# Cost Comparison of Light Rail Transit with Automated and Non-Automated Bus Systems in a Corridor

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**Corresponding Author:**
Jennifer E. Day, MS
jennieday@berkeley.edu
301.347.9144 (work)
415.613.4969 (mobile)
301.347.0101 (fax)
Current Affiliation
University of California, Berkeley
Department of City and Regional Planning
Wurster Hall
Berkeley, CA 94720
Affiliation During Project Research
San Jose State University
Department of Civil and Environmental Engineering
One Washington Square
San Jose, CA 95192

7535

Additional Authors:

Jan L. Botha, Ph.D.
San Jose State University
Department of Civil and Environmental Engineering
One Washington Square
San Jose, CA 95192
408.924.3953 (phone)
jbotha@email.sjsu.edu
408.924.4004 (fax)

Nagabhargavi Adibhatla, MS
nadibhatla@korve.com
510.622.6637 (work)
510-608-0552 (mobile)
510-834-5220 (fax)
Affiliation During Project Research
San Jose State University
Department of Civil and Environmental Engineering
One Washington Square
San Jose, CA 95192
Current Affiliation
Korve Engineering
155 Grand Avenue, Suite 400
Oakland, California 94612

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## ABSTRACT

Automated bus systems hold the potential to increase vehicle throughput by allowing vehicle convoying to shorten headways, thereby decreasing costs associated with vehicle operating and drivers, and reducing the amount of time spent waiting and in transit by system users. Vehicle automation could also reduce costs associated with system infrastructure, and has the potential to improve safety. In this study, an automated bus system (ABUS) was compared with more-conventional light rail and bus-on-dedicated-lane (BDL) alternatives. For the ABUS, buses were assumed to operate in convoys with a driver only in the lead vehicle, and on a dedicated lane; buses in the BDL system were also assumed to operate on a dedicated right-of-way, but with a driver in each bus. The benefits and costs were assessed from a societal perspective. Safety and environmental costs were not included in the analysis, and demand was assumed to be constant for all systems. The study concludes that the proposed bus alternatives could have substantially-lower costs than a functionally-equivalent light rail system for relatively-low passenger volumes, with the primary cost savings resulting from cost differences between road-based and rail-based infrastructure. No significant difference was found between the ABUS and BDL options at existing volumes for a study section, though each system has unique cost advantages. Additional research is recommended that addresses safety, demand change, and other impacts of the systems considered in this study.

# INTRODUCTION

## Background and Objectives

Vehicle automation holds the potential to aid in increasing vehicle throughput by allowing vehicle convoying to shorten headways, thereby decreasing costs associated with vehicle operating and drivers, and reducing the amount of time spent waiting and in transit by system users. Vehicle automation could also reduce costs associated with system infrastructure, and has the potential to improve safety. With developing technologies, bus automation may, in the near future, provide the opportunity to combine the flexibility of bus modes with the convoying capacities of fixed-route rail transit systems.

The primary goal of the study discussed in this paper was to compare the costs of an automated bus system with more-conventional bus and rail transit alternatives. An economic analysis was performed to determine the least-cost alternative among the following options:

- Conventional Light-Rail System
- Automated Bus System (ABUS)
- Bus-on-Dedicated-Lane (BDL) System

It should be noted that determination of economic feasibility was not an objective of the study. To determine feasibility, the transit alternatives should also be compared to a base condition featuring no transit alternatives, and an incremental analysis should be undertaken to determine the best alternative.

For the purposes of brevity, it was often necessary, in this paper, to provide only brief descriptions of the research methodologies. Detailed procedures are discussed in a previous report by Botha, Day, and Adibhatla *(1)*.

This paper presents the evaluation and comparison of the aforementioned transit systems in the following format:

1. Discussion of the base system (i.e. – the system used as a point of departure), and of the operating concepts for the alternative systems
2. Outline of the approach to the economic evaluation, including the types of costs included in the analysis
3. Cost estimations for each alternative system
4. Conclusions based on the results of the analysis, and a discussion of the potential effects of higher passenger volumes
5. Recommendations for future research.

# STUDY SECTION AND SYSTEM OPERATING CONCEPTS

## Study Section and Route Location

The basic approach followed in the study was to base the comparisons on existing systems so as to make the comparisons as realistic and consistent as possible. The analyses presented here were based on the route and passenger characteristics of a portion of the light rail system of the Santa Clara Valley Transportation Authority (VTA) in California. It is noteworthy that all costs in this study were calculated based on local data.

The route location chosen as a basis for the analysis is a 5.19-mile stretch of the 20.8-mile VTA Guadalupe light-rail line, located north of the downtown area and extending from the Baypointe station to the Japantown/Ayer station. This portion of the route – shown in Figure 1 – is located on city streets, features northbound and southbound rails operating side-by-side, and was chosen as a basis for the analysis because it was considered to have the characteristics of a main transit route.

VTA light rail system 2002 passenger volumes were assumed to apply to the light rail study system, and also the ABUS, and BDL systems. It is noteworthy that the passenger volumes used for the base condition calculations, which are discussed in this paper, are relatively low compared to some other urban rail systems. Changes in costs and relative costs due to increased levels of ridership are discussed by Botha, *et al (1),* and the results of that discussion are addressed briefly in the conclusions of this paper.

## System Operating Concepts and Designs

Operating and design details for each alternative, summarized here, are discussed in detail in two reports *(1,2)*. All systems are assumed to operate in the median of an existing roadway. For functional equivalence, the speed of operation for all of the alternatives was assumed to be equivalent to the current speed of existing light rail operations on the study section. It should be noted that, in reality, vehicles could operate at different speeds and at different safety standards, depending on the system. Barriers to divide traffic flowing in opposite directions and to separate vehicles using the dedicated lanes from the regular traffic stream were not considered in the cost estimates, but should be considered in future studies, depending on the physical conditions and desired safety standards.

### *Light Rail*

Trains on this portion of the system operate with minimum headways of 15 minutes *(3)*. According to VTA personnel, three-, two-, and one-car trains are currently used, depending upon demand (unpublished data, Joonie Tolosa).

