Title

SmartBRT: A Set of Planning, Analysis and Evaluation Tools for Bus Rapid Transit: Final Report Year 1 of 2

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Publication Date

2003-02-01

CALIFORNIA PATH PROGRAM
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UNIVERSITY OF CALIFORNIA, BERKELEY

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California PATH Research Report

UCB-ITS-PRR-2003-7

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

Final Report for MOU 3022

February 2003

ISSN 1055-1425

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FTA

Federal Transit
Administration

OUTLINE OF THE FINAL REPORT

This final report of Year 1 consists of following main sections:

Section 1. Executive Summary
Section 2. Bus Rapid Transit in SmartBRT
Section 3. SmartBRT: A Simulation, Evaluation and Visualization Framework
Section 4. Application of SmartBRT to the Metro Rapid Transit System in Los Angeles
Section 5. Continuing Work on SmartBRT
Section 6. Summary and Plan Forward

Section 2 introduces the relevant aspects of bus rapid transit (BRT) operation, system elements, operation variables and performance measures. Also, it discusses how we selected and calculated these with the help of the T Manual.

Section 3 discusses SmartBRT, the tool that was built based on the elements, relationships and calculation methods discussed in Section 2. Section 3 discusses the three building blocks of SmartBRT: 1. simulation, 2. evaluation and 3. visualization. In discussing the development of SmartBRT's simulation core, the first building block, we address our dual approach of using SHIFT and Paramics, their advantages and disadvantages and how they compliment each other to build SmartBRT. The second building block, evaluation, is addressed only briefly, since it is a Year 2 task to complete. The section on the third building block, visualization, discusses the fusion of SHIFT, Paramics and visualization. Finally, Section 3 discusses our plans for Year 2 work on the SmartBRT tools.

Section 4 of the final report discusses the application of SmartBRT v.1.0 to the Wilshire-Whittier (W-W) Corridor in Los Angeles. The section starts with introducing the W-W corridor and its Metro Rapid BRT system, and then proceeds to the presentation of our two preliminary analyses to explore:

1. *How the number of stops, use of low-floor buses, signal priority and increased frequency affects the on-board travel time; and*
2. *How increased vehicle capacity and / or increased operating frequency could accommodate increasing demand.*

The end of this section summarizes the overall findings from these preliminary analyses.

Section 5 lists the future work that is necessary to develop a fully functional SmartBRT. The section discusses future work on all levels: input data, model and "toolbox" level, and recaptures some of the questions that a fully developed SmartBRT can assist in answering.

Section 6 summarizes the accomplishments of Year 1 and presents our goals for Year 2 and our plans to achieve them.

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1 EXECUTIVE SUMMARY

We report Year 1 results from a two-year project to develop a computer simulation, evaluation and visualization “toolbox”, *SmartBRT*, to describe and evaluate operational aspects of bus rapid transit (BRT) concepts in order to aid decision-making. In conceiving and developing *SmartBRT*, we have maintained two objectives:

- To provide FTA, Caltrans and local decision-makers with a rigorous and defensible, yet intuitive BRT operation evaluation method along with a general purpose BRT simulator/communication tool; and
- To provide example applications of *SmartBRT* to actual BRT concepts and to document these applications in a “cookbook” manner to allow the widest dissemination of the “toolbox” to the practitioner community.

In order to accomplish these objectives, our “toolbox” provides “hooks” for stakeholders – compelling *visualizations* for local decision-makers*, interfaces to conventional traffic modeling tools* for the transportation engineering community (and others on the FTA team), *interfaces to planning tools* for transportation planners, powerful *analytical tools* for BRT concept developers and researchers, and *short-term results* for all the potential constituency above.

Within *SmartBRT*, any specific BRT concept (characterized by physical facilities, bus configurations, operation schedules and policies, etc) and local demand models (including local passenger and traffic demand) can be defined by the user. Outputs are performance measures that the user chooses from a predefined list. The core tool of *SmartBRT* is a microsimulation, augmented with bus and infrastructure geometric libraries and three-dimensional (3D) graphics. *SmartBRT* simulates the operation of a BRT system, and evaluates and displays operation parameters and system performance measures. *SmartBRT*’s simulation core aids in understanding the interactions and tradeoffs within rapid transit system operation by performing the testing of different operation concepts quickly, consistently and inexpensively. It is also an ideal tool for quickly evaluating the incremental effect of adding ITS technologies to rapid transit operation without the high capital investment of field tests.

We have designed *SmartBRT* for multiple uses:

- In *planning* – to assess the anticipated benefits of implementing BRT system along specific corridors, by representing its principal attributes in the simulation tool and evaluating its performance (e.g., select between BRT concepts to determine which works better along a specific corridor);
- In *evaluation* – to aid in improving operation of existing BRT systems by seeding the simulation with real data and then varying input in order to evaluate different operation concepts and assess impacts that are hard to measure directly (e.g., bus operating profiles to determine fleet emissions); and
- In *analyzing the impact of technology* - to determine the BRT system performance enhancements that can be gained from implementing specific new technologies for BRT by represented the operational effects of these new technologies within the *SmartBRT* microsimulation (e.g., reduced lane widths with lateral guidance technologies).

For example, a transit operator could use *SmartBRT* to determine overall improvements in a BRT system that would result from a change in fare collection methods, or changes to other elements of the system. Furthermore, the operator could use *SmartBRT* to introduce a new system to users through 3D visual simulation, or to promote a change in operation of an existing system by quantifying improvements that would result from systemic change. A traffic engineer could develop a new signal priority algorithm for a BRT system and use the *SmartBRT* framework to test the effects of the new algorithm on BRT operation and on traffic flow. Finally, a researcher could introduce new technologies to the BRT system and evaluate their cost-effectiveness. Examples of such technology include automatic vehicle location, automatic vehicle monitoring, signal priority, fare collection strategies, precision docking and automated BRT operations.

1.1 Development Effort

SmartBRT is being developed under MOU 3022 by the UC Berkeley-based Partners for Advanced Transit and Highways (PATH) program. Year 1 development effort was funded by FTA and Caltrans New Technology and Research. The focus of the FTA portion of the funding was on developing the tool (*SmartBRT* v1.0), while the focus of the Caltrans portion of the funding was on developing a case study (two analyses addressing the Wilshire-Whittier Rapid Metro BRT in Los Angeles, CA).

Year 2 (*SmartBRT* v2.0) will again be partially funded by FTA and Caltrans. As with the development of *Smart BRT* v1.0, Federal funding will focus on further development and refinement of *SmartBRT*, whereas the Caltrans funding will focus on new application scenario(s). At this writing, Federal funding has not yet been obtained, but it is expected to fund refinements to the simulation and evaluation models, and user interface for the microsimulation and performance evaluation.

1.2 Deliverables of Year 1

Year 1 effort focused on developing the simulation core of *SmartBRT* and to provide example analyses and visualization in order to demonstrate the capabilities of the simulation core. As a result of our first year effort we have provided three sets of deliverables:

- *Smart BRT* v1.0, a BRT evaluation framework, featuring the general-purpose BRT simulator. The calculation of performance measures has been derived from the "Transit Capacity and Quality of Service Manual" (TCQoS Manual), and dynamic calculations within *SmartBRT* models. In the next year, we will develop a user-friendly interface for the framework, comprised of a "menu" of options to build specific application sites and to select an appropriate subset of performance measures;
- Example applications focused on the Metro Rapid BRT line in Los Angeles, CA, on the Wilshire-Whittier corridor. These preliminary analyses illustrate the use of *SmartBRT* for various levels of analyses and its high-end visualization mode. At this writing, next year's application site has not yet been selected, but it is expected that the final example will show full functionality of the simulation/evaluation framework and the visualization; and

- Photo-realistic simulation visualization showing the BRT in-lane operation and a two-dimensional "engineering" simulation of BRT operation.

1.3 Summary of Year 1 by Tasks of the Statement of Work

In this section we detail the deliverables following the outline of the tasks specified in the statement of work.

1.3.1 Task 1.1: Tailor HARTCAS Evaluation Methodology to BRT Needs

With the cooperation and input from FTA and selected transit operator(s), develop measures of effectiveness (MOEs) and subsequently, more detailed (quantitative) measures of performance (MOPs) with which to generally assess BRT.

> In developing performance measures to quantitatively assess the performance of a BRT system first we researched the Transit Capacity and Quality of Service Manual to understand operational variables and performance measures of a transit system (Section 2.1), second we reviewed BRT system elements and operation (Section 2.2), then, third, we quantified these important performance measures (Section 4.2.2). In understanding the local demand, TCRP Report 47 helped us understand the importance of consumer-defined service, while LACMTA provided us with specific information about their passengers' priorities, BRT system elements and operation variables. Based on these three resources we have developed a performance measure to assess the performance of BRT systems (Section 4.2.2).

1.3.2 Task 1.2: Adapt *SmartAHS* to a General Purpose BRT Simulator

Expand the scope of the simulation to cover all FTA-chosen deployment sites and deployment options, as well as a wide range of generic BRT systems.

> *SmartAHS* is a library of components for describing vehicles, roadways, and their interactions. The library is implemented in the SHIFT simulation language with C subroutines. The original purpose of *SmartAHS* was studying technologies proposed for use in highway automation, and consequently the library is especially suited to small-scale, highly-detailed simulations emphasizing controllers, sensors, detailed engine models, etc.
>
> For *SmartBRT*, we reused the basic road and utility component types from *SmartAHS* (see Appendix 3). We developed components for buses, passengers, bus stops and traffic signals largely from scratch, focusing on high-level transit system issues rather than hardware issues (Section 3.3.1). The simulation has been used to evaluate signal priority algorithms and scheduling policies (Section 4).
>
> In addition, we used Paramics to develop an exploratory simulation of buses with signal priority (Section 3.3.2).

1.3.3 Task 1.3: Customize *SmartBRT* Graphical Display Mode

Generate photorealistic 3D output with adequate detail to make the deployment site recognizable, and importantly, to make the salient features and benefits of the BRT implementation understandable. Elements of this infusion will include physical models of appropriate buses and inclusion of elements of a BRT civil infrastructure as individual components within a "BRT geometrics library" (e.g., entry/exit ramps, low resolution models of "typical" BRT stations).

We have worked with the University of California, Los Angeles (UCLA) Urban Simulation Team (UST) to develop a high resolution, photorealistic visualization of a selected portion of the Wilshire-Whittier corridor (Section 3.5). To create the roadway model used in our *SmartBRT* case study, we combined roadway and bus stop data into a composite model of the W-W corridor (Section 4.5). In the region of the "Miracle Mile", the geometric model is accurate to meter resolution[1]. Outside of the Miracle Mile, we used GPS coordinates for each bus stop along the route, and these coordinates are accurate to within 100 meters. In addition, we provided two-dimensional "engineering" visualization of the entire corridor that runs concurrently with the simulation (Section 4.5). It allows users to observe the behavior of their models without waiting for the simulation run to end.

1.3.4 Task 1.4: Conduct Site-Specific *HARTCAS-SmartBRT* Analysis

Working with the local transit agency (LACMTA), collect appropriate data, as well as BRT implementation details, and then develop a "node and link" concept of a BRT. Additionally, work alongside local transit officials to determine locally tailored version of MOEs and MOPs. Simulate and illustrate this concept within SmartBRT to produce an initial analysis showing benefits (if any) of the system.

We have obtained data from LACMTA about the Metro Rapid transit system on the W-W corridor (Section 4.1). This information included passenger priorities, data on the road network and operational parameters of the Metro Rapid system. Based on the information about the preferences of local passengers we have developed locale specific performance measures to qualitatively assess the performance of the Metro Rapid system (Section 4.2.2). Based on information of the local consumer base and LACMTA's operation of the BRT system and their policies we have developed questions to be tested by *SmartBRT* with the goal of improving BRT operation (Section 4.2.3). We primarily focused on travel time, and secondarily on overcrowding and reliability (measures through waiting time). Also, based on this data we modeled the Metro Rapid BRT system in *SmartBRT*'s simulation core (Section 4.2.4).

We have performed preliminary Analysis 1 to test travel time, since LACMTA's survey showed that passengers' primary desire is short travel time. We tested travel time as a

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[1] The Miracle Mile data was obtained from the UST, and extends along Wilshire Avenue, bounded on the west by Fairfax, and on the east by Western.

function of demand, signal priority, operation frequency and bus type (conventional vs. low floor) (Section 4.3). The results of preliminary analysis 1 showed that

- Adding signal priority (SP) to local bus operation lowered travel time. Switching from local operation (no signal priority) to BRT saved more time then adding SP to local operation. Adding SP to BRT operation further lowered travel time. The overall travel time gain from local operation without signal priority to BRT operation with signal priority was 26-27%; and
- Using the results of preliminary Analysis 1 we showed how *SmartBRT* can assist the decision-making process.

We performed analysis on additional performance measures: waiting time, overcrowding, occasion and number of people affected by overcrowding within our preliminary Analysis 2 (Section 4.4). The results of preliminary Analysis 2 showed that:

- Increasing demand can indeed be accommodated by either larger buses or by increasing frequency of operation. Our analysis showed the different consequences of these two choices and that of applying them together; and
- It would be very hard, if not impossible, to develop a single mathematical formula that would capture the relationship between operation variables, performance measures and passenger arrival rate, but *SmartBRT* allows us to study such relationships without analytical representation.

1.3.5 Task 1.5: Conduct Additional Off-line BRT Analyses

Conduct supplementary analyses in areas of efficiency and accessibility for FTA consideration. While they are not SmartAHS-based analyses per se, they would still fit into the HARTCAS framework but as macrosimulation-layer studies.

Our simulation tool based on *SmartAHS* is a microsimulation—it models individual vehicles. Paramics is also a microsimulation in this sense, but because of its simplistic models of vehicle motion and driver behavior, it is capable of simulating much larger networks (Section 3.3.2).

In our ongoing work, Paramics and *SmartAHS* have complementary roles and occupy different levels in the evaluation hierarchy. The high fidelity of the *SmartAHS* simulation allows us to study the effect of BRT elements on dwell time, bus travel speed, passenger flow rates, and so on. These performance measures are in turn inputs to the Paramics simulation, whose outputs are network-level performance measures of traffic congestion and of the bus system itself.

2 BUS RAPID TRANSIT IN *SMARTBRT*

Since *SmartBRT* is being developed to simulate and evaluate BRT operation, we needed to understand bus transit operation in general and the special aspects of BRT operation: what are its elements, how do they work together, what do we need to measure, what do we need to calculate. We had three main sources:

1. The Transit Capacity and Quality of Service (TCQoS) Manual provided background information on the operation of transit systems (operation policies), its components (running way, buses, passenger demand), variables that characterize elements of the system (such as dwell time), and variables that characterize the system as a whole (such as route capacity);
2. Project A-23 brochure provided general information about BRT system elements and operation; and
3. LACMTA provided us with specific information about the elements and operation parameters of the Metro Rapid BRT system. (Metro Rapid transit is discussed in Section 4.)

In Section 2 we discuss transit system elements, performance measures and the relationships between them in the general sense based on the Manual. Then we briefly discuss BRT as distinct from "regular" bus transit. This introduction of transit systems is necessary in order to be able to present *SmartBRT,* the tool, in Section 3.

2.1 Transit Operation Variables and Performance Measures

Our first and major source of information on transit systems was the TCQoS Manual. The TCQoS Manual, the first such manual for transit, is intended to be a fundamental reference document for public transit practitioners and policy makers. Its creation (inspired by the Highway Capacity Manual) was an ambitious effort to providing the transportation community with the transit equivalent of the Highway Capacity Manual. It provides definitions, background, principles, default values, statistics and procedures for planning, design and operation for various type of transit. We used the Manual to understand the workings of transit, as well as interactions and tradeoffs within the system, to determine what needed to be quantified and how, and how to evaluate quantified system measurements.

2.1.1 Decomposition of TCQoS to Relevant *SmartBRT* Parameters

"Transit capacity" is a complex concept that deals with the movement of people and vehicles. It depends on operation policy and reflects the interaction between passenger demand, transit operation and general traffic flow. The Manual introduces capacity concepts and ways to calculating capacity. "Quality of service" is not only a complex concept, but also one that changes with location because it measures how well the users' needs are met. Therefore, the definition of a "high quality service" changes from location to location, based on the local community's needs and preferences. The Manual gives some guidance, but local surveys need to establish the local priorities in determining service quality. First we discuss transit capacity and then quality of service in detail.

Transit Capacity

The Manual defines individual variables that are necessary to estimate the different capacity measures, gives default values for these and presents capacity estimation. However, these variables or the capacity measures are not independent of each other. Figure 1 in Appendix 1 shows the connection between different capacity measures and their dependencies.

Some capacity measures (such as capacity of individual buses, load factor and bus route capacity) have been used by the profession. However, the rest of these capacity measures are new concepts in the transit field. Their usefulness and meaning for decision makers is not yet fully understood. Furthermore, LACMTA[2] currently does not use these new capacity measures. Therefore, in addition to the few "old" capacity measures we focused on the quality of service measures that are more established in the transit field today, are already tied in the decision-making process of transit agencies and are used by LACMTA in their own system performance evaluation.

Transit Quality of Service

With a focus on how users make their decision about using transit, the Manual defines quality of service as a measure of both availability of transit service and its quality (comfort and convenience). Availability measures addresses spatial and temporal availability of transit, such as where, how often and how long transit service is provided. Availability describes whether transit is a transportation option at all. Assuming that transit service is available, quality measures are used to express comfort and convenience, which directly affect whether people chose to use the available transit as their transportation option.

The Manual assigns different availability and quality measures to describe elements of the transit system (such as stops and route segments), and to describe the whole system. Combination of the two performance measures (availability and quality), and the three elements (stops, route segments and whole system) resulted in the matrix presented below in Figure 2. Figure 2 shows that each element of the system is characterized by both availability and quality. Both availability and quality could be quantified by more then one measure. Some measures can be used to measure the performance of more then one element of the system. The Manual assigns only one performance measure to each element's availability and quality. These are printed in capital letters.

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[2] Information about LACMTA operation of BRT is gathered through personal communication with Rex Gephart, LACMTA. References to information obtained from LACMTA refer to this communication from here on.

Figure 2: Quality of Service Framework

Category	Service & Performance Measures		
	Transit Stop	**Route Segment**	**System**
Availability	FREQUENCY Accessibility Passenger load	HOURS OF SERVICE Accessibility	SERVICE COVERAGE % Person-Minutes Served Indexes
Quality	PASSENGER LOADS Amenities Reliability	RELIABILITY Travel Speed Transit/Auto Travel Time	TRANSIT/AUTO TRAVEL TIME Travel Time Safety

(Performance measures in capital letters are the primary measures of performance.)
Source: Manual

These quality of service performance measures are not independent. Their relationships and dependencies are shown in Figure 3 in Appendix 1.

Availability is determined by the agency providing the transit service. In terms of the Metro Rapid Transit, availability measures are given. They are inputs to the simulation as route coordinates, stop locations coordinates, hours of operation and schedule or frequency of operation. *SmartBRT* estimates the quality measures based on inputs that among others include availability measures.

2.2 Bus Rapid Transit System Elements

Bus rapid transit is a high-quality bus transit, much like light rail but with the additional benefit of buses serving as their own feeder system. BRT is aimed at transporting a high number of passengers at high speed while providing high ride quality. Here we shortly address elements of the BRT system as they are characterized for *SmartBRT* development purposes:

- Running way is characterized by their degree of separation from the rest of the traffic. While BRT can operate in mixed traffic, BRT running ways are usually dedicated to BRT to varying degree (from diamond lane to segregated, grade separated dedicated lane);
- Bus stops are characterized by their spacing (location), number of bus loading area per stop (number of buses that can stop at a stop at the same time);
- Vehicles are characterized by the height of the vehicle floor (conventional high floor or low floor) number and width of doors, use of doors for alighting and boarding (whether alighting and boarding are separated or take place at the same door), clearance time (time required to reenter traffic flow if stops are off line), whether bicycles are allowed and maximum speed;
- Signal priority is often employed to give priority to BRT vehicles if BRT operates in at grade level, crossing regular traffic. Signal priority is characterized by location (which intersections have it) and the length of priority hold (number of extra green seconds for the transit vehicle); and

- Operational policies are characterized by frequency of operation, and whether buses are allowed passing slower buses.

SmartBRT, the simulation, evaluation and visualization toolbox is built on the transit system elements, operation variables and performance measures that are discussed in Section 2. In the next section we discuss the tool.

3 *SMARTBRT*, A SIMULATION, EVALUATION AND VISUALIZATION FRAMEWORK

Our goal is to build a simulation, evaluation and visualization toolbox that is capable to simulate bus movement, traffic, passenger flow and BRT operation, and to prepare and present the simulation results for the user in a graphical way. We grouped these requirements into three functional building blocks: simulation, evaluation and visualization. The simulation core models different operation policies and technologies. The evaluation part calculates and communicates the results of the simulation to the user in a clear and systematic way. The visualization communicates the characteristics and performance measures of the BRT systems, making numerical results vivid and tangible.

The goal of a BRT system is to improve service by applying innovations in transit technology and operation. Many BRT system designs are still hypothetical. Making informed judgments about such systems depends on the ability to model BRT elements in the context of transit systems and to evaluate those models. Stakeholder acceptance of hypothetical systems requires that BRT designers clearly communicate the characteristics and effects of the BRT systems, making quantitative results vivid and tangible. This section presents our methodology for solving these evaluation and communication problems, and gives an overview of the software components involved.

3.1 The Need for Simulation and Visualization

Evaluating a proposed BRT element in the context of a transit system with given characteristics is too complex a problem to be solved analytically with closed-form equations. The performance measures that are of interest to a planner, such as travel times or throughput, cannot easily be expressed as formulas in terms of the characteristics of buses, passengers, traffic, and infrastructure; the dynamically evolving interactions between these entities are too chaotic for static methods. The problem is even more difficult when several BRT elements are studied in conjunction; “rule of thumb” formulas, calibrated against observations of installed systems, may not apply to new, untested combinations of BRT elements. Furthermore, the results of an analytical study are not readily intelligible by the broader community outside research institutions. Formulas may or may not be able to quantify the effects of certain technologies or policies, but they cannot present a visual experience of the proposed system.

