Sensitivity Analysis of Light Rail Transit Unit Capital Costs

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Costs for 24 light-rail transit (LRT) lines and extensions were analyzed with a sensitivity analysis to find unit costs for types of right-of-way (R.O.W.) construction. Data about light rail systems was rigorously checked from multiple sources. A sensitivity analysis was used to limit the error and arrive at the final unit costs for each R.O.W. type. A tool for estimating costs in feasibility studies was produced. The tool had an average error of 6% for the projects studied.

INTRODUCTION:

The purpose of this work is to make a tool that can quickly produce a rough estimate of light rail construction based only on mileage. This is for use at only the most conceptual stages to answer the question: How much are we talking for this? In conceptual development only the approximate mileage and type of R.O.W. is know. At this stage of planning, the concept has not determined the number of stations or vehicles. Of course, it the planning would have no way of predicting costs such as yards and shops, systems, special conditions and soft costs. Yet, the level of detail required of currently available estimations require at least knowing number of vehicles, and possibly even costs of systems.

These methods are too complex for feasibility study cost estimation. What is commonly done in feasibility studies is to find a system that is similar to the one proposed and then scale the cost up or down.

Finding a roughly accurate cost estimate from the beginning is important because the initial cost estimate is often used by the public as an indicator or being on budget. Several studies exist on cost overruns. (*1, 2, 3*) These studies compare the final actual cost to the earliest cost estimates and conclude that since the actual cost is much higher there are overruns. However, increases in project scope are often responsible for the costs being higher than estimated. (*4*) Another contribution to overrun is not foreseeing risk. Having an estimation tool that looks at the final cost of systems per mile will take into account an average level of risk because real costs are analyzed instead of estimated costs.

Extensive work has been done in producing cost estimating tools for final engineering estimation. (*5, 6, 7*) The focus of these methods is to find the component cost of items such as steel track then use it to find the total system cost. However at the preliminary level, there is no way of predicting costs such as yards and shops, systems, special conditions and soft costs.

Other work has presented per mile estimates of costs. One is out of date since it was before a majority the current light rail systems. (*8*) The other requires too much detail for a conceptual level estimate. (*9*) The number of stations and vehicles must be estimated. Additionally, this work presents no methodology for how the results were reached, but seems to be numbers that have been passed around without peer review. Also, there are no instructions for adjusting for local cost of living. A large portion of costs are local costs such as labor and soil conditions that need to be adjusted from site to site. (*10*)

TABLE 1 Systems Included in Sensitivity Analysis

City-Year	Extension name
Buffalo-1985	Metro Rail
Dallas-1996	Red and Blue Lines
Denver-1995	Central Corridor
Denver-2000	Southwest Corridor Ext.
Denver-2003	Platte Valley Corridor Ext.
Houston-2004	Red Line
Hudson-Bergen-2000	HBLRT MOS I and II
Los Angeles-1990	Blue Line
Los Angeles-1995	Green Line
Los Angeles-2003	Pasadena Gold Line
Minneapolis-2004	Hiawatha Line
Portland-1986	Eastside MAX (Blue Line)
Portland-1998	Westside MAX (Blue Line)
Portland-2001	Portland Airport MAX (Red Line)
Sacramento-1987	Red Line
Sacramento-2003	South Sacramento Corridor Extension
St. Louis-1993	Metrolink Original Line
St. Louis-2001	St. Claire Ext.
Salt Lake City-1999	Trax
San Diego-1997	Mission Valley West
San Diego-2004	Mission Valley East
San Francisco-2005	Third Street
San Jose-1999	Tasman West Extension
San Jose-2001	I-880 Extension

The method developed here uses a more rigorous basis for comparison with existing systems. The goal was to find the schematic costs of units such as a mile of elevated track. This will aid in making more accurate feasibility studies and help in limiting costs from the beginning conceptual phases.

This study was limited to heavier electric LRT vehicle lines and did not include rapid streetcar or heritage trolley systems. Table 1 shows systems included in the study. Table 2 shows systems not included and the reasons.

