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Project Cost Models for Mode Choice between Light Rail and Bus Rapid Transit Systems

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ABSTRACT

In this study, project cost models along with an applicable costing methodology are developed for LRT and BRT systems' cost analyses to better aid the transportation planners and decision makers in the selection process. In evaluating transit systems, project cost has always been a major consideration. Without an applicable project cost model or methodology, the choice between LRT and BRT systems would be controversial among the transit advocates in the early stages of corridor planning or system analysis. The developed models in this paper can be applied to compare the LRT and BRT systems that operate on various right-of-way categories, guideway or running way alignment configurations, and different given transit demand volumes.

Key words: light rail transit, bus rapid transit, project cost models

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INTRODUCTION

Traffic congestion is a nightmare to millions of American people as they commute to work in automobiles each day. Time delay, wasted fuel and pollution are substantial impact caused from this congestion. For the medium sized cities, fully grade separated Rapid Transit systems are not feasible because of the enormous investment of the systems. Light Rail Transit (LRT) and Bus Rapid Transit (BRT) are appropriated public transportation systems for medium sized cities. LRT is comprised of electrically propelled vehicles that operate singly or in trains. BRT uses conventional bus vehicles, along with a combination of restricted lanes and signal prioritization to provide a rail like service. Although both systems utilize similar Right-Of-Way (ROW) categories, they do use different technology and have dissimilar operating characteristics.

A number of transit agencies in the United States have been building LRT system or BRT system in order to provide a more reliable and effective high-speed transit service to attract auto users taking public transit and to eliminate delays and provide faster service for public over the past years. The mode choice between LRT and BRT has been controversial for many years and unfortunately, with no suitable closure until now. In the Hartford region of Connecticut, the BRT system was selected to upgrade their mass transit systems, but many still argue that LRT would be a better choice than the BRT system. Many still criticize that the BRT system is probably valid for the Austin area due to lower capital cost than the LRT system.

In evaluating transit systems, project cost estimation is a major factor. Without an applicable project cost model or methodology to estimate project cost, the choice between LRT and BRT systems tend to be more controversial among the transit advocate in the early stages of corridor planning or system analysis. The average capital cost of LRT systems is generally higher than BRT systems when compared on a cost per mile basis. However, LRT system has less Operating and Maintenance (O&M) cost than BRT system. The LRT system is more capital-intensive, while the BRT system is more labor-intensive.

REVIEW

In evaluating different modes, both capital and operating costs, expressed as unit costs ($/sp-km or $/prs-km), are usually considered (*1*). Li and Wachs (2) presented a widely used cost estimation method in the transit industry by featuring the average unit costs in allocation method. The capital costs are typically one-time cost, including infrastructure cost with the construction of ROW and facilities, as well as the acquisition of equipment and vehicles (3). Federal Transit Administration (FTA) provides the capital cost information for five selected LRT systems and recommends the capital cost components of LRT systems be classified into eight cost components (*4*). The Diaz et al have classified the capital cost components of BRT systems into five cost components (*5*). In 2005 FTA implemented a capital costing format guideline workbook, the Standard Cost Categories (SCC), to establish a consistent format for the reporting, estimating, and managing of capital costs for New Starts projects. The transit agencies follow the criteria of "Reporting Instructions for the Section 5309 New Starts Criteria, May 2007" to report their project costs for eligibility of being granted federal funding (*6,7*). When the project estimate, project schedule and the implementation schedule are determined, the escalation rate are input to the FTA workbook. Thus, the expenditure costs estimated for the year will then be automatically calculated in the FTA workbook. However, the differences of the predicted capital costs or operating expenses between the actual capital costs or operating expenses are unclear.

The capital costs vary considerably due to the complexity of the construction and various ROW types. The average capital cost of LRT systems is generally higher than BRT systems when compared on a cost per mile basis because of the need for rails, electrification and signaling, and higher vehicle costs. The capital costs for LRT systems show a wide range of variability, ranging from a low $16.5 million per mile for the Orange Line in San Diego to a high $106.0 million per mile for the 6.4 mile LRT system in Buffalo (77% tunneling). However, the BRT tunnels in Seattle and Boston (a section of the Silver Line) have the cost as high as the most expensive rail tunnels, such as the Silver Line tunnel section with a cost estimated at about $500 million per mile (*8*).

The O&M cost is the costs incurred by the regular operation of the system and typically, regular costs involved in daily operations include operating cost and maintenance cost. The National Transit Database (NTD) provides the historical data of the O&M cost for the public transportation systems. However, most of the transit agencies do not collect or maintain O&M cost for BRT systems or their individual lines. The O&M cost of the BRT systems was calculated or estimated by the transit agencies according to the average O&M cost of regular bus service. The transit O&M cost is mainly influenced by fleet size, frequency, passenger capacity and route structure. Khistry and Lall (*9*) found a quicker way to determine transit O&M cost through application of unit costs to get an approximate cost calculation. It is based on 1) distance-related costs: the cost related to energy, maintenance, and servicing of vehicles, 2) time-related costs: the cost related to operating staff wages, and 3) route-related costs: the cost related to maintenance of roadway, track, signals and stations.

The fleet size of the system has a significant impact on capital cost and O&M cost. Only after the fleet sizes of both LRT and BRT have been calculated, can estimations of the costs be conducted. Hsu and Wu (*10*) developed a fleet size model, equation (1), on determining the number of vehicles required in maximum service for both LRT and BRT systems operating under various ROW configurations. Factors taken into consideration in the fleet size model include vehicle characteristics, passenger demand volume, ROW configurations, numbers of stations, headway, size of vehicle, and traffic signal timing at the intersections.

$$N = \frac{p\left\{[T_A + T_B + T_C] + \left[2\left(2\left(\frac{p}{m}\right)ht_p + \left(\frac{t_t}{60}\right)\right)\right]\right\}}{C_v \alpha} \qquad (1)$$

where,

N = number of vehicles needed in maximum service,
T_A = the round trip travel time excluding the dwell time at the stop or station of the vehicle running on the exclusive ROW (ROW A), (hr),
T_B = the round trip travel time excluding the dwell time at the stop or station of the vehicle running on the reserved ROW (ROW B), (hr),
T_C = the round trip travel time excluding the dwell time at the stop or station of the vehicle running on the mixed traffic ROW (ROW C), (hr),
p = passengers per hour per direction (pphpd),
t_t = layover and recovery time (min),
t_p = passenger boarding/alighting time (hr/passenger),
h = headway (hr),
m = number of loading areas per stop for BRT; LRT system m =1,
C_v = seats per vehicle, and
α = loading factor.

