

Bus Rapid Transit Simulation Model Research and Development

Final Project Summary Report
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1. Executive Summary

Background

A top priority for transit is clearly to provide service that offers travel times competitive with the single-occupant automobile. Bus Rapid Transit (BRT) is viewed as a potentially effective addition to transit networks in many metropolitan areas because it should address some of the current deficiencies in bus transit that are causing a reduction in bus mode share. In areas that do not have near-term potential for rail, BRT is considered a possible stepping stone to eventual rail service implementation. It may even prove to be a desirable alternative to light and heavy rail transit if it can be deployed with similar travel characteristics at a significantly lower cost per mile. A 1994 study preceding the federal governments' BRT program stated:

While rail transit clearly provides an attractive, environmentally friendly transit system that offers high level of service, it is feasible only in major corridors where high ridership justifies its high investment. Improvements of bus services have a much lower threshold in terms of ridership volume and therefore present a great potential for improved transit in a number of cities.¹

From this perspective, facilitating initial planning and, ultimately, implementation of new BRT projects with new tools such as a specific BRT microsimulation application is a worthwhile national transportation goal.

A simulation model developed specifically for BRT would equip planning professionals, both inside and outside of transit agencies, with a tool that reduces the costly overhead associated with fully-coded, traffic-centric microsimulation models. This approach is consistent with observations that improvements in various components of bus transit route design have a higher likelihood of improving bus performance than efforts to improve traffic flow. Such a tool would therefore need to readily answer questions about how the potential operating factors of a BRT system can improve performance.

The research and development (R&D) effort performed by the Multisystems project team for this Small Business Innovation Research Program (SBIR) Phase 1 grant is applicable to full-featured BRT systems. In addition, it would enable communities to test individual advanced bus strategies that are transitional steps to BRT as well as worthwhile enhancements on their own. Facilitating incremental planning and implementation is supported by the FTA's Bus Rapid Transit (BRT) Demonstration Program, as indicated in its publication *Bus Rapid Transit Demonstration Program*.²

Summary of Research Findings

One of the most important conclusions of this R&D study is that a BRT microsimulation model, which could be readily applied to different study corridors, could be best built using a traditional traffic microsimulation platform adapted to the particular circumstances of transit agencies. The project team found that this approach was better than using general process engineering microsimulation products. Use of a non-transportation microsimulation platform was determined to have no apparent advantage in creating a BRT simulation model. In fact, this would create programming requirements that traditional traffic software platforms either limit or eliminate.

One outcome of this finding, the project team chose to use the VISSIM© microsimulation software for its BRT research and development work. VISSIM© was chosen partly because its user interface offered the simplicity and flexibility that was determined necessary for transit agency use, especially when creating the BRT alignment and related traffic network. While certainly not the only possibility, this choice was supported by two important facts:

¹ Vuchic, Dr. Vukan et al. "The Bus Transit System: Its Underutilized Potential." Federal Transit Administration, Report No. DOT-T-94-20. May 1994: page 1.

² National Bus Rapid Transit Forum. "Bus Rapid Transit Demonstration Program." Federal Transit Administration, January 15, 1998: page 5.

- VISSIM© had been rated highly for transit system modeling by an extensive research project commissioned by the European Union on microsimulation software; and
- Existing BRT implementation projects, such as the Lane Transit District and the Miami Dade Transit District, have been using the software for full-fledged modeling and design, and traffic signal priority modeling, respectively.

Another essential finding was that the simulation model's purpose needed to be clearly defined. In this regard, the project team determined that the BRT model should be transit- rather than traffic -centric, emphasizing transit inputs and outputs and usability for transit agencies while de-emphasizing traffic elements. This finding was critical for the research and development effort, as it helped to focus the research and the application design and testing process.

Other findings related to this particular application of microsimulation software are listed by category below.