For some of the cost calculations associated with the length of the light rail trackway, it was necessary to estimate costs based on a figure that accounted for crossover and yard rail miles, which are not included in the 5.19-mile, double-track section. An "effective system mileage" of 5.36 was calculated for the study section. For this calculation, it was assumed that the proportion of crossover and yard track miles to overall system mileage was the same for the VTA system and for the study section. Crossover and yard miles were provided by VTA (unpublished data, Tony Galam).

Calculations related to light rail system planning and design, and infrastructure (excluding ROW costs) were based on the effective system mileage, as were costs associated with tangent and curved track section rehabilitation. All other calculations for the light rail system were based on the actual mileage.

According to VTA personnel, a 28.9-foot minimum width is necessary to operate two VTA light rail tracks side-by-side at normal speeds (unpublished data, Deborah Tidwell). This width includes only rail and vehicle operating space, and does not include station platforms, electrical facilities, or other space used to support operations.

*ABUS*

Like a conventional light rail system train, ABUS vehicles would operate in "bus convoys." The buses would be electronically linked together using automation technology. It was assumed that the maximum length of a convoy will be no more than five vehicles and that a train of five buses would be technologically feasible and safe. The length of five vehicles is somewhat arbitrary, but was selected so that the capacity of a five-bus train would be approximately the same as that of a three-car light-rail train.

Like a conventional light rail system, the ABUS design includes a traveled way for vehicles in each direction, without a breakdown lane, and could be placed in the median of the roadway. It is noteworthy that, unlike the corresponding light rail calculations, the ABUS system cost calculations do not account for effective mileage, since the extra mileage required for light rail crossovers would not be applicable to a paved-road system, and yard miles add minimal expense.

Two separate cross-sectional design scenarios were developed for the ABUS system. The following dimensions, which include travel lanes in both directions, were determined to be the minimum total required ROW width for the ABUS system:

Design Scenario 1: 26 feet
Design Scenario 2: 19 feet.

Design Scenario 1 follows AASHTO design standards for tangent ramp sections, which require a 15-foot pavement width to be used in this case to accommodate any design bus in one direction *(4)*. However, included in this 15-foot width are two feet that account for wandering of the vehicle within the lane. Because it is assumed that automating technology will guide these buses without the wandering associated with manual steering, these two feet were subtracted from the lane width. The resulting requirement is a 13-foot pavement width for each direction of travel. Additional widths may be required for horizontal curves.

Cross-sectional dimensions for Design Scenario 2 are based on design recommendations from Dr. Steven Shladover of PATH, which specify that travel lanes for trucks and buses using automated technologies need be only 30 cm (0.98 feet) wider than the vehicles using them (unpublished data). The chosen design vehicle, the City Bus, is 8.5 feet wide *(5)*.

*Bus-On-Dedicated-Lane*

The Bus-On-Dedicated-Lane (BDL) system operating concepts are similar to those of the ABUS except that the buses do not convoy, the buses operate with uniform headways, and a driver is required in each bus. Also, because the steering is not automated, the full 15-foot AASHTO-recommended design width would be required *(4)*. Thus, for dedicated bus lanes running in both directions, a total cross-sectional width of 30 feet was assumed.

## BASIC APPROACH TO THE COMPARISON

### Least-Cost Analysis

The ultimate goal of the cost analysis was to compare the total costs of alternative systems that were, as far as possible, functionally equivalent (this term is discussed later). Total costs to build and operate the system were calculated. The approach used was to consider real costs, which requires eliminating taxes and financing costs from the amounts.

The costs were assessed from a societal perspective (i.e. - no differentiation was made as to whom the costs accrue to). Ideally, projects that employ public funds should all be evaluated from this point of view before other stakeholder viewpoints are considered.

When conducting a cost analysis, all values have to be brought to a common basis. The comparisons were based on equivalent uniform annual costs (EUACs), with a Gross Domestic Product (GDP) deflator used to convert all costs to 2001-equivalent U.S. dollars *(6)*. The project life assumed for the analysis was 30 years. The discount rate used was six percent, which is a discount rate used by the California Department of Transportation *(7)*.

### Functional Equivalence

Every effort was made to assure that the transit systems being compared were functionally equivalent (i.e. - that they convey the same passenger volume in the same amount of time between any two points in the study section).

In order to achieve functional similarity, the light rail study section length and location, placement of stations, and passenger volume data were also applied to the ABUS and BDL systems. Ideally, the comparison should be made among optimally-configured systems that are functionally equivalent at a specified traffic volume level. Determining the optimal configuration for each alternative was outside the scope of this project. The configurations that were used were considered to be reasonable because they were based on current VTA light rail operations.

### Cost Categories

The following costs categories were identified for the analysis.

Agency Costs

- System Planning and Design Costs
- Construction, Rehabilitation, and Other Infrastructure Costs
- Vehicle Operations Costs
- Vehicle Maintenance Costs
- System (Non-Vehicle) Maintenance Costs
- System Administration Costs

User Costs

- Passenger Wait Time
- Passenger On-Board Travel Time

Vehicle operations costs include costs associated with driver wages and fringe benefits, fuel, tires, and other materials, supplies, wages, fringe benefits, and miscellaneous expenses. Vehicle operating costs will be fundamentally different for all of the systems because of the difference in the vehicle types and capacity, the number of vehicle-miles and vehicle-hours operated, and the number of operators needed.

The only user costs considered here were those associated with travel time, since counting the fare as a cost would actually amount to double-counting. Travel time, in this study, consisted of user on-board travel time and passenger wait time. Egress time was not included in the analysis because it was assumed to be equal for all systems. The system boundaries were chosen such that only users and vehicles operating along the specified trunkline are considered to be within the project domain. Consequently, the feeder and distribution system, and the user costs associated with buses operating on them, was excluded.

**Basis of the Analysis**

System planning, design, construction, rehabilitation and other infrastructure costs for the three systems were based on recent construction projects and historic rehabilitation data from VTA and the City of San Jose. The costs associated with vehicle operations, vehicle maintenance, system (non-vehicle) maintenance, system administration, and user costs were considered to be a function of the number of operating hours and/or operating miles each system uses annually, and of the unit cost for each expense incurred in terms of operating hours and operating miles. Determination of these costs are discussed in subsequent sections of this paper, and in detail in Botha, *et al (1)*.