PROBLEM

In most previous articles and studies, the comparison between LRT and BRT systems took either capital cost or O&M cost, not both into consideration. However, cost comparisons among different modes should be examined on the basis of total costs, including capital cost and O&M cost, because the provision of transit service incurs both types of costs. Owing to different planning and complicate operation scenarios, it is necessary to develop project cost models to properly estimate LRT and BRT systems' costs for evaluation and comparison. Therefore, the problems addressed in this paper are: 1) to obtain the cost components of capital and O&M costs for both LRT and BRT systems, 2) to examine the unit costs of the cost components of capital and O&M costs from existing LRT and BRT systems, 3) to develop project cost models in order to estimate the capital cost and O&M cost for both LRT and BRT systems operating on various ROW configurations or alignments, and 4) to find a preferable system between LRT and BRT systems by comparing both capital cost and O&M cost in terms of cost per passenger mile. In other words, the one with the lower cost per passenger mile is the preferable and more cost-effectiveness system. The cost allocation technique and standard cost components will be applied to construct the project cost models in order to avoid unnecessary complications.

PROJECT COST MODELS DEVELOPMENT

The developed project cost models can estimate LRT and BRT costs for evaluation and comparison. The costs estimated from the models are capital cost, annualized capital cost (depreciation cost), O&M cost and cost per passenger mile. The developed project cost models are established on a unit cost basis. The unit costs are established by applying the historical data of the existing systems. The historical costs of the existing systems were obtained from multiple resources, including the FTA, the Urban Mass Transportation Administration (UMTA), Transit Cooperative Research Program (TCRP) report, General Accounting Office (GAO) report, NTD, local transit agencies, and published papers.

Capital Cost

In accordance with the estimating methodology by FTA, capital cost components of LRT systems are classified into eight cost categories: guideway, yards and shops, systems, stations, ROW, special conditions, vehicles and soft cost (Table 1).

Table 1. The Cost Components of LRT Capital Cost

Components		Unit	Unit Cost (Million)		Life Time (Years)
Guideway	At-grade	$/Mile	High	$8.6	30
			Low	$2.9	
	Elevated	$/Mile	High	$21.0	30
			Low	$2.9	
	Subway	$/Mile	High	$60.0	100
			Low	$45.0	
Yards and shops		$Shop/Vehicle	High	$0.9	30
			Low	$0.2	
System		$/Mile	High	$6.2	30
			Low	$1.3	
Station*		$/Station	High	$3.6	30
			Low	$0.2	
Vehicle		$/Vehicle	High	$2.4	30
			Low	$0.9	
Right-of-way		$/Mile	High	$2.7	100
			Low	$1.1	
Special condition		$/Mile	High	$8.9	0
			Low	$1.3	
Project soft cost		10%~40% of total project cost			

Sources and Notes:

1. LRT vehicles, stations, power distribution systems and the roadway or track structure were depreciated over 30 years which is the design life of most equipment; tunnel and right-of-way were depreciated over 100 years (*11*)
2. The cost of guideway, system, special conditions (*12*). Year 1990 costs will be escalated to year 2000 using 1.32 escalation rate
3. The cost of yards & shops, station, systems, vehicle (*4*). Year 1994 costs will be escalated to year 2000 using 1.16 escalation rate
4. Project soft cost (*11, 12*)
5. * Each elevated station costs $3.6 million; tunnel station costs between $8 million to $33 million, average $21 million (*12*). Year 1990 costs are escalated to year 2000 using 1.32 escalation rate

Typically, the BRT system is classified into three categories: busway, bus-HOV (High Occupancy Vehicle, HOV) lanes and BRT on arterial streets. The capital cost structure of the BRT system is dissimilar to that of the LRT system because they utilize different technology. Table 2 lists the capital cost components and the unit costs of the BRT system. The unit costs for the components come from the historical data and references of the construction costs of freeways and highways in the United States.

Table 2. The Cost Components of BRT Capital Cost

Components			Unit	Unit Cost (Million)		LifeTime (Years)
Running Way	At-grade	Arterial	\$/Lane Mile	High	\$0.27	30
				Low	\$0.009	
		Busway	\$/Lane Mile	High	\$2.7	
				Low	\$2.3	
		HOV	\$/Lane Mile	High	\$9.4	
				Low	\$6.0	
	Elevated* (Exclusive Busway)		\$/Lane Mile	High	\$27.6	30
				Low	\$11.0	
	Subway (Exclusive Busway)		\$/Lane Mile	High	\$96.6	100
				Low	\$55.2	
Stop, station**			\$/Stop	High	\$3.6	30
				Low	\$0.2	
Traffic signal priority			\$/Intersection	High	\$0.04	10
				Low	\$0.008	
Vehicle			\$/Vehicle	High	\$1.5	12
				Low	\$0.3	
Project soft cost (Miscellaneous)			15% of total project cost			

Source: Running way cost (*5*, *13*); Traffic signal priority cost (*5*, *14*); Vehicle cost (*13*)

Note: 1. Costs are in year 2000 U.S. dollars

2. * These facilities can be a major highway (*5*)

3. ** The stop and station cost of BRT assumes the same as LRT system. Each elevated station costs \$3.6 million; tunnel station costs between \$8 million to \$33 million, average \$21 million (*12*). Year 1990 costs are escalated to year 2000 using 1.45 escalation rate

As the equation (2) and (3) shown below, the LRT and BRT capital cost can be calculated using the cost allocation technique:

$$C_{LRT} = \frac{1}{1-U_{so}} \Big[\left(G_1 U_{g1} + G_2 U_{g2} + G_3 U_{g3} + U_s + U_r + U_{sp}\right) L + \left(U_y + U_v\right) N_L + \left(G_1 U_{stL1} + G_2 U_{stL2} + G_3 U_{stL3}\right) S \Big] \quad (2)$$

where,

C_{LRT} = LRT capital cost (\$million),
G_i = structure percentage: at grade i= 1; elevated i= 2; tunnel i= 3,
L = route length (mile),
S = number of stops and stations,
N_L = number of LRT vehicles,
U_{so} = soft cost (% of the total project cost),
U_{gi} = LRT guideway cost (\$ million/mile): at grade i= 1; elevated i= 2; tunnel i= 3,
U_s = LRT system cost (\$million/mile),
U_r = LRT right-of-way cost (\$million/mile),

U_y = LRT yards and shops cost ($million/vehicle),
U_{sp} = LRT special condition cost ($million/mile),
U_{vL} = LRT vehicle cost ($million/vehicle), and
U_{stLi} = LRT stop or station cost ($million/stop or station):at grade i=1;elevated i=2; tunnel i=3.