TABLE 2 Systems Not Included in Sensitivity Analysis

City	Year	Extension name	Reason not included
Baltimore	1992	Central LR	Unable to break down into ST, DT, and phases. Some extra work may have been done with initial Single Track in expectation of coming back with DT.
Baltimore	1997	BWI/Penn Station Extension	Unable to break down into ST, DT, and phases.
Denver	2006	Southeast Extension	Too new to get complete data from multiple sources.
Portland	2001	Portland Streetcar	Rapid Streetcars have different cost profiles.
Sacramento	2003	Folsom Corridor Extension	Could not get recent aerial photos.
San Jose	1992	Guadalupe Line	Unsure if costs found included several incremental enhancements to original line.
Seattle	2009	Central Link	System is not complete, so final total costs are not known.
Tacoma	2003	Tacoma Link	Rapid Streetcars have different cost profiles.

DATA ACQUISITION AND VALIDATION:

Estimation of a final engineering budget is done by getting the most up-to-date quotes from suppliers such as track and vehicle manufacturers. However, in this study the data needed was the mileage and total cost data which is produced by the transit agencies themselves. The agencies distribute the data to the Federal Transit Agency (FTA) and other organizations. Since the data comes from many sources, there is a much greater probability of reporting error. Therefore, the data needs to be independently verified from several sources. The purpose of checking the data is not to make judgments against an agency but to get the most accurate data into the model.

One source of data for the study was the transit agencies themselves through their web pages and Freedom of Information Act inquiries. Other primary sources were the FTA (*4*) and the American Public Transportation Association (APTA) (*11*). This data was further validated through personal direct observation, aerial photography, and other photographs. Table 3 shows the system mileage in major cost categories.

An example of a major data disagreement is the tunnel length of the Hiawatha Line in Minneapolis. The FTA (*4*) cites the tunnel length to be 27.76% of the total length, which would be 3.14 miles of tunnel. However, all other sources and observations indicate that the tunnel length is half that. The source of the error is possibly that the tunnel under the airport is two side-by-side tunnels, one for each track. The tunnel length is correct in terms of directional route miles, but not correct when compared to the total length of the system as a double track system. Another possible source of error is that all the sub-grade work including trenches was lumped together in the reference.

DATA NORMALIZATION:

Costs vary over time due to inflation. Costs vary from place to place due to local cost of living. These factors were normalized out to arrive at a single cost.

First, system costs were converted to 2007 dollars using the consumer price index. The components of transit systems do not all rise equally with the consumer price index. For example, steel cost fluctuates with political agendas such as a steel tariff. However, on average the cost of light rail transit inflates at a rate roughly equal to the consumer price index. (*4*) In the last couple years the construction price index has exceeded the consumer price index. If this work is used to predict future systems the prediction should be inflated with the projected construction price index.

TABLE 3 System Miles

City-Year	In-Street (mi) (*a*)	In-Median (mi) (*b*)	Rail R.O.W. (mi) (*c*)	Embank, Trench (mi) (*d*)	Elevated, Bridges (mi) (*e*)	Tunnel (mi) (*f*)
Buffalo-1985	1.2	0	0	0	0	5.20(*g*)
Dallas-1996	1.2	2.9	10.9	0	1.7	3.25(*h*)
Denver-1995 (*i*)	1.9	0	3.0	0	0.6	0
Denver-2000	0	0	14.2 (*j*)	0	1.6	0
Denver-2003 (*i*)	0	0	3.5 (*j*)	0	0.04	0
Houston-2004	6.1	1.3	0	0	0.1	0
Hudson-Bergen-2000	1.3	0	16.0	0	2.5	0.70 (*k*)
Los Angeles-1990	5.9	0	11.9 (*l*)	0	3.5	0.70
Los Angeles-1995	0	8.7	0	0	11.3	0
Los Angeles-2003	0.75	1.5	8.6 (*m*)	1.3 (*n*)	2.1	0.44 (*n*)
Minneapolis-2004	0.6	6.8	1.4	0	0.9	1.70 (*o*)
Portland-1986 (*p*)	2.1	0	7.4 (*q*)	5	0.5	0
Portland-1998	2	2.7	9.9 (*r*)	0	0.4	3.02 (*s*)
Portland-2001 (*i*)	0	4.8	0	0	0.7 (*t*)	0.07
Sacramento-1987 (*u*)	4.1	1.7	11.0	0	1.5	0
Sacramento-2003 (*i*)	0	0	12.4 (*l*)	0	0.1 (*v*)	0
St. Louis-1993	0	0	15.6	0	1.3	0.1 (*w*)
St. Louis-2001 (*i*)	0	0	15.7	0.8	0.9	0
Salt Lake City-1999	2.8	0	18.1 (*x*)	0	0.1	0
San Diego-1997 (*i*)	0	2.7	0.4	0.2	2.8	0
San Diego-2004 (*i, y*)	0	1.5	0	1.6	2.1	0.75
San Francisco-2005	5.3	0	0	0	0.2 (*z*)	0
San Jose-1999	2	3.3	1.3	0	1	0
San Jose-2001 (*i*)	0	1.8	0	0	0.1	0
Totals	36.0	39.7	161.3	8.9	36.0	10.7