**Costs and Considerations Not Addressed in the Analysis**

The analyses were undertaken using the existing passenger volumes as a starting point. A zero growth rate was assumed for the passenger volumes because assuming a nonzero growth rate would have added complexity to the analysis, and would not have added more insight or clarity to the study.

Also, in this analysis, several potential sources of cost differences were not considered because they lie outside the scope of the study. These are:

- Effects on surrounding transportation systems
- Differences in demand among the systems
- Quality of service
- Air quality impacts
- Comfort
- Accident costs
- Salvage values

It is also noteworthy that the cost comparison does not account for the cost differentials associated with buses moving in and out of convoys, passenger transfers on the system, or driver transfers between buses on the system.

## COST CALCULATIONS

Table 1 summarizes the final cost calculations for all of the system alternatives. Details of the cost calculations appear below.

### Light Rail Costs

*Light-Rail System Planning, Design, and Infrastructure Costs*

The costs for the VTA Tasman West light-rail project were used as a basis for estimating planning, design, and infrastructure costs for the study section, with the exception of ROW costs, which were estimated based on a 28.9-foot minimum width necessary to operate two VTA light rail tracks side-by-side at normal speeds. The 7.6-mile double-track Tasman West line was completed in 1999. The costs associated with the construction of this line were chosen as a basis for the analysis because the recency of its completion. Costs associated with the original construction of the study section could also have been used, but are more dated.

The unit costs shown in Table 2 were found by extrapolating from the Tasman project cost data and adjusted for inflation. Tasman project costs data were supplied by VTA personnel (unpublished data, Scott Ritter). The unit costs were multiplied by effective study section length to obtain the total 2001-equivalent costs for the proposed light rail study section.

Right-of-way (ROW) costs were calculated at a rate of $23.65 per square foot. For the purposes of this project, it was assumed that the full project-area ROW would be acquired, either through a fee acquisition or through an easement agreement. This unit cost was derived from Tasman West ROW-acquisition figures, provided by VTA personnel (unpublished data, Tony Galam). This unit cost is the quotient of the total Tasman ROW acquisition costs and the total square footage acquired. Implicit in this unit cost is the assumption that the ratio of easement to fee-acquired ROW would be the same for the Tasman project and the light rail study section.

*Light-Rail Fleet Purchase*

The cost of an average light rail vehicle purchased in 2001 was $2.5 - $3 million, depending on a number of factors (unpublished data, Art Dowes). A cost of $3 million per light-rail vehicle was assumed for the purposes of this project.

To determine the costs of the light rail vehicles allocated to the study section, it was assumed that the number of vehicles allotted would be proportional to the length of the study section for the base volume condition. As of May 2003, 21 vehicles were operated on the 20.8-mile VTA Guadalupe line (unpublished data, Joonie Tolosa). Therefore, 6.288 vehicles were determined to be necessary for the study section. Table 2 shows the costs.

*Light-Rail Rehabilitation Costs*

Rehabilitation costs associated with a light-rail system can be subdivided into three categories:

- Tangent track section rehabilitation
- Curved track section rehabilitation
- Wayside Rehabilitation

The light rail rehabilitation data shown in Table 2 is based on data provided by VTA (unpublished data, Curtis Nicks) and some assumptions outlined in Botha, *et al (1)*. Tangent track sections are shown to have zero rehabilitation costs because the rehabilitation cycle is longer than the 30-year assumed life of this project.

*Light Rail Fleet Renewal Costs*

Modern light rail vehicles are built to have a useful life of 30 years (unpublished data, Matt Tucker). Since the assumed life of this project is also 30 years, fleet renewal was assumed to be zero.

*Light Rail Operational Agency Costs*

Operational agency costs include those costs associated with vehicle operations, vehicle maintenance, system (non-vehicle) maintenance, and system administration. Costs in these categories were considered to be a function of annual vehicle-miles and –hours, and of unit costs (per vehicle-mile and –hour) for each type of cost incurred. The revenue-miles and –hours used for calculation of costs of the light rail system were based on service characteristics on the VTA light rail study section as of June 2002, and on the constitution of the trains (i.e. – 3, 2, or 1-car) during the same period. Detailed calculation methodologies can be found in Botha *et al (1)*. The calculated vehicle-miles and –hours are:

Vehicle-Revenue-Miles: 448,068
Vehicle-Revenue-Hours: 25,061
Train-Revenue-Miles: 276,035
Train-Revenue-Hours: 15,439

Unit costs for light rail operations were extrapolated from data given in VTA's 1999-2000 annual report to the National Transit Database (NTD) *(8)*, and were found in terms of vehicle-revenue-miles, vehicle-revenue-hours, train-revenue-miles, and train-revenue-hours. Operational Agency Costs are summarized in Table 1.

***Light Rail User Costs***

User costs were based on on-off ridership data for the VTA light rail system (unpublished data, Joonie Tolosa). In order to quantify user wait time, a value of $8.32 per passenger-hour in 2001-equivalent dollars was assigned *(7)*. Then, the daily and annual user-hours were calculated. On-board user-hours were based on the speed of travel and the length of each passenger trip. In the calculations for passenger wait-time, passenger arrivals at the bus stops were assumed to be uniformly distributed in each headway interval. Thus, the average wait per passenger is equal to half of the train headway. Table 3 shows a summary of calculated user costs for the study segment.

## ABUS Costs

*ABUS System Planning, Design, Construction, Rehabilitation, and Other Infrastructure Costs*

The costs associated with ABUS planning, design, construction, rehabilitation, and other infrastructure are shown in Table 4 for ABUS Design Scenario 1. A corresponding table for Design Scenario 2 is not shown, due to space limitations. All cost differences between ABUS Designs 1 and 2 arise from differences in pavement widths.