Transit Application

- Simplifying the data requirements for a BRT simulation model can limit data collection needs to existing bus operating data and basic arterial traffic information and configuration. These data can be readily obtained from the local transit agency and traffic department.
- Selection of model components and variables should be based on whether they might impact the selected BRT performance measures, since the number of variables being modeled should be kept to a minimum.
- Use of a microsimulation platform that includes animation is important for the design, testing, and use of a BRT planning application because the combination of component behaviors and relationships are sometimes better understood with visual inspection. Animation is also important for internal review by agency staff who are more comfortable with pictures than with numerical and statistical output.
- Validation of a test BRT network will involve primarily those measures derivable from data that are typically collected by a transit agency and that are available from a traffic agency. Such data may include some combination of bus travel time, passenger boarding/alighting activity, and dwell time. The data may need cleaning and summarization to create the format required for the BRT simulation model. The project team found that validation using historical field data is more reliable than existing schedule data, as actual bus operations show considerable variability from the schedule.

Incorporating Traffic Impacts

- Measuring the traffic impacts of a BRT system using a simulation application with a transit-centric focus has limitations that require further design efforts. The most readily measurable traffic impacts under such a structure are changes in total green time on the mainline corridor and number of signal priority requests granted.
- A BRT microsimulation application can incorporate the general impact of estimated traffic volumes on a BRT operation (e.g., lane changing impedance and queuing) without coding the entire traffic corridor. Adjustment factors are probably needed when the modeled network does not include the actual number of lanes in the corridor, although it remains to be seen whether this would significantly improve model output.
- Other traffic impacts of mainline traffic volumes on BRT operation – impacts of right turns and other probabilistic variables such as lane violations – should also be included in a BRT simulation application; the software tools exist in the platform chosen for this project.

Potential Future Development

- The default random distributions within the BRT application need further investigation to determine if ranges created from historical transit data from the study corridor would change the model output significantly.

- Some model components that appeared to work correctly during verification testing, such as the conditional priority algorithm, did not perform correctly during validation. These will require further testing iterations to incorporate them into the validated version of the model.
- The project team was able to create traffic signal subroutines that used existing model data flows to allow the addition of dual-condition signal priority. The two conditions used were schedule adherence and bus occupancy. Further modeling of this feature would be valuable for modeling minimization of priority signals granted, a likely desire of traffic engineers.
- The baseline BRT simulation application developed during the project is capable of modeling real-time transit operational control strategies. The project team was able to create a model subroutine that could be used to invoke headway maintenance in the model. The VISSIM© simulation platform could be used with schedule adherence, but the software is limited and is highly dependent on accurately estimating the stop-to-stop offsets (travel times). Further testing and development are necessary to refine schedule inputs so that the headway maintenance component can be developed as an operational control measure.
- With respect to the VISSIM© software platform, modeling the cumulative operating impacts of round-trip operation of a BRT system requires special programming.
- More effort needs to be expended on creating the user front end. The existing model interface does not provide for batch processing of changes to input text files. This limits the speed with which key simulation model parameters can be tested and limits the application's use as a rapid simulation environment. For example, during the R&D effort, this limitation made it difficult to perform sensitivity analyses regarding bus stop spacing. Stop spacing has been identified in a wide variety of research reports as *the* basic ingredient in improving bus performance.
- More effort needs to be expended on creating the user back end to facilitate easy processing and evaluation of system performance. Given the number, size, and complexity of the output files generated by the software, this improvement would also give the model the rapid scenario testing it needs.

2. Introduction and Project Background

Congestion on the nation's roads has been rapidly increasing due to a variety of land use and socioeconomic factors. While use of transit could alleviate congestion, the fact that most transit service involves buses operating on mixed traffic facilities means that the increasing congestion continues to degrade the quality of public transit. Transit becomes an unattractive mode under congested conditions, particularly for commuters who typically represent a large percentage of transit ridership. Choice riders would be similarly disinterested. Facing degrading transit performance and reliability, more and more transit riders are choosing non-transit modes.