Notes:

a. In-street, also called in-road or in-lanes is LRT with traffic or in dedicated R.O.W. or pedestrian mall that was a previous traffic lane.
b In freeway, divided road, or nearby grassy area.
c. Former or current freight or interurban R.O.W.
d. New embankments or trenches only. Existing is included with other categories.
e. New or rehabilitated bridges or elevated sections.
f. New tunnel only.
g. (Tunnel Boring Machine) TBM method.
h. Does not include underground station added in 2000. TBM method.
i. Cost and estimate exclude maintenance facility.
j. Contained within a active freight rail corridor.
k. Hard rock tunnel.
l. Active freight rail R.O.W.
m. One mile is active rail R.O.W.
n. Tunnel was reported as much longer, but was actually a trench.
o. Three tunneling methods used. The tunnel length was reported to FTA was double the actual because each track had its own tunnel.
p. Transit work was simultaneous with freeway widening. We assume that highway work completely covered new embankment costs.
q. Extensive in-street length was mostly a former interurban route.
r. Former interurban route.
s. Deepest underground transit station in North America.
t. Bridges and elevated segments are Single Track (ST). Additionally some other short segments are ST.
u. Initial line almost entirely ST.
v. Couple of short overpasses. Road bridges should also been included in cost.

w. Short cut and cover tunnel. Two underground stations constructed for 1.2 miles abandoned freight tunnels.
x. Track is used by freight in off hours.
y. In median on top of triple box culvert for 1 mi. Retaining walls: 4 mi. Used cut and cover tunneling and 1000 feet of (New Australian Tunneling Method) NTM.
z. Rehabilitation of cantilever drawbridges.

Second, system costs were normalized to a cost of living of 100 which is the national level. A majority of the costs in construction are local costs, so the same system costs more in a higher cost of living area. About 85% of the costs are local materials and labor, and 15% of the costs are imported from other areas. (*4*) The costs of imports are the same no matter which region the system is constructed in. Even if the LRT vehicles are produced in the same region, the cost of the vehicles would be the same for all regions. A sensitivity analysis is performed in the next section to confirm the local content of the cost.

The following equation is used to convert between national costs and local costs with 85% local contribution.

$$Local\ Cost = \left(\left(\frac{Cost\ of\ Living\ Index}{100} - 1 \right) * 0.85 + 1 \right) National\ Cost$$

SENSITIVITY ANALYSIS:
A sensitivity analysis is a study of how the variation in output such as system costs is a function of the inputs. (*12*) The inputs are the costs of types of R.O.W. The miles of R.O.W. are constants. The output that was analyzed was the average absolute error, which is the average of the difference between the estimated and actual cost for each system. The sensitivity analysis is performed by optimizing the error to a minimum value. R.O.W. costs are varied, and by measuring the change in total costs or error, the sensitivity to that variable is known. In optimization the value converges from an initial estimate to a final estimate at the value of minimum error. Minimizing average absolute error results in cost estimates for the majority of the systems that are closer to the actual costs. An absolute error of 0.07 is 7% error, which could be positive or negative error.