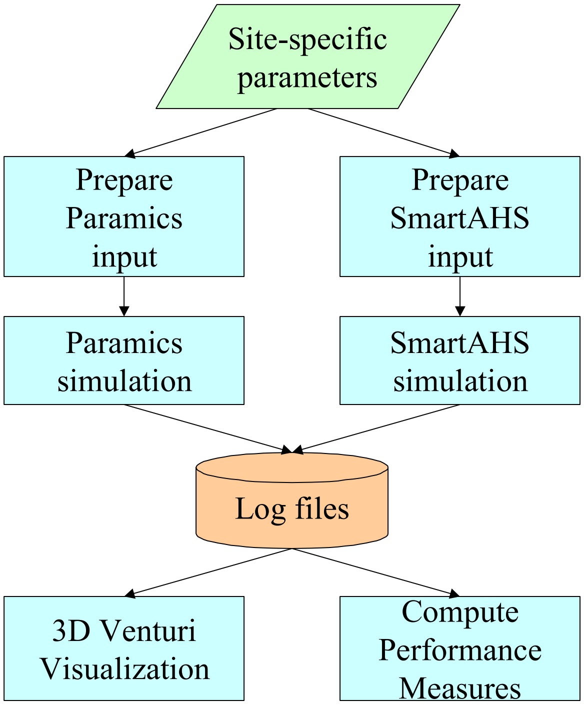
We therefore use computer simulation and visualization to model, evaluate and visually communicate the effects of BRT systems. Models of BRT elements, such as a fare collection system, a signal priority algorithm or a bus scheduling plan, can be integrated into a simulation along with tested models of vehicles and their dynamics, of traffic flow, and of driver behavior. If the vehicle dynamics models are sufficiently accurate, the simulation can be used to study small-scale vehicle behavior (e.g., bus precision docking) and can generate vehicle trajectories for use in realistic 3-D animation. If the models are well calibrated against traffic data, the simulation can be used for system planning in the context of a transportation network.

Unfortunately, accurate vehicle models make high demands on computing resources and are not practical for large-scale network simulations. As a result, most simulation tools choose to focus on either the large or the small scale. The *SmartBRT* project goals include both quantitative analysis of network performance (requiring large scale simulations) and visual communication of BRT designs (requiring small scale simulation). Our approach to these requirements is put together a toolkit that includes one simulation tool that works well on a small scale and another that works well on a large scale. In addition, we developed a protocol for sharing results between the tools, so that the toolkit functions as a single tool, delivering results that the individual tools cannot. The following sections describe these two simulation programs, their interaction, and additional software for analysis and visualization of results.

3.2 *SmartBRT* System Architecture

Our toolkit contains simulation, evaluation and visualization tools, as well as utilities to connect them. Figure 4 shows the overall structure of the current (Year 1) toolkit, with arrows representing the flow of data under typical usage patterns. Site-specific data is fed into either the Paramics simulation, which specializes on large-scale effects, or the *SmartAHS*-based simulation, which specializes on small-scale effects. The results can be sent to the 3-D visualization and performance evaluation tools. Each part of the toolkit is described in this chapter. A detailed *SmartBRT* User Manual is attached in Appendix 3.

Figure 4: *SmartBRT* System Architecture



3.3 The Simulation Tools

Both Paramics and *SmartAHS* are microsimulations; they model vehicles as physical objects with distinct trajectories. Large-scale traffic patterns are not modeled directly, but are consequences of the dynamics laws and control algorithms (human-based or automatic) that govern those trajectories.

Each simulation tool is capable of simulating bus movement, other vehicles and passenger flow. Neither tool comes equipped with a full set of BRT models; most BRT elements have to be modeled and implemented from scratch. Beyond these similarities, however, the two software packages differ in many ways:

1. The level of detail in dynamics laws and control algorithms, which is necessary for small-scale accuracy. In this respect, SmartAHS is better;
2. The maturity of the simulation components available for network and traffic modeling, which is necessary for large-scale accuracy. In this respect, Paramics has the advantage; and
3. The set of BRT elements that are available or can be readily defined. Neither has a more complete set, but the extension architecture of SHIFT/*SmartAHS* is more powerful than that of Paramics.

In the following sub-sections we discuss SHIFT/*SmartAHS* and Paramics in detail and explain the differences summarized above. We then discuss using them together as complementary parts of the *SmartBRT* tool.

3.3.1 *SmartAHS* and SHIFT

SmartAHS is a software library, originally developed for the study of Automated Highway Systems (AHS), consisting of simulation components that model vehicles, roadways with varying shape and connectivity, drivers, automated controllers, sensors, etc. For the *SmartBRT* tool kit we have extended this library to include buses, passengers, stops, signals and related components. All of these components are implemented in the SHIFT programming language, with some extensions written in C. SHIFT and *SmartAHS* were developed at California PATH. Appendix 3 documents these component models and usage of the software.

SHIFT

SHIFT is a programming language for describing dynamic networks of hybrid automata. Such systems consist of components that can be created, interconnected and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases (governed by differential equations) separated by discrete-event transitions (governed by logical decision making). Components may evolve independently or they may interact through their inputs, outputs and exported events. The interaction network itself may evolve.

The SHIFT language offers a level of abstraction suitable for describing complex applications such as automated highway systems, air traffic control systems, robotic shop floors, coordinated submarines and other systems whose operation cannot be captured easily by conventional models. Typical SHIFT applications have emphasized detailed modeling of processes that involve mechanical and electronic systems. However, because of its generality, SHIFT is potentially capable of simulating systems like traffic networks or queuing systems, which are best studied in abstraction from their underlying physical and mechanical nature.

Strengths and Weaknesses of SHIFT for SmartBRT Application

SHIFT is a powerful tool for working with a large class of complex problems. It is both a language for describing problems in simple terms and a software package for solving them and reporting the results. However, it has limitations and hidden complexities. The *SmartBRT* project brought out both the best and the worst in SHIFT.

For numerically solving systems of differential equations, SHIFT's integration capabilities are reliable and fast. The notation for specifying equations is elegant and natural. These capabilities were essential for describing the physical laws governing bus motion, and these laws were in turn essential for producing high fidelity 3-D animated output.

SHIFT is unusual among integration packages in that it combines discrete behavior with continuous behavior. A component can make a transition to another state in which it obeys a different set of equations after some condition becomes true. This is a very natural way to describe vehicle hardware and its behavior in relation to the world.

SHIFT is not as well suited to describing processes that are more algorithmic, symbolic or logical in nature than they are continuous. The *SmartBRT* simulation has several such processes, involving passenger flow, bus stops and traffic signals. Some of the difficulties are due to inherent limitations in the language. For example, the synchronous event mechanism is awkward for describing asynchronous message passing, such as in cause-effect relations. Other difficulties result from the need to work around bugs and limitations in the current implementation, especially with primitives for manipulating collections (sets and arrays) of components (there is no easy way to sort an array, for example). In a large-scale, loosely coupled simulation such as this one, asynchronous message passing and collections are of central importance.

Aside from the ability of SHIFT to describe "hybrid systems" with continuous and discrete behavior, there are larger programming issues that come up in building a task-directed simulation tool such as *SmartBRT*. SHIFT has no built-in constructs for configuring a simulation run using input files or for collecting and storing data for analysis. The language can be extended with C functions through a simple but limited interface, but this makes the software somewhat sluggish to respond to changing input/output needs. SHIFT also has no inheritance mechanism for reusing code.

SmartAHS

SmartAHS is a collection of SHIFT components for vehicle simulations that was originally intended for the study of automated highway systems (AHS) and their enabling technologies. It includes models for vehicles and road segments, as well as utility classes for such tasks as coordinate transformations and proximity detection. Most of *SmartAHS* is optimized for small-scale, highly detailed simulations emphasizing controllers, sensors, detailed engine models and so on. Different types of vehicles (trucks, buses, passenger vehicles) with different types of drivers can coexist in the simulated world. Driver and infrastructure interaction protocols can be specified. The motion of each vehicle is simulated individually. The simulation environment has model libraries of vehicles, sensors and actuators at varying degrees of detail. The simulator can also model complex road geometries.

The current version *SmartAHS*/SHIFT is available at http://www.path.berkeley.edu/shift/, and it contains the following features:

- Highway Models: Supports user-defined description; can specify lane, segment, section, block, barrier, weather, source, sink;
- Vehicle Models: Provides simple, 2-D, three levels of intermediate vehicle models (between 2- and 3-D), 3-D and articulated simple vehicle dynamics;
- Controllers: Provides physical layer (steering, throttle, brake and tire burst) controllers; also supports open loop trajectory following controller and cooperative individual vehicle controller. Human driver models are currently being implemented;
- Communication Models: Provides spherical, perfect receiver, transmitter and message communications;
- Sensor Models: Provides spherical, perfect closest vehicle sensor. We plan on applying generic sensor models, particularly with laser and mmw; and
- Animation: Allows simple, 2-D (top view) animation and high fidelity texture-mapped 3-D animation. Allows full vehicle/environment/roadway processing and interaction.

For Year 1 of *SmartBRT*, only the basic road and utility component types were used for the simulation. Components for buses, passengers, bus stops and traffic signals were developed from scratch, focusing on high-level system design issues rather than hardware issues. Future work with mixed traffic and intersections will require substantial modification and extension of *SmartAHS*.

Highways in *SmartAHS* format are generated from a highway input file by a preprocessor called the highway compiler. The input format for this program is designed for simple geometric constructions: lines and arcs. It is not well suited to highways specified by a sequence of real-world coordinate points. For *SmartBRT* we needed an additional preprocessing step, and the results are still not a perfect match with the real world coordinates as displayed by the 3-D visualization system.

3.3.2 Paramics

Paramics is a commercial software package widely used in the transportation industry for modeling and simulating traffic flows. It is distributed by Quadstone Limited of Edinburgh, Scotland. In the *SmartBRT* toolbox, Paramics contributes the ability to model large volumes of traffic involving buses as well as passenger cars, and intersecting city streets as well as limited-access expressways. It includes tools for interactively setting up networks and traffic, for 2D visualization of the evolving simulation, and for statistical analysis of simulation output. It has relatively wide use among researchers as well as planners.

Introduction to Paramics

Paramics provides a portable, scalable, high-performance traffic simulator that can be used in a number of markets, with problem scalability from single junction design, through urban area simulation. Like *SmartAHS*, it is a microsimulation, with models of individual vehicles; Paramics, however, focuses on larger networks with less detail. The software package includes five programs: Modeler, Processor, Analyzer, Programmer and Monitor.

In the Modeler individual vehicles are modeled in detail for the duration of their entire trip, providing accurate and dynamic information about traffic flow, transit time and congestion. The Modeler has been validated against existing macroscopic modeling tools, traffic survey information and site observation. The Modeler provides three fundamental operations of model build, traffic simulation and statistical output. In general, the Modeler features:

- Support for networks of up to 1 million nodes, 4 million links and 32,000 zones;
- Simultaneous editing, simulation and visualization;
- Intuitive graphical network editor;
- Comprehensive statistical output;
- Integrated urban and freeway modeling; and
- 3-D visualization with DXF, BMP or TGA overlays.

The Processor allows the user to set up network simulations to be run in batch mode that runs Paramics simulations offline at high speed and saves results for each simulation to specified directories. It provides a graphical user interface, which allows the user to:

- Set simulation parameters;
- Select various statistics for output; and
- Vary the attributes of vehicles released onto the network.

The Analyzer is an analysis tool whose primary function is to display and compile reports on statistical data output from running the Paramics Modeler traffic simulation. The analyzer module includes an Excel Wizard (spreadsheet macro) that is used to filter the mass of simulation data to produce comparisons and mean statistics from multiple simulation runs. These comparisons allow the user to quickly pinpoint average simulation results as well as boundary results where the variation in the model output produces upper and lower limits for simulation. The Analyzer features:

- On-screen graphical and numeric display;
- Output report files in ASCII text format;
- Shows statistics disaggregated by vehicle type;
- Link statistics can be displayed and customized to user specification; and
- User definable MOE and LOS criteria

The Programmer is an Application Programming Interface (API) to the Modeler. It provides users with the capability to simulate additional features within Paramics's extensive traffic modeling framework. By developing plug-in code, the Programmer users can carry out comprehensive modeling and analysis of the very latest transportation technologies and techniques. The Programmer features and benefits:

- Application Programming Interface (API) to underlying simulation model;
- Ability to link Modeler to third-party software by development of plug-in code;
- Flexibility to develop and test user-defined algorithms and functionality;
- Analysis of Intelligent Transportation Systems (ITS) performance prior to installation;
- Customization of network-wide configuration parameters; and
- Ability to adjust simulation models and parameters.

Paramics Monitor calculates the levels of traffic emission pollution on a road network. The pollution levels are collected for every link in the network by summing the emissions for all vehicles on the link. These levels can be written to a statistics life at regular intervals, and can also be viewed graphically while the simulation is running. The Monitor features:

- Graphical display of levels of emissions;
- Display incorporates a simple dispersal model;
- Emission statistics may be output in ASCII text format; and
- Vehicle characteristics (time on network, acceleration) and network characteristics (link gradient) are cross-referenced to pollution emission data.

Strengths and Weaknesses of Paramics for SmartBRT Application

Paramics is well suited to evaluating the behavior of traffic and bus systems, using the features described above. However, it does have some drawbacks, as far as the *SmartBRT* project is concerned:

- Vehicle movements are not very smooth; this is a necessary tradeoff for modeling large networks in a reasonable run time. Consequently, Paramics is not suited to generating 3-D animations of individual buses with resolution well below 1 meter; which is why we developed Venturi (Section 3.5.1);
- It is possible to develop accurate site models. However, for all but the smallest networks, this process is painstaking and labor-intensive. The scripts mentioned below partially solve the problem, but only for networks that are limited in shape, though possibly large. Further work with raw data from other sources will require more complex scripts;
- Models in Paramics are opaque: they are proprietary, closed-source products of Quadstone Ltd., whereas SHIFT and *SmartAHS* are open source. Only limited sets of parameters are exposed to the user. The role these parameters play in model behavior is not completely documented (those behaviors are a business asset), hence it is hard to know whether the models, perhaps very accurate in one location with one population of drivers, will be at all useful in another setting;
- Extending Paramics with new models and new behaviors for existing models is possible through the Paramics API (Application Program Interface). The API is a set of C function calls and callback protocols that allow third parties to modify model behavior in ways defined by Quadstone. This rigid interface between user-defined models and the rest of the simulation is in contrast with SHIFT, in which there is no such distinction and in which adding new models is a natural part of the language (in fact, it is the essence of the language); and
- Not many BRT elements are provided “out of the box” in Paramics. Some of the missing elements are advanced bus stops, low-floor buses, fare collection systems, precision docking, lateral guidance and operational policies. Some of these might be

implementable using the API. Others (lateral guidance and precision docking) are probably not appropriate in the high-level context of Paramics.

Our work with Paramics was primarily exploratory. A simple network composed of two signalized intersections was built through Paramics Modeler to address the following tests:

- Performance measures (total delay, total travel time, bus delay, bus travel time) without bus priority signal (basic or current situation);
- Performance measures with bus priority signal, without dedicated bus lane; and
- Performance measures with bus priority signal, with dedicated bus lane.

Traffic signal timings can be modified within Paramics either individually, through the interactive interface, or in sets through a file-based interface. It would also be possible to incorporate signal-timing modifications with an on-line optimization process.

We also developed scripts to convert raw network and operational data to Paramics input file format. These data include roadway GPS coordinates, bus capacity and service frequency, bus stop and traffic signal location and passenger demand. The raw data is obtained directly from transit agencies, map databases, local governments and so on, and cannot be expected to be in Paramics format. (There are also scripts to convert this raw format into *SmartAHS* specifications.) However, these scripts are currently limited to a single corridor consisting of nodes connected by straight links.

3.3.3 Using SmartAHS and Paramics Together

Our initial work has envisioned the two tools used for two disjoint sets of applications:

- SmartAHS for realistic space-time trajectories and for studies of the interactions of passenger flow, bus travel time and signal priority algorithms; and
- Paramics for the effects of BRT technologies on overall network characteristics.

As we develop new uses for each tool, there are several ways in which their application may overlap and connect:

1. Performance measures that can be extracted from either simulation can be compared;
2. We could use *SmartAHS* to study, at a very detailed level, BRT elements that may not be available in Paramics (precision docking, fare collection, bus stop design, sensors and communication). The results of the study would then calibrate more abstract models in Paramics (such as dwell time), whose behavior in the Paramics simulation would lead to network-level evaluations;
3. Conversely, if a local planning agency publishes a Paramics model of local traffic patterns, we could use flow rates on and across the transit corridor to calibrate the traffic levels in the *SmartAHS* simulation; and
4. Barring technical difficulties, simulations of each type could share data at run-time, in effect distributing the entire simulation problem into fragments that are well suited to one tool or the other. However, this will only be feasible if the time step and network complexity can be chosen in each simulation so that the two progress at roughly the same

rate (in terms of model time units per real time units). This may impose a limit on what can be studied (e.g., probably not precision docking).

3.4 Evaluation

The evaluation tool must be capable of preparing inputs, processing outputs and presenting the simulation results in a way that the user can readily understand and use to make decisions.

Our vision of the *SmartBRT* toolkit includes components that prepare input data, process output data and analyze the simulation results. These components should be usable by transit specialists with no programming or simulation background. Developing this part of the toolbox is a Year 2 task. In this section, we describe our approach to manual data analysis in Year 1 and how the evaluation tool will perform this function in Year 2.

In our first year efforts, we manually configured input files to each of the simulations for the site under study. This is a labor intensive and error-prone process. For testing of different variables we made changes directly in the input files. This is not a user-friendly way to change input variables, so our Year 2 effort will develop a user interface for easier data input.

In our first year efforts for our analysis we worked directly with the output log files. We manually exported the raw data from the log files into Excel to calculate further results (such as averages, maximums, variance, etc.) and to create graphs. This is also labor intensive and not user-friendly. Therefore, our Year 2 effort will develop a user interface that allows the user to select which variables he/she wants to display and in what format.

3.5 Visualization

The visualization tool must make it possible to communicate the effects of the simulated BRT system in a graphical way, making quantitative results vivid and tangible.

Within the collection of *SmartBRT* components are tools that are used to visually display information computed by the simulation core. Visual information display includes visual simulation and scientific, or information, visualization. Visual simulation, as shown in Figure 5 in Appendix 2, is the process of combining high-fidelity geometric models with physically accurate kinematics or dynamics to create visually engaging images. Images of this type are often useful for communicating results to a wide range of stakeholders.

Scientific visualization, by contrast, attempts to represent large, complex datasets in a way that makes evident the relevant properties, correlations and trends. This kind of visualization includes plots and charts of various kinds. In the *SmartBRT* toolkit, it also includes a 2-D plan-view representation of vehicles and the roadway with extra information; examples are shown in Figure 6 in Appendix 2. By presenting the objects with minimal visual detail, but more detail about their internal state and characteristics, this kind of visualization is especially useful to planners and engineers.

3.5.1 Visual Simulation

Visual simulation in *SmartBRT* represents the final product of a good deal of painstaking and detail-oriented effort. One challenging issue is the process of creating the high-resolution geometric model itself. We have subcontracted to the Urban Simulation Team (UST) at UCLA to create a high-resolution model of a portion of the Wilshire-Whittier bus route in Los Angeles. To create such a model, the UST gathered a variety of data, including as-built drawings of roadways and freeways, high-resolution digital color aerial photography and high-resolution digital terrain models (DTMs). Data from these sources are integrated using a combination of custom and commercial software modeling tools to produce a hierarchical model that is accurate to meter resolution, and is of such high visual fidelity that graffiti is clearly legible.

Another challenging aspect of visual simulation is ensuring that the geometric model used by the visual simulation software is spatially consistent with the model used by the numerical simulation (Shift or Paramics in this project). We have combined data obtained from UCLA and other sources to create a composite model used in our *SmartBRT* case study of the W-W corridor. Our composite model combines the high-resolution model created by UCLA with bus stop locations outside the region modeled by UCLA, and effectively spans approximately 27 miles of roadway.

Figure 5 in Appendix 2 was created using Venturi, a visual simulation software tool created by California PATH. Venturi uses as input the high-resolution geometric model created by the UST for the “stage” and uses output from one of two simulation codes to move vehicles along the roadway. As of this writing, Venturi is used only in a visual simulation capacity, but could easily be extended to include visual display of other types of information.

3.5.2 Two-dimensional “Engineering” Visualization

The *SmartBRT* toolkit also includes a simple 2-D plan-view visualization that, unlike Venturi, runs along with the simulation. Its purpose is for system designers and traffic engineers to observe the behavior of their models without waiting for the simulation run to finish. The Year 1 version, called TAVIS for historical reasons, includes scrollable, zoomable windows showing the roadway and vehicles. Additional windows allow the user to inspect and graph of the state of simulation components, such as vehicles, passenger queues and signals (see Figure 6 in Appendix 2). This tool will evolve to include visualizations of the BRT technologies to be studied in Year 2.

3.6 Future Functionality

Future growth in *SmartBRT* will extend not only the base-level functionality of the software collection, but also serve to make the overall system easier to use and manage. A fundamental challenge to be addressed is the issue of the conflicting needs of production versus research software. This section addresses the future functionality of *SmartBRT*, taking each of its three main components in turn.

3.6.1 Simulation

We continue to refine and extend the models of *SmartBRT* to increase accuracy and applicability of the simulation. Some of the directions we are investigating include:

- Mixed traffic (passenger cars in the same lane as the bus), which requires:
  - Bus driver models for behavior in traffic;
- Cross-traffic generation models:
  - Governed by parameters that can be calibrated from real-world data or Paramics simulations;
- More flexibility in designing signal priority algorithms;
- More bus, stop and passenger characteristics (door count, fare collection protocol, low floors, enclosed bus stops);
- Operational level bus control (e.g., scheduling to avoid bunching, logic for passing other buses); and
- Dynamic passenger demand model. (Currently, we assume that passenger demand is independent of bus service. In Year 2 this assumption will be relaxed to allow for demand elasticity with respect to service characteristics).