Costs associated with planning, designing, and constructing the ABUS system infrastructure were calculated based on a recent City of San Jose roadway widening and improvement project, the Hope Street project. The ABUS study system construction cost calculations are based on the conservative assumption that the smaller Hope Street project costs remain constant in the elevated quantities necessary for completion of the larger ABUS system. It is also assumed here that the costs for planning and designing an automated bus system are akin to the corresponding costs for a conventional dedicated lane, with some additional costs related to the presence of automating technology. The underlying assumption here is that the automating elements of the system (i.e., magnetic reference markers along the route and automating technology aboard the bus) would probably not drastically change roadway design elements, other than lane width.

For all costs except those associated with ROW acquisition, unit costs, e.g. cost per square foot, were taken from the Hope Street Project contract bid documents (unpublished data, Frances Guevarra). Unit quantities (e.g. - number of square feet in the project area) were scaled up from the Hope Street project to the ABUS project based on project square footage. Details of this procedure can be found in Botha *et al (1)*. The same procedure was used to calculate system planning and design costs, which were estimated by project engineers for the City of San Jose to be roughly $96,000 in 2002 (unpublished data, Frances Guevarra). Final calculated values are shown in Table 4.

Costs associated with ROW were calculated similarly to the corresponding light rail costs.

*ABUS Non-Infrastructure Capital Costs*

Costs for non-infrastructure capital expenses include bus fleet purchase and purchase of automation technology for outfitting the vehicles to operate in an automated mode. Fleet purchase costs were a function of fleet size and automating technology costs. In determining fleet size, it was assumed that fleet requirements would be determined by the number of buses needed during the weekday period with the highest volume and the lowest average headways (this is the PM peak northbound direction).

To assure functional equivalence between the ABUS and light rail systems, bus-convoy sizes were calculated that would provide a capacity approximately equal to that of the corresponding light rail train sizes. It was assumed that bus-convoy sizes of these magnitudes would be possible and safe. The following equivalencies represent light-rail-train and equivalent bus-convoy sizes:

- 3 light rail vehicles = 5 buses
- 2 light rail vehicles = 3 buses
- 1 light rail vehicle = 1 bus

It was also assumed that approximately 20 percent of vehicles are not in service at any given time, for maintenance and contingency purposes (unpublished data, Art Dowes). Under these assumptions, it was determined that 10.180 buses would be required to operate an ABUS system that operates equivalently to the VTA light rail on the study segment. Three significant figures were retained to distinguish this number as a derived quantity.

Automation technology would be purchased for every vehicle at a cost of roughly $25,000 per bus. It is believed that costs could be reduced to as low as $5,000 per vehicle if large numbers of vehicles are outfitted (unpublished data, Professor Randolph Hall, University of Southern California). Table 4 shows fleet and technology purchase costs for Design Scenario 1.

*ABUS Periodic Capital Costs*

Rehabilitation costs for the ABUS system include:

- Major Rehabilitation – Pavement Resurfacing
- Minor Rehabilitation –Seals
- Magnetic Reference Marker Replacement

Costs and other information pertaining to rehabilitation are historic costs based on previous projects completed by the City of San Jose. The unit costs are all-inclusive, so potholing, overhead, engineering, etc., are included in the figure.

For minor rehabilitation, costs were calculated based on a seal application frequency of 5 to 7 years and a unit cost of $3.90 per square yard (in 2002 dollars). For major rehabilitation, a conservative 10-year resurfacing cycle was assumed, and a unit cost of $17.21 per square yard (in 2002 dollars) was used (unpublished data, Amanda Lei).

It was assumed that magnetic reference markers, mounted on the pavement to guide automated vehicles, would be replaced every time the roadway is sealed or resurfaced. In this study, the replacement frequency for magnetic reference markers is five years at a cost of $5000 per mile. At the 6 percent interest rate assumed for this study, this amounts to an annualized cost of $8,550 for the 5.19-mile study section.

The applicable values are shown in Table 4 for Design Scenario 1.

*ABUS Fleet Renewal*

Fleet renewal includes vehicle replacement costs and vehicle automation technology replacement costs. VTA typically replaces an operating bus after 14 years of service (unpublished data, Art Dowes).

For compatibility with the ABUS study system 30-year life cycle, a 15-year fleet replacement cycle was assumed. Thus, $1/15^{th}$ of the fleet is assumed to be replaced each year, at a per-bus cost of $287,257 (in 2001-equivalent dollars). With 10.180 buses required to service the study segment, and assuming that $1/15^{th}$ of these are replaced each year, then the annual cost, in 2001-equivalent dollars would be $287,257*(10.180/15) = $194,959.

Vehicle automating technology is assumed to be replaced as the host bus is replaced, at a rough cost of $25,000 per bus. Thus, costs in this category are calculated using an identical methodology as for fleet renewal in the previous section. Fleet and technology renewal and calculations are identical for Design Scenarios 1 and 2. The applicable values are shown in Table 4 for Design Scenario 1.

*ABUS Operational Agency Costs*

The revenue-miles and –hours associated with the ABUS system were found by configuring the ABUS system so that it is functionally-equivalent to the light rail. This was done by assuming that the ABUS convoys operate with the same frequencies as the light rail trains in the VTA system and also by assuming the rail-to-bus vehicle ratios given above.

Cost determination for ABUS operational costs was conducted using identical methodologies as used in the corresponding light rail calculations, with unit costs primarily derived from data on the VTA bus system operation. Unit costs were derived from the VTA Report to the NTD *(8)*.

Convoy-revenue-miles and –hours are equivalent to the light rail train-revenue-miles and-hours due to functional equivalence. Annual revenue-miles and –hours are as follows:

Vehicle-Revenue-Miles: 620,101
Vehicle-Revenue-Hours: 34,683
Train-Revenue-Miles: 276,035
Train-Revenue-Hours: 15,439

Differences in costs for the light rail and ABUS systems result from the following sources:

1. The ABUS system, operated in a functionally-equivalent manner to the light rail under the equivalences discussed earlier, operates more revenue-miles and –hours annually than the light rail system.
2. Unit costs differ between the two systems because the ABUS unit costs were based on unit costs derived from VTA bus data, and the light rail costs based on unit costs derived from the VTA light rail data. There were two exceptions to rule: costs associated with the ABUS driver wages and fringe benefits, and also those associated with system administration costs, were based on the correspondent VTA light rail data. This was done because costs for drivers and system administration for an automated bus system were assumed to be better represented by the light rail cost than by the corresponding bus costs.