Engineering estimates were made for different types of R.O.W. For example, at the national cost of living the cost of elevated mileage was estimated to be $45 M / mi using Means Cost Estimates. Then the sensitivity analysis varied the costs to find the minimum error. For elevated track this is shown in Figure 1.

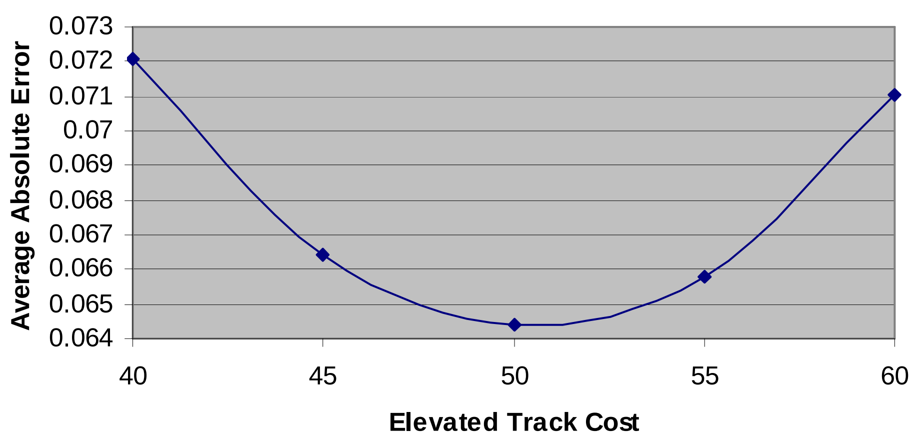

FIGURE 1 Sensitivity Analysis of Elevated Track Cost

For elevated track the minimum error existed when the cost was $50 M / mi. The final estimate is shown in Table 4. All of the estimates were simultaneously renormalized to keep the total estimated cost of all systems equal to the actual cost. Not renormalizing all variables at the same time would introduce error in that the total costs did not match.

It is important to keep close to the initial estimated cost of $45 M / mi for elevated track because this is based on engineering estimates. Therefore, limits are set on the amount that cost estimates are allowed to change in a sensitivity analysis. A very strong reason would have to exist to allow the estimates to change by more than 10 to 20%.

The sensitivity analysis for In-road track construction is shown in Figure 2. From the initial estimate of $55 M / mi the analysis iterated to a cost of $50-52 M / mi. A cost of $52 M / mi would have a slightly smaller absolute error than for $50 M / mi.