In its 1999 Phase 1 program solicitation, the Small Business Innovation Research Program (SBIR) recognized that transit agencies considering Bus Rapid Transit (BRT) projects will need planning tools designed specifically for the development of BRT systems. The SBIR research and development (R&D) project completed by the Multisystems project team examined the development of a microsimulation model application designed for transit agencies that are in the planning stages of BRT deployments. The research concluded that transit agencies need a planning tool, one that seeks to reduce barriers to their use by reducing the resources typically needed to utilize a traditional traffic-centric microsimulation tool. However, contrary to an initial hypothesis, the research team established that development of such an application is better done using a traditional transportation simulation tool rather than a microsimulation platform designed for other purposes, such as process flow modeling.

2.1 BRT Background

In 1999, the Federal Transit Administration (FTA) commenced its Bus Rapid Transit (BRT) Demonstration Program using dedicated funding from the Transportation Equity Act for the 21st Century (TEA-21). Recognizing that BRT has the potential to provide flexible and cost-effective alternatives to rapid transit and light rail transit systems, the agency planned to spend approximately \$1.5 million on the program during 1999 and will seek up to \$2.0 million per year for the remaining years of TEA-21.

In its publications *Issues in Bus Rapid Transit*³ and *Bus Rapid Transit Demonstration Program*,⁴ the FTA identified a number of primary features of a BRT system. These included the following:

- Bus lane-related right-of-way enhancements;
- Bus signal preference and preemption;
- Vehicle design;
- Stop spacing and design;
- Fare collection;
- Marketing, information, and Automatic Vehicle Location (AVL) and other ITS features; and
- Land use policy.

The BRT Demonstration Program⁵ identified a number of performance measures to test the effectiveness of these features, most of which contribute to measuring transit travel time and delay. These included measures related to operational performance, customer satisfaction, and traffic. Key objectives of the federal BRT Demonstration Program researched for this project are increasing bus speed by reducing travel time and improving service reliability for customers.

2.2 Overview of Initial Simulation Model Concept

The R&D project described in this report is consistent with the FTA's strategy to provide technology assessment and technical assistance to transit agencies embarking on BRT planning efforts. The proof-of-

³ Federal Transit Administration Office of Research, Demonstration, and Innovation, "Issues in Bus Rapid Transit." Federal Transit Administration, No date: pages 2-3.

⁴ "Bus Rapid Transit Demonstration Program." Op. Cit., pages 16-17.

⁵ Ibid., pages 16-17.

concept application proposed for this project focused on those performance measures that would be of most interest to a transit agency (in particular, travel time performance, service reliability, and derivations of these measures). The R&D did not attempt to address all of the potential FTA performance measures, nor a variety of metrics developed and used in other research projects,⁶ for reasons described in the body of this report.

The project team confirmed its initial belief that a BRT microsimulation application should enable transit agencies to readily test a variety of aspects related to BRT deployment including from operational, customer service, and traffic impact perspectives. In particular, the project team believed that transit agencies would need a reasonable assessment of BRT features and related benefits to convince internal decision-makers of its potential. Moreover, this information would be essential for a transit agency to have when it began coordination with local traffic agencies.

As the R&D project progressed, the project team realized that the wide range of potential BRT features, variables, and their potential impacts would need to be limited for a BRT simulation application. This finding was the result of a lack of research conclusively demonstrating the benefits of many BRT features that were consistent with the performance measures identified. Additionally, the assumption that transit agencies need a straightforward, transit-centric model also supported this approach to model development.

2.2.1 Preliminary Research Hypotheses

Based on the project team's experience with a wide range of transit service planning projects and its previous research on BRT and related bus system enhancements, a number of initial hypotheses were identified to guide the R&D project. Two primary hypotheses are worth highlighting. First, it was assumed that transit agencies would be more likely to initiate BRT projects than would local traffic agencies because traffic agencies perceive that BRT only has negative impacts on traffic operations. Consequently, the project team believed that transit agencies would need an order of magnitude assessment of BRT improvements to present internally and to local traffic and other municipal agencies when coordination efforts began.

Second, the costly overhead of high data collection and preparation requirements, staff training, model design testing, and validation of traditional traffic microsimulation approaches would be an impediment to transit properties undertaking this type of modeling. These same factors would be potentially significant impediments for transit agencies that may be hesitant to commit significant resources in the initial planning stages for BRT. The traditional traffic approach would be an additional impediment for transit agencies that do not employ a practicing traffic engineer who is familiar with microsimulation of traffic. A more cost-effective approach would thus be required.