*ABUS User Costs*

Because the ABUS system is assumed to run with the same headways and at the same speed as the light rail system, and to carry the same passenger volumes, there is no variation in cost between ABUS user costs and light rail user costs. ABUS user costs are summarized in Table 1.

## BDL Costs

*BDL System Planning, Design, Construction, Rehabilitation, and Other Infrastructure Costs*

The BDL system planning, design, construction, and other infrastructure costs were calculated using the same methodologies as the corresponding costs for the ABUS, except that costs associated with automation are not considered. The results are shown in Table 1. The differences in the ABUS and BDL infrastructure, planning, and design costs arise primarily from the differences in pavement width, and additional costs for the automation technology associated with the ABUS system. In terms of non-infrastructure capital costs, periodic capital costs, and fleet renewal, the BDL costs less due to the elimination of need for building and maintaining automating technologies, though the cost savings is marginal compared to the ABUS infrastructure savings. The total differences between the ABUS and BDL due to pavement width is between $716,000 and $1.5 million, depending on the ABUS design scenario, while the difference between the two systems due to automation costs is $44,000.

*BDL Operational Agency Costs*

BDL study system vehicle operating costs were determined using identical methodologies as were used for the ABUS study system vehicle operating costs, with the exception of driver-related costs (i.e. – salaries and wages, fringe benefits) and system administration costs. All costs for the BDL system, including driver-related costs, were based upon vehicle-revenue-miles and –hours, and were based on data reported to the NTD by VTA on its bus system *(8)*. This is a departure from the ABUS methodology, where driver-related costs were calculated based on convoy-revenue-miles and –hours, and unit costs for both driver expenses and system administration were based on light rail data.

Annual vehicle-revenue-miles and –hours used in the calculations for the BDL system were identical to those used in the ABUS calculations, since the same number of buses would have to operate in order to maintain functional equivalence to the ABUS.

*BDL User Costs*

The BDL study system is assumed to operate at the same speed as the light rail and ABUS study systems, and to carry the same passenger volumes, in order to maintain functional equivalence for the cost comparison. For this reason, there is no variation in cost between BDL, light rail, and ABUS on-board travel time costs. However, due to functional equivalence, the BDL study system is assumed to run the same number of buses as the ABUS system, but without convoying. This implies that BDL headways would be shorter. In this study, they were assumed to be uniformly distributed throughout each time period, resulting in a smaller total passenger wait time for the BDL than for the ABUS/light rail systems. User wait-time costs were calculated according to the same method used for the ABUS wait-time cost calculations. The difference in cost between the ABUS and BDL wait-time costs arises solely from these decreased headways. Table 1 shows a summary of calculated user costs for the BDL system.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

In the interpretation of the study results, it should be kept in mind that the cost calculations are dependent on the accuracy of a large number of parameters. These parameters were not only related to the cost calculations themselves (such as unit costs and interest rates), but also to the operating concepts and the associated conditions, such as traffic volumes, etc. For this reason, the interpretation of the results should be viewed from a holistic perspective.

Based on the findings of this study (see Table 1), the ABUS and BDL systems have substantially lower costs than a functionally-equivalent light rail system at the passenger volumes seen on an existing section of the VTA light rail system. Depending on the bus system, costs range from about 40 percent to approximately 50 percent of those for a comparable light rail system. The primary source of the difference comes from the relatively-high costs for planning, designing, and constructing the light rail system. The analysis indicates some differences in user wait-time costs (a subcategory of user costs), which favors the BDL system. It is noteworthy that VTA passenger volumes are relatively low compared to other urban rail systems.

Table 1 also indicates that, at these relatively-low base volume levels, the overall costs of the ABUS scenarios were comparable to those of the non-automated BDL system, with the BDL favored slightly. ABUS is the favored alternative in terms of infrastructure (due to narrower lanes) and driver-related vehicle operating costs (due to bus convoying). The user cost savings of the BDL system over the ABUS is due to the shorter headways, and thus less wait time-related costs for passengers.

Although the wait-time savings reflected in this study for the BDL are significant, on-board travel hours account for substantially more of the total user travel time than do wait time (Table 3 illustrates this with respect to the light rail system). It follows that, for all of the proposed systems, finding ways to decrease on-board travel time may be an effective way to reduce travel-time costs. That could entail increasing the speed of operations on the system, which could require a better-protected right-of-way, and consequently, increased construction, rehabilitation, and maintenance costs.

The analysis presented here does not attempt to quantify safety considerations as part of the evaluation of the systems, nor does it attempt to quantify the differences in costs among the systems resulting from environmental factors, ridership and user diversion, or impact on the surrounding transportation systems. Due to the different natures of the ABUS, BDL, and light rail systems, it is possible that costs associated with these variables could be different for each of the systems studied. The resultant differences in costs could be substantial, and could alter the outcomes of the analysis and, consequently, the conclusions presented here.

The topic of increased passenger volumes, though not addressed in this paper due to space limitations, was discussed in Botha *et al (1)*. The results of that discussion are addressed briefly here because the analysis would be incomplete without them. At all but very large passenger volume increases, the bus systems would continue to outperform the light rail system from an economic perspective because of the large infrastructure cost differences. At significantly-large volumes, the light rail system could be the preferred system. It would be capable of offering a larger capacity than the other systems, and probably at higher safety standards.

## Recommendations

Aside from presenting a framework for the study of bus automation, this study advances the state of the art by highlighting specific areas where further research is vital before implementation of automated bus systems becomes a reality. Given the constraints of the study, a conclusion cannot be made that there would be obvious promise in creating an ABUS system, but it is recommended that this evaluation be continued and refined. Safety considerations should be added to the analysis, as should more-rigorous evaluations of significantly-increased ridership. Also, refining the costs and some other aspects of the analysis could indicate where the most gains could be made through further development of automation, and specifically with buses operating in convoys. Possible benefits due to optimization of convoy sizes, vehicle speeds, and minimum headways, could be ascertained. This could lead to better decisions regarding how to target research and spending to yield the largest possible cost reductions, given finite funds for research and development of automation.