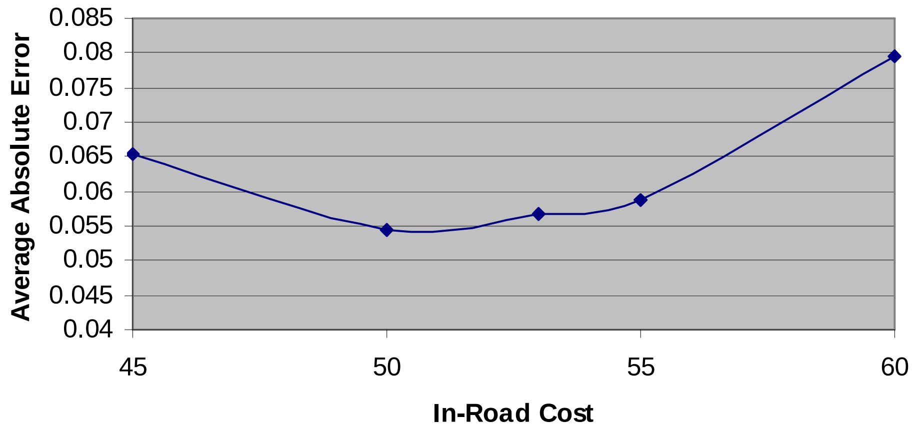

FIGURE 2 Sensitivity Analysis of In-Road Track Cost

TABLE 4 Unit Costs

Unit Cost	Median Cost $M/mi. (2007 $'s, normed to US Cost of Living)	Cost Range $M/mi (2007 $'s, normed to US Cost of Living)
In-Street	52	50-55
In-Median	26	25-36
Abandoned Rail or Interurban R.O.W.	20	17-23
Active Freight Rail R.O.W.	29	22-35
Embankments and Trenches	25	(*a*)
Elevated and Bridges	50	(*a*)
Tunnel Rehabilitation	50	(*a*)
Cut and Cover Tunnel	110	(*a*)
NTM Arch Tunneling	160	(*a*)
TBM Bored Tunneling	229	(*a*)
New Underground Stations in rehabbed tunnel		$100-250 M ea.

Notes:
a. Insufficient data to predict a range.

The assumption about the local content of materials and labor in a transit project can be checked with a sensitivity analysis. Figure 3 shows that by varying the local content assumption, that the least error can be found when local content is assumed to be around 80%. The curve is very flat in this region and the sensitivity analysis was very close to 85% cited in references (*4*), therefore 85% was used as the local content.

Notice that the greatest error occurs when it is assumed that there is no local content, but all regions should pay exactly the same price for the same system. This causes the high cost-of-living areas to be unexplainably more expensive than other areas. There is also some error when assuming that all costs are local. This causes the high cost-of-living areas unexplainably cheaper than other areas.

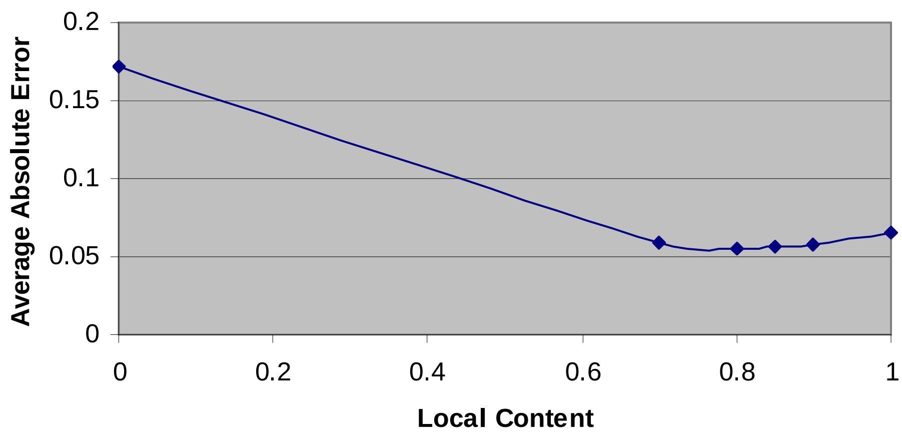

FIGURE 3 Sensitivity Analysis of Local Content

The final costs per unit mile of light rail based on type of right-of-way are shown in Table 4. The comparison of actual cost versus estimated cost for the 24 studied lines and extensions is shown in Table 5. The worst error from any line or extension is 20%. The average error from all estimates is less than 6%.

From Table 5 it is clear that using a single median cost does not exactly estimate light rail transit construction. There are other things beyond the variables considered that cause cost unpredictability. Some of the soft issues that cause this are: who bid on the construction contract, fluctuations in steel price, vehicle supplier and whether significant public artwork was included in the cost. Also, at this level of estimation, it is hard to predict the number of parking spots needed at stations.

However it is possible to calculate the ranges that the cost would have so that every system could be estimated exactly. The third column in Table 4 shows the range of costs that could exactly estimate each system.

Some influences that were noticed in causing the cost to be higher or lower than the median are enumerated here. In-road construction is influenced by the extent of utility upgrades and other street improvements. In-median cost is influenced by the extent of drainage culvert work needed. The upper range of cost is for when the track is completely on box culvert. Railroad conversion cost is a function of property acquisition cost and degree of accommodation for active freight. The method of fixation of track to elevated structures and whether it is in an earthquake zone influences its cost. Earthwork estimates are a function of the type of soil, water table level, and whether embankments or trenches require retaining walls.

