2000-kw range. The results are as follows:

P (kw)	y ($/lft)
1000	99.05
1250	94.98
1500	92.85
1750	93.38
2000	95.58

CONCLUSIONS

Conflicting views have been expressed with regard to the selection of traction power substation rating and spacing. On one side there is the view that the substations should be frequently spaced and as small as possible, each substation just large enough to withstand its share of the current of two accelerating trains in the vicinity. There are also proponents of the opposing view, that traction power substations should be as large and spaced as far apart as allowed by the line feeder size, technical feasibility, or practicality or by some other considerations of a technical nature such as excessive track potentials. However, neither of these approaches ensures minimum overall system cost.

The method presented herein is an attempt to develop a systematic and analytical procedure for finding a combination of TES parameters that results in the least expensive technically acceptable system. It requires somewhat greater engineering effort in the design stage, but the reward can be a significant reduction of the traction electrification system capital cost. In the sample case, there is $6.2/lft differential between the maximum and the minimum values of the unit cost function. This is equivalent to $682,000 or approximately 8 percent of the actual procurement cost.

More experience with TESs that have various load patterns and with different components of cost structure is needed, however, before generalized assessments of the magnitude of potential savings can be made.