$$C_{BRT} = \frac{1}{1-U_{so}}\Big[2L(G_{11}U_{R11}+G_{12}U_{R12}+G_{13}U_{R13}+G_2U_{R2}+G_3U_{R3}) + (U_tS+U_{vB}N_B)+S(G_1U_{stB1}+G_2U_{stB2}+G_3U_{stB3})\Big] \quad (3)$$

where,

C_{BRT} = BRT capital cost ($million),
N_B = number of BRT vehicles,
G_{ij} = structure percentage:
i= 1 at grade; i= 2 elevated; i= 3 tunnel; j=1 arterial; j=2 busway; j=3 HOV lane,
U_{Rij} = BRT running way cost ($million/lane mile):
i= 1 at grade; i= 2 elevated; i= 3 tunnel; j=1 arterial; j=2 busway; j=3 HOV lane,
U_{stBi} = BRT stop or station cost ($million/stop or station):
i= 1 at grade; i= 2 elevated; i= 3 tunnel,
U_t = BRT traffic signal priority cost ($million/intersection), and
U_{vB} = BRT vehicle cost ($million/vehicle).

Annualized Capital Cost (Depreciation Cost)

For the purpose of making a cost comparison between LRT and BRT systems, the capital costs should be annualized to calculate the total annual costs, which are the sum of annualized capital cost and annual O&M cost. The capital costs are annualized and represent depreciation and interest changes. The annual capital recovery factors have been determined based on a FTA-prescribed 7% interest rate (*11*) in order to construct the annualized capital cost. The LRT and BRT annualized capital costs can be calculated through equation (4) and (5), respectively:

$$CP_{LRT} = \frac{1}{1-U_{SO}}\Big\{A_{30}\big(L(G_1U_{g1}+G_2U_{g2}+U_s)+N_L(U_y+U_{vL})+S(G_1U_{stL1}+G_2U_{stL2})\big) + A_{100}(U_rL)+A_{100}(G_3)(U_{g3}L+U_{stL3}S)\Big\} \quad (4)$$

$$CP_{BRT} = \frac{1}{1-U_{so}} \left\{ A_{30}\left[2L\left(G_{11}U_{R11} + G_{12}U_{R12} + G_{13}U_{R13} + G_2U_{R2}\right) + S\left(G_1U_{stB1} + G_2U_{stB2}\right)\right] + A_{10}\left(SU_t\right) + A_{12}\left(N_BU_{vB}\right) + A_{100}G_3\left(2LU_{R3} + SU_{stB3}\right) \right\} \quad (5)$$

where,

CP_{LRT} = LRT annualized capital cost ($million),
CP_{BRT} = BRT annualized capital cost ($million), and
A_i = annual capital recovery factor: A_{10}=0.142, A_{12}=0.126, A_{30}=0.081, A_{100}=0.07; (i =10,12,30,100 yrs).

O&M Cost

The NTD provides the historical data of the O&M costs of the public transportation systems. The components of LRT and BRT O&M costs are similar, which can be broken down into vehicle operation cost, general administrative cost, vehicle maintenance cost, and non-vehicle maintenance cost. Vehicle operation and general administrative costs are the costs of staff wages, fringe benefits, administration, ticketing and fare collection, and system security. Vehicle maintenance cost is the costs of fuel, tires, and serving of vehicle. Non-vehicle maintenance cost is the costs of maintenance of roadway, track, signals and stations. Vehicle operation and administrative costs are time-related cost; vehicle maintenance cost is distance-related cost; non-vehicle maintenance cost is the route-mile related cost.

Breakdown of the O&M costs of nine existing LRT systems and seven existing bus systems is listed in Table 3. In Table 3, the major part of O&M costs is the vehicle operation and administration costs, for which LRT accounting about 61% and BRT accounting 75%. The significant O&M cost is the costs related to labor expenses, especially claims. Most of the data reported by transit agencies to the NTD do not separate the BRT buses from general buses in the system. Consequently, estimates of the BRT O&M cost are derived from the regular bus systems operating expenses. Because the cities selected have both regular bus and BRT services, accounting of the BRT O&M cost would be more consistent.

Table 3. Breakdown of the O&M Costs of the Selected LRT and Bus Systems

LRT Systems						
City	Rail-Total Directional Route Miles	Vehicle Operation	General Administration	Vehicle Maintenance	Non-Vehicle Maintenance	Total
Sacramento	40.7	$8,091,248	$4,306,463	$4,819,471	$2,111,784	$19,328,966
Salt Lake City	29.6	$3,834,812	$458,701	$1,589,763	$1,476,417	$7,359,693
San Diego*	96.6	$14,220,561	$7,454,215	$6,098,982	$4,380,931	$32,154,689
Dallas	40.8	$12,314,721	$7,945,759	$5,482,530	$7,112,018	$32,855,028
Baltimore	57.6	$13,750,555	$2,706,672	$5,315,633	$6,962,551	$28,735,411
Portland	64.9	$11,949,492	$9,495,758	$9,836,077	$10,059,334	$41,340,661
St. Louis	34.0	$8,701,097	$2,479,112	$3,762,139	$4,648,018	$19,590,366
Denver	28.0	$4,369,476	$2,217,512	$2,536,271	$2,056,867	$11,180,126
Buffalo	12.4	$5,963,005	$1,756,469	$3,247,109	$3,549,432	$14,516,015
Average Percentage		40%	21%	19%	20%	100%
Bus Systems						
City	Vehicles Operated in Maximum Service	Vehicle Operations	General Administration	Vehicle Maintenance	Non-Vehicle Maintenance	Total
Seattle	892	$151,902,827	$26,470,045	$46,341,860	$19,268,839	$243,983,571
San Jose	427	$85,661,821	$53,304,424	$36,029,440	$7,300,665	$182,296,350
Los Angeles	1888	$346,252,299	$112,586,578	$157,160,824	$21,680,487	$637,680,188
Pittsburgh	848	$102,988,809	$23,749,931	$43,436,807	$11,219,354	$181,394,901
Dallas	441	$64,701,387	$37,390,858	$26,760,162	$7,713,013	$136,565,420
Denver	639	$83,047,498	$33,865,201	$40,694,718	$12,751,070	$170,358,487
Miami	530	$92,197,192	$18,479,944	$32,122,633	$8,055,418	$150,855,187
Average Percentage		53%	22%	19%	6%	100%

Source: Compiled year 2000 data from NTD

Note: 1. * Many of the administration costs are not included in San Diego LRT system (*15*)