As mentioned in Section 3.3.3, using *SmartAHS* and Paramics as complementary, rather than competing, tools may be the best way to address some of these issues.

3.6.2 Evaluation

We continue to develop *SmartBRT* as an evaluation tool for BRT systems for:

- Operational scenarios in both mixed traffic and on dedicated lane (from diamond lane to barrier separation) to determine the effect of traffic on transit system performance and the effect of transit operation on traffic flow;
- Gauging the effect of the number and placement (far side vs. near side) of stops on transit performance and traffic flow;
- Investigating different operation parameters on transit system performance and on traffic flow;
- The effect of implementing advanced technologies on transit performance;
- Cost-effectiveness of each scenario;
- Assessing the interaction between the BRT system and the rest of the transportation system (for example, testing the potential redistribution of traffic demands due to the provision of bus-only lanes);
- Interface development to directly support decision-making;
- Complete the set of testable performance measures; and
- Visualization development to help convey BRT operation and image.

A fully developed *SmartBRT* v2.0 will assist the operator and the planner in answering practical questions, e.g.:

- What is the effect of adding and removing one or more stops on travel time?;
- What effect would different fare collection methods have on dwell time and travel time?;

- At what traffic volume should we switch from mixed traffic to diamond lane, to dedicated running way?;
- What are the time-saving gains and the cost differences between different running way options?;
- At what passenger volume does it make sense to purchase articulated buses?; and
- Should we implement a signal priority system and how much time would it save?

The user interface will be developed to make these uses possible for the non-programmer. This includes the process of entering inputs, extracting useful information from output data, and graphing that information.

3.6.3 Visualization

Generic Urban Visual Models

For broader use of *SmartBRT*, we need to develop visual models of the urban background, e.g., buildings, sidewalks, bus stops and so on, that are realistic, yet generic enough that they can be used to adequately represent any urban location. Local transit planners could use these models as a construction set to prepare 3-D animations that demonstrate site-specific BRT elements in the context of site-specific urban landscapes.

Web-based Interface and Delivery

While SHIFT and Paramics have different forms of input, a BRT system in general consists of a set of quantifiable parameters that can be represented in a simulation-neutral way. We envision a web infrastructure that will permit a user to set up a problem for study: a route consists of some number of stops, a schedule, a passenger demand model, vehicles with known capacity characteristics and operating costs, and so forth. These parameters can be translated into a form suitable for use by the underlying simulation. In some cases, such conversion will require third-party software tools, thereby increasing the overall system complexity.

Many have discovered that a web portal model can serve to hide the complexities of a large and heterogeneous software system from the user, thereby increasing the usability of the system. The portal model will allow each individual user to set up a problem then save it for later editing, to share it with colleagues, to run one or more simulation tools on the problem and to view results. Ideally, the portal interface will consist of a thin client implementation, so that the user need only use a current web browser.

Web-based Information Visualization

The thin client approach is well suited to information visualization. The client needs to display plots and tables showing performance measures, such as plots of travel time vs. fare collection methods. Emerging standards for web-transmitted graphics, such as Scalable Vector Graphics (SVG), make this possible.

Visual Simulation Development

While a good deal of the portal model can be implemented using a thin client, other types of software are best implemented as a thick client, or standalone application. One good example of this is a visual simulation application. Typically, these place significant demands upon system resources, and consume significant amounts of data. For example, the geometric model created by the UST for *SmartBRT* consists of approximately 100 Megabytes of raw geometry. It would be impractical to download this much data to the client for each simulation run.

A future growth area will be to explore alternatives to a heavy Performer-based application that can be used for visual simulation and visualization. The overall goal is to reduce platform dependency: Performer is available only for IRIX and Linux platforms. There are a number of reasonable alternatives that can be explored ranging from cross-platform scene graph technology through truly platform independent implementations such as Java3D. A careful analysis of the tradeoffs and a clear specification of needs will provide direction in future growth in this area.

3.7 Summary of Section 3: *SmartBRT*, the Toolbox

The operation of a Bus Rapid Transit system, from the level of individual bus movement and passenger behavior up to the level of system operation, is so complex that simulation methods are required to study hypothetical technologies and policies. Furthermore, we came to the conclusion that this complexity is best broken down into two tools, one at each level of detail, which are used in cooperation. In our first year, we developed the lower-level simulation, starting with SHIFT and *SmartAHS*, into a tool capable of answering questions about signal priority, bus travel times and passenger flow (Section 4). We also developed a proof-of-concept simulation at the higher level, using Paramics. Using the urban modeling work of UCLA-UST, we developed a photorealistic 3-D visualization system capable of replaying the simulated movements of the buses through an urban transit corridor.

4 APPLICATION OF *SMARTBRT* TO THE METRO RAPID SYSTEM IN LOS ANGELES

As part of the first year effort we applied *SmartBRT* v1.0 to a real case site, the Metro Rapid transit of LACMTA on the Wilshire-Whittier (W-W) corridor in Los Angeles, CA. Metro Rapid is a BRT system operated by LACMTA, which (as of this writing) is one of the eight participating projects, supplementing the ten BRT demonstration projects funded by FTA. All eighteen transit agencies (to include demonstration and other participating projects) are in the FTA-sponsored "BRT Consortium". Caltrans and FTA have facilitated our contracts with LACMTA with the purpose that we illustrate the relevancy and potential of *SmartBRT* with a "BRT Consortium" real-world application scenario. We have performed two preliminary analyses for this site.

In Section 4 we introduce the W-W corridor and its Metro Rapid BRT system, model the case site in *SmartBRT* and then present our two preliminary analyses to explore:

1. How the number of stops, use of low floor buses, signal priority and increased frequency affects the on-board travel time; and
2. How increased vehicle capacity and/or increased operating frequency could accommodate increasing demand.

4.1 Wilshire-Whittier Corridor and the Metro Rapid Transit System

The W-W corridor in Los Angeles, CA is an approximately 27 miles long urban corridor that goes through downtown LA. Metro Rapid is a BRT system, operated by LACMTA, that runs on the W-W corridor. Figure 7 in Appendix 4 show the map and Figure 8 in Appendix 4 shows the schematics map of the corridor and the 30 Metro Rapid stops.

There were local and express transit operations in place on the corridor. LACMTA, seeking to increase quality of service, surveyed its consumers. The results of the survey revealed that passengers want:

- Low travel time;
- Reliable service (not yet evaluated); and
- No overcrowding (*7*).

Before implementing Metro Rapid, LACMTA studied the causes of delays:

- 25% of total bus running time was spent at bus stops loading and unloading passengers; and
- 20% waiting at red lights (*5*).

Therefore, in order to reduce travel time, LACMTA converted the express transit on W-W into Bus Rapid Transit, called Metro Rapid, by:

- Investing in low floor buses;
- Investing in signal priority software and hardware (detailed later);
- Reducing the number of stops from 135 to 30;

- Implementing new operation policy: faster buses can pass slower buses;
- Placing BRT stops generally on the far side of intersections. (Local stops are opposite side.);
- Reducing headway to the minimum 3 minutes in peak time;
- Introducing prepaid fare (although passengers can still pay the driver) and encouraging use of back door for alighting;
- Applying color code to convey identity of BRT service (*6*); and
- Operating buses on a diamond lane during peak-period (This diamond lane is used by other traffic for right turn and is generally poorly enforced).

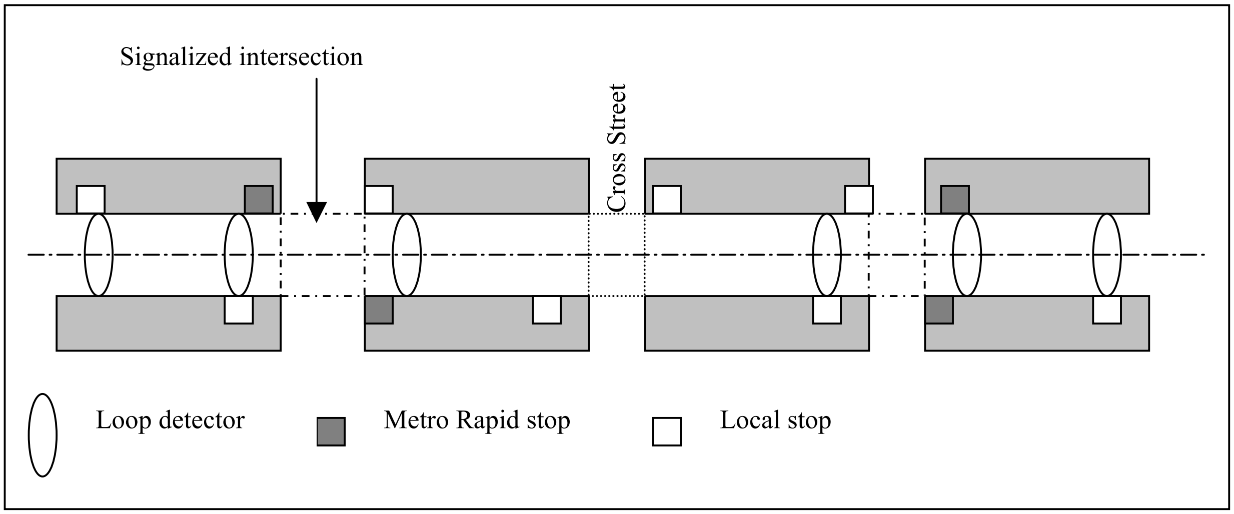
Metro Rapid transit system is described by its elements as follows:

- *Running Way*: Metro Rapid operates in mixed traffic off-peak and on a poorly enforced diamond lane during peak period;
- *Stops*: There are 135 local stops and 30 Metro Rapid bus stops on the W-W corridor. Their names and locations are listed in Figure 9 in Appendix 4. Local stops are generally near side, while Metro Rapid stops are generally far side;
- *Headway*: Currently Metro Rapid buses operate at 3 minutes headway in peak period and 5 minutes headway off peak times. Local bus operation is schedule-based;
- *Vehicles*: LACMTA runs low-floor buses that have a seating capacity of 42 people, and two single doors;
- *Demand*: (Number of passengers per stop, per hour) At the time of the development and application of *SmartBRT* v1.0 to the Metro Rapid transit, LACMTA could not provide actual passenger data;
- *Operation Policy*: Boarding takes place at the front door. Use of the back door is encouraged for alighting but it is not the rule. Prepaid tickets are available, but passengers can still pay exact fare at boarding; and
- *Signal Priority on the W-W Corridor*: Currently, there is loop detector-activated signal priority installed on part of the Wilshire-Whittier Corridor. The signal priority system is not installed all the way through the corridor because it goes through several different governmental jurisdictions, including the cities of Santa Monica, Beverly Hills, Los Angeles and unincorporated parts of L.A. County. MTA (in partnership with City of L.A./LADOT) has full control only on the parts of the route within the municipal boundaries of the city of L.A. The other jurisdictions want to see the benefits of implementing signal priority before they invest in the technology. MTA forecasts that if the other jurisdictions were part of the signal priority system, then travel time could be further reduced.

  Hardware consists of hardwired loop detectors at signalized intersections and transponders. Loop detectors are connected to the controller. A central computer makes the decision about giving signal priority.

  Loop detectors are installed at every signalized intersection. Metro Rapid stops are usually far side, while local stops are near side. This, however, is not an absolute rule and there are some exceptions. Figure 10 shows the stylized model of the corridor with loop detectors at signalized intersection and the stop locations.

Figure 10: Stylized Model of W-W Corridor Signal Priority System's Loop Detectors and Stop Spacing



Total signal cycle time is 90-100 sec. Signal priority may take away time from the cross traffic green cycle up to a maximum of 10% of total cycle time. (This 10% was chosen arbitrarily by LACMTA.) When a Metro Rapid bus approaches an intersection and its green light is about to turn red, the algorithm extends the green light for the bus by at most 10% of the total signal cycle. On average signal priority takes 5 sec away from the cross street green time. It never takes away from pedestrian green time, i.e., when signal is flashing "Walk". It takes two cycles (3 min) for the signal to recover after giving priority.

LACTMA has implemented the following signal priority options:

1. All Metro Rapid buses get priority at all times when it asks (which is when the bus reaches a signalized intersection within 10 seconds of its green signal's end). Implementing this signal priority achieved 25% time reduction; and
2. LACTMA tries to reduce bus bunching by adjusting the signal priority algorithm. The system does not give priority to Metro Rapid buses if:
    a. The signal cycle has not recovered yet; and/or
    b. The bus asking for priority is ahead of its "schedule" by 50% of the headway.

4.1.1 Results of Implementing BRT on the W-W Corridor

The results of implementing BRT operation on the W-W Corridor as described above are:

- 29% reduction in travel time from local transit time (Figure 11); and
- 25% increase in ridership (*5*).

Figure 11: Travel Time Improvement as a Result of BRT Operation on the W-W Corridor

Speed Improvement	W-W Corridor
Overall Speed Improvement	29%
Eastbound (Range)	31% (18-40%)
Westbound (Range)	28% (21-32%)

Source: Draft Long Range Transportation Plan for Los Angeles County

LACMTA estimates that 1/3 of the improvement resulted from implementing bus signal priority, while the other BRT elements accounted for the remaining 2/3 of the timesavings.

Since Metro Rapid transit is still capacity-constrained, LACMTA seeks to further increase capacity and service quality.

4.2 Modeling: From the Case Site to *SmartBRT*

In order to improve service quality, the operating agency must know what is important to its service's customers and must be able to measure how its service performs in these important attributes. Then the agency needs to evaluate/interpret these performance measures and make decisions based on the evaluation results to increase system performance. In translating this real life case study of improving system operation into a problem set to be solved by *SmartBRT*, we take the following steps:

1. Determine what is important to local passengers – customer-defined service;
2. Quantify these important performance measures – locale specific performance measures;
3. Determine how to improve service – questions to test by *SmartBRT*; and
4. Represent the case site in *SmartBRT* – apply *SmartBRT* to the case study.

4.2.1 Customer-defined Service

People select transit because the quality of the service – from total travel time, to comfort, safety and price – is better than other alternatives offered. If operators want to increase ridership, they need to increase the level of service to their customers. Since quality of service spans an array of attributes, the operator needs to know the preferences of current and potential passengers. This requires a consumer-based perspective from transit operators, practitioners and policy-makers.

TCRP Report 47 helped us to understand transit demand; why users choose transit. This handbook focuses on how to identify, measure and evaluate customer satisfaction and how to develop and implement customer-defined quality transit service. The emphasis is on "customer-defined" quality. The handbook provides a comprehensive list of transit service-quality measures from the customers' perspective. Some of the most important transit service-quality measures are:

- Reliable buses that come on schedule;
- Frequent service so that wait times are short;
- Buses that are not overcrowded (not left behind);
- Availability of seats on the bus;
- Hours of service (Service span) on weekdays and weekends;
- Safety: Bus traveling at safe speed; safe driver, etc.;
- Cost effectiveness, affordability and value;
- Frequency of delays for repairs/emergencies;
- Freedom from the nuisance of others; and
- Short wait time for transfers.

TCRP Report 47 emphasizes that all riders are not equal. Sort waiting time is more important in the cold winter then on a sunny California day. Comfort and seat availability may not be important at all on short, fast trips, but may be important on long trips. In TCRP Report 47, a method for ranking service-quality measures were applied to account for location specific variation in customers' perspective.

While the same general performance measures are applicable to all transit systems, which of these performance measures carry weight in the eyes of local riders needs to be determined by location-specific surveys. Transit systems need to rank high in those performance measures that are high on the whish list of their own riders. For example, two systems with the same travel speed, seating capacity and reliability would rank very differently in a high-density, fast-paced city like Los Angeles, than in a small, low-density city with a rural life style.

We did not have time or resources to perform our own survey of the riders of the W-W Corridor, but LACMTA has provided us with their assessment of their riders' preferences:

1. Getting to one's destination fast is the most important for L.A. transit users. (This can be measured by average speed, or travel time.);
2. No one likes to be left behind because of overcrowding on the bus. (Therefore, capacity is important.); and
3. Reliability is important because bunching increases wait time, which works against timesavings.

Next, we translate these rider preferences into quantifiable performance measures.

4.2.2 Locale-Specific Performance Measures

The Manual provides performance measures and means to calculate and interpret locale-specific performance measures for a generic transit system (see Section 2). These we adapted to our specific case, the W-W Corridor Metro Rapid transit. Combined with site-specific information about the system (Section 4.1) and its users (Section 4.2.1), we have developed a set of performance measures (shown Figure 12 in Appendix 5), unique to this corridor, that targets users' needs and provides relevant information to the operating agency to increase system performance. (In Figure 12 in Appendix 5 Blue color indicates availability and quality performance measures that are from the Manual.)

4.2.3 Questions to be Tested by *SmartBRT*

Now that we have determined what is important to the local passengers (Section 4.2.1) and specified and quantified these important variables and performance measures (Section 4.2.2), in this section we formulate questions that are targeted at improving these performance measures. The simulation capability of *SmartBRT* provides the opportunity to test the effect of many different variables individually and in combination on travel time, overcrowding and reliability. *SmartBRT* v1.0 focuses mainly on the most important performance measure of this system: travel time. However, as shown previously, travel time, reliability and overcrowding are all connected. For example, in order to achieve uniformly increased speed, operators need to avoid bunching. Less bunching allows for more reliable arrival time, and thus the possibility of overcrowding is lower.

Customer-Based Performance Measures

Based on the customer-defined performance measures – travel time, overcrowding and reliability – the following questions could be tested by *SmartBRT*:

- By how much does travel time decreases if different variables (such as headway, dwell time, traffic volume, etc.) change?;
- What are the most significant variables influencing overcrowding and by how much? (such as headway, bus capacity, demand characteristics, etc.); and
- What are the variables affecting reliability and by how much? (such as headway, demand, signal priority).

In addition to defining questions based on the most significant performance measures from the W-W Corridor's riders' point of view, we have defined a few additional interesting questions based on the unique deployment history of rapid transit on the corridor and LACMTA's plan for the future.

Incremental Deployment Tests

On the Wilshire-Whittier corridor the total travel time between origin and destination is 25% less for Metro Rapid (MR) buses than for local buses[3]. They achieved this 25% reduction in travel time by introducing all the following measures at once:

- Low floor buses;
- Encouraging use of back door for alighting;
- Introducing prepaid fare (although one can still pay the driver);
- Introducing signal priority;
- Color coded buses and stations;
- Frequent headways;
- Far side stop for MR; and
- Reducing number of bus stops to the minimum (they will have to add some back).

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[3] Draft Long Range Transportation Plan for Los Angeles County, Section 2, Metro Rapid Bus Program

LACMTA introduced all improvement at once in order to achieve a big, very visible impact on travel time. (Overall speed improvement is 29% on the W-W corridor.) People generally react stronger to big changes then to small, incremental changes. The 33% increase in transit use on the W-W corridor seems to support their thinking. Because all improvements were applied at once, however, it is not possible to separate out the impact of each individual improvement. LACMTA estimates that 1/3 of travel time saving can be attributed to the bus signal priority system, while the other elements accounted for the remaining 2/3 of the benefit. *SmartBRT* gives an opportunity to go back in time and implement each improvement individually and see their effect on travel time and other performance measures.

Aiding Future Decision-making

The Metro Rapid system is so new that it still needs to be calibrated to best-serve demand. For example, some stops need to be added back to the corridor per popular demand and signal priority needs to be completed and fine tuned for the entire corridor.

Furthermore, LACMTA has ambitious future plans for the W-W corridor. They plan to further reduce travel time by:

- Introducing universal fare collection system that covers all transit modes (such as rail and bus) in the entire area of LA (not only the jurisdictional area of MTA, but across agencies as well);
- Introducing articulated buses with four doors in order to provide higher capacity with less peak period frequency along the route;
- Incremental introduction of dedicated bus lane; and
- Introduce multiple-door boarding and alighting.

Based on our discussions with LACMTA, we have developed the following list of additional interesting questions for *SmartBRT* to answer:

- What is the effect of adding or removing one or more stops on travel time?;
- What effect would different fare collection methods have on dwell time? (Switching to pass, such as monthly pass or eventually switching to Smart Card);
- What is the threshold for switching from mixed traffic to diamond lane, to dedicated ROW? (What are the timesaving gains and the cost difference between these options?); and
- What are the timesavings and cost differences between articulated buses with more doors and faster fare collection on mixed traffic and current operation (i.e., non-articulated, standard bus size)? And dedicated diamond lane?

Based on the above discussions we have selected two questions to demonstrate the capabilities of *SmartBRT* v1.0:

1. How the number of stops, use of low floor buses, signal priority, and increased frequency affects the on-board travel time; and
2. How increased vehicle capacity and/or increased operating frequency could accommodate increasing demand.

In the following three sections we discuss the application of *SmartBRT* v1.0 to the Metro Rapid transit on the W-W corridor and then these two specific analyses.