Other preliminary research hypotheses for the R&D effort included the following:

- A BRT simulation application is needed within transit agencies to help them determine whether a BRT system would be beneficial and which elements would provide the most benefit;
- In most U.S. transit environments, different BRT rights-of-way will, by necessity of urban environment, be incorporated into a single system, requiring BRT simulation application that could readily change and test competing configurations;
- The number of variables and therefore components in the model would need to be limited to create a workable and consistent model; and
- The model would need to produce output on potential traffic impacts sufficient to show local transit agency's understanding of traffic concerns to local traffic agencies.

A related hypothesis was that few of the commercially available traffic simulation products on the market (including the FHWA-sponsored Traffic Software Integrated System [TSIS] suite) are capable of

⁶ For example, Run Time Ratio (RTR) and Excess Wait time (EW) as described by Strathman, James G. et al. "Automated Bus Dispatching Operations, Control, and Service Reliability." Transportation Research Record 1666. September, 1999: pages 28-36.

modeling the basic transit inputs needed to test a BRT system without coding a complete traffic network.⁷ Even those that could be configured to do so would require, as noted above, extensive collection and input of data regarding traffic volumes and flow, vehicle classification and percentage of total volume, lane and intersection geometry, and traffic signal timing and coordination.

While the project team understood that such detailed information would be needed during the final design phases of a BRT project, these data were assumed to be nonessential during the early stages of BRT development. Even without extensive detail related primarily to traffic operations, such a tool would enable transit agencies and other planning organizations to make more informed decisions about whether a BRT approach has potential operational merit, which aspects of BRT would be most critical to achieve the desired performance gains, and whether the BRT planning effort should continue into engineering phases.

2.2.2 Research and Development Objectives

The overall technical objective for the Multisystems R&D project was to research, design, and validate a BRT microsimulation model. The model would need to be comprehensive and robust enough to provide transit planners with an understanding of how the range of BRT strategies could enhance service quality and efficiency. The model intended for development would need to be readily usable by a variety of transit agencies and other planning organizations, without the need to code full-fledged transportation networks. It would need to have a simple user interface that would allow transit planners to readily change the BRT system parameters and produce output that could be easily interpreted and assimilated and communicated to transit decision-makers. The BRT microsimulation application would also need an easy-to-use back end to facilitate rapid processing, analysis, and interpretation of the results of different BRT configurations. It became apparent that a transit-centric application of the model would be most appropriate.

Other preliminary objectives for this R&D changed as the R&D progressed. While the research proposal called for incorporating a broad set of operating variables, including factors related to bus design, fare media, dwell time, ITS technology, bus right-of-way characteristics, and passenger demand, the inclusion of all these variables was modified for a variety of reasons. For example, the VISSIM© software platform provided for input of single boarding and alighting rates, requiring that these rates be estimated based on the impact of features affecting dwell time (such as vehicle design, fare collections, loading, etc.). Similarly, the incorporation of traffic impact factors was modified. Although the original intention was to use friction factors based on Highway the Capacity Manual (HCM) Level of Service (LOS) guidelines to simulate the affect of adjacent traffic volumes, the VISSIM© platform enabled the project team to include the stochastic impacts of traffic directly using microsimulation of traffic at key points in the model. The project team concluded that this produced more “realistic” results in its BRT simulation application while reducing the demand on the model user.

The identification and/or development of mathematical representations of BRT operating factors was limited. Instead, the project team used many default values of the VISSIM© simulation platform, which had been validated in many other applications of that product. Based on the availability of literature on dwell time, a decision was made to combine its constituent factors into the boarding/alighting rates used for the BRT application. These are described later in the report.

The original objective to produce model output that could be readily transferred into transit agencies’ operating and capital cost models was modified by the project team. The potential outputs of the model should be sufficient for agency operating cost models that rely on vehicle revenue miles, vehicle revenue hours, and peak bus requirements. As indicated in the project proposal, an integrated cost module could be developed during an SBIR Phase 2 project.