2. Costs are in year 2000 U.S. dollars

Three factors are taken into consideration to estimate the O&M cost: 1) distance-related costs ($/vehicle-mile, 2) time-related costs ($/vehicle-hour), and 3) route-related costs ($/route-mile of LRT; $/vehicle of BRT). In Table 3, the historical data of the existing LRT and bus systems are applied to calculate cost per vehicle hour, cost per vehicle mile, and cost per route mile for LRT or cost per vehicle for BRT. The calculation results of the three unit costs of the O&M cost are illustrated in Table 4. The O&M cost can be expressed as shown in equation (6) below:

$$O\&M = \underbrace{\left(\frac{2 \times x_1 \times x_2 \times x_3 \times x_6}{x_5}\right)}_{\text{distance-related cost}} + \underbrace{\left(\frac{x_1 \times x_2 \times x_4 \times x_7}{x_5}\right)}_{\text{time-related cost}} + \underbrace{\left(2 \times x_3 \times x_8\right)}_{\text{route-mile-related cost}} \qquad (6)$$

where,

$O\&M$ = operating and maintenance cost ($million),
x_1 = $/vehicle-mile,
x_2 = $/vehicle-hour,
x_3 = $/route-mile for LRT; $/vehicle for BRT,
x_4 = the round trip travel time (hr),
x_5 = peak headway (hr),
x_6 = operating hour (hr),
x_7 = cars per train for LRT; buses per stop or station for BRT, and
x_8 = route length (mile) for LRT;
vehicles required in maximum service (vehicle) for BRT.

Table 4. Three Unit Costs of O&M Cost

LRT Systems					
City	Vehicle-Hour	Vehicle-Mile	**$/Vehicle-Hour**	**$/Vehicle-Mile**	**$/Route-Mile**
Sacramento	111,752	2,267,721	$72.40	$4.02	$142.16
Salt Lake City	75,464	1,508,956	$50.82	$1.36	$136.65
San Diego	338,801	7,166,547	$41.97	$1.89	$124.25
Dallas	155,624	2,451,300	$79.13	$5.48	$477.57
Baltimore	174,408	2,770,769	$78.84	$2.90	$331.17
Portland	293,828	5,079,456	$40.67	$3.81	$424.65
St. Louis	126,749	2,550,783	$68.65	$2.45	$374.54
Denver	123,367	1,565,100	$35.42	$3.04	$201.26
Buffalo	76,849	907,063	$77.59	$5.52	$784.23
		High	**$79.13**	**$5.52**	**$784.23**
		Low	**$35.42**	**$1.36**	**$124.25**

Bus Systems					
City	Vehicle-Hour	Vehicle-Mile	**$/Vehicle-Hour**	**$/Vehicle-Mile**	**$/ Vehicle**
Seattle	2,701,471	40,040,176	$56.23	$1.82	$72
San Jose	1,604,158	22,649,071	$53.40	$3.94	$57
Los Angeles	6,978,567	92,451,378	$49.62	$2.92	$38
Pittsburgh	2,578,768	36,422,988	$39.93	$1.84	$44
Dallas	1,599,967	22,291,782	$40.44	$2.88	$58
Denver	2,110,567	33,875,388	$39.35	$2.20	$67
Miami	2,070,989	27,871,134	$44.52	$1.82	$51
		High	**$56.23**	**$3.94**	**$72**
		Low	**$33.18**	**$1.82**	**$38**

Source: Compiled year 2000 data of vehicle hour and vehicle mile from NTD
Note: Costs are in year 2000 U.S. dollars

In equation (6), we assume: 1) operating hours of transit systems are 20 hours per day, 2) three peak hours in the day and three peak hours in the evening, and 3) off-peak headway is twice the time of peak headway. 300 equivalent working days in a year are used as a default value to estimate the annual O&M cost. Therefore, O&M cost of the LRT or BRT can be estimated through equation (7) shown below:

$$O\&M_{L/B} = 300 \times \left[\left(\frac{26nL}{h} \times x_1 \right) + \left(13N \times x_2 \right) + C_L \left(2L \times x_3 \right) + C_B \left(N \times x_3 \right) \right] \quad (7)$$

where,

$O\&M_{L/B}$ = LRT or BRT operating and maintenance cost ($million),
n = cars per train for LRT; buses per stop or station for BRT,
h = peak headway (hr),
L = route length (mile),
N = number of vehicles,
C_L = 1, when transit system is LRT; 0, when transit system is BRT,
C_B = 1, when transit system is BRT; 0, when transit system is LRT,
x_1 = $/vehicle-mile,
x_2 = $/vehicle-hour, and
x_3 = $/route-mile of LRT; $/vehicle of BRT.

Cost per Passenger Mile

After the capital cost, annualized capital cost and O&M cost are calculated; the estimation of the cost per passenger mile can be conducted. The cost per passenger mile can be estimated using equation (8) as shown below:

$$\text{Cost per passenger mile} = \frac{CP + (O\&M)}{P \times T_{adj} \times 300} \qquad (8)$$

$$T_{adj} = \frac{(T+6)}{2}$$

where,

CP = annualized capital cost ($million),
$O\&M$ = operating and maintenance cost ($million),
P = passengers per peak hour per direction (pphpd),
T_{adj} = adjusted operating hour (hr), and
T = operating hour (hr).

MODEL VERIFICATION

The developed project cost models will be validated by comparing the cost estimates derived from the developed models with existing costs of the selected systems.

Capital Cost

It is necessary to investigate the ROW categories, the alignment configurations, number of vehicles and number of stops and stations of the selected LRT and BRT

Table 5. Model Results vs Existing Capital Costs of Selected LRT and BRT Systems

Model Results vs Existing Capital Costs of Selected LRT Systems							
	Existing Data		Cost Model Data				
City	Capital Cost ($Million)	$Million/Mile	Capital Cost ($Million)		$Million/Mile	Comments	% difference
Buffalo	$718	**$112**	High	$976	$152.6	ROW A: 77% ROW B: 23% 77% Tunnel; 14 stations; 27 vehicles; Route Mile=6.4	-3%
			Low	$407	$63.6		
			Average	$692	**$108.1**		
Salt Lake City	$315	**$21.3**	High	$628	$40.5	ROW B: 86% ROW C: 14% 100% At-Grade; 20 stations; 23 vehicles Route Mile=14.8	15%
			Low	$148	$9.4		
			Average	$388	**$24.6**		
Denver	$320	**$23.0**	High	$653	$46.0	ROW A: 83% ROW B: 17% 25% Elevated; 20 stations; 31 vehicles Route mile=14.0	25%
			Low	$164	$11.5		
			Average	$408	**$28.8**		
Portland	$1366	**$41.0**	High	$1844	$55.9	ROW A: 36%; ROW B: 63% ROW C: 1% 9.4% Tunnel; 17% Elevated; 50 stations; 72 vehicles Route mile=33.0	-11%
			Low	$560	$17.0		
			Average	$1202	**$36.3**		
Dallas	$1770	**$38.0**	High	$2630	$56.3	ROW A: 35% ROW B: 59% ROW C: 6% 16% Tunnel; 12.3% Elevated; 44 stations; 95 vehicles Route mile=46.7	-0.5%
			Low	$899	$19.3		
			Average	$1765	**$37.8**		