4.2.4 Application of *SmartBRT* v1.0 to the Metro Rapid Transit

Based on the actual Metro Rapid transit operation on the W-W corridor we built the models of *SmartBRT* v1.0 (simulation core is SHIFT based), on which the hypothetical scenarios' analyses are based in the following ways:

1. Running Way:
   SmartBRT v1.0 assumes a dedicated lane operation in peak time; therefore interaction with traffic is none to minimal.
2. Stops:
   There are 135 local stops and 30 Metro Rapid bus stops on the corridor.
3. Headway:
   Based on actual operation practice, for BRT operation *SmartBRT* v1.0 assumes from a maximum of 5-minute to a minimum of 3 minutes headway operation in peak period. While in reality local bus operation is schedule-based we assume a 5-minute headway operation. This simplifying assumption was applied to reduce consumption of computer resources.
4. Demand (number of passengers per stop, per hour):
   Due to the lack of real data, passenger demand is modeled by a simple passenger flow model: passengers arrive at each stop at the same rate with a negative-exponentially distributed inter-arrival times; the destination for passengers starting from any stop is uniformly distributed along all stops ahead in the bus line; and the passenger demand, i.e., arrival rate at each stop, is independent of bus service and ranges between a minimum 30 and a maximum of 100 passenger per hour per BRT stop. We assumed that 4 percent of all passengers have bicycle and 2 percent use wheelchair.
5. Vehicle:
   We assumed a low-floor vehicle with two single doors, with 2-second door opening/closing time; only the front door is used for both boarding and alighting, exact change fares are paid at boarding, and standees are not permitted. Based on these characteristics, for dwell time calculation we used default values based on those given by the TCQoS Manual. As default, bus capacity was assumed at 40 seats per vehicle. Bus movement characteristics (speed, acceleration and deceleration rate, and door opening-closing time) are held constant.
6. Dwell Time:
   For dwell time calculation we assumed a low floor vehicle type with two single doors with 2-second door opening-closing time. We assumed that the use of the back door for alighting is encouraged but not the rule, fares are paid at boarding, and standees are not permitted. Also, we assumed that 4 percent of passengers have bicycle to load onto the bus and 2 percent of all passengers use wheelchair. Based on these characteristics, in our preliminary tests we used default values, as shown in Figure 13 in Appendix 5. Standard passengers default values are close to that given by the manual. The Manual gives higher values for the impact of bicycles on dwell time (20-30 seconds). However, in the default value set this

time is not added to the dwell time. A bus's dwell time is determined using the greater of the passenger boarding/alighting time or the bicycle loading/unloading time. For simplicity, the program simply adds 10 second to the dwell time to the passenger boarding/alighting time. The ramps used in low floor buses for providing wheelchair access require 30-60 seconds (including the time required to secure the wheelchair inside the bus). The higher value relate to a small minority of inexperienced or severely disadvantaged users. We also assumed that the wheelchair is secured while other passengers are boarding or alighting; the program therefore simply ads half the ramp's cycle time to the passenger boarding or alighting time.

In addition to the default values of the simulation, one set of test was run with alternative boarding and alighting times (Figure 13 in Appendix 5) in order to test the affect of boarding/alighting times on travel time. Based on the Manual, higher values were chosen for bicycle and wheelchair users and lower values for standard passengers.

7. Signal Priority:

   SmartBRT models an actuated signal priority system on the corridor: if the light is about to turn red as the bus approaches the intersection, the priority system will delay the red signal by up to 9 seconds if it helps the bus get through the intersection. Total signal cycle time is 90 sec. It takes two cycles (3 min) for the signal to recover after giving priority. *SmartBRT* allows turning on and off signal priority along the entire corridor at once or by individual intersections. The length of the priority hold (the maximum time in second by which the bus's green cycle is lengthened) can be chosen by the user and set to any value for the entire corridor at once or by individual intersections.

In *SmartBRT* v1.0, in addition to the above-discussed variables, the following variables were set constant at these values through tests targeting travel time:

Bus Operation Characteristics	
Speed	20 m/sec
Max Speed	20 m/sec
Acceleration	2 m/sec/sq
Door Opening and Closing Time	2 sec
Bus Capacity	40 (all seated, standees not permitted)
Traffic Signal Characteristics	
Green-phase	45 sec
Red-phase	45 sec

While we present and discuss our analyses and their results, we must emphasize that *SmartBRT* v1.0 is not fully developed yet (as discussed in Section 3).

4.3 Preliminary Analysis 1: Testing of Travel Time in *SmartBRT* v1.0

The objective of the first analysis is to demonstrate how *SmartBRT* assists in decision-making about system operation. In the specific case of the Wilshire-Whittier corridor, the question was how to achieve lower travel time.

4.3.1 Travel Time as a Performance Measure

Travel time is the most important performance measure for users of the W-W corridor. For users, this means "door-to-door" travel time: the time it takes to get from origin to destination. This includes time to get to the stop, waiting time, travel time on the transit vehicle and time to get to the destination from the transit stop. This same trip could be made by private automobile as well (in which case travel time would include the time it takes to drive, find parking, park and get to the destination from parking). The transit/auto travel time difference – difference in travel time from origin to destination by transit and by automobile – is a significant factor in one's decision in selecting form of transportation. However, measuring and modeling the "door-to-door" travel time has never been the intent of *SmartBRT*; we instead focus on the part of travel time that is related to operational elements of bus service. Therefore, we use an alternative performance measure, which is a subset of "door-to-door" travel time: "transit travel time", which is the sum of waiting time at the stop and travel time on board the transit vehicle. This alternative performance measure is suggested for use by the Manual where higher-speed service is being considered between two locations.

Factors influencing transit travel time are:

- Bus movement characteristics (speed, acceleration and deceleration rate and door opening-closing time);
- Dwell time (time spent at stops);
- Traffic volume (time lost due to interaction with traffic); and
- Intersections (time lost due to waiting at red light)

Bus movement characteristics (speed, acceleration and deceleration rate and door opening/closing time) depend on the vehicle's type, condition, maintenance and the allowed speed limit. In *SmartBRT* bus movement characteristics are held constant.

One major component of travel time is dwell time, the time the bus spends at a stop. Dwell time primarily depends on the vehicle (such as number of doors and their size, door opening/closing time, bus floor height), operation policy (such as whether back door is used for alighting, whether standees are permitted onboard or method of fare paying) and on the demand (such as the total number of interchanging passengers at the busiest door, percent of passengers with special needs). *SmartBRT* v1.0 assumes a set of default values for the calculation of dwell time while allowing users to change them.

Traffic volume affects travel time of the bus, and the presence of transit vehicles affect travel times of other vehicles as well. This effect can range from zero (dedicated transit facility) to a high value (congesting on mixed traffic lanes). *SmartBRT* v1.0 assumes that buses are operated on a diamond lane, which is the case for the W-W corridor; therefore interaction with traffic is none to minimal. *SmartBRT* v1.0 will be able to model mixed traffic and different kinds of dedicated bus lane scenarios.

Waiting at red lights at signalized intersections can greatly increase travel time. In *SmartBRT*, the length of the traffic light cycles is set to default values (see below) with users allowed to change them. *SmartBRT* models the corridor with and without signal priority for buses (see detailed discussion in Section 3).

As the above discussion shows, travel time depends on a great number of interacting variables. The interdependencies are best modeled in a simulation, which gives us an effective way of understanding the tradeoff between these variables and their effects on travel time.

4.3.2 Problem Definition for Simulation and Tested Scenarios

Preliminary Analysis 1 explores how transit travel time (waiting time and on-board travel time) changes as a function of different variables and demonstrates how *SmartBRT* can support decision-making about BRT operation. LACMAT, wanting to lower travel time, could:

- Invest in:
  - Low floor buses;
  - Signal priority;
- Change operation practices:
  - Increase frequency ;
  - Reduce number of stops;
- Implement any combination of these.

Therefore, we test how transit travel time changes as a function of the following variables:

- Number of stops: Reducing the number of stops from 135 local to 30 BRT;
- Headway: 5 and 3 minutes;
- Bus type (conventional vs. low floor): distinguished by a different set of boarding and alighting times (default and Manual based boarding/alighting time sets);
- Application of signal priority: two variables are tested: (1) signal priority turned on vs. off; (2) if on: length of priority hold: 5 or 9 sec maximum; and
- Demand: 30, 50, 75, 100 passenger per hour per BRT stop and the equivalent of these demand levels for local stops, 7, 11, 17, 22 passenger per hour per local stop, respectively.

We have built hypothetical scenarios to test the effect of these four key variables and some combinations of them on travel time under increasing demand. In each run only one variable was changed, all else held constant. Scenarios are summarized in Figure 14 in Appendix 5.

The difference between the travel time of these test scenarios shows:

- A – B = travel time saving due to reduced number of stops;
- A – C = travel time saving due to application of signal priority to local transit;
- A – D = travel time saving due to reduced number of stops and application of signal priority;

- B – D = additional travel time saving due application of signal priority for rapid transit operation; and
- F – B = additional travel time saving due different boarding and alighting times for rapid transit operation

4.3.3 Simulation Run Results

We performed a deterministic test for travel time with *SmartBRT* v1.0. Each scenario (defined by its set of variables) was run once. Each scenario was simulated through the 3 hours peak period. Average running time was approximately 20 minutes for BRT operation and 45 minutes for local bus operation. During this period of time, in each run an average of 15 buses completed the entire corridor during local transit operation, while during BRT operation an average of 20 (if headway was 5 minutes). Their travel time was recorded by *SmartBRT* into log files that were exported for use in Excel to create comparative graphs. We calculated the average of bus travel times within each run in order to make simple comparisons between scenarios/runs. The results are listed in Figure 14 in Appendix 5. We must emphasize that since *SmartBRT* v1.0 is not fully developed yet these tests were conducted more to demonstrate the capabilities of *SmartBRT*, than to arrive at quantitative results.

4.3.4 Preliminary Observations from Analysis 1

<u>Local Transit Operation</u>

1. Higher demand results in longer on-board travel time over the length of the corridor, naturally, in both local and BRT operations. Figure 15A and B and 16 in Appendix 5 shows the increase in on-board travel time over the entire length of the corridor as a function of demand.

2. Adding signal priority to local operation lowers travel time over the corridor. However, the trend in marginal change is not clear, therefore further investigation is required (Figure 17 in Appendix 5).

   For example, using series E and G, at 30pass/hr/stop travel time dropped by 439.7 sec (or 7.47%), while at 50 pass/hr/stop travel time dropped by 499.5 sec (or 8.27%) as shown in Figure 17 in Appendix 5. (Data is not available for demand level of 75 pass/hr/stop.) However, at 100 pass/hr/stop the reduction is only 6.75%. Based on the previous two data points and on the similar comparisons of BRT scenarios, this number was expected to be higher than 8.28%. In *SmartBRT* v2.0 this phenomenon needs further investigation.

3. Interestingly, the effect of the length of priority hold seems insignificant and is not clear.

   For example, using series G2, changing priority hold from max 5 sec to max 9 sec resulted, at 30pass/hr/stop in travel time increase by 44.86sec (or 0.83%), while at 50 pass/hr/stop in travel time decrease by 55.25 sec (or 0.98%). Further investigation is needed.

4. The more realistic alighting/boarding time set generally increased travel time. Without signal priority the more realistic time set resulted in higher travel time at low demand, but lower travel time at higher demand, although these changes were insignificant. With signal priority the more realistic time set resulted slightly more significant increase in travel time.

   For example, comparing the no-signal priority series A and E, at 30pass/hr/stop travel time increased by 36.66sec (or 0.63%), while at 50 pass/hr/stop travel time dropped by 75.54 sec (or 1.27%). With signal priority enabled (9 sec), at 30 pass/hr/stop travel time increased by 237.06sec (or 4.55%), while at 50 pass/hr/stop travel time increased by 240.21sec (or 4.53%).

<u>BRT Operation</u>

1. Switching from local to BRT operation saves travel time (Figure 15 and 15 in Appendix 5). The higher the demand, the smaller the reduction in travel time for any given hourly demand (or for any individual traveler). However, since at higher demand more travelers enjoy the time saving of BRT operation, it is possible that total travel time saving (total time saving due to BRT operation) increases as demand grows.

   For example, comparing series E and F, at 30 pass/hr/stop travel time is shorter by 1135 sec; while at 50 pass/hr/stop travel time is shorter by 1106 sec. (Naturally, actual saving will depend on trip length as well.)

2. More frequent BRT service results in lower travel time, naturally. The higher the demand, the higher this reduction in travel time is.

   For example, using series F, at 30pass/hr/stop travel time decreased by 155.0sec (or 3.26%), while at 50 pass/hr/stop travel time dropped by 183.99 sec (or 3.73%). (Again, actual savings will depend on passenger miles as well.)

3. Adding signal priority to BRT operation further lowers travel time (Figure 18 in Appendix 5). Given the same headway and priority-hold period, the higher the demand, the higher this reduction is.

4. The length of priority-hold seems to have an insignificant effect on travel time.

   For example, using series D, at 30pass/hr/stop travel time dropped by 11.74sec (or 0.28%), while at 50 pass/hr/stop travel time dropped by 84.19 sec (or 1.95%).

5. The more realistic boarding/alighting time set resulted in higher travel time for BRT operation (with or without signal priority). The increased boarding/alighting time has a greater effect at higher demand.

For example, without signal priority, using series B and F, at 30 pass/hr/stop travel time increased by 147.13sec (or 3.20%), while at 50 pass/hr/stop travel time dropped by 128.53sec (or 2.28%).

6. Generally, travel times within each run were scattered randomly around the average. However, if operation demand was low on the system (such as in runs B3, B4, D1, D3, and D4), a regular pattern started to emerge, as shown in Figures 19A and B in Appendix 5. Currently, reasons for this phenomenon have not been tested. However, one might speculate that this pattern forms only on dedicated lane operation (in mixed traffic it will probably disappear) and that perhaps signal priority removes some randomness of the operation (since the pattern is much stronger in Figures 19A in Appendix 5, the case with signal priority). Further investigation of this phenomenon is needed.

<u>Comparing Local and BRT Operation</u>

1. Figure 15B and 16 in Appendix 5 shows that adding signal priority to local bus operation lowered travel time by 7.5-8%. Switching from local operation (no signal priority) to BRT saved more time (18-19%) than adding SP to local operation (8%). Adding signal priority to BRT operation further lowered travel time by an additional 8%. The overall travel time gain from local operation without signal priority to BRT operation with signal priority was 26-27%.

2. Adding signal priority to BRT operation saved slightly more time (8.63%) than adding signal priority to local operation (8.28%) (at 50 pass/hr/stop demand, and 5 min headway) (Figure 15.B in Appendix 5). This difference, however, seems insignificantly small.

4.3.5 Using Simulation Results in Assisting Decision-making

In this section we give an example for how the results of *SmartBRT* can assist decision-makers. For this exercise we build up an example related to the W-W corridor and use the results of preliminary Analysis 1.

Let's go back in time and assume that the W-W corridor still has local and express transit (before the implementation of the Metro Rapid transit). LACMAT did a survey of the passengers using transit on this corridor and found that passengers want faster travel. Wanting to lower travel time LACMTA could:

- Invest in:
    - Low floor buses;
    - Signal priority;
- Change operation practices:
    - Increase frequency;
    - Reduce number of stops;
- Implement any combination of these.

Before investing in any of these options they would like to know: (1) how much travel time saving results from each and their combinations, (2) how much would they cost and (3) how these changes would affect other performance measures. In short, which is the most cost-effective way to achieve service level improvement within budget? LACMTA used *SmartBRT* to perform an analysis. Let us use the results of our preliminary Analysis 1 – with a small modification – as their results.

Before we can use the results of preliminary Analysis 1 to show how *SmartBRT*'s results can help decision-makers, we have to make one modification. In our preliminary analysis we tested two boarding/alighting time sets: (1) the default values and (2) a more realistic set of values that were based on the Manual data for low-floor buses. As it turned out the default values resulted in lower travel time then the more realistic time set. For this example we are going to use these two time sets to represent low-floor and conventional (high-floor) buses' boarding/alighting time. Since boarding/alighting takes less time to/from a low-floor bus, we assume, only for example (in Section 4.3.5), that: (1) the default values represent the boarding/alighting time of a low-floor bus and (2) the more realistic time set represent the boarding/alighting time of a high-floor bus.

Given an "existing base case", local operation with conventional buses, the simulation estimated timesavings from two investment actions (low-floor buses and signal priority) and from two operational changes (reducing the number of buses and increasing service frequency) individually and their combination. Results are shown in Figure 20 in Appendix 5. Knowing how much time would be saved by each individual action or their combination, the operator could choose a solution that achieves the desired service quality.

However, all transit agencies are constrained by budget. Figure 21 in Appendix 5 shows a different base case: rapid transit with conventional buses. In addition, this table has a column for future cost-effectiveness estimation. If there were cost data available, *SmartBRT* would be able to estimate cost-effectiveness (time saving for every $1000 invested). Decision-makers need to know not only how much time each option would save, but also how much each option would cost so that they can achieve the greatest service improvement within their budget.

Including cost data into analyzing service improvement options is important. For example, assume that for all BRT operation scenarios on the corridor, the passenger demand model indicates one bus stop with very high hourly passenger traffic in peak period. This high demand at this stop could be the result of an existing transfer point to other transit lines or a planned park and ride (P&R) facility. The passenger model in the simulation would not differentiate between these two cases since the only data it uses is the number of passengers. Furthermore, performance measures calculated based on this passenger demand model would be the same whether there is a transfer point or a P&R facility at this stop. However, an additional cost-effectiveness analysis would note the difference: if it is an existing transfer point, little additional infrastructure cost could provide the connecting facility; while if a P&R facility needs to be constructed, then higher capital cost investment would be needed. Such cost difference could influence decision-making.

So far we have looked at only onboard travel time, for simplicity. However, LACMTA determined by its survey that its passengers don't like to be left behind at a stop because the arriving bus is already full and that they prefer reliable service. Figure 22 in Appendix 5 shows two additional performance measures – overcrowding occasions and average travel time – for these options. While these two performance measures were not analyzed in detail in preliminary Analysis 1, these two figures show that travel time is not the only performance measure determining overall service quality. LACMTA needs to select the improvement option that achieves an overall service improvement (not only travel time reduction) with the focus on those performance measures that are the most important for the local passengers. Next, in preliminary Analysis 2, we show how *SmartBRT* can test and show such tradeoffs between many performance measures.

4.4 Preliminary Analysis 2: Description of Passenger Flow Scenario

The objective of preliminary Analysis 2 is to demonstrate the usefulness of *SmartBRT* in studying complex relationships between operation parameters and performance measures of BRT systems. In this analysis we examine how LACMTA could accommodate increasing demand by:

- Investing in bigger buses;
- Increasing service frequency; or
- Both of the above.

4.4.1 Problem Definition for Simulation and Tested Scenarios

We design this analysis to study how bus performance measures (such as overcrowding, load factor and waiting time) change as a function of bus vehicle capacity and service frequency at three passenger demand levels. The three input variables are:

- Passenger demand level: 30, 40 and 50 passenger per hour per stop;
- Bus service frequency (headway): 5 or 4 minutes; and
- Capacity of individual vehicle: 40 or 60 passenger per vehicle.

For easier reference, we regard the service of :

1. 5 minute headway with vehicle capacity of 40 passengers as the "base" service;
2. 5 minute headway with vehicle capacity of 60 passengers as the "increasing capacity" service;
3. 4 minute headway with vehicle capacity of 40 passengers as the "increasing frequency" service; and
4. 4 minute headway with vehicle capacity of 60 passengers as "increasing frequency and capacity" service.

For each scenario, we simulate three hours bus operation by running the simulation once.

Other parameters and specifications in the simulation model are described in detail in the previous section of description of the simulation model. We assume that these settings, such as the percentage of passengers of each type and corresponding boarding and lighting times, are the same for all scenarios in the simulation experiment.

4.4.2 Simulation Run Results

The simulation results for the 12 scenarios are listed in Figure 23 in Appendix 5. Columns 2, 3 and 4 specify the three input variables. The following five columns are performance measures that are derived directly or through simple calculations from the output of the simulation model. The data for the first three performance measures, "waiting time", "waiting time percentage", and "passenger travel speed", are the mean values of each corresponding metric for all passengers within the three-hour peak period. "Waiting time" is passengers' waiting time at bus stops, in seconds. "Waiting time percentage" is the percentage of each passenger waiting time in his/her total travel time (total travel time is the sum of waiting time and onboard travel time). "Passenger overall travel speed" is the travel speed for passengers, with each passenger's speed calculated by dividing his travel distance by his total travel time, in miles per hour. The data for the last two measures, "bus load factor" and "overcrowding percentage" are the mean values of averages corresponding to bus stops, over the total number of occasions when a bus docks at a bus-stop within the three hour peak-period. "Bus load factor" is the ratio of the number of passengers onboard and the total seating capacity of the vehicle. "Overcrowding percentage" is the percentage of times that a bus docks at a stop but cannot take all passengers waiting because the bus is full.

4.4.3 Preliminary Observations from Analysis 2

1. For any arrival rate, all performance measures of all three service scenarios are better than, or at least equal to, those with the "base" service. Thus, increasing passenger demand was indeed accommodated by increasing frequency and / or increasing vehicle capacity. The marginal performance improvement resulted from increasing service frequency or bus capacity is greater in the high demand scenarios than in the low demand scenarios (Figure 24 in Appendix 5).

   For example, as shown in Figure 24 in Appendix 5, from the "base" service to the "increasing capacity" service, the waiting time for passengers is 2 percent and 17 percent shorter when the arrival rate is 30 or 40 persons per hour respectively, and the waiting time will be 60 percent shorter when the passenger arrival rate is 50 persons per hour. From the "base" service to the "increasing frequency" service, the waiting time for passengers is 17 percent and 10 percent shorter when the arrival rate is 30 or 40 persons per hour respectively, but the waiting time will be 60 percent shorter when the passenger arrival rate is 50 persons per hour.

2. It would be very hard, if not impossible to develop a single mathematical formula that would capture the relationship between these performance measures, passenger arrival rate and bus service indices. But *SmartBRT*'s output allows us to study such relationships without analytical representation. Based on the simulation output, we can calculate passenger waiting-time as a percentage of total travel time at any levels of demand for any operation scenario (Figure 25 in Appendix 5).

For example, the results, given in Figure 25 in Appendix 5 show that for "base" service and "increasing capacity" service higher arrival rate results in longer waiting time, as indicated by the positive percentage changes in these two columns. This relationship is also true for "increasing frequency" service and "increasing capacity and frequency" service when the arrival rate changes from 30 persons per hour to 40 persons per hour. However, in these two operating scenarios as passenger arrival rate increased from 40 pass/hr/stop to 50 performance measures (such as waiting time) decrease, as the negative sign indicates in the respective columns of Figure 25 in Appendix 5. One possible reason for this counter-intuition result could be that at higher arrival rate, there will be more passengers missing the bus or waiting for the bus, but our calculation of average passenger waiting time is based solely on the total number of passengers who have already arrived at their destinations within three hours in our experiment. Therefore, only using our calculated "average waiting time" as an index is not sufficient to capture the performance for the whole system.