⁷ Gunnar, Lind et al. “Best Practice Manual.” Simulation Modeling Applied to Road Transport European Scheme Tests (SMARTTEST), Institute for Transport Studies, University of Leeds. May 1999.

2.2.3 *Specific Technical Questions*

The answers to the specific technical questions identified in the project team's proposal will be addressed throughout the remainder of this document. Several comments are appropriate here.

The project team determined that the range of operating variables relevant to BRT systems could be integrated into a BRT application. However, these variables might take different forms than originally intended. For example, the impact of an AVL/CAD system would be difficult to model directly, but modeling the input of AVL-enabled control strategies is possible. Model objects can be coded into the model that allow measurement of operational control strategies that would be possible with an AVL/CAD system, such as schedule adherence or headway maintenance. In fact, a headway maintenance subroutine was developed, although it was not used in the validation version of the model. Finally, operating parameters of various model components related to running time and reliability were adapted from existing research.

The question of developing a BRT microsimulation application that minimizes the transit user's data input requirements – without substantially affecting the relative accuracy of the model's output – remains to be answered. Due to inherent limitations in the test data for model input and validation obtained from the transit agency whose corridor was used in the validation phase, additional model component verification,⁸ validation runs, and scenario testing must be performed using statistical confidence measures.

As discussed in Section 2.2.2, the use of traffic LOS measures to estimate traffic impacts on BRT operation was not required. Because of the flexibility of the VISSIM© simulation platform, it was possible to introduce estimated traffic volumes into the bus right-of-way and in an adjacent traffic lane to simulate the impact of traffic on the BRT system.

Lastly, the technical question about integrating the BRT simulation application with a full-fledged microsimulation project became a moot point when this kind of product was adopted as the research and development platform.

⁸ In fact, in many ways the data were excellent for service planning purposes. Its utility is limited only in the context of developing and validating the simulation model.

3. Research Tasks and Findings

Research for the BRT microsimulation project was undertaken to develop a thorough understanding of the potential elements for inclusion in the BRT microsimulation application. This task formed the basis for:

- Evaluating the primary project hypotheses;
- Establishing a clear purpose for the model application;
- Determining the simulation approach and methods;
- Defining the user needs and functional requirements of the model; and
- Selecting an appropriate microsimulation platform for developing the BRT simulation application.

The research included a crosscutting review of literature related to BRT features, a review of the FTA's BRT program and related documentation, and an investigation of potential software platforms for building the BRT microsimulation application.

3.1 Evaluate Primary BRT Research Hypotheses

This section evaluates the primary project hypotheses that guided – and were changed by – the SBIR R&D effort.

3.1.1 *Transit Agencies Need a Tailored BRT Modeling Tool*

Two recent studies conducted by researchers at the California PATH Program (University of California at Berkeley) explored the institutional issues surrounding BRT planning and implementation and contained several findings relevant to the BRT simulation model development. In their description of intergovernmental issues, the PATH researchers identified the inherently different and often competing objectives that organizations such as transit agencies and traffic departments might have regarding BRT systems. More specifically, the first study states that, “To have a system that works effectively requires the transit agency to achieve agreement with localities and other agencies on infrastructure, operations, and responsibilities.”⁹ The report further notes that transit agencies are often regarded as “tenants” of traffic departments’ roadways and that BRT planning and implementation requires the cooperation of these organizations.

The PATH researchers investigated intra-agency barriers that may develop within transit agencies. “For many transit agencies most of the BRT strategies are foreign. Agencies may need time and resources to locate or develop both design and operational standards for many of these strategies.”¹⁰ In the second study, which expands on the first with a survey of FTA Bus Rapid Transit Consortium members, the researchers identified the need to integrate the multiple, sometimes competing objectives of agencies involved in BRT development. They also found that educating the public while managing expectations was particularly important to transit agencies.¹¹

The project team’s interpretation of these important research findings confirms two of its initial hypotheses. First, transit agencies’ status as “tenants” supports the assertion that they will generally be responsible for initiating discussions about BRT development with traffic agencies. In doing so, they would be well served to have done sufficient modeling of a BRT system to communicate which features, including possible traffic flow or infrastructure changes, appear to provide the most benefit to transit

⁹ Miller, Mark A. and Stephen M. Buckley. Institutional Aspects of Bus Rapid Transit – A Macroscopic Examination. California PATH Working Paper, UCB-ITS-PWP-2000-7. July 2000: page 11.