Other impacts of implementing each of the systems should also be further evaluated, quantified, and added to the analysis. These could include noise and air pollution, impacts of the implementation of the alternative systems on the surrounding street system (e.g. – delay), and impacts on bicyclists and pedestrians.

One of the assumptions used in this study was that passenger volumes would be the same for all three systems under study. Changes in demand due to the attributes of each system could alter the outcomes of the analysis, and the extent to which each system would attract users should be examined in future research. Presumably, the bus systems could have a relative advantage over the light rail with respect to demand because buses could enter a dedicated lane from a feeder route and thereby eliminate the need for passengers to transfer from a feeder mode. However, that advantage could be lost on both bus systems if passengers must transfer from feeder buses once on the system, and to feeder buses when exiting the system. The costs associated with driver transfer to and from ABUS buses could further reduce the advantages of that system. Further research on the impacts of transferring on the cost differentials among the systems should be undertaken.

In addition, further research is recommended on the passenger volumes appropriate for each type of system. Based on the results of this study, including the discussion of increased passenger volume impacts, one could envision that the light rail would be more effective on very high-ridership corridors, the BDL on corridors with relatively-lower passenger volumes, and the ABUS at some intermediate state. Thus, the future of ABUS may be in areas where passenger volumes are high enough to warrant convoying, but not high enough to make light rail cost-effective.

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FIGURE 1 Santa Clara Valley Transportation Authority (VTA) Light Rail System

**TABLE 1 Light Rail, ABUS, and BDL Cost Comparison**

| Cost Category | Costs ($) Based on Revenue-Miles | | | | Costs ($) Based on Revenue-Hours | | | |
|---|---|---|---|---|---|---|---|---|
| | Light Rail | ABUS | | Bus-On-Dedicated-Lane | Light Rail | ABUS | | Bus-On-Dedicated-Lane |
| | | Scenario 1 | Scenario 2 | | | Scenario 1 | Scenario 2 | |
| System Planning and Design | 7,348,425 | 147,994 | 108,150 | 170,817 | 7,348,425 | 147,994 | 108,150 | 170,817 |
| Construction, Rehabilitation, and Other Capital Costs | 11,258,212 | 2,888,056 | 2,233,054 | 3,117,012 | 11,258,212 | 2,888,056 | 2,233,054 | 3,117,012 |
| Infrastructure Costs[a] | 9,599,788 | 2,321,461 | 1,697,467 | 2,594,214 | 9,599,788 | 2,321,461 | 1,697,467 | 2,594,214 |
| Non-Infrastructure Capital Costs[a] | 1,370,424 | 230,944 | 230,944 | 194,952 | 1,370,424 | 230,944 | 230,944 | 194,952 |
| Periodic Capital Costs[a] | 287,999 | 123,725 | 92,717 | 132,894 | 287,999 | 123,725 | 92,717 | 132,894 |
| Fleet Renewal[a] | 0 | 211,927 | 211,927 | 194,952 | 0 | 211,927 | 211,927 | 194,952 |
| Vehicle Operations | 2,029,153 | 2,057,312 | 2,057,312 | 2,830,775 | 1,680,746 | 1,610,770 | 1,610,770 | 2,059,252 |
| Vehicle Maintenance | 1,371,208 | 1,190,627 | 1,190,627 | 1,190,627 | 1,137,063 | 866,123 | 866,123 | 866,123 |
| System (Non-Vehicle) Maintenance | 1,041,014 | 272,609 | 272,609 | 272,609 | 863,252 | 206,855 | 206,855 | 206,855 |
| System Administration | 2,592,359 | 3,587,679 | 3,587,679 | 1,695,023 | 2,149,693 | 2,975,054 | 2,975,054 | 1,233,048 |
| User | 4,843,378 | 4,843,378 | 4,843,378 | 4,130,120 | 4,843,378 | 4,843,378 | 4,843,378 | 4,130,120 |
| TOTAL COST | 30,483,749 | 14,987,655 | 14,292,808 | 13,406,982 | 29,280,770 | 13,538,231 | 12,843,384 | 11,783,227 |

[a] *This is a subheading of Construction, Rehabilitation, Infrastructure, and Other Capital Costs*

TABLE 2 Light Rail System Planning, Design, Construction, Rehabilitation, Infrastructure, and Other Capital Costs