3. Based on the selected performance measures of our experiment we noticed that not all performance measures change in the same trend.

   For example, comparing the "increasing capacity" service to the "increasing frequency" service for the arrival rate of 30 passengers per hour (scenario 2 and 3 in Figure 23 in Appendix 5), "increasing frequency" service has better "waiting time", "waiting time percentage", "passenger travel speed", and "maximum waiting time", while "increasing capacity" service has better "load factor" and "percentage of bus skipping". Therefore, it is important to recognize the existence of the trade-offs between the different aspects of system performance, and to focus resources to improve those performance measures that are valued highest by riders.

4. Increasing bus capacity can significantly improve the system performance (Figure 26 in Appendix 5); the higher the passenger demand, the larger the benefit that can be obtained from increasing bus capacity.

   For example, from the last four rows in Figure 23 in Appendix 5, comparing the "base" service to "increasing capacity" service and comparing the "increasing frequency" service to "increasing capacity and frequency" service, we find that "waiting time" is reduced by 284 seconds and 41 seconds respectively, and the "percentage of bus skipping" is reduced by 24.5% and 9.8%, if the bus capacity is increased from 40 passengers per bus to 60 passengers per bus. The results are shown in Figure 26 in Appendix 5.

In addition to considering tradeoff between the performance measures a decision-maker would have to consider: (1) which option achieves the most within the given budget and (2) how each option affects the general traffic flow.

Generally, high frequency operation requires a larger number of drivers and consumes more energy, while the larger bus size involves mainly larger capital cost. Generally, the operation cost is much larger than the vehicle capital cost to bus operations. Therefore, without detailed information and calculation on the cost at this moment, we can reasonably assume that "increasing capacity" service is less costly than "increasing frequency" service, while the benefit from these two services are similar, according to our experiment.

While in our evaluation we focused exclusively on the BRT system, this transit system interacts with the rest of the transportation system. While it is our goal to increase quality of service to transit riders, we want to achieve this so that the net (social) effect on the total transportation is positive. Each option tested in our preliminary analyses effects the transportation network. For example, large size buses are relatively difficult to operate and maneuver in the traffic stream, and has stricter requirement for the layout of bus stop; while increasing frequency increases chances for buses to interfere with other traffic. These effects of the transit system on the rest of the transportation network needs to be taken into account as well.

4.5 Visualization of the Wilshire-Whittier Corridor

In Year 1 we focused on developing the tool and demonstrating its current capabilities and future potential. Including in this demonstration is our Year 1 effort of showing *SmartBRT*'s visualization capabilities. Figure 27 in Appendix 5 shows a still image from the visual simulation.

To create the roadway model used in our *SmartBRT* case study, we combined roadway and bus stop data into a composite model of the Wilshire-Whittier corridor. In the region of the "Miracle Mile", the geometric model is accurate to meter resolution[4]. Outside of the Miracle Mile, we used GPS coordinates for each bus stop along the route, and these coordinates are accurate to within 100 meters. We created a series of software filters that convert from GPS coordinates into the "state plane" coordinates used by the UST in their modeling efforts, then computed the distance between each of the bus stops. Next, we created straight roadway segments that lie outside, but join with, the Miracle Mile, and placed the bus stops along the roadway in such a way that the inter-stop distance is accurate to the limits of the original GPS coordinates.

4.6 Preliminary Work with Paramics: Bus Signal Priority

In addition to applying the SHIFT-based *SmartBRT* v1.0 to the W-W corridor, our Year 1 work involved an exploration of applying Paramics as the simulation software. As the first stage, a simple network composed of two signalized intersections was built through Paramics Modeler to address the following tests:

- Performance measures (total delay, total travel time, bus delay, bus travel time) without bus priority signal (basic or current situation);
- Performance measures with bus priority signal, without dedicated bus lane; and

---

[4] The Miracle Mile data was obtained from the UST, and extends along Wilshire Avenue, bounded on the west by Fairfax, and on the east by Western.

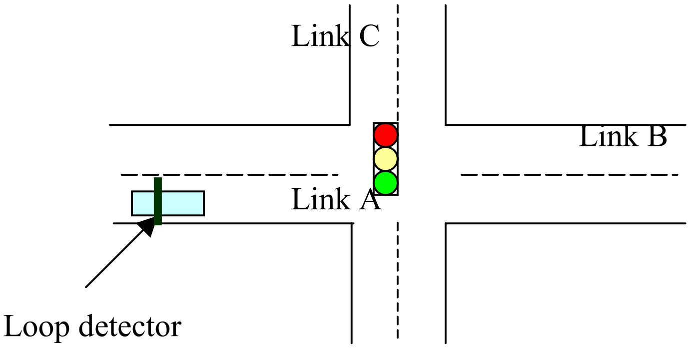
- Performance measures with bus priority signal, with dedicated bus lane.

The simulation time of the demonstration was sixty minutes. In the first 30 minutes buses were modeled by queuing with other vehicles. This allows buses to be given priority even though they may be delayed by other vehicles. The second 30 minutes mimics the effects of dedicating one lane to buses.

The signal timings are optimized to benefit the buses by either extending a current green signal (an extension) or causing succeeding stages to occur early (a recall). Extensions could be awarded centrally. In our example the signal controller was programmed to implement extensions locally on street (a local extension). Paramics provides another programming interface called Plan Language to model actuated traffic signals. In our example, signal priority plans were designed by Plan Language instead of by writing API.

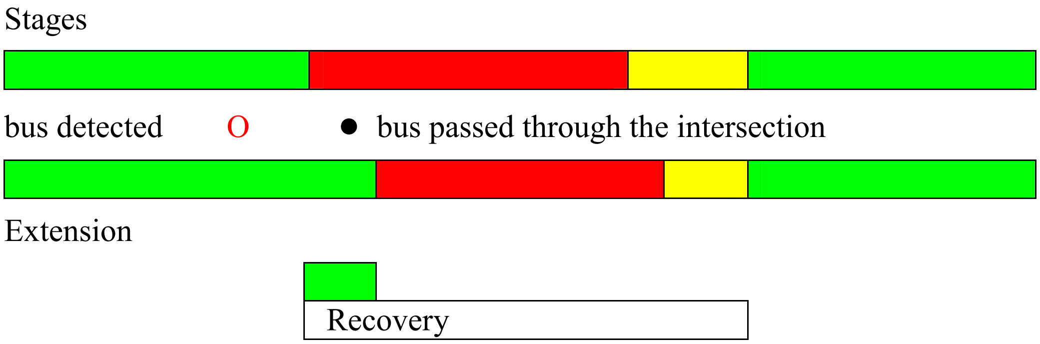
Only the buses traveling slower than the schedule were given priority at the signalized intersections. As illustrated in Fig.1, a bus on link A is detected approaching the intersection at time *t*, this arriving time is then compared with its scheduled arriving time at this intersection, only the bus running lack of schedule time will be given priority at the intersection.

Figure 29: Bus is Detected at the Signalized Intersection



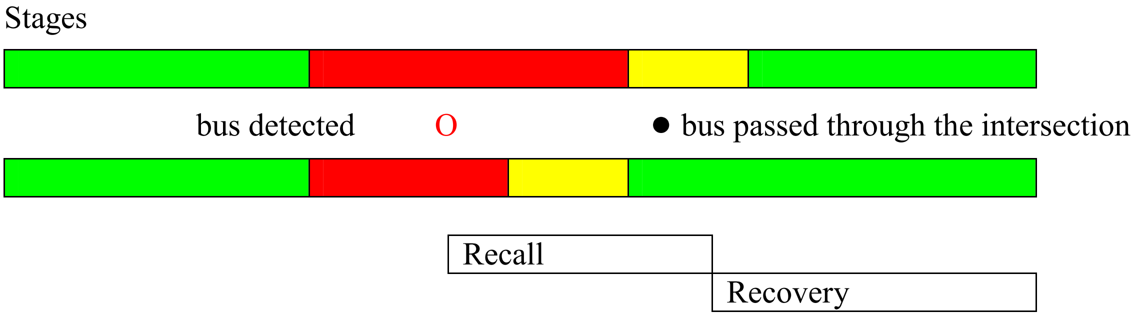
The signal gives the selected bus priority either by “extension” or by “recall”. If the bus gets detected at the end of Stage "1", which is a green period on Link "A", it will get an extension as illustrated in Figure 30.

Figure 30: Signal Priority-Extension



If the bus gets detected during a red period e.g. Stage "2", therefore it gets a recall as illustrated in Figure 31:

Figure 31: Signal Priority-Recall



4.6.1 Restrictions on Priority

The amount of priority given to buses can be restricted depending on the saturation of the junction as modeled by Paramics. This is controlled by target degrees of saturation for extensions and recalls. These are the degrees of saturation to which the non-priority stages can be run in the case of a priority extension or recall respectively. Normally the target saturations should be set so that the junction is not allowed to become over saturated, although some degree of over saturation may be allowed to service an extension. This means that bus priority will be most effective at junctions, which have spare capacity. In this example, the saturation degree at both signalized intersections is predetermined with the value of 0.65.

4.6.2 Preliminary Results of Paramics Simulation

The simulation results (total delay, total travel time, bus delay, bus travel time) for the first question, i.e. current situation without bus priority signal are taken as the basic data set to compare with the other two data sets derived from Paramics:

1. Bus priority signal for mixed traffic (without exclusive bus lane); and
    - Total delay for all vehicles increased (compared with basic data set) 11%, delay for cars increased 21%, delay for all (instead of selected) buses decreased 27%;
    - Travel time for all vehicles increased 6%, travel time for cars increased 11%, travel time for all buses decreased 7%; and
    - Occurrence of bus "bunching" decreased from 4 to 1 within the simulation time period.

2. Bus priority signal with exclusive bus lanes;
    - Total delay for all vehicles increased 106%, delay for cars increased 189%, delay for buses decreased 56%; and
    - Travel time for all vehicles increased 54%, travel time for cars increased 101%, travel time for all buses decreased 72%.

4.7 Summary of the Application of *SmartBRT* v1.0 to the Metro Rapid Transit System and Overall Findings

As part of the first year effort we applied *SmartBRT* v1.0 to a real case site, the Metro Rapid transit of LACMTA on the W-W corridor in Los Angeles, CA. Metro Rapid is a BRT system operated by the LACMTA. Caltrans and FTA have facilitated our contracts with LACMTA with the purpose that we illustrate relevancy and potential of *SmartBRT* with a "BRT Consortium" real-world application scenario. We have performed two preliminary analyses for this site:

- How the number of stops, use of low floor buses, signal priority, and increased frequency effects the on-board travel time; and
- How increased vehicle capacity and/or increased operating frequency could accommodate increasing demand.

In Section 4 we introduce the W-W corridor and its Metro Rapid BRT system and described the process of modeling the case site in *SmartBRT.* First we determined what is important to local passengers. In understanding the local demand TCRP Report 47 helped us understand the importance of consumer-defined service, while LACMTA provided us with specific information about their passengers' priorities. Based on this information we primarily focused on travel time, and secondarily on overcrowding and reliability (measures through waiting time). Second, we developed locale specific performance measures to qualitatively assess the performance of the Metro Rapid system. Third, we determined questions aimed at service improvement to be tested by *SmartBRT* in order to quantify these performance measures. Finally, we represented the W-W corridor and the Metro Rapid transit in *SmartBRT* simulation core.

We performed two preliminary analyses:

1. Tested on-board travel time as a function of demand, bus type, frequency and signal priority; and
2. Tested overcrowding and waiting time as a function of demand, bus size and frequency.

We presented out preliminary findings, emphasizing that since *SmartBRT* the tool has not been fully developed yet these results are more indicative of relationships and trends then precise quantitative measurements.

The results of preliminary Analysis 1 showed that:

- Adding signal priority to local bus operation lowered travel time. Switching from local operation (no signal priority) to BRT saved more time then adding SP to local operation. Adding signal priority to BRT operation further lowered travel time. The overall travel time gain from local operation without signal priority to BRT operation with signal priority was 26-27%; and
- Using the results of preliminary Analysis 1 we showed how *SmartBRT* can assist the decision-making process.

The results of preliminary Analysis 2 showed that:

- Increasing demand can indeed be accommodated by either larger buses or by increasing frequency of operation. Our analysis showed the different consequences of these two choices and that of applying them together; and
- These results showed that it would be very hard, if not impossible to develop a single mathematical formula that would capture the relationship between operation variables, performance measures and passenger arrival rate, but *SmartBRT* allows us to study such relationship without analytical representation.

We demonstrated the visualization capabilities of *SmartBRT* by developing an example of simulation visualization of the Metro Rapid transit on the W-W corridor and by showing an example of the two-dimensional “engineering” simulation run in real time with the simulation.

Finally, we explored the possibilities of using Paramics as the software of *SmartBRT*’s simulation core.

Overall Findings

While we have to emphasize that *SmartBRT* v1.0 is not yet fully developed, our preliminary analysis already demonstrates the potential and capabilities of *SmartBRT*, toolbox. *SmartBRT* is indeed the appropriate tool to:

- Test complex systems with numerous interconnected variables;
- Test the effect of changing individual variables or many in combination on other variables (performance measures);
- Perform what-if studies;
- Test new technologies without the costly investment of field test (due to the capabilities inherent in SHIFT); and
- Aid decision-makers in improving BRT operation.

We also found that performing the two preliminary analyses was the best way to determine where and in what direction *SmartBRT,* the tool, needs further development. This is presented in the next section.

5 CONTINUING WORK ON *SMARTBRT*

Even though *SmartBRT* is not yet fully developed and not all input data were available, version 1 already demonstrates the capabilities of the tool and its potential to assist decision-making and provide deeper understanding of the tradeoffs within transit operation. The objective of Year 1 was to build the models and demonstrate the capabilities and usefulness of the tool. In the second year the tool will be refined on all levels to reach its full capabilities. This section summarizes the current areas of work.

5.1 Inputs

We continue our effort to obtain realistic, locale-specific data, such as:

- Accurate geometry for entire road;
- Accurate signal and stop locations;
- Passenger data:
    - Arrival rates by stop;
    - Passenger types (reflected in alighting and boarding time per passenger); and
    - Realistic origin-destination distributions.
- Traffic volumes, both across and within the transit corridor; and
- Cost data (capital and operation) for cost-effectiveness analysis.

5.2 Modeling

We continue to refine and extend the models of *SmartBRT* to increase accuracy and applicability of the simulation, as described in Section 3.6.1. Our work will use the complementary features of *SmartAHS*, as we have adapted it for BRT systems, and Paramics.

5.3 Software Toolbox for BRT Evaluation

We are developing graphical user interfaces to the *SmartBRT* simulation, so that it can be used as an evaluation tool by local transit planners. We hope to make much of this functionality available through a web interface, as noted in Section 3.6.3, further removing the technical details from the users. Users with more simulation experience (in Paramics, for example) will still be able to work with the simulation at that more technical level.

5.4 Venturi for 3-D Visualization

SmartBRT's fully-developed two and three-dimensional visualization of system operation and performance will be a powerful tool to facilitate better communication between stakeholders. As discussed in Section 3.6.3, we intend to make this tool suitable for use in a wide variety of urban settings.

6 SUMMARY AND PLAN FORWARD

Our first year *SmartBRT* effort delivered a simulation and visualization tool intended to assess and visually describe local BRT operation concepts. During our Year 1 work we:

- Reviewed transit operation variables, capacity and quality measures;
- Reviewed BRT operation to understand elements of BRT systems, operation concepts and relationships;
- Developed performance measures for BRT systems;
- Developed *SmartBRT* v1.0:
    - Adopted *SmartAHS* to BRT operation;
    - Added macrosimulation software, Paramics; and
    - Added visualization software to perform simulation visualization and two-dimensional visualization.
- Applied *SmartBRT* v1.0 to the Metro Rapid BRT system of Los Angeles:
    - Developed locale specific performance measures;
    - Developed questions to be tested by *SmartBRT*; and
    - Adapted *SmartBRT* to the Metro Rapid system.
- Performed two preliminary analyses:
    - Tested travel time as a function of demand, signal priority, bus type, and operation frequency; and
    - Tested accommodating increasing demand by increasing operation frequency or vehicle capacity or both.
- Showed the capabilities of *SmartBRT*; and
- Determined future work

We expect to continue this work into a second year by supplementing the current effort with approximately $250K Federal funding, cost shared with $250K Caltrans funding, for a total of $500K. The Federal funding will allow us to expand and refine *SmartBRT*'s functionality as discussed in Section 6. The Caltrans funding will allow us to apply *SmartBRT* to another real case site example (as yet not defined location) using these second-year technical developments. The following is a brief work statement for our intended second year effort:

Potential Year 2 FTA-Funded Tasks:

Task F1: Enhance General Purpose BRT Simulator. Add interfaces to one of several potential traffic models and include signal prioritization capabilities. Also include animation models of humans to populate BRT stations.

Task F2: Convert *SmartBRT* to PC (Windows NT). [Completed]

Potential Year 2 Caltrans-Funded Tasks:

Task C1: Conduct Site-Specific *HARTCAS-SmartBRT* Analysis. Working with other TBD local transit agency/agencies, collect appropriate data, as well as BRT implementation details, then develop an operational concept of a BRT. Additionally, work alongside local transit officials to determine locally tailored version of MOEs and MOPs. Simulate and illustrate concept(s), which can include signal prioritization, within

SmartBRT to produce both an initial analysis showing benefits (if any) of the system. Work with other BRT developers and interface with their tools to show other regional benefits and comparison between BRT and light rail alternatives.

Task C2: Conduct Additional Off-Line BRT Analyses. We again suggest several supplementary analyses in areas of efficiency and accessibility for consideration, with the second-year studies based primarily upon comparison of BRT concepts with rail or other competitor concepts.

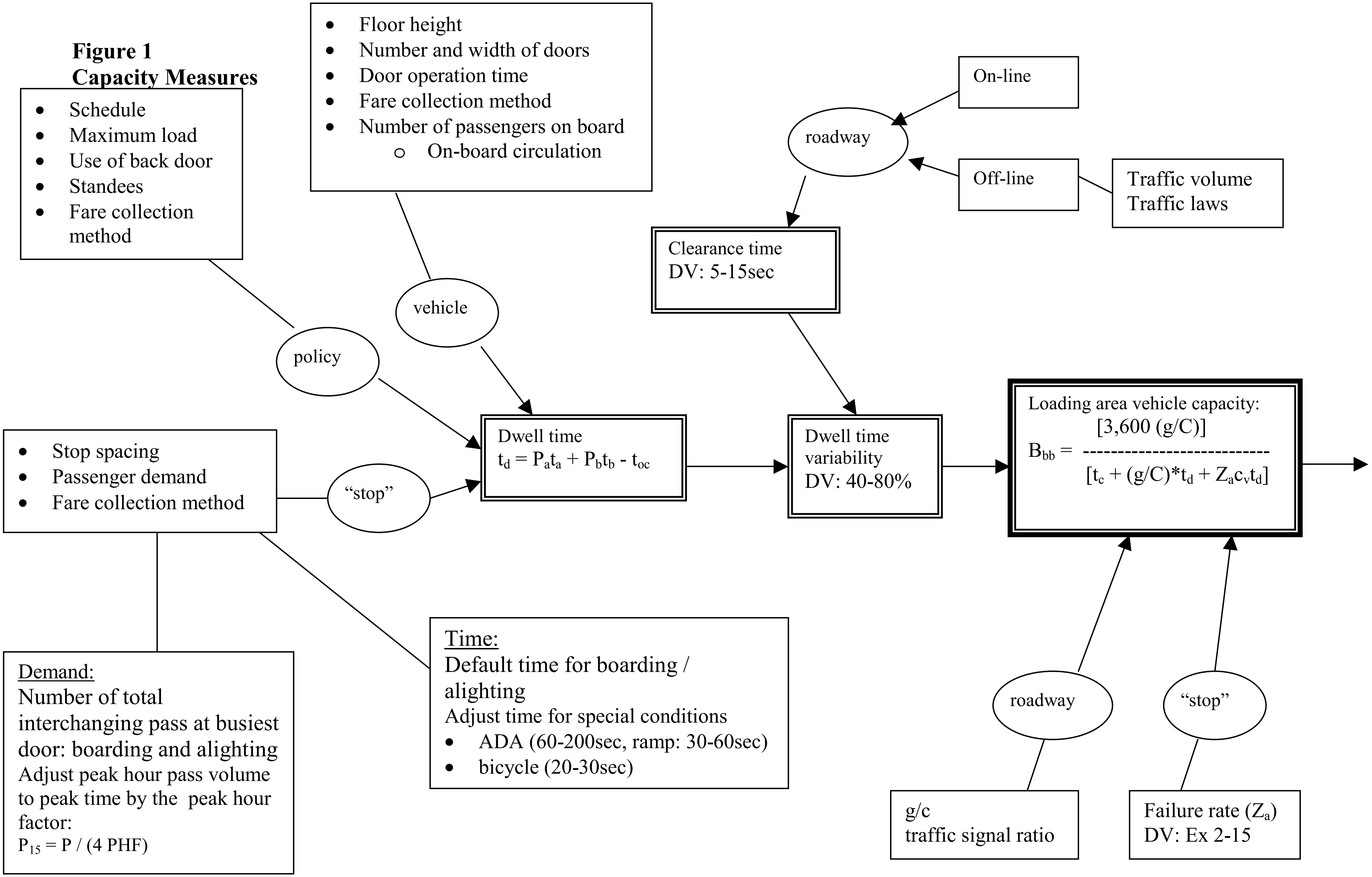
Products delivered at the end of the second twelve months would consist of:

- Deliverable of an extension of *SmartBRT* to interface with the CORSIM family of models or with Paramics or MITSIM; this will include signal-controlled intersections within *SmartBRT*. (From this, full representation of signal priority concepts and linkages to models to evaluate corridor effects could be done.);
- Possible inclusion of models of moving people for *SmartBRT* animation purposes;
- Additional BRT example(s) at FTA's discretion; options would include:
    - Other exclusive lane analyses;
    - Use of *SmartBRT* to evaluate BRT operation in non-access controlled roads, to include signal prioritization; and
    - Interface with other FTA-contracted tool development efforts by Mitretek and/or Volpe to combine detailed *SmartBRT* corridor analyses with their toolset(s).
- For each BRT example analysis, realistic animation of the *SmartBRT* output in video cassette format, showing the BRT in-lane operation at the chosen analysis site;
- Additional BRT-related analyses performed at FTA's discretion and within the capabilities available at PATH; and
- Conversion of *SmartBRT* from UNIX workstation to work with PC-hosted operating systems. [Completed]

We regard these aforementioned products as a menu, from which FTA can choose particular elements of interest within their interest and budget availability for this program. We would be willing to shift the deliverable schedule to accommodate a third year.