¹⁰ Ibid., page 12.

¹¹ Miller, Mark A. and Stephen M. Buckley. “Institutional Issues of Bus Rapid Transit: The Route from Research to Experience.” California PATH Program, Institute of Transportation Studies, University of California at Berkeley. Draft paper submitted August 2000 for presentation and publication at the 80th Annual Meeting of the Transportation Research Board, January 2001: pages 13, 14, 16, and 20.

customers and operations. Showing an appreciation for, and understanding of, potential traffic impacts would also be important when initiating talks. For example, demonstrating to traffic engineers that conditional signal priority can vastly reduce the impact on the signal system (in terms of reducing the number of priority requests granted) could be crucial in establishing initial cooperation.

The PATH studies also appear to support the project team's hypothesis that providing tools capable of performing the type of analyses proposed herein was well founded. The project team feels that its BRT simulation application would increase transit agencies' internal understanding of how advanced technologies might be used in the context of BRT development. Readily interpretable and reasonably "realistic" performance measures would help transit agencies decide whether or not to proceed with BRT development, when and how to initiate coordination efforts with local agencies, and how to manage both internal and external expectations.

3.1.2 *Minimize Simulation Overhead*

Because minimizing the start-up overhead of BRT simulation is one of the essential elements defining this R&D project, it was important to research its validity. A number of sources were instructive in this regard.

In a study of bus transit improvements preceding the BRT Program, the obstacles to implementing bus service improvements were defined.¹² Lack of funding was identified as the predominant obstacle by the 24 transit experts who took part in the study's survey. Although the funding issue was not specifically focused on transit planning resources, the project team believes the authors' research findings support the start-up overhead hypothesis. That is, planning costs for BRT must be reasonable, even in the initial stages, especially because other projects and needs are competing for the same staff and budgetary resources.

Other common obstacles noted in the report were lack of ideas and initiatives, lack of cooperation with other agencies, poor understanding of operational problems, unawareness about possible feasible solutions, and lack of data and technical material.¹³ The SBIR research team determined that each of these barriers could potentially be overcome with a BRT microsimulation model tailored to the needs of the transit industry.

In another report about overcoming the hurdles to using simulation for modeling ITS deployment efforts (which have many applications in BRT), the authors note that:

...simulation has long been recognized as a powerful tool for such analysis [but] it has not been greatly utilized by practitioners. This can largely be attributed to the lack of software tools for preparation and manipulation of the required input data for the simulators...the fundamental problem has to do with the access and use of essential information. Specifically, collecting, storing, checking, and updating traffic data required in simulation is usually a long and arduous task. In addition, entering that information into a specific simulator often requires many intense hours of effort.¹⁴

This study helped confirm the project team's working hypothesis that the overhead of using traditional traffic-centric microsimulation tools is a major barrier for transit properties that need to simulate BRT systems.

3.2 Establish Model Purpose

A critical first step in researching and developing the BRT microsimulation model was to establish its context and purpose. This is a prerequisite for developing any simulation model. In the project proposal, the purpose was intentionally broad, owing to the fact that the model purpose could not be fully defined

¹² "The Bus Transit System: Its Underutilized Potential." Op. Cit., page 3.

¹³ Ibid., page 28.