Model Results vs Existing Capital Costs of Selected BRT Systems							
	Existing Data		Cost Model Data				
City	Capital Cost ($Million)	$Million/Mile	Capital Cost ($Million)		$Million/Mile	Comments	% difference
Seattle (Tunnel Busway)	$593	**$282**	High	$671	$319.7	ROW A: 100% 99% Tunnel; 5 stations/stops Route mile=2.1	-17%
			Low	$308	$146.7		
			Average	$490	**$233.1**		
Miami* (Busway)	$63.1	**$7.4**	High	$121	$15	ROW B:100% 100% At-Grade; 16 stations/stops Route mile=8.2	3%
			Low	$4	$0.5		
			Average	$62	**$7.6**		
Los Angeles**	$127.3	**$11.6**	High	$184	$17.7	ROW A:100% 100% At-Grade; 3 stations/stops Route mile=11.0	3%
			Low	$78	$7.1		
			Average	$131	**$11.9**		
Pittsburgh (East Busway)	$175.5	**$25.7**	High	$310	$45.7	ROW A: 100% 100% At-Grade; 6 stations/stops Route mile=6.8	7%
			Low	$65	$9.5		
			Average	$188	**$27.6**		
Pittsburgh (South Busway)	$63.34	**$14.7**	High	$119	$27.7	ROW A: :88% ROW C: 12% 8 stations/stops Route mile=4.3	21%
			Low	$33	$7.8		
			Average	$76	**$17.8**		

Source: Capital cost data of the LRT systems (*15*, *16*), NTD 2000
Capital cost of the BRT systems (*13*, *14*, *17*)

Note: 1. * Existing capital cost data in Miami do not include additional buses cost (*14*)
2. ** The BRT system in Los Angeles is San Bernardino HOV lane (El Monte Busway)
3. The soft cost in the developed cost model is 10% of total project cost intended to estimate capital cost of the LRT or BRT system
4. Costs are in year 2000 U.S. dollars

systems in order to estimate the capital cost. The data collected from the selected systems will input into the developed models. The comparison of the capital costs estimated from the project cost models with the existing capital costs of the selected LRT and BRT systems are listed in Table 5.

Five LRT systems were selected. The system in Buffalo was selected to verify the project cost models because it has the highest portion of underground alignment among the LRT systems in the United States. Five BRT systems were selected to verify the cost models. In Table 5, the existing capital cost of each selected system falls between the high and low cost ranges of the estimated costs. The average capital cost estimated from the project cost models is close to the existing capital cost of each selected LRT or BRT system. The percentage differences of the systems between the existing capital cost and the average estimated capital cost are among 0.5% to 25%. The average percentage difference is 15.5%.

O&M Cost

Route mile (L), number of vehicles required (N), peak headway (h), cars per train (n) of the LRT system, buses per stop or per station (n) of the BRT system, and O&M cost are collected from the selected LRT and BRT systems (Table 6). The data collected input into the developed models to estimate the O&M cost. The comparison of the results between O&M costs estimated from the developed models and existing O&M costs obtained from the selected LRT and BRT systems are listed in Table 6.

Table 6. Model vs Existing O&M Costs of Selected LRT and BRT Systems

Model O&M Costs vs Existing O&M Costs of Selected LRT Systems					
	Existing Data	Model Data			
City	O&M Cost ($Million)	O&M Cost ($Million)		Comments	% difference
Pittsburgh	**$27.8**	High	$37.6	n=1.38 h=4 minutes N=47 Route mile=35 Vehicle-mile=1,893,842 Vehicle-hour=130,778	-7%
		Low	$14.4		
		Average	**$26.0**		
Newark	**$9.1**	High	$11.7	n=1.0 h=2.6 minutes N=16 Route mile=8.3 Vehicle-mile=540,518 Vehicle-hour=45,312	-10%
		Low	$4.6		
		Average	**$8.2**		
Boston	**$89.1**	High	$111.3	n=1.9 h=2.6 minutes N=154 Route mile=51 Vehicle-mile=6,334,450 Vehicle-hour=422,297	-12%
		Low	$46.0		
		Average	$78.6		
Baltimore	**$28.7**	High	$40.0	n=2.45 h=13 minutes N=40 Route mile=57.6 Vehicle-mile=2,770,769 Vehicle-hour=174,408	-6%
		Low	$13.9		
		Average	**$27.0**		
Cleveland	**$15.9**	High	$23.6	n=1.9 h=9.2 minutes N=25 Route mile=30.8 Vehicle-mile=1,158,015 Vehicle-hour=76,173	1%
		Low	$8.4		
		Average	**$16.0**		
Los Angeles	**$61.4**	High	$77.9	n=1.65 h=5.0 minutes N=51 Route mile=82.4 Vehicle-mile=4,709,915 Vehicle-hour=205,207	-13%
		Low	$29.0		
		Average	**$53.4**		

Model O&M Costs vs Existing O&M Costs of Selected BRT Systems					
	Existing Data	Model Data			
City	O&M Cost ($Million)	O&M Cost ($Million)		Comments	% difference
Seattle	**$6.6**	High	$8.6	n= 2.5 h= 3 minutes N^{**} = 25 Route mile=2.1	2%
		Low	$4.8		
		Average	**$6.7**		
Los Angeles (Wilshire-Whittier)	**$32.7**	High	$47.4	n= 1.0 h= 2 minutes N^{**} =90 Route mile=26	11%
		Low	$25.1		
		Average	**$36.3**		
Los Angeles (Ventura Metro Bus)	**$12.5**	High	$15.0	n= 1.0 h= 4 minutes N^{**} = 29 Route mile=16	-8%
		Low	$8.0		
		Average	**$11.5**		
Pittsburgh (East)	**$43.0 ***	High	$44.7	n= 3.0 h=1.7 minutes N^{**} = 86 Route mile=6.8	8% ***
		Low	$23.8		
		Average	**$34.2**		
Pittsburgh (South)		High	$16.1	n= 2.0 h= 4 minutes N^{**} = 37 Route mile=4.3	
		Low	$8.8		
		Average	**$12.4**		

Source: Data of the selected BRT systems (*13*)

Note: 1. * O&M cost in Pittsburgh is estimated as 43,000 average weekday trips x $0.15 per passenger mile x 11.1 route length x 2x 300 day per year = $43 million (*14*)

2. ** Applying equation (1) to estimate N, number of vehicles required

3. *** 8% = ((34.2 + 12.4) – 43) / 43
4. n: cars per train of LRT or buses per stop or station; h: headway; N: number of vehicles required
5 . Costs are in year 2000 U.S. dollars

In Table 6, the existing O&M cost of each selected system falls between the high and low cost ranges of the estimated cost, which are estimated applying the developed project cost models. For each system, the existing O&M cost of selected LRT or BRT system is close to the O&M cost estimated from the project cost models.The percentage differences of systems between the existing O&M cost and the average estimated O&M cost are among 1% to 13%. The average percentage difference is 7.8%.