7 APPENDIX 1: OPERATION VARIABLES AND PERFORMANCE MEASURES OF TRANSIT SYSTEMS BASED ON THE TRANSIT CAPACITY AND QUALITY OF SERVICE MANUAL

Figure 1
Capacity Measures



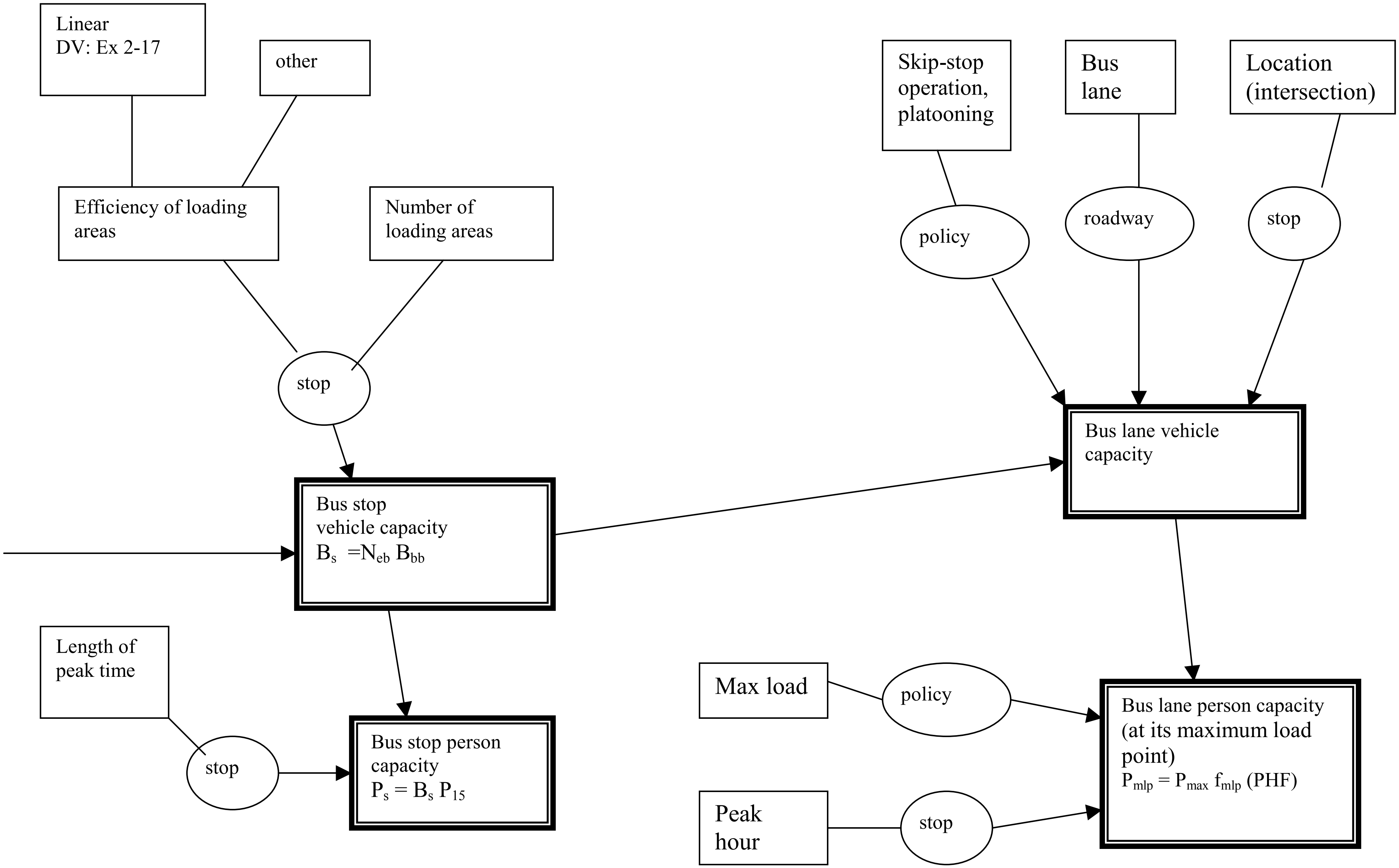
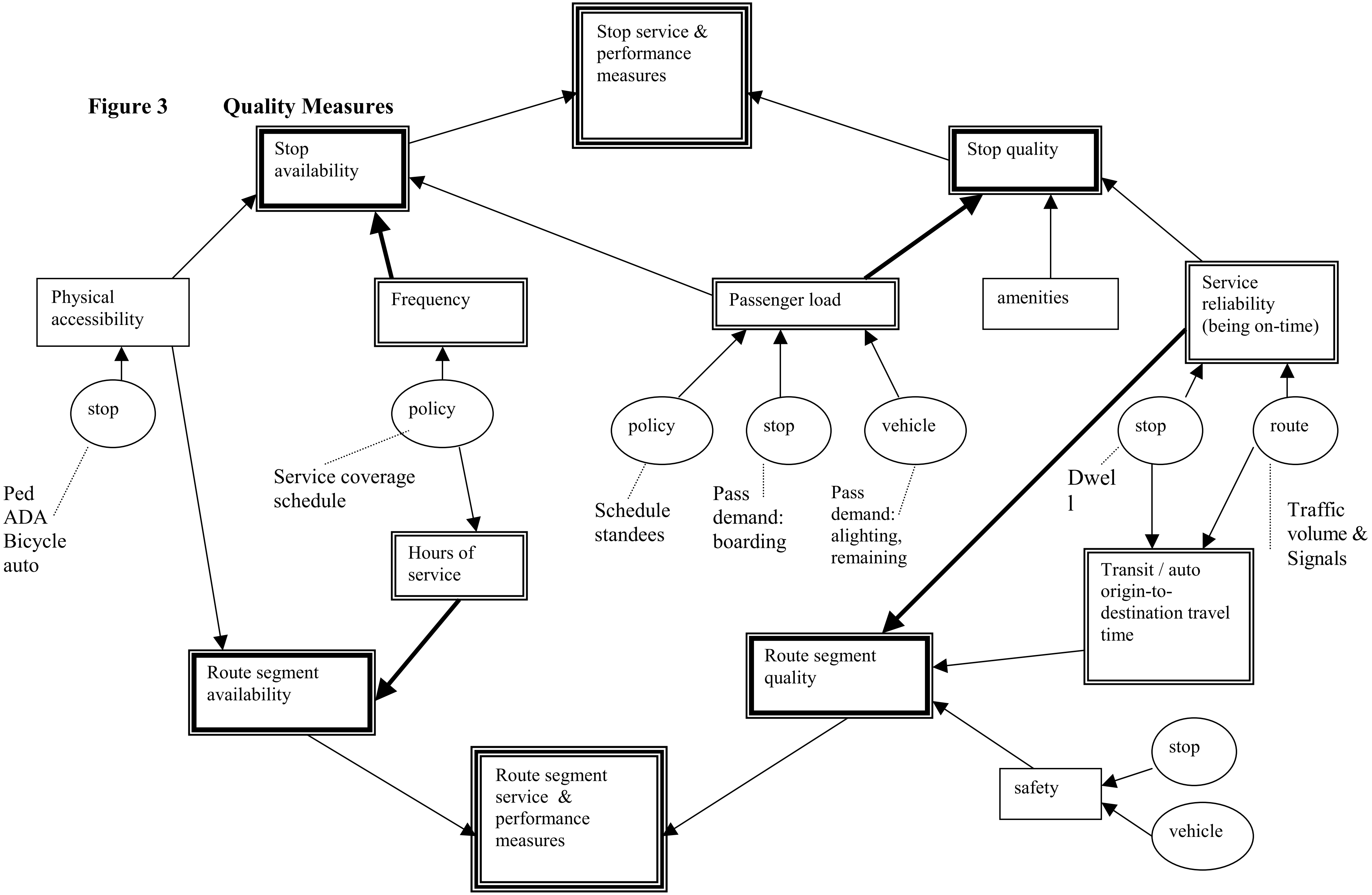

Linear
DV: Ex 2-17
other
Efficiency of loading areas
Number of loading areas
stop
Bus stop
vehicle capacity
$B_s = N_{eb} B_{bb}$
Length of peak time
stop
Bus stop person capacity
$P_s = B_s P_{15}$
Skip-stop operation, platooning
Bus lane
Location (intersection)
policy
roadway
stop
Bus lane vehicle capacity
Max load
policy
Peak hour
stop
Bus lane person capacity (at its maximum load point)
$P_{mlp} = P_{max} f_{mlp}$ (PHF)

Figure 3 **Quality Measures**



8 APPENDIX 2: VISUALIZATION

Figure 5: Visual Simulation of Wilshire Blvd.
(Model Courtesy of UCLA Urban Simulation Team)

Figure 6: Two-dimensional “Engineering” Visualization

9 APPENDIX 3: SMARTBRT USER MANUAL

SmartBRT User Manual

System requirements

SmartBRT runs best with at least 64 MB of memory and requires Windows. (A Solaris version can be generated if there is demand.) No additional commercial software is required.

Installing SmartBRT

First, install Tcl/Tk and BLT, in that order. Installers are in the same web page as the `SmartBRT.zip` file, http://path.berkeley.edu/~vjoel/SmartBRT/, or can be obtained from www.scriptics.com.

You must have Administrator rights to properly install Tcl/Tk. Accept the default settings. The installation target directory should be `C:\Program Files\Tcl`. The installer may ask you to reboot after the installation. After installing, go into your System control panel and set the environment variable `TCL_LIBRARY` to
"`C:\Program Files\Tcl\lib\tcl8.3`"
In Win2K, the environment setting is under the "Advanced" tab. Set this variable as a System variable (rather than a User variable) to apply to all users of this PC.

If you plan on changing the number, positions, and individual behaviors of stops and signals, you will need to install the Ruby language, which is used to process the wilshire.dat file into a format that SmartBRT can read directly. The installer is also on the same web page as the SmartBRT archive, or you can download it from rubycentral.com.

Uninstalling SmartBRT

SmartBRT itself is entirely contained in the directory extracted from the archive and can simply be deleted. Tcl/Tk/BLT and Ruby can be removed using the Add/Remove Programs control panel.

Running SmartBRT

The project directory contains the simulation executable and its inputs. The simulation writes its outputs to this directory. The input and output files are documented in SmartBRT_Simulation.doc, which is available on-line in the documentation directory of the aforementioned web site

The easiest way to run the simulation is to double-click one of the two .bat files in the project dir:

File	Description
run.bat	command line interface (CLI) version
run_visual.bat	graphical user interface (GUI) version

For most purposes, the GUI version is best. The CLI version is useful for batch processing.

To begin, press the “Press here to start” button in the PC SHIFT window. You can minimize the console window that also appears when running `run_visual.bat`. Then the Play, Step, and Stop buttons can be used to control the progress of the simulation. Other buttons display an animated roadway, graphs, and “inspector” windows showing the state of simulation objects. None of these buttons are required to generate the output files.

Additional documentation

The simulation, including its implementation, models, inputs, and outputs, are documented in the file `SmartBRT_Simulation.doc`. The user interface is documented in `Tavis.doc`. (The name ‘Tavis’ stands for Threat Assessment VISualization, a relic from an earlier project.) Both files are in the documentation directory on the distribution web site.

Connecting to Venturi

The connection between the SmartBRT simulation engine and the Venturi 3D visualization tool is though a single file. The `project\vehicle_log` file is generated by SmartBRT and read by Venturi. For details, see the Venturi manual.

Important: Venturi assumes there is only one bus. You must set `source_period` to a high number, say 10000, in the `parameters` file to prevent two vehicles from existing at the same time.

Modifying stop and signal layouts

The layout of stops and signals on the road, as well as their individual characteristics such as passenger arrival frequency and priority time, is contained in the `project\layout` file. This file is in a format convenient to the SmartBRT simulation and cannot easily be modified. However, the file can be generated from a more user-friendly file by running a script. The `data\wilshire-express` and `data\wilshire-local` directories each contain a `wlishire.dat` file and a `.bat` file.

The format of the `wilshire.dat` file is described in the section on inputs in `SmartBRT_Simulation.doc`. After editing this file, double-click on the `.bat` file to generate the `project\layout` file. When you run the simulation again, it will use the modified layout. This requires that the Ruby language be installed. See the installation instructions above.

Gathering data

After running the simulation, you may want to copy output files to some other directory so that they will not be overwritten when the simulation is run again.

10 APPENDIX 4: THE WILSHIRE-WHITTIER CORRIDOR AND THE METRO RAPID TRANSIT OF LOS ANGELES

Figure 7: Map of Los Angeles Showing the Wilshire-Whittier Corridor

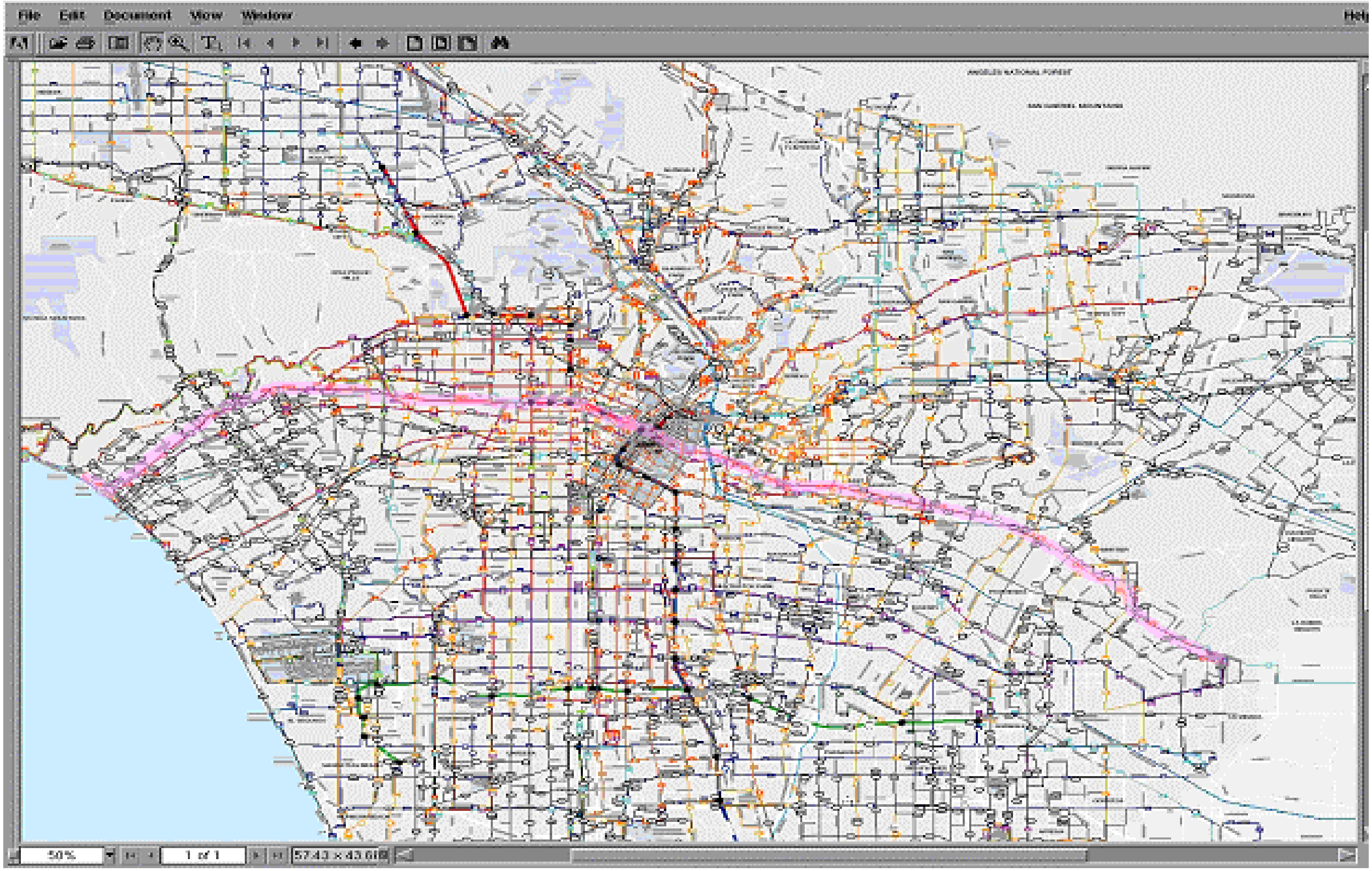


Figure 8: Metro Rapid Transit on the Wilshire-Whittier Boulevards, Showing the 30 Metro Rapid Stops

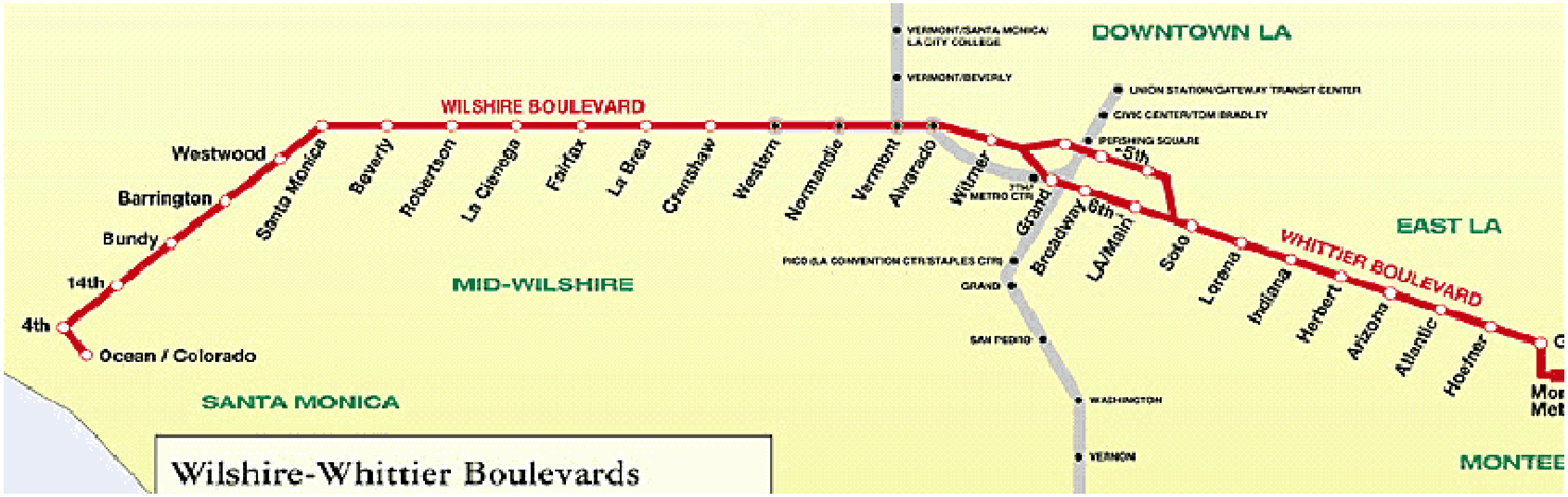


Figure 9: List of Bus Stops on the Wilshire-Whittier Corridor; X Marks the BRT Stops

ROUTE	ST_DIR	STREET	AT_BET	AT_ST	BET_ST	NEAR_FAR	TURN	JURISD	COMM1	Rapid stops
20	N	OCEAN	A	PICO		F		SM	TERMINAL 20/22	x
20	N	OCEAN	A	COLORADO		N		SM		
20	N	OCEAN	A	BROADWAY		N		SM		
20	N	OCEAN	A	SANTA MONICA		N		SM		
20	N	OCEAN	A	ARIZONA		N		SM		
20	N	OCEAN	A	WILSHIRE		N	BR	SM		
20	E	WILSHIRE	A	2ND ST		N		SM		
20	E	WILSHIRE	A	4TH ST		N		SM		x
20	E	WILSHIRE	A	6TH ST		N		SM		
20	E	WILSHIRE	A	LINCOLN		F		SM		
20	E	WILSHIRE	A	11TH ST		N		SM		
20	E	WILSHIRE	A	14TH ST		N		SM		x
20	E	WILSHIRE	A	16TH ST		N		SM		
20	E	WILSHIRE	A	18TH ST		N		SM		
20	E	WILSHIRE	A	20TH ST		N		SM		
20	E	WILSHIRE	A	22ND ST		N		SM		
20	E	WILSHIRE	A	24TH ST		N		SM		
20	E	WILSHIRE	A	26TH ST		F		SM		
20	E	WILSHIRE	A	YALE		F		SM		
20	E	WILSHIRE	A	BERKELEY		N		SM		
20	E	WILSHIRE	A	MCCLELLAN		N		LA3	CARMELINA	
20	E	WILSHIRE	A	BUNDY		N		LA3		x
20	E	WILSHIRE	A	BROCKTON		N		LA3		
20	E	WILSHIRE	A	WESTGATE		N		LA3		
20	E	WILSHIRE	A	BARRINGTON		N		LA3		x
20	E	WILSHIRE	A	FEDERAL		N		LA3	SAN VICENTE	
20	E	WILSHIRE	A	VETERANS HOSP		N		CO3	MIDWAY STOP	
20	E	WILSHIRE	A	SAWTELLE		N		CO3	OVERPASS	