¹⁴ Michalopoulos, Panos G. and John Hourdak. "Simplifying Simulation for ITS Applications." Proceedings of ITS America 10th Annual Meeting and Exposition. August 1999; page 3.

until the research had commenced. The purpose of a simulation model should be to explain the general use of the tool. Bossel underscores this by stating:

The original problem setting circumscribes a certain domain of application in which the model can be expected to supply valid answers. This means that the range of possible answers is limited. This range of answers determines the model purpose. Modeling efficiency requires limiting the application domain and the model purpose.¹⁵

As described in Section 2.1 above, the FTA's BRT Demonstration Program provided a wealth of information regarding the BRT program's context and purpose, which pertained to establishing the purpose of the BRT modeling application. However, the project team's research on simulation modeling showed that the context and range of potential purposes evidenced by the FTA's objectives were too broad for this R&D project. In the context of an SBIR Phase 1 research project, it would be impossible and counterproductive to research and construct a proof-of-concept BRT simulation model that incorporates most of FTA's goals. Law and Kelton, authors of a major text on simulation modeling, encourage the notion that the development process must include far less detail than the actual or desired system to be modeled.

Although there are few firm rules on how one should go about the modeling process ... The model should contain only enough detail to capture the essence of the system for the purposes for which the model is intended; it is not necessary to have a one-to-one correspondence between elements of the model and elements of the system.¹⁶

These experts also state that models with excessive detail may be too costly to execute, which was one of the project team's primary concerns. With this in mind, the project team determined that it would need to be very selective in choosing which BRT elements to model and how to do so. Therefore, the originally broad purpose was narrowed down to focus on a transit-centric approach which would incorporate a subset of BRT components that emphasizes transit route operation and quality of service. Any features shelved because of this approach would need to be included in future builds of the application.

3.3 Determine Simulation Approach

The model's purpose and the simulation approach are interdependent. Therefore, the simulation methods that are chosen must be consistent with the model's purpose. Therefore, it was important to consider the different simulation approaches before determining which software platform to employ. For example, it would not be very effective to model a system with numerous sources of variability using a deterministic modeling tool.

There is a wide range of simulation model techniques to consider in developing BRT simulation model. Some of the major options, drawn from Law and Kelton, are shown in Table 3.1.¹⁷

The project team determined that BRT system modeling would be most accurate using dynamic, stochastic, and discrete simulation techniques. Dynamic simulation was selected even though it is time-dependent because the route schedule and actual field conditions can change dramatically due to fluctuations in passenger demand and traffic (congestion) as the operating/modeling period progresses.

A stochastic approach to modeling BRT systems was deemed necessary by the project team because of the numerous sources of random variation in operating bus routes. Few factors in bus operations, if any, are actually deterministic. The challenge would be to decide which stochastic variables to include.

The discrete event method was selected because microsimulation of the behavior of individual buses and other model objects such as cars would be needed to capture the "realistic" interaction of these objects as

¹⁵ Bossel, Harmut. Modeling and Simulation. A K Peters, Ltd., 1994: page 36.

¹⁶ Law, Averill M., and W. David Kelton. Simulation Modeling and Analysis. McGraw-Hill, Inc., 1999: page 107.

¹⁷ *Ibid.*, pages 6-7.

it might occur in a real BRT system. This means creating a model that can simulate the impedance or friction among individual model objects.

On a more fundamental level, the discrete event technique was adopted because discrete simulation output is in countable units of change in model variables. This form is needed to quantify changes in the system so that the impact of different options can be easily compared. This decision is consistent with the perspective that simulation modeling is best suited to compare different system configurations but not to produce absolute results. In contrast, continuous simulation focuses on rates of change. This form of output is not suitable for measuring the BRT system variables required for the model purpose identified.

Table 3.1: Simulation Model Approaches

Simulation Modeling Choices	Comparison
Static vs. Dynamic	Static simulation is best for modeling systems that do not change over time. Dynamic simulation is used for systems that evolve over time.
Deterministic vs. Stochastic	Deterministic models are best suited for systems that do not contain random variations in operation. Stochastic modeling is required when randomness needs to be captured in model output.
Continuous vs. Discrete	Continuous simulation can be used when the behavioral impact of objects (such as buses and cars) in the model can be aggregated. Discrete modeling is preferable when the behavior of individual model objects is important for accurate representation of the system being studied.