With the verification results, there are relative minor differences between the existing costs of the selected systems and the costs estimated from the developed models. They indicate that the developed project cost models can deal with the actual problems to estimate the capital cost and O&M cost for the systems' comparison between LRT and BRT.

APPLICATION AND COMPARATIVE ANALYSES

The demonstration applying the project cost models for systems' comparison, break-even analyses and sensitivity analyses are presented as follows in order to have a further understanding of how the project cost models work.

Capital Metro is proposing a phased implementation of the Austin, Texas area LRT system with the development of a 14.6 mile, 16 station Minimum Operable Segment (MOS) of the LRT system from the McNeil Road in north Austin to downtown. The line includes about 9 miles of exclusive ROW and 5.6 miles of mixed traffic, and will involve about a half mile of above grade construction. The passenger demand will be 3,400 passengers per peak hour per direction in the year 2008. LRT service is proposing to operate at 10-minute frequencies during peak periods. The service frequencies of BRT will be three minutes during peak hour. Many still criticize that the BRT system is probably valid for the Austin area due to a lower capital cost than the LRT system.

The comparison of LRT and BRT is at the same corridor and has the same environment in order to get a more reasonable result. Hsu's fleet size model in equation (1) is applied to estimate the number of vehicles needed in the maximum service. After the fleet sizes of LRT or BRT are calculated, estimates of project costs can be conducted. The project cost models' results in Table 7 show that the LRT systems have higher capital costs than the BRT systems; however, the LRT systems have much lower O&M costs than the BRT systems.

Table 7. Project Cost Models' Results of the LRT and BRT Systems

	LRT-1	LRT-2	BRT-1	BRT-2 (Articulated Bus)
Input				
Route Length (mile)	14.6			
Passenger Demand (pphpd)	3400			
Number of Stops and Stations	16			
Cycle Length (sec)	100 (green time 45 seconds)			
Operating Hour (hr)	20			
ROW	ROW A: 68 %; ROW B: 0%; ROW C: 32%			
Alignment	At grade: 97 %; Elevated:3 %			
Peak Headway (min)	LRT:10; BRT:3			
Vehicle Passenger Capacity				
Passenger per Vehicle	190	250	45	67
Seats per Vehicle	68	190	50	74
Output				
	LRT-1	LRT-2	BRT-1	BRT-2 (Articulated Bus)
Number of Vehicles Required *	42	31	118	74
Capital Cost ($Million)	$509.1	$477.0	$311.0	$257.0
$Million/Mile	$34.8	$32.7	$21.3	$17.6
O&M Cost ($Million)	$27.0	$21.6	$62.4	$38.4
Depreciation Cost ($Million) **	$29.6	$27.1	$31.2	$24.1
Total Annual Costs ($Million)	$56.5	$48.6	$93.6	$62.5
$/Passenger Mile	$0.146	$0.125	$0.242	$0.162

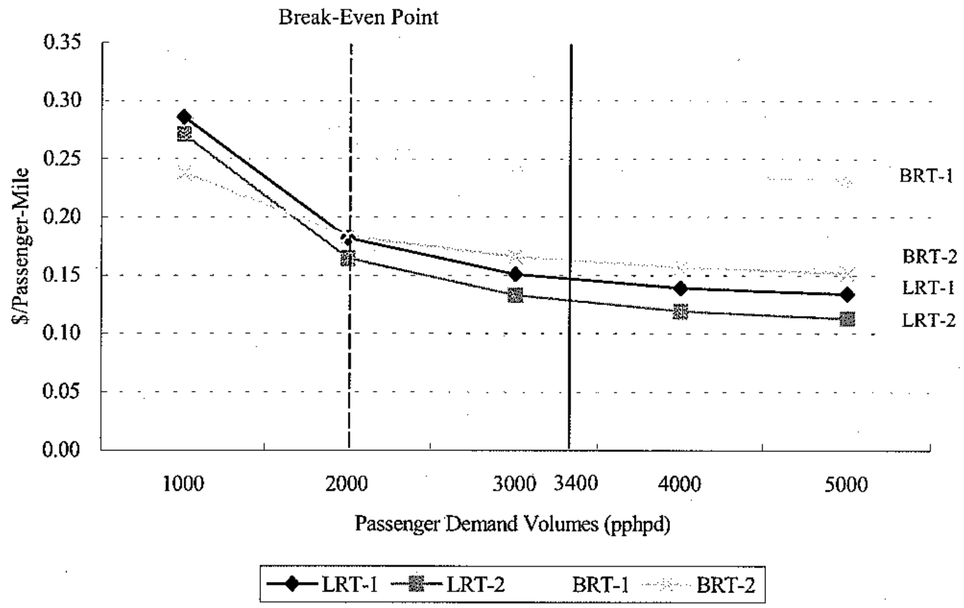
Note: 1. * Number of vehicle required is estimated by applying equation (1)
2. ** Depreciation Cost is annualized capital cost
3. Year 2000 costs are escalated to year 2008 using 1.26 escalation rate
4. Costs are in year 2008 U.S. dollars