| Cost Element | Item | Year | VTA Total Cost ($) | Unit Cost ($)[a] | Unit | Unit Cost (2001-Equiv. $) | Unit | # of Units in Study Section | Unit | One-Time Cost ($) | EUAC (2001-Equiv. $) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System Planning and Design Costs | Design Consultants | 1999 | 60,266,983 | 3,964,933 | track mile | 4,104,895 | track mile | 10.73 | track miles | 44,027,686 | 3,198,563 |
| | Professional Consultants | 1999 | 49,651,941 | 3,266,575 | track mile | 3,381,885 | track mile | 10.73 | track miles | 36,272,930 | 2,635,189 |
| | VTA Labor | 1999 | 25,086,106 | 1,650,402 | track mile | 1,708,661 | track mile | 10.73 | track miles | 18,326,506 | 1,331,401 |
| | Non-Technical Services | 1999 | 3,453,199 | 227,184 | track mile | 235,204 | track mile | 10.73 | track miles | 2,522,714 | 183,272 |
| | TOTAL | | | | | | | | | | 7,348,425 |
| Infrastructure Costs | Property Costs/ ROW Acquistion | 1999 | 34,166,626 | 23.65 | sq. foot | 24.49 | sq. foot | 791,952 | sq. feet | 19,391,768 | 1,408,791 |
| | Utility Relocations | 1999 | 9,015,859 | 593,149 | track mile | 614,087 | track mile | 10.73 | track miles | 6,586,482 | 478,501 |
| | Material and Equipment | 1999 | 12,619,406 | 830,224 | track mile | 859,531 | track mile | 10.73 | track miles | 9,219,032 | 669,753 |
| | Civil/Structural Construction | 1999 | 113,150,901 | 7,444,138 | track mile | 7,706,916 | track mile | 10.73 | track miles | 82,661,718 | 6,005,284 |
| | Systems | 1999 | 19,547,712 | 1,286,034 | track mile | 1,331,431 | track mile | 10.73 | track miles | 14,280,465 | 1,037,460 |
| | TOTAL | | | | | | | | | | 9,599,788 |
| Non-Infrastructure Capital Costs | Fleet Purchase (Vehicle Purchase) | 2001 | N/A | 3,000,000 | vehicle | 3,000,000 | USD per veh | 6.288 | vehicles | 18,863,654 | 1,370,424 |
| Periodic Capital Costs | Major Rehabilitation (Tangent Track Sections)[b] | 2002 | N/A | 0 | year | 0 | per year per veh | N/A | N/A | 0 | 0 |
| | Major Rehabilitation (Curved Track Sections) | 2002 | N/A | 134,228 | per 10 years per track mile | 8,319 | per year per track mile | 4.037 | track miles | N/A | 33,586 |
| | Major Rehabilitation (System/ Wayside Maintenance) | 2002 | N/A | 50,000 | per year per double-track mile | 49,020 | per year per double-track mile | 5.19 | double-track miles | N/A | 254,414 |
| | TOTAL | | | | | | | | | | 287,999 |
| Fleet Renewal | Vehicle Replacement Costs | | | 0 | per year per veh. | 0 | per year per veh. | 0 | veh. | 0 | 0 |
| TOTAL CONSTRUCTION, REHABILITATION, AND OTHER INFRASTRUCTURE COSTS | | | | | | | | | | | 11,258,212 |
| TOTAL SYSTEM PLANNING, DESIGN, CONSTRUCTION, REHABILITATION, AND OTHER INFRASTRUCTURE COSTS | | | | | | | | | | | 18,606,637 |

*[a] Based on 7.6-mile line length, double-track system, for a total of 15.2 trackway miles.*

*[b] Rehabilitation of tangent track sections is estimated by VTA personnel to occur every 75 to 100 years. This time period is beyond the scope of this study, and tangent section rehabilition is thus considered to be negligable.*

**TABLE 3 Light Rail Total User Costs**

| Day | Element | Daily User-Hours | Cost/User-Hour ($) | Daily Cost ($) | Annual Cost ($) |
|---|---|---|---|---|---|
| Weekday | Wait Time | 733 | 8.32 | 6099 | 1,591,724 |
| | On-Board Travel Time | 1126 | 8.32 | 9366 | 2,444,462 |
| Saturday | Wait Time | 408 | 8.32 | 3395 | 176,532 |
| | On-Board Travel Time | 601 | 8.32 | 4999 | 259,952 |
| Sunday | Wait Time | 346 | 8.32 | 2877 | 149,625 |
| | On-Board Travel Time | 511 | 8.32 | 4252 | 221,084 |
| TOTAL WAIT TIME | | | | | 1,917,881 |
| TOTAL ON-BOARD TRAVEL TIME | | | | | 2,925,498 |
| TOTAL | | | | 30,987 | 4,843,378 |

**TABLE 4 ABUS System Planning and Design, Construction, Rehabilitation, and Other Infrastructure Costs - Design Scenario 1: Design Follows AAASHTO Standards**