20	E	WILSHIRE	A	VETERAN		N		CO3		
20	E	WILSHIRE	A	WESTWOOD		F		WLA		x
20	E	WILSHIRE	A	GLENDON		F		WLA		
20	E	WILSHIRE	A	SELBY		N		WLA		
20	E	WILSHIRE	A	WESTHOLME		N		WLA		
20	E	WILSHIRE	A	WARNER		F		WLA		
20	E	WILSHIRE	A	BEVERLY GLEN		N		WLA		
20	E	WILSHIRE	A	COMSTOCK		N		CC		
20	E	WILSHIRE	A	LA COUNTRY CLUB		N		CC		
20	E	WILSHIRE	A	WHITTIER		N		BH		
20	E	WILSHIRE	A	SANTA MONICA		N		BH		x
20	E	WILSHIRE	A	LINDEN		F		BH		
20	E	WILSHIRE	A	ROXBURY		F		BH		
20	E	WILSHIRE	A	PECK		F		BH		
20	E	WILSHIRE	A	EL CAMINO		N		BH		
20	E	WILSHIRE	A	BEVERLY DR		F		BH		x
20	E	WILSHIRE	A	CRESCENT		F		BH	CANON	
20	E	WILSHIRE	A	REXFORD		N		BH		
20	E	WILSHIRE	A	PALM		F		BH		
20	E	WILSHIRE	A	DOHENY		N		BH		
20	E	WILSHIRE	A	LA PEER		F		BH		
20	E	WILSHIRE	A	ROBERTSON		F		BH		x
20	E	WILSHIRE	A	WILLAMAN		F		BH		
20	E	WILSHIRE	A	STANLEY		N		BH		
20	E	WILSHIRE	A	LA CIENEGA		F		BH		x
20	E	WILSHIRE	A	GALE		F		BH		
20	E	WILSHIRE	A	SAN VICENTE		N		BH		
20	E	WILSHIRE	A	CAPISTRANO WAY		N		LA3	LA JOLLA	
20	E	WILSHIRE	A	MC CARTHY VISTA		N		LA3	CRESCENT HTS	
20	E	WILSHIRE	A	FAIRFAX		N		LA3		x
20	E	WILSHIRE	A	OGDEN		F		LA3		
20	E	WILSHIRE	A	CURSON		N		LA3		

20	E	WILSHIRE	A	MASSELIN		F		LA3		
20	E	WILSHIRE	A	RIDGELEY		F		LA3		
20	E	WILSHIRE	A	DUNSMUIR		F		LA3		
20	E	WILSHIRE	A	CLOVERDALE		F		LA3		
20	E	WILSHIRE	A	LA BREA		N		LA3		x
20	E	WILSHIRE	A	MANSFIELD		N		LA3		
20	E	WILSHIRE	A	HIGHLAND		N		LA3		
20	E	WILSHIRE	A	LONGWOOD		N		LA3		
20	E	WILSHIRE	A	KENISTON		N		LA3	JUNE	
20	E	WILSHIRE	A	RIMPAU		F		HANP		
20	E	WILSHIRE	A	ROSSMORE		F		HANP		
20	E	WILSHIRE	A	LUCERNE		N		HANP		
20	E	WILSHIRE	A	PLYMOUTH		N		HANP		
20	E	WILSHIRE	A	CRENSHAW		N		HANP	LORRAINE	x
20	E	WILSHIRE	A	NORTON		N		LA3		
20	E	WILSHIRE	A	WILTON PL		N		LA3		
20	E	WILSHIRE	A	ST ANDREWS PL		N		LA3		
20	E	WILSHIRE	A	WESTERN		F		LA1	METRO RED LINE STATN	x
20	E	WILSHIRE	A	SERRANO		N		LA1		
20	E	WILSHIRE	A	HARVARD		N		LA1		
20	E	WILSHIRE	A	KINGSLEY		F		LA1		
20	E	WILSHIRE	A	NORMANDIE		N		LA1	METRO RED LINE STATN	x
20	E	WILSHIRE	A	ALEXANDRIA		N		LA1		
20	E	WILSHIRE	A	CATALINA		N		LA1		
20	E	WILSHIRE	A	VERMONT		N		LA1	METRO RED LINE STATN	x
20	E	WILSHIRE	A	WESTMORELAND		N		LA1	E JOG	
20	E	WILSHIRE	A	COMMONWEALTH		N		LA1	VIRGIL	
20	E	WILSHIRE	A	CORONADO		N		LA1		
20	E	WILSHIRE	A	PARK VIEW		N		LA1		
20	E	WILSHIRE	A	ALVARADO		F		LA1		x
20	E	WILSHIRE	A	BONNIE BRAE		N		LA1		
20	E	WILSHIRE	A	UNION		N		LA1		

20	E	WILSHIRE	A	VALENCIA		N		LA1		
20	E	WILSHIRE	A	WITMER		N		LA1		x
18	E	6TH ST	A	WITMER		N		LA1		
18	E	6TH ST	A	LUCAS		N		LA1		
18	E	6TH ST	A	BIXEL		N		LA1		
18	E	6TH ST	A	ST PAUL		N		LA1		
18	E	6TH ST	B	HOPE	GRAND	M		LA1		x
18	E	6TH ST	A	HILL		N		LA1		
18	E	6TH ST	A	BROADWAY		N		LA1		x
18	E	6TH ST	A	SPRING		F		LA1		
18	E	6TH ST	A	LOS ANGELES		N		LA1		x
18	E	6TH ST	A	WALL		N		LA1		
18	E	6TH ST	A	SAN PEDRO		N		LA1		
18	E	6TH ST	A	TOWNE		N		LA1		
18	E	6TH ST	A	GLADYS		N		LA1		
18	E	6TH ST	A	KOHLER		N		LA1	CENTRAL	
18	E	6TH ST	A	ALAMEDA		N		LA1		
18	E	6TH ST	A	MATEO		N		LA1		
18	E	WHITTIER	A	BOYLE		N		LA7		
18	E	WHITTIER	A	SOTO		N		LA7		x
18	E	WHITTIER	A	ORME		F		LA7		
18	E	WHITTIER	A	CAMULOS		F		LA7		
18	E	WHITTIER	A	EUCLID		N		LA7		
18	E	WHITTIER	A	FRESNO		N		LA7	E JOG	
18	E	WHITTIER	A	LORENA		N		LA7		x
18	E	WHITTIER	A	SPENCE		N		LA7		
18	E	WHITTIER	A	ESPERANZA		N		LA7		
18	E	WHITTIER	A	INDIANA		N		LA7		x
18	E	WHITTIER	A	DITMAN		F		ELA		
18	E	WHITTIER	A	EASTMAN		F		ELA		
18	E	WHITTIER	A	HERBERT		N		ELA		x
18	E	WHITTIER	A	DOWNEY		F		ELA		

18	E	WHITTIER	A	BRANNICK		F		ELA		
18	E	WHITTIER	A	EASTERN		F		ELA		
18	E	WHITTIER	A	FORD		F		ELA		
18	E	WHITTIER	A	MC BRIDE		F		ELA		
18	E	WHITTIER	A	ARIZONA		F		ELA		x
18	E	WHITTIER	A	FERRIS		F		ELA		
18	E	WHITTIER	A	VANCOUVER		N		ELA	CLELA	
18	E	WHITTIER	A	ATLANTIC		N		ELA		x
18	E	WHITTIER	A	GOODRICH		F		ELA		
18	E	WHITTIER	A	HOEFNER		N		ELA		x
18	E	WHITTIER	A	GERHART		N		ELA		
18	E	WHITTIER	A	KEENAN		N		ELA		
18	E	WHITTIER	A	LEONARD		F		ELA		
18	E	WHITTIER	A	FINDLAY		F		ELA		
18	E	WHITTIER	A	WESTSIDE DR		N		ELA		
18	E	WHITTIER	A	SAYBROOK		N		ELA		
18	E	WHITTIER	A	VIA DEL ORO		F		ELA		
18	E	WHITTIER	A	GARFIELD		F		MTB		x
262	S	GARFIELD	A	WHITTIER		F		MTB		
262	S	GARFIELD	A	ALLSTON		F		ELA		
262	S	GARFIELD	A	OLYMPIC		N		ELA		
262	S	GARFIELD	A	FERGUSON		F		CMRC		
262	S	GARFIELD	A	FLOTILLA		F		CMRC		
66	S	MONTEBELLO MLINK STA	A	BAY 5 OR 6		N		MTB	TERMINAL	x
262	N	GARFIELD	A	FLOTILLA		F		CMRC		
262	N	GARFIELD	A	FERGUSON		F		CMRC		
262	N	GARFIELD	A	OLYMPIC		F		ELA		
262	N	GARFIELD	A	ALLSTON		N		ELA		
262	N	GARFIELD	A	WHITTIER		F		MTB		
18	W	WHITTIER	A	GARFIELD		F		MTB		x
18	W	WHITTIER	A	VIA DEL ORO		F		ELA		
18	W	WHITTIER	A	SAYBROOK		F		ELA		

18	W	WHITTIER	A	FINDLAY		F		ELA		
18	W	WHITTIER	A	LEONARD		F		ELA		
18	W	WHITTIER	A	KEENAN		F		ELA		
18	W	WHITTIER	A	GERHART		F		ELA		
18	W	WHITTIER	A	HOEFNER		F		ELA		x
18	W	WHITTIER	A	GOODRICH		F		ELA		
18	W	WHITTIER	A	ATLANTIC		N		ELA		x
18	W	WHITTIER	A	CLELA		F		ELA	VANCOUVER	
18	W	WHITTIER	A	FERRIS		F		ELA		
18	W	WHITTIER	A	ARIZONA		F		ELA		x
18	W	WHITTIER	A	MC BRIDE		F		ELA		
18	W	WHITTIER	A	FORD		F		ELA		
18	W	WHITTIER	A	EASTERN		N		ELA		
18	W	WHITTIER	A	DOWNEY		N		ELA		
18	W	WHITTIER	A	HERBERT		N		ELA		x
18	W	WHITTIER	A	EASTMAN		N		ELA		
18	W	WHITTIER	A	DITMAN		N		ELA		
18	W	WHITTIER	A	INDIANA		N		LA7		x
18	W	WHITTIER	A	ESPERANZA		N		LA7		
18	W	WHITTIER	A	SPENCE		N		LA7		
18	W	WHITTIER	A	LORENA		N		LA7		x
18	W	WHITTIER	A	FRESNO		N		LA7	E JOG	
18	W	WHITTIER	A	EUCLID		N		LA7		
18	W	WHITTIER	A	CAMULOS		F		LA7		
18	W	WHITTIER	A	MOTT		N		LA7	ORME	
18	W	WHITTIER	A	SOTO		N		LA7		x
18	W	WHITTIER	A	CHICAGO		N		LA7	BOYLE	
18	W	6TH ST	A	MATEO		F		LA1		
18	W	6TH ST	A	ALAMEDA		N		LA1		
18	N	CENTRAL	A	6TH ST		F	AR	LA1		
18	W	5TH ST	A	CENTRAL		F	AL	LA1		
18	W	5TH ST	A	TOWNE		N		LA1		

18	W	5TH ST	A	SAN PEDRO		N		LA1		
18	W	5TH ST	A	WALL		N		LA1		
18	W	5TH ST	A	MAIN		N		LA1		x
18	W	5TH ST	A	SPRING		F		LA1		?
18	W	5TH ST	A	HILL		F		LA1		?
18	W	5TH ST	A	GRAND		F		LA1		x
18	W	5TH ST	A	FLOWER		N		LA1		
18	W	6TH ST	A	ST PAUL		N		LA1		
18	W	6TH ST	A	BIXEL		N		LA1		
18	W	6TH ST	A	LUCAS		N		LA1		
18	W	6TH ST	A	WITMER		F		LA1		x
20	W	WILSHIRE	A	WITMER		N		LA1		
20	W	WILSHIRE	A	VALENCIA		N		LA1		
20	W	WILSHIRE	A	UNION		N		LA1		
20	W	WILSHIRE	A	BONNIE BRAE		N		LA1		
20	W	WILSHIRE	A	ALVARADO		N		LA1		x
20	W	WILSHIRE	A	PARK VIEW		N		LA1		
20	W	WILSHIRE	A	CORONADO		F		LA1		
20	W	WILSHIRE	A	COMMONWEALTH		N		LA1		
20	W	WILSHIRE	A	VIRGIL		F		LA1		
20	W	WILSHIRE	A	WESTMORELAND		F		LA1	E JOG	
20	W	WILSHIRE	A	VERMONT		N		LA1	METRO RED LINE STATN	x
20	W	WILSHIRE	A	CATALINA		N		LA1		
20	W	WILSHIRE	A	ALEXANDRIA		N		LA1		
20	W	WILSHIRE	A	NORMANDIE		N		LA1	METRO RED LINE STATN	x
20	W	WILSHIRE	A	KINGSLEY		N		LA1		
20	W	WILSHIRE	A	HARVARD		N		LA1		
20	W	WILSHIRE	A	SERRANO		N		LA1		
20	W	WILSHIRE	A	WESTERN		N		LA1	METRO RED LINE STATN	x
20	W	WILSHIRE	A	ST ANDREWS PL		N		LA3		
20	W	WILSHIRE	A	WILTON PL		N		LA3		
20	W	WILSHIRE	A	NORTON		N		LA3		

20	W	WILSHIRE	A	LORRAINE		F		HANP	CRENSHAW	x
20	W	WILSHIRE	A	PLYMOUTH		N		HANP		
20	W	WILSHIRE	A	LUCERNE		N		HANP		
20	W	WILSHIRE	A	ROSSMORE		N		HANP		
20	W	WILSHIRE	A	RIMPAU		N		HANP		
20	W	WILSHIRE	A	JUNE		F		LA3	KENISTON	
20	W	WILSHIRE	A	MC CADDEN		N		LA3	LONGWOOD	
20	W	WILSHIRE	A	HIGHLAND		F		LA3		
20	W	WILSHIRE	A	MANSFIELD		F		LA3		
20	W	WILSHIRE	A	LA BREA		N		LA3		x
20	W	WILSHIRE	A	CLOVERDALE		F		LA3		
20	W	WILSHIRE	A	DUNSMUIR		F		LA3		
20	W	WILSHIRE	A	RIDGELEY		F		LA3		
20	W	WILSHIRE	A	MASSELIN		F		LA3		
20	W	WILSHIRE	A	CURSON		F		LA3		
20	W	WILSHIRE	A	OGDEN		F		LA3		
20	W	WILSHIRE	A	FAIRFAX		N		LA3		x
20	W	WILSHIRE	A	CRESCENT HGTS		N		LA3	MCCARTHY VISTA	
20	W	WILSHIRE	A	LA JOLLA		N		LA3	CAPISTRANO WAY	
20	W	WILSHIRE	A	SWEETZER		N		LA3	SAN VICENTE	
20	W	WILSHIRE	A	GALE		F		BH		
20	W	WILSHIRE	A	LA CIENEGA		N		BH		x
20	W	WILSHIRE	A	STANLEY		F		BH		
20	W	WILSHIRE	A	WILLAMAN		N		BH		
20	W	WILSHIRE	A	ROBERTSON		F		BH		x
20	W	WILSHIRE	A	LA PEER		F		BH		
20	W	WILSHIRE	A	DOHENY		F		BH		
20	W	WILSHIRE	A	PALM		F		BH		
20	W	WILSHIRE	A	REXFORD		F		BH		
20	W	WILSHIRE	A	CANON		F		BH		
20	W	WILSHIRE	A	BEVERLY DR		F		BH		x
20	W	WILSHIRE	A	RODEO		F		BH		

20	W	WILSHIRE	A	CAMDEN		F		BH		
20	W	WILSHIRE	A	BRIGHTON WAY		F		BH		
20	W	WILSHIRE	A	LINDEN		N		BH		
20	W	WILSHIRE	A	SANTA MONICA		N		BH		x
20	W	WILSHIRE	A	WHITTIER		F		BH		
20	W	WILSHIRE	A	LA COUNTRY CLUB		N		CC		
20	W	WILSHIRE	A	COMSTOCK		N		CC		
20	W	WILSHIRE	A	BEVERLY GLEN		N		CC		
20	W	WILSHIRE	A	WARNER		F		WLA		
20	W	WILSHIRE	A	WESTHOLME		N		WLA		
20	W	WILSHIRE	A	SELBY		N		WLA		
20	W	WILSHIRE	A	GLENDON		N		WLA		
20	W	WILSHIRE	A	WESTWOOD		N		WLA		x
20	W	WILSHIRE	A	VETERAN		N		WTWD		
20	W	WILSHIRE	A	SAWTELLE		N		CO3	OVERPASS	
20	W	WILSHIRE	A	VETERANS HOSP		N		CO3	MIDWAY STOP	
20	W	WILSHIRE	A	SAN VINCENTE		F		LA3	FEDERAL	
20	W	WILSHIRE	A	BARRINGTON		N		LA3		x
20	W	WILSHIRE	A	WESTGATE		N		LA3		
20	W	WILSHIRE	A	BROCKTON		I		LA3		
20	W	WILSHIRE	A	BUNDY		N		LA3		x
20	W	WILSHIRE	A	CARMELINA		N		LA3	MCCLELLAN	
20	W	WILSHIRE	A	BERKELEY		N		SM		
20	W	WILSHIRE	A	YALE		N		SM		
20	W	WILSHIRE	A	26TH ST		N		SM		
20	W	WILSHIRE	A	24TH ST		N		SM		
20	W	WILSHIRE	A	22ND ST		N		SM		
20	W	WILSHIRE	A	20TH ST		N		SM		
20	W	WILSHIRE	A	18TH ST		N		SM		
20	W	WILSHIRE	A	16TH ST		N		SM		
20	W	WILSHIRE	A	14TH ST		N		SM		x
20	W	WILSHIRE	A	11TH ST		F		SM		

20	W	WILSHIRE	A	LINCOLN		N		SM		
20	W	WILSHIRE	A	6TH ST		N		SM		
20	W	WILSHIRE	A	4TH ST		N		SM		x
20	W	WILSHIRE	A	3RD ST		F		SM		
20	S	OCEAN	A	WILSHIRE		F	AL	SM		
20	S	OCEAN	A	ARIZONA		F		SM		
20	S	OCEAN	A	SANTA MONICA		F		SM		
20	E	COLORADO	A	OCEAN		F	AL	SM		x
20	S	MAIN	B	COLORADO	PICO	M		SM	OPP CITY HALL	X

11 APPENDIX 5: APPLICATION OF SMARTBRT TO THE METRO RAPID TRANSIT SYSTEM IN LOS ANGELES

Figure 12: Locale Specific Performance Measures (Blue color indicates availability and quality performance measures that are from the Manual)

Depends On	Variable	Effects
Policy, Federal mandate?	Allowed passenger load (on-peak vs. off-peak) Number of pass on the bus input, [#/bus]	Dwell time, allowed pass load factor, Person capacity (increasing passenger load increases person capacity, reduces comfort), frequency,
Policy, Federal mandate?	Allowed passenger load factor [number, max 2.0] Number of pass on the bus / number of seats Input [#]	Dwell time, allowed pass load factor, Person capacity, frequency,
Frequency, vehicle size, demand,	**Passenger load** Calculated, [# pass/bus]	Dwell time, person capacity, load factor, Person capacity, frequency PM_m: stop quality
Frequency, vehicle size, demand,	**Passenger load factor** [number, max 2.0] Number of pass on the bus / number of seats Calculated, [#]	Dwell time, person capacity, load factor, Person capacity, frequency
Number of loading area/ stop, number of buses at stop / unit time; dwell time, clearance time,	Failure rate probability of a queue *not* forming behind a bus stop input, [%] (design variable) or calculated	Bus stop capacity, reliability, (higher failure rate increases bus stop capacity, decreases reliability),
Demand, policy on passenger load, scheduling,	Frequency Input, given by headway, [min] Unless we do scheduling. Then it is calculated from demand and allowed max passenger load	Passenger load, dwell time, number of passengers carried (person capacity of lane), PM_m: stop availability

Depends on	**Variable**	**Effects**
passenger volumes and passenger service time: bus stop spacing; vehicle type f(floor height, type of doors used, number of doors used); number of boarding and alighting passengers at the highest demand door, total interchanging demand; on-board circulation f(standees permitted, use of back door, maximum load); fare collection method; ADA and bicycle access; p2-7	**dwell time** calculated [sec]	Effects all PM_m; frequency, reliability, load factor,
Same as dwell time	**dwell time variability** Calculated [coefficient of variation of dwell time]	Reliability, load factor,
start up and travel own length; if offline stop, add reentry delay f(speed of adjacent traffic, traffic rules and enforcement) p 2-9	**Clearance time** Calculated [sec]	Travel time; reliability if reentry delay added;
bus volume, probability of queue formation, loading area design, traffic signal timing; p2-12	Number of loading area at a bust stop Input, [#] Unless we do scheduling, and / or designing	Capacity of bus stop; cost of infrastructure,

Depends on	**Variable**	**Effects**
vehicle capacity of the individual loading areas in the bus stop, number of loading areas provided and their design; stop location (near / far side) p2-10	**Vehicle capacity of a bus stop** number of buses /bus stop / hour Calculated [buses/hr]	PM
bus lane type; capacity of the critical bus stop (highest volume of passenger movements) along the lane; skip-stop operation; platooning, stop location (near / far side); p2-12	**Vehicle capacity of a bus lane** number of buses by the max load point / hour Calculated [buses/hr; at the max load point]	PM
number of people boarding and alighting at the peak in peak time p2-22	**Person capacity of a bus stop** **Number of passengers moving at the stop in the peak-in-peak** Calculated [pass/hr]	PM influences vehicle capacity of a loading area and through that it influences the vehicle capacity of the bus stop.
maximum allowed passenger loading per bus f(policy); number of buses operated during the analysis period f(bus frequency at the route's maximum load point per hour, peak hour factor) *Maximum person capacity of a bus lane* at its maximum load point f(bus lane's maximum vehicle capacity) per hour	**Person capacity of a bus route** or lane at its maximum load point Calculated [pass/hr, at max load point] **bus lane's maximum vehicle capacity** = bus lane vehicle capacity per hour * peak hour factor * max allowed passenger loading per hour	PM