Break-Even Analyses

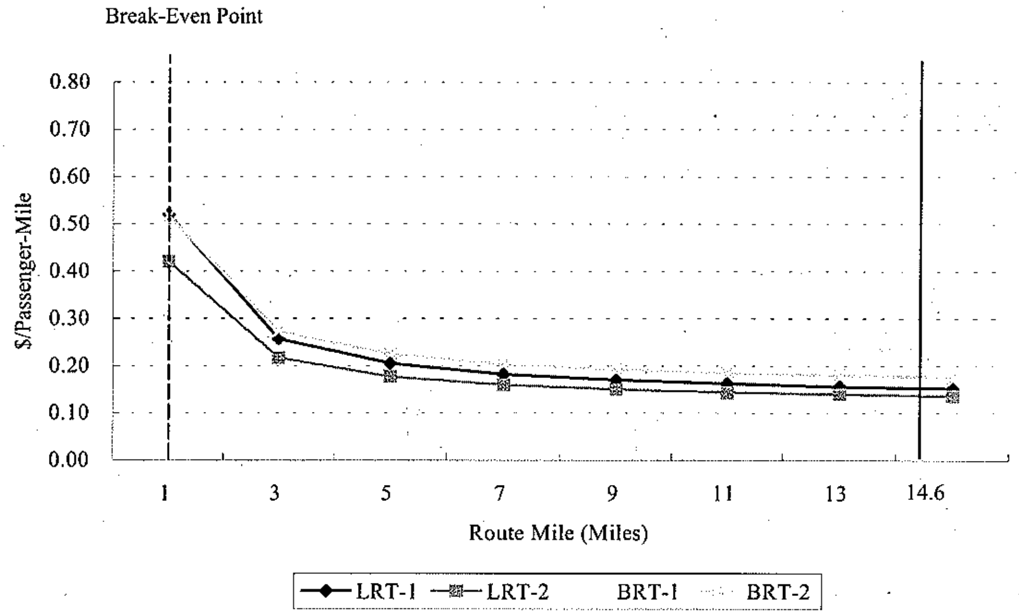
As the break-even analyses in Figure 1-(a), LRT-1 and BRT-2 have the same level of costs when the passenger demand volume is 2,000 passengers per hour per direction. When the passenger demand volume exceeds 2,000 passengers per hour per direction, costs per passenger mile of the LRT will be lower than those of the BRT. Therefore, the LRT system is preferred to the BRT system when the transit volume exceeds 2,000 passengers per hour per direction. In this example, prediction of the passenger demand is about 3,400 passengers per hour per direction. From the comparative analyses in Figure 1, the LRT system would be a suitable transit system for the 14.6-mile transit plan in Austin, Taxes. In Figure 1-(b), the systems' comparison is evaluated for route length to see how the route length affected the project cost. As the break-even analyses in Figure 1-(b), LRT-1 and BRT-2 have the same level of costs for the route length at 1 mile. Costs per passenger mile of the LRT systems have less cost per passenger mile than those of the BRT systems when the route length greater than 1 mile. Four types of vehicles with different vehicle passenger capacity are applied in this example. The vehicle passenger capacity affects the number of vehicles required to accommodate the passenger demand volume. The vehicle passenger capacity and vehicle requirements have a significant impact on costs. The changes of the passenger demand volume, route length or vehicle requirements in the project cost models would be needed to have LRT and BRT at the same level of costs.

Sensitive Analyses

Both LRT and BRT can operate on various ROWs. The project cost with respect to ROW configuration in Table 8-(a), LRT or BRT systems operated on a non-exclusive ROW have higher capital and O&M costs than those operated on an exclusive ROW.



(a)



(b)

Figure 1. Comparative Analyses: (a) Project Cost vs Passenger Demand Volume; (b) Project Cost vs Route Length

The different capital costs or O&M costs of BRT that operated on a non-exclusive ROW and on an exclusive ROW are greater than those of the LRT, with the same passenger demand volume and route length. The O&M cost of BRT depends mostly on ROW configuration. The project cost with respect to guideway or running way alignment configuration in Table 8-(b), the capital costs of both systems will increase greatly if the system is to be elevated or put underground, especially in a case of tunneling. The capital cost of the BRT is more expensive than that of LRT if there is a portion of elevated or tunnel alignment. The O&M costs of BRT systems are more expensive than those of LRT systems. However, the O&M cost will not change no matter how the change of ROW construction may be. In this example, all-stop

Table 8. Project Cost with Respect to ROW Configuration, Alignment Configuration, and Number of Stops/Stations

(a). Project Cost with Respect to ROW Configuration

NO	ROW (%)			LRT		BRT	
	A	B	C	Capital Cost ($Million/Mile)	O&M Cost ($Million)	Capital Cost ($Million/Mile)	O&M Cost ($Million)
1	100	0	0	31.5	23.8	18.0	52.6
2	40	50	10	32.0	24.6	19.1	55.8
3	20	60	20	32.4	25.0	19.8	57.7
4	5	65	30	32.7	25.4	20.4	59.5
5	5	95	0	32.1	24.6	19.1	55.7

(b). Project Cost with Respect to Alignment Configuration

NO	Alignment (%)			LRT		BRT	
	At Grade	Elevated	Tunnel	Capital Cost ($Million/Mile)	O&M Cost ($Million)	Capital Cost ($Million/Mile)	O&M Cost ($Million)
1	100	0	0	32.0	24.9	17.4	57.6
2	50	50	0	37.2	24.9	40.3	57.6
3	40	50	10	45.9	24.9	61.9	57.6
4	40	40	20	53.5	24.9	78.9	57.6
5	40	30	30	61.2	24.9	95.9	57.6

(c). Project Cost with Respect to Number of Stops and Stations

NO	Number of Stops and Stations	LRT		BRT	
		Capital Cost ($Million/Mile)	O&M Cost ($Million)	Capital Cost ($Million/Mile)	O&M Cost ($Million)
1	0	28.9	24.1	16.0	54.7
2	4	29.7	24.3	16.9	55.4
3	8	30.6	24.5	17.9	56.2
4	12	31.4	24.7	18.8	56.9
5	16	32.3	24.9	19.7	57.6

Note: passenger demand volume= 3400 pphpd; route length= 14.6 mile;number of stations/stops= 16; LRT = 68 seats/vehicle, 2.8 passengers/seat; BRT = 50 seats/vehicle, 0.9 passengers/seat;

services are provided and stops and stations are equally spaced along the route. The project cost with respect to number of stops and stations in Table 8-(c), shows that LRT and BRT would have less O&M cost if the systems provide non-stop services. The O&M costs of BRT are affected greatly if the number of stops and stations is increased or decreased, but less impact on O&M costs of LRT. An increase in station/stop facility will increase capital cost.

Findings and Discussions

The capital cost varies considerably depending on the vehicle requirements, ROW, type of construction, alignment length, and number of stops and stations. On a capital cost per mile basis, the longer the route length, the lower the cost for both LRT and BRT systems. The estimates of costs from the project cost models indicate that BRT is less expensive to construct than LRT, however, the overall cost of BRT vehicles would be similar to LRT vehicles due to lower vehicle passenger capacity and shorter life expectancy of BRT vehicles. The capital cost increases if there is a portion of tunnel and elevated alignments. BRT is less advantageous than LRT when the system has larger portions of elevated and underground structures. In other words, when ROW construction demands larger portions of elevated and underground structures, the LRT is favored.