One effect that was accounted for was whether extensions used existing maintenance facilities or had their own. An extension that relies on an existing facility would have costs at the lower ends of the ranges. A starter line with a larger maintenance facility in anticipation of future expansion would have higher costs. Error calculations were adjusted so that a proportionately sized maintenance facility was included.

Example:
The cost estimation for the San Diego 1997 extension of the Mission Valley West line from Old Town to Mission is illustrated here. The extension cost \$223 M in 1997. The net present value factor for 1997 to 2007 is 0.78. The cost of living index for San Diego is 1.41. With 85% local content, the adjusted cost of living is 1.359. Therefore, the nationally normed cost in 2007 is \$223 M / 0.78 / 1.359 = \$212 M.

TABLE 5 Actual Versus Estimated Cost Using Median Cost

System Extension	Actual Cost, 85% local content, 2007$'s ($M / mi)	Estimated Cost, ($M / mi)	Ratio Estimated to Actual Cost
Buffalo-1985	192.6	193.8	1.01
Dallas-1996	59.3	58.6	0.99
Denver-1995	28.0	29.4	1.05
Denver-2000	26.7	32.0	1.20
Denver-2003	28.5	29.1	1.02
Houston-2004	45.5	46.4	1.02
Hudson-Bergen-2000	34.0	36.3	1.07
Los Angeles-1990	41.1	38.0	0.93
Los Angeles-1995	35.5	35.7	1.00
Los Angeles-2003	36.5	34.6	0.95
Minneapolis-2004	51.2	48.9	0.96
Portland-1986	24.2	24.8	1.03
Portland-1998	60.9	60.7	1.00
Portland-2001	25.3	26.5	1.05
Sacramento-1987	14.7	15.4	1.05
Sacramento-2003	33.2	26.9	0.81
St. Louis-1993	38.9	37.5	0.96
St. Louis-2001	23.3	20.4	0.87
Salt Lake City-1999	25.4	26.1	1.03
San Diego-1997	34.8	33.5	0.96
San Diego-2004	66.4	59.6	0.90
San Francisco-2005	58.6	55.6	0.95
San Jose-1999	34.3	36.9	1.08
San Jose-2001	29.8	26.4	0.89

The segment lengths for this extension are shown in Table 3. Multiplying by the median costs in Table 4 gives an estimate of $230 M. Since no maintenance facility was included, $25 M was subtracted to give an estimate of $205 M. This is a 4% error compared to the actual cost of $212 M.

Next, the cost can be predicted exactly by varying the unit costs within the ranges. Varying the cost of constructing In-median R.O.W. to $30 M / mi gives zero error in the prediction.

CONCLUSIONS:

The costs of light rail lines and extensions were found by comparing 24 construction projects. The cost and mileage data were rigorously validated. Engineering estimation and sensitivity analysis were used to minimize error between the cost estimates and actual costs.

Ranges were given for how much the unit costs vary. Also, median values of unit costs were listed. The median estimates were not exact, but in the worst case would predict a system cost within 20% of actual costs. Using the median unit costs, the error was less than 6%. It likely that with further data validation, error would be found in the number of route miles for a system shown in Table 3. However, small changes in the route miles would not significantly change the results. At this level of accuracy the significance of public artwork becomes more important than measuring the tunnel length to the nearest inch.

Contingency is a large part of the cost estimates in final design. An equivalent concept in the preliminary estimation given here is that there is a range of error of up to 20%. The procedure given here will produce the mean value. A contingency of 20% added to this would give an upper bound estimate.

Estimation of schematic costs per mile for each type of right-of-way suits the purpose of providing a tool for conceptual planning of light rail transit systems. During engineering design, cost estimation is based on the component costs such as lineal feet of rail needed. This level of detail is in excess of what is needed or what is convenient for conceptual planning. The construction price index should predict changes in costs due to inflation. However, changes in technology may reduce costs and this project could be repeated after evidence exists that changes in technology have been influencing the costs.

An Excel spreadsheet is available from the author to speed estimation of light rail transit system costs.

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