| | Item | Year | Unit Cost ($) | Unit | Unit Cost (2001-Equiv. $) | Unit | # of Units in ABUS System | One-Time Cost (2001-Equiv. $) | EUAC (2001-Equiv. $) |
|---|---|---|---|---|---|---|---|---|---|
| System Planning and Design Costs | | | | | | | | | |
| | VTA Personnel Labor Costs and Design Expenses | 2002 | 2,077,842 | One-Time | 2,037,115.83 | One-Time | 1 | 2,037,116 | 147,994 |
| Construction, Rehabilitation, and Other Infrastructure Capital Costs | | | | | | | | | |
| Infrastructure Costs | Right-of-Way Acquisition | 1999 | 23.65 | Sq. Foot | 24.49 | Sq. Foot | 712,483 | 17,445,882 | 1,267,424 |
| | Street Clean-Up | 2002 | 150.00 | Day | 147.06 | Day | 433 | 63,660 | 4,625 |
| | Mobilization | 2002 | 10,000.00 | Lump Sum | 9,804.00 | Lump Sum | 21.64 | 212,200 | 15,416 |
| | Traffic Control | 2002 | 2,000.00 | Lump Sum | 1,960.80 | Lump Sum | 21.64 | 42,440 | 3,083 |
| | Clearing, Grubbing, and Removal of Obstructions | 2002 | 2,500.00 | Lump Sum | 2,451.00 | Lump Sum | 21.64 | 53,050 | 3,854 |
| | Roadway Excavation | 2002 | 30.00 | Cu. Yard | 29.41 | Cu. Yard | 7,359 | 216,444 | 15,724 |
| | Subgrade Preparation-Class A | 2002 | 1.00 | Sq. Foot | 0.98 | Sq. Foot | 467,514 | 458,351 | 33,299 |
| | Imported Fill Materials | 2002 | 30.00 | Cu. Yard | 29.41 | Cu. Yard | 7,359 | 216,444 | 15,724 |
| | Deeplift/Base AC (8" max.) | 2002 | 70.00 | Ton | 68.63 | Ton | 13,203 | 906,092 | 65,827 |
| | AC Surface Course | 2002 | 80.00 | Ton | 78.43 | Ton | 5,757 | 451,561 | 32,805 |
| | AC Base Course | 2002 | 80.00 | Ton | 78.43 | Ton | 9,091 | 712,991 | 51,798 |
| | Cold Planing | 2002 | 1.50 | Sq. Foot | 1.47 | Sq. Foot | 21,644 | 31,830 | 2,312 |
| | Pavement Reinforcing Fabric | 2002 | 1.00 | Sq. Yard | 0.98 | Sq. Yard | 75,755 | 74,270 | 5,396 |
| | Gravel Conform | 2002 | 50.00 | Ton | 49.02 | Ton | 433 | 21,220 | 1,542 |
| | Traffic Stripes and Pavement Markings | 2002 | 800.00 | Lump Sum | 784.32 | Lump Sum | 21.64 | 16,976 | 1,233 |
| | Street Lighting System | 2002 | 60,000.00 | Lump Sum | 58,824.00 | Lump Sum | 21.64 | 1,273,197 | 92,496 |
| | Geotextile | 2002 | 3.00 | Linear Foot | 2.94 | Linear Foot | 23,809 | 70,026 | 5,087 |
| | Site-SpecificWork Items | 2002 | 9,828,623.28 | Lump Sum | 9,635,982.26 | Lump Sum | 1.00 | 9,635,982 | 700,044 |
| | Magnetic Reference Markers - Includes Installation | 2001 | 5,000.00 | Lane Mile | 5,000.00 | Lane Mile | 10.38 | 51,900 | 3,770 |
| | TOTAL INFRASTRUCTURE COST | | | | | | | | 2,321,461 |
| Non-Infrastructure Capital Costs | Fleet Purchase | 2002 | 293,000.00 | Bus | 287,257.20 | Bus | 10.180 | 2,924,389 | 212,311 |
| | Automation Technology Outfitting for Vehicle | 2001 | 25,000.00 | Bus | 25,000.00 | Bus | 10.180 | 254,510 | 16,967 |
| Periodic Capital Costs | Minor Rehabilitation - Seals | 2002 | See Botha *et al* (1) | | N/A | N/A | N/A | N/A | 30,732 |
| | Major Rehabilitation - Resurfacing | 2002 | See Botha *et al* (1) | | N/A | N/A | N/A | N/A | 84,443 |
| | Magnetic Reference Markers - Includes Installation | 2001 | See Botha *et al* (1) | | N/A | N/A | N/A | N/A | 8,550 |
| Fleet Renewal | Bus Replacement Costs | 2002 | 293,000.00 | Bus | 287,257.20 | Bus | 10.180 | N/A | 194,959 |
| | Vehicle Automation Technology Replacement Costs | 2001 | 25,000.00 | Bus | 25,000.00 | Bus | 10.180 | N/A | 16,967 |
| TOTAL CONSTRUCTION, REHABILITATION, AND OTHER INFRASTRUCTURE COSTS | | | | | | | | | 2,866,390 |
| TOTAL DESIGN, PLANNING, CONSTRUCTION, REHABILITATION, AND OTHER INFRASTRUCTURE COSTS | | | | | | | | | 3,034,385 |

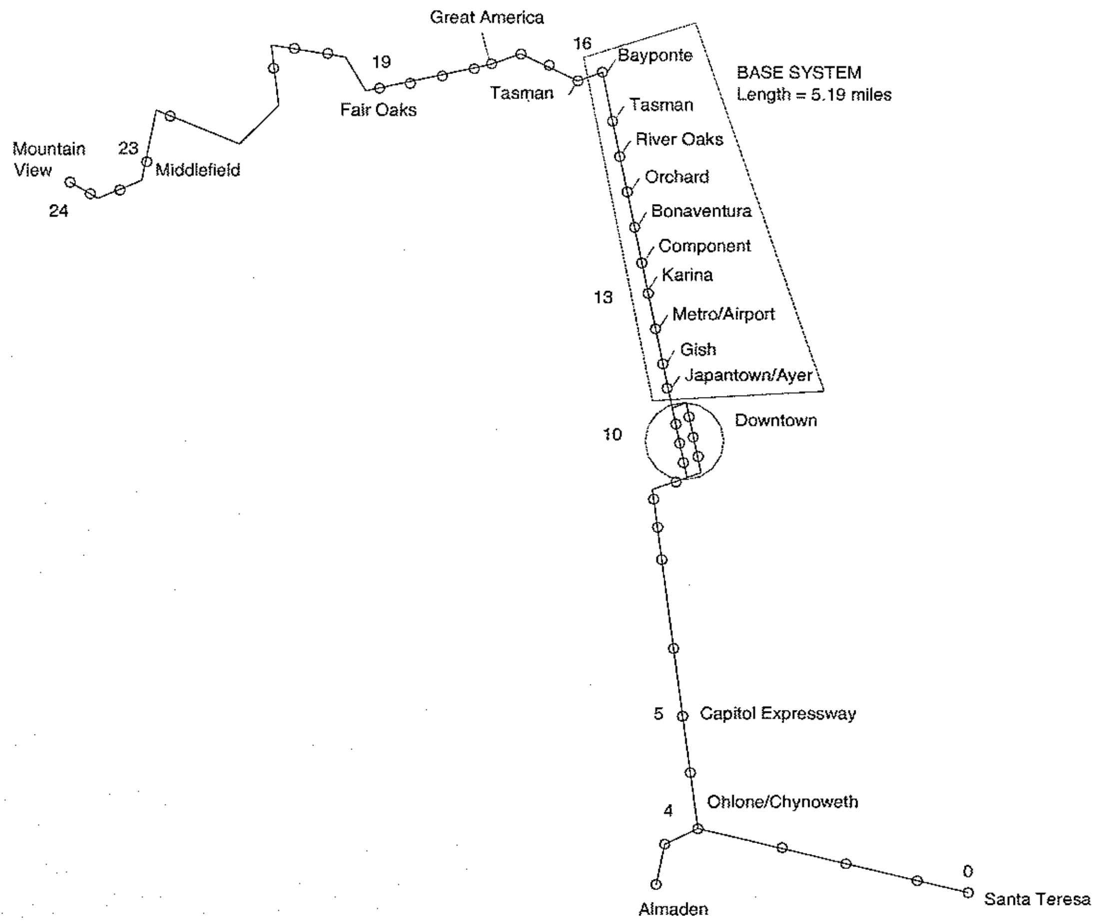


**FIGURE 1 Santa Clara Valley Transportation Authority (VTA) Light Rail System.**