With longer route length or higher transit volume, O&M cost of the BRT is higher than that of the LRT. As with capital costs, the O&M cost varies due to passenger demand volume, route length, the number of stations, the frequency of service, and vehicle requirements. As passenger demand volume increases, O&M cost increases. It also causes more need for BRT vehicles than LRT vehicles due to their smaller size of vehicle. The O&M cost of BRT depends mostly on ROW configuration. Every BRT operation is just a little different; however, more or less exclusive ROW and signal priority will significantly affect the O&M cost and demand. The LRT has higher capital cost per mile but lower O&M cost than the BRT. In the end, a need for high transit volumes with longer distance trips suggests an LRT system, which will be a more beneficial and suitable plan for that area.

CONCLUSION

In order to establish project cost models, this paper develops a method to aid the transportation planners and decision makers in the selection of the better mode between LRT and BRT systems in the early stages of corridor planning or system analysis. The developed project cost models serving as a simplified and sketching planning tool can estimate LRT and BRT costs for evaluation and comparison. The models estimate costs for LRT and BRT systems that operate on various ROW categories, alignment configurations, and different given transit demand volumes. The costs estimated from the models are capital cost, annualized capital cost (depreciation cost), O&M cost and cost per passenger mile. Only after those costs are calculated, can the systems' comparative analyses be conducted.

The developed models are established through application of unit costs available in the historical data of the existing systems. However, the unit costs might vary to a larger extent with a system's characteristics, locations, and various uncertainties, such as possible design modifications, unknown environmental and engineering conditions, construction schedule, and price inflation. The capital and O&M costs of LRT might be affected while LRT is operated under Federal Railroad Administration Rules. The availability of the data about the BRT O&M costs in the NTD is deficient; however, the O&M costs are derived from the experience of the transit agencies, and from the published papers. Since the accurate costs are difficult to obtain, the high and low cost ranges are used to provide more reasonable estimates. The average costs derived from the calculation of the project cost models are the costs used for systems' comparison process. However, the capital costs can vary widely for the tunnel construction such as cut and cover or a bored tunnel, so that the unit costs of upper bound or lower bound could be used in the estimates. Based on the systems' comparative analyses, the one with the lower cost per passenger mile is the preferable and more cost-effectiveness system. The comparative analyses can distinguish which system would be a better mode for the respective areas so long as the passenger demand volume is given.

As a result of the system comparison and analyses in this research being limited to the cost performance standpoint, the coverage of the cost mainly focuses on capital and O&M costs, which play a central role in the economic and financial evaluation. However, public transportation planning is a complex and difficult process. Evaluation and comparative analysis of the systems might add other cost variables to improve the project cost models, such as travel-time savings, waiting time cost and safety cost. The quality of service and impacts could be added to the evaluation of the systems' selection process; however, they are difficult to quantify or to assign dollar costs.

REFERENCES

1. Vuchic, V.R. *Urban Transit: Operations, Planning, and Economics*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2005.
2. Li, J., and M. Wachs, " *A Test of Inter-Modal Performance Measures for Transit Investment Decisions*," Transportation 27, 2000, pp. 243-267.

3. Biehler, A.D. "*Exclusive Busways Versus Light Rail Transit - A Comparison of New Fixed- Guideway Systems.* Light Rail Transit – New System Successes at Affordable Prices, Special Report 221, Transportation Research Board, Washington, D.C., 1989, pp. 89-97.
4. Federal Transit Administration (FTA), *Characteristics of Urban Transportation Systems-Revised Version.* Distributed in Cooperation with Technology Sharing Program, U.S. Department of Transportation, DOT-T-93-07, Washington, D.C., 1992.
5. Diaz, R. B., M. Chang, G. Darido, E. Kim, D. Schneck, M. Hardy, J. Bunch, M. Baltes, D. Hinebaugh, L. Wnuk, F. Silver, and S. Zimmerman, *Characteristics of Bus Rapid Transit for Decision-Making.* Federal Transit Administration, Project No. FTA-VA-26-7222-2004.1, Washington, D.C., 2004.
6. Federal Transit Administration (FTA), *Reporting Instructions for Section 5309 New Starts Criteria.* U.S. Department of Transportation, Washington D.C., 2007.
7. Federal Transit Administration (FTA), Proposed Guidance on New Starts/Small Starts Polocies and Procedures, U.S. Department of Transportation, Washington, D.C., 2008.
8. Vuchic, V.R., *Urban Transit Systems and Technology*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.
9. Khisty, C. J., and B. K. Lall, 2003. *Transportation Engineering.* Englewood Cliffs, Prentice-Hall Inc., New Jersey, 2003.
10. Hsu, L. R., and J. W. Wu, "*A Fleet Size Model for Light Rail and Bus Rapid Transit Systems*," Accepted for Presentation and Publication (Paper 08-0282),

the 87th Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C.

11. Parsons Brinckerhoff Quade & Douglas (PBQD), Inc., *Technical Memorandum: Capital Cost Estimating Methodology-North/Southeast Corridor Study Alternative Analysis/Draft Environmental Impact Statement.* Prepared for Jacksonville Transportation Authority and Florida Department of Transportation, 2001.
12. Schneck, D. C., R. M Amodei, and M. G Ferreri, *Light Rail Transit Capacity Cost Study.* U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA), Office of Technical Assistance and Safety, Washington, D.C., 1991.
13. Levinson, H., S. Zimmerman, J. Clinger, S. Rutherford, R. L. Smith, J. Cracknell, and R. Soberman, *Transit Cooperative Research Program (TCRP) Report 90 Bus Rapid Transit- Volume 1, Case Studies in Bus Rapid Transit, and Volume 2, Implementation Guidelines.* National Research Council, Transportation Research Board, Washington, D.C., 2003.
14. Fleming de Garmo, A. *Bus Rapid Tranist-A Feasibility Study For Austin, Texas.* Thesis, The University of Texas at Austin, Texas, 2000.
15. Watkins, K. E., *A Comparison of Bus Rapid Transit and Light Rail Transit in Ten North American Cities.* Thesis, Department of Civil Engineering, University of Connecticut, Storrs, Connecticut, 2003.
16. Hsu, J. J., *Development of a Medium-Capacity Guideway Transit Planning Guide.* Ph.D. Dissertation, Department of Civil and Environmental Engineering, Florida International University, Miami, Florida, 2003.

17. Mass Transit-Bus Rapid Transit Shows Promise, Report No. GAO-01-984. United States General Accounting Office (GAO), Washington, D.C., 2001.