Depends on	**Variable**	**Effects**
passenger load, reliability, {amenities}	**Stop quality** Calculated {passenger load [area / pas]} or [load factor {#}]	PM
hours of service, {accessibility}	**Route segment availability** Calculated {house of service [hrs]}	PM
reliability, travel speed, transit-auto time	**Route segment quality** Calculated {reliability}	PM_m: Route segment quality
schedule, dwell time, passenger load; travel speed f(transit priority measures, traffic volume); failure rate; vehicle maintenance, staff availability;	**Reliability** Calculated [min late/early] [var] [prob]	PM Waiting time, frequency (through bunching), passenger load,
dwell time, priority measure, traffic in mixed operation	**Travel speed / travel time** between origin and destination on lane/route Calculated [m/h] / [min]	PM
	Transit/auto time Calculate	PM
Frequency, reliability, overcrowding, information availability,	**Waiting time** Calculated [min]	PM
Frequency, passenger load, vehicle capacity, reliability,	**Not overcrowded** No one is left behind Calculated	PM

Figure 13: Alighting and Boarding Times

Boarding Time	Default Values [sec]	Low Floor Bus Values [sec]
Standard	2	1.6
Bicycle	10	20
Wheelchair	15	30

Alighting Time	Default Values [sec]	Low Floor Bus Values [sec]
Standard	1	0.8
Bicycle	8	20
Wheelchair	12	30

Figure 14: Preliminary Analysis 1: Average Travel Time for all Scenarios

Scenario Number	Scenario Code	Headway [min]	Demand [pass/hr/st]	Signal Priority	Average travel time [sec]	Average travel time [min]
1	A1	5	7	NO	5845.588	97.42647
2	A2	5	11	NO	5960.394	99.3399
3	B1	5	30	NO	4600.075	76.66792
4	B2	5	50	NO	4801.289	80.02148
5	B3	3	50	NO	4626.652	77.11086
6	B4	3	30	NO	4507.409	75.12348
7	C11	5	7	5 sec	5232.784	87.21307
8	C12	5	7	9 sec	5204.942	86.74904
9	C21	5	11	5 sec	5442.917	90.71528
10	C22	5	11	9 sec	5296.174	88.26956
11	D11	5	30	5 sec	4183.655	69.72758
12	D12	5	30	9 sec	4171.896	69.53159
13	D21	5	50	5 sec	4308.291	71.80485
14	D22	5	50	9 sec	4224.1	70.40167
15	D31	3	50	5 sec	4198.263	69.97105
16	D32	3	50	9 sec	4151.108	69.18513
17	D41	3	30	5 sec	4124.419	68.74032
18	D42	3	30	9 sec	4074.787	67.91311
19	E1	5	7	NO	5882.253	98.03756
20	E2	5	11	NO	6035.938	100.599
21	F1	5	30	NO	4747.211	79.12018
22	F2	5	50	NO	4929.82	82.16367
23	F3	3	50	NO	4745.826	79.0971
24	F4	3	30	NO	4592.164	76.53606
25	G11	5	7	5 sec	5397.676	89.96127
26	G12	5	7	9 sec	5442.544	90.70907
27	G21	5	11	5 sec	5591.639	93.19398
28	G22	5	11	9 sec	5536.383	92.27306
29	H12	5	30	9 sec	4272.627	71.21045
30	H21	5	50	5 sec	4529.282	75.48803
31	H22	5	50	9 sec	4409.083	73.48471
32	75_f_no	5	75	NO	5031.005	83.85009
33	100_f_no	5	100	NO	5068.105	84.46842
34	150_f_no	5	150	NO	5053.14	84.219
35	75_h_9	5	75	9 sec	4524.273	75.40455
36	100_h_9	5	100	9 sec	4529.967	75.49944
37	L_100_e	5	100	NO	6110.547	101.8424

Figure 15A: Travel Time [sec] as a Function of Demand (Given 5 min Headway; if Signal Priority is Enabled, Priority-hold is 9 sec)

Demand [pass/hr/stop]	30	50	75	100
Local	5882.253	6035.938	No data	6110.547
Local with SP	5442.544	5536.383	No data	5697.9
BRT	4747.211	4929.82	5031.005	5068.105
BRT with SP	4272.627	4409.083	4524.273	4529.967

Figure 15B: Travel Time Reduction [%] from the Local Operation and Incrementally (as a Function of Demand Given 5 min Headway; if Signal Priority is Enabled, Priority-hold is 9 sec)

Demand [pass/hr/stop]	30		50		75		100	
	Total	Δ	Total	Δ	Total	Δ	Total	Δ
Local	0	0	0	0			0	0
Local with SP	7.48	7.48	8.28	8.28			6.75	6.75
BRT	19.30	11.82	18.33	10.05	0.00	0.00	17.06	10.31
BRT with SP	27.36	8.07	26.95	8.63	10.07	10.07	25.87	8.81

Figure 16: Travel Time as a Function of Demand (Given 5 min Headway, if Signal Priority is Enabled, Priority-hold is 9 sec)

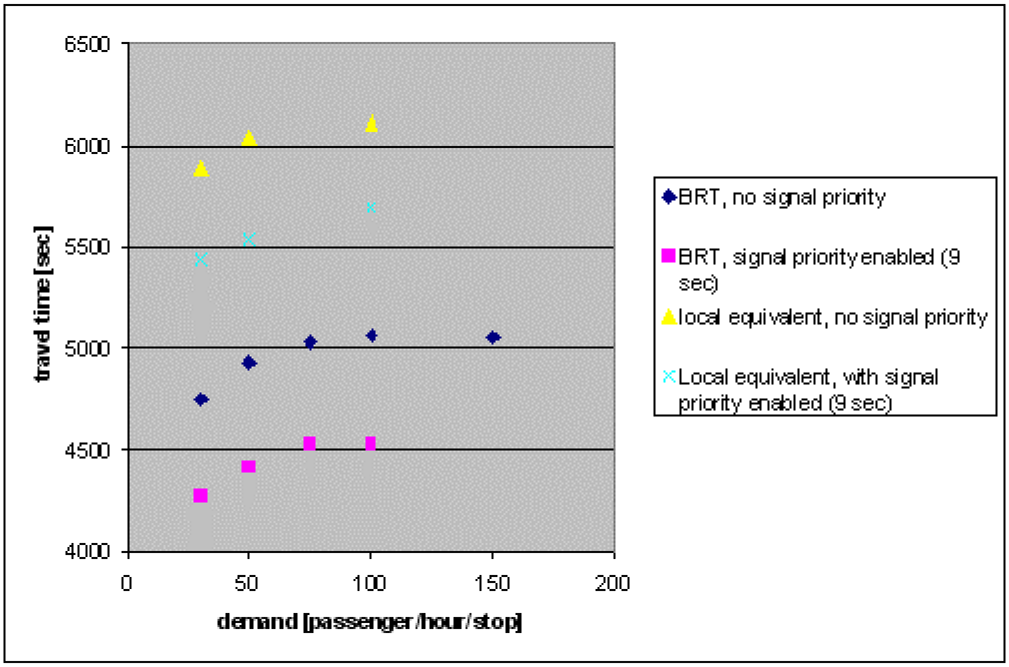


Figure 17: Travel Time Reduction in Local Transit Operation due to Signal Priority Implementation

Local Demand	Travel Time Reduction	
	seconds	%
30	439.71	7.48
50	499.55	8.28
75	No data	No data
100	412.67	6.75

Figure 18: Travel Time Reduction in BRT due to Signal Priority Implementation

BRT	Travel time reduction	
Demand [pass/hr/stop]	seconds	%
30	474.58	9.99
50	520.73	10.56
75	506.73	10.07
100	538.13	10.62

Figure 19A: If Operation Demand is Low on the System, Travel Times of Individual Buses Tended to Form a Pattern.

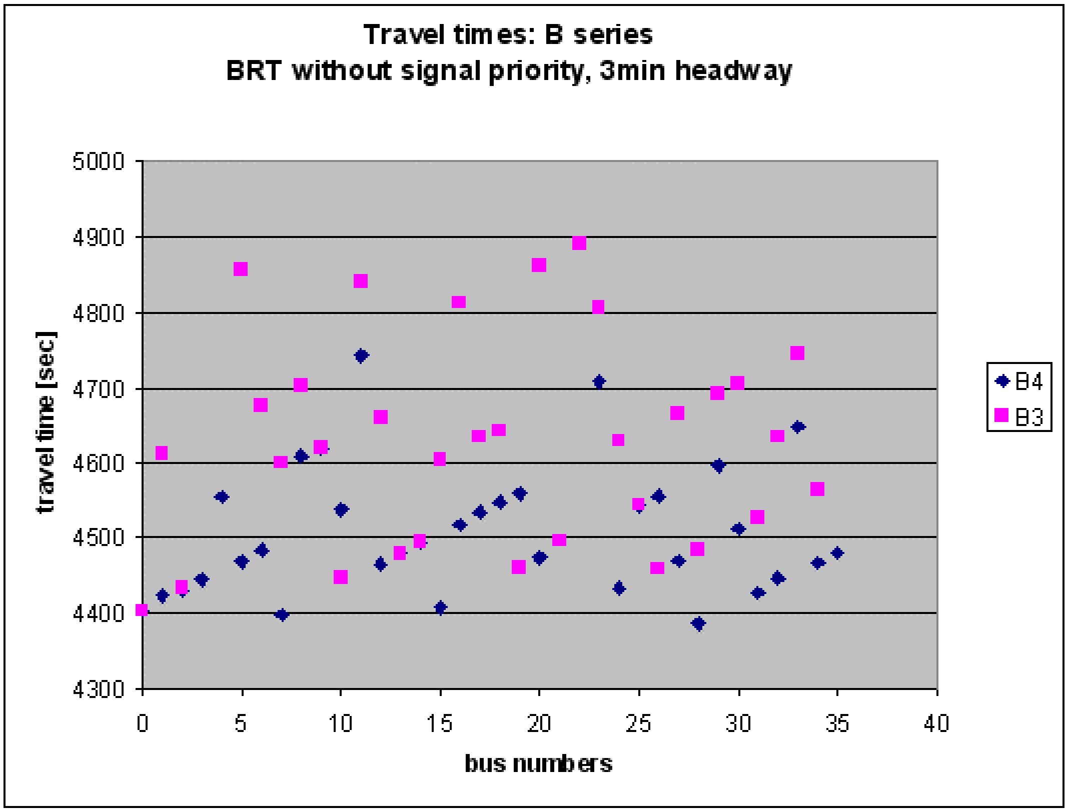


Figure 19B: If Operation Demand is Low on the System, Travel Times of Individual Buses Tended to Form a Pattern.

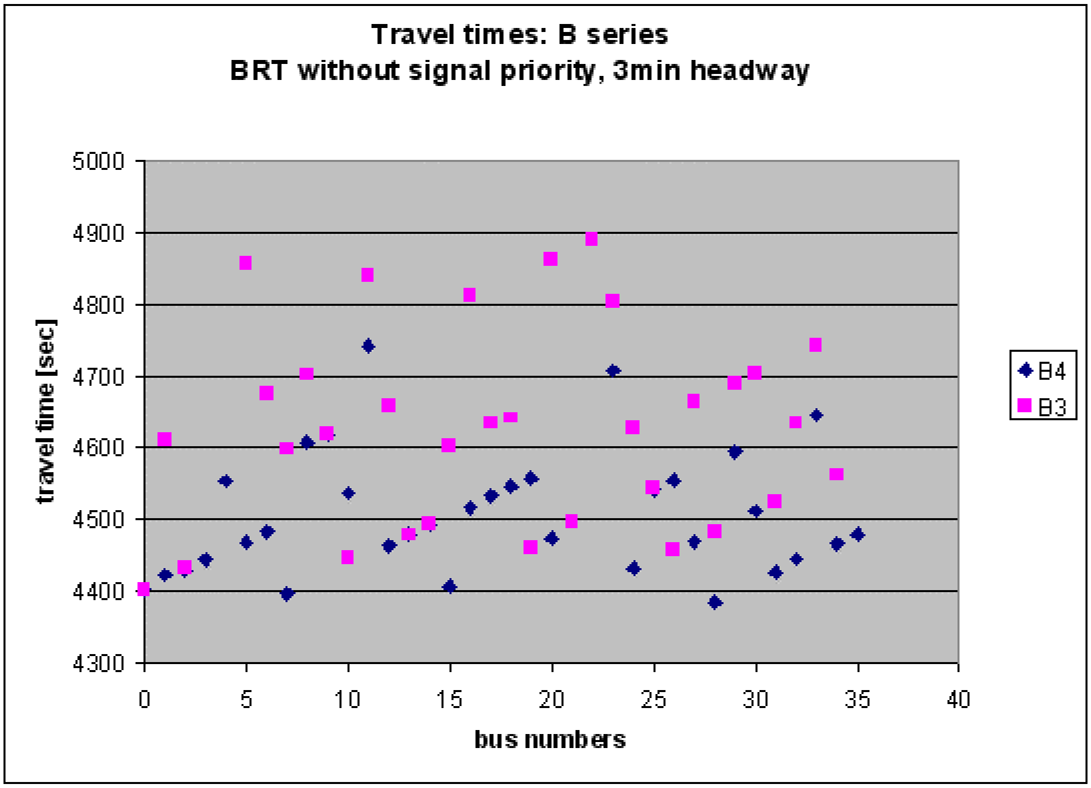


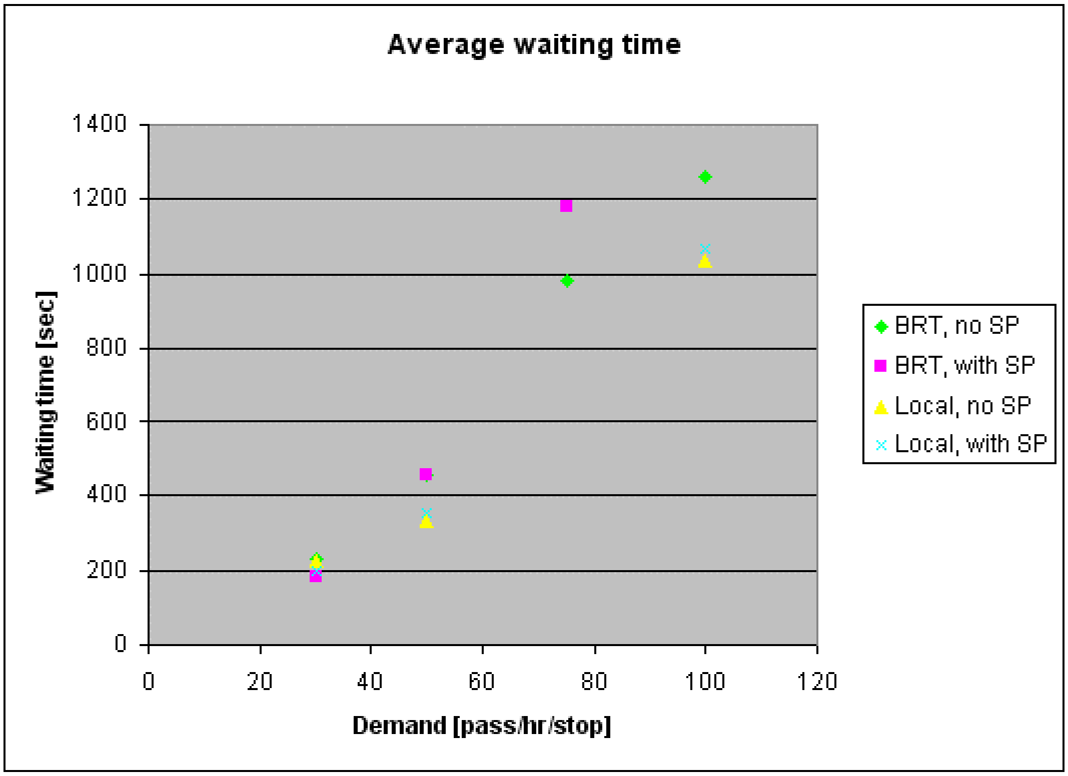
Figure 20: Preliminary Example of *SmartBRT* Supporting Decision-making

	Scenario Travel time [sec] % reduction from base case
Base case or current	Local, conventional bus 6035.92 sec
Investing in low floor bus	Local, low floor 5960.39 sec – 1.3%
Investing in signal priority	Local, conventional, SP-9 5536.38 sec – 8.2%
Reducing number of stops	Rapid, conventional, no SP 4929.82 sec – 18.3%
Reducing headway	NA
Investing in low floor bus and signal priority, Reducing number of stops	Rapid, low floor, SP-9 4224.1 sec – 30%

Figure 21: Preliminary Example of *SmartBRT* Supporting Decision-making with Future Cost-effectiveness Capability Indicated

	Scenario Travel time [sec} % reduction from base	Cost-effectiveness Time saving for every $1000 invested
Baseline or current	Rapid transit, conventional 4929.82 sec	Future work
Investing in low floor	Rapid, low floor bus, no SP 4801.3 sec – 2.6%	Future work
Investing in signal priority	Rapid, conventional bus, SP-9 4409.1 sec – 10.5%	Future work
Reducing headway	Rapid, conventional bus, no SP, 3 min 4745.8 sec – 3.7%	Future work
Investing in low fool bus and signal priority, Reducing headway	Rapid, low floor bus, SP-9, 3 min 4151.11 sec – 15.8%	Future work

Figure 22: Preliminary Analysis 1: Average Waiting Time and Over-crowding Occasions (given 5 min headway; if Signal Priority is Enabled, Priority-hold is 9 sec)



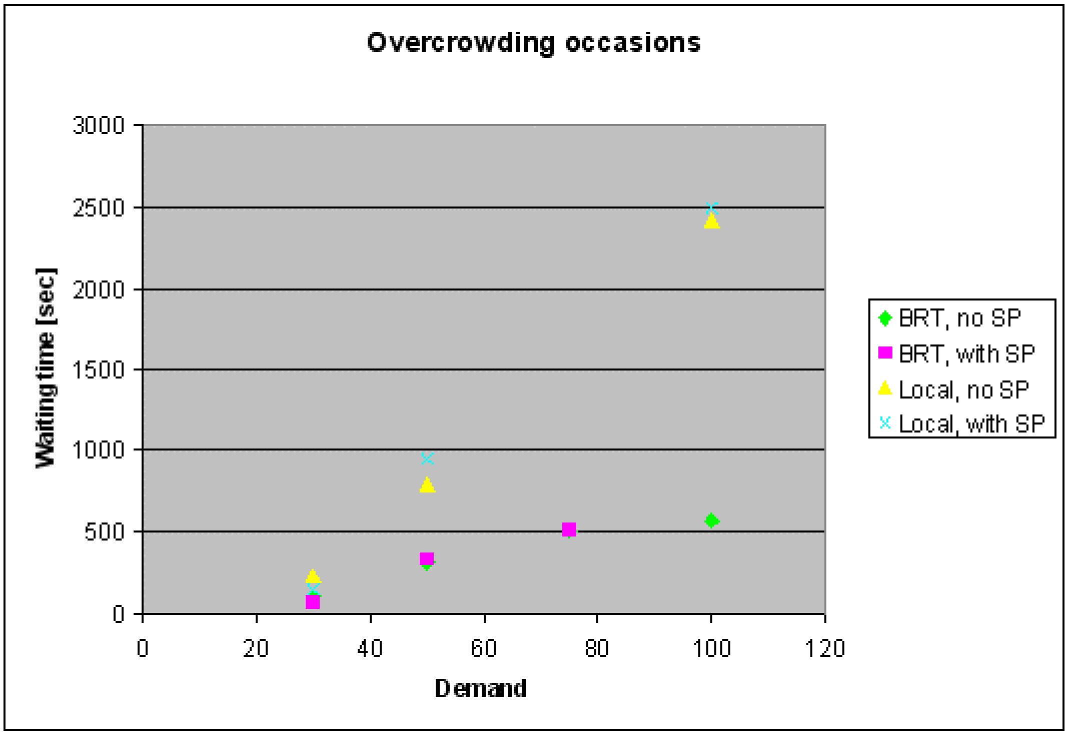


Figure 23: Preliminary Analysis 2: Results

Scenario	Arrival rate [p/h/s]	Service frequency [min]	Bus capacity	Waiting time [sec]	Waiting time percentage	Pass. travel speed [m/hr]	Bus load factor	Percentage of overcrowding
1	30	5	40	188	15.7	17.53	0.43	2.5
2	30	5	60	185	15.3	17.45	0.29	2.6
3	30	4	40	156	13.4	18.00	0.35	4.2
4	30	4	60	155	13.4	18.01	0.23	4.2
5	40	5	40	224	18.2	16.63	0.58	14.6
6	40	5	60	185	14.8	17.19	0.39	7.3
7	40	4	40	201	16.5	17.04	0.48	15.2
8	40	4	60	175	14.4	17.40	0.32	14.8
9	50	5	40	474	39.0	14.85	0.67	37.6
10	50	5	60	190	15.0	16.79	0.49	13.1
11	50	4	40	187	15.4	17.17	0.59	21.8
12	50	4	60	146	11.8	17.82	0.39	12.0

Figure 24: Reduction in "% of Passenger Waiting Time" Due to Improved Service

Demand [pass/hr/stop]	From "base" service to "increasing capacity" service	From "base" service to "increasing frequency" service
30	2%	17%
40	17%	10%
50	60%	60%

Figure 25: Changes in "% of Passenger Waiting Time" due to Increasing Demand

Demand changes [pass/hr/stop]	"base" service	"increasing capacity" service	"increasing frequency" service	"increasing frequency and capacity" service
From 30 to 40	16%	0%	17%	11%
From 40 to 50	112%	3%	-7%	-16%

Figure 26: Reduction in "Waiting Time" and "Over-crowding Percentage" Due to Increasing Bus Capacity, at 50 Passengers Per Hour, Per Stop

	"waiting time" reduction	"overcrowding percentage" reduction
From "base" service to "increasing capacity" service	284s	24.5%
From "increasing frequency" service to "increasing capacity and frequency" service	41s	9.8%

Figure 27: Simulation Visualization of the Metro Rapid Transit System on the Wilshire-Whittier Corridor