3.4 Develop User Needs and Functional Requirements

In the SBIR R&D proposal, the project team presented an overview of user and functional requirements. User requirements are intended to explain how users will interact with the model – what technical know-how they will need, what data will be required, and how easily it will be to produce the desired output. The SMARTEST traffic microsimulation research project, which included most of the major commercial and private research simulation software packages, offers a succinct summary of user requirements in its “Best Practice Manual.” It states, “Specific user requirements are user-friendliness, short lead-time before use, validated results, limited need for expensive data acquisition and high cost effectiveness when comparing quality of result and resources in time and money spent in the simulation.”¹⁸ Moreover, the review task of the SMARTEST study found that only 53% of the software packages supported limited data acquisition; 41% supported easy integration with other modes; and 31% could be integrated with GIS and other databases.¹⁹

The functional requirements are intended to describe how the model should work. This includes a description of the desired model components, required and optional data inputs, user-defined parameters, and default or lookup values where specific data are not available. As described in Section 2.1, the FTA’s BRT Demonstration Program covers such a vast range of potential model features that it was necessary to develop high-level functional requirements that could guide the production of a proof-of-concept version within the project scope. Law and Kelton provide some direction in this regard: “The level of model detail should be consistent with the type of data that are available. In some simulation studies, time and

¹⁸ “Best Practice Manual.” Op. Cit., page 13.

¹⁹ Although the original SBIR project scope included a telephone user needs assessment, this task was eliminated. The project team learned from the researchers at PATH of the previously cited studies that their work would likely obtain much of the user information required. When their preliminary results were reviewed and determined sufficient for the user needs assessment, the project resources were reallocated.

money constraints are a major factor in determining the amount of model detail.”²⁰ Since the incorporation of full traffic and roadway geometry were minimized, that meant relying on the available transit operations data that could be readily obtained.

As the BRT model research progressed, the delineation between user and functional requirements blurred as their interdependence became more obvious. Therefore, the discussion in the remainder of this section combines the two concepts without necessarily distinguishing between them.

3.4.1 *Functional Requirements Chosen from the BRT Demonstration Program*

Material from the FTA’s BRT Demonstration Program provided a wealth of information to refine the model’s functional requirements. However, since a first phase SBIR R&D project could not address all of the features identified in the federal program, the project team decided to focus on a subset that were considered most likely to achieve a primary objective of the BRT Demonstration Program – reducing travel time and delay.²¹ This choice required a good deal of debate among project team members to determine what elements would be included. Law and Kelton provide excellent direction in this regard when they observe that, “Modeling each aspect of the system will seldom be required to make effective decisions, and will also be infeasible due to time, money, or computer constraints.”²²

With this in mind, the project team assessed which parts of the FTA’s BRT Program could be included in the general functional requirements, which would form the foundation of the actual simulation model. The solution was to focus the BRT simulation model on those elements that would contribute to measuring travel time, delay, and related metrics. These included the following:

- Bus speed and reducing travel time;
- Reductions in dwell time;
- Service reliability such as improved on-time performance; and
- Signal priorities granted.

As discussed in Section 4 below, the functional requirements used during model development categorized these measures into three categories: operational performance, customer satisfaction, and traffic impacts. Productivity measures, such as passengers per vehicle hour and passengers per vehicle mile, were also considered as potential model outputs.

The FTA’s BRT Demonstration Program also indicated that technical support should enable BRT developers to quantify incremental deployment of BRT systems. This would allow implementation to be phased in stages to “relieve the budgetary pressures on transit agencies...(so that)... the operator can realize incremental benefits in terms of reduced delays.”²³ This provided another important guideline for the project team’s functional requirements.

Other elements of the FTA BRT Demonstration Program, such as marketing and land use impacts, were not included in the proof-of-concept application since they were deemed incompatible with the basic model purpose, emerging structure, required input, and desired output. Moreover, the research literature that was necessary to quantify their impacts was perceived to be scarce, based on the preliminary literature search.

Consistent with the potential output measures listed above, the following FTA BRT strategies were finally considered by the project team for inclusion in functional requirements:

- Right-of-way changes, such as operation on bus lanes, in mixed traffic, or on busways and related traffic management improvements, etc.;
- Components that had been identified to reduce bus stop dwell time, such as alternative or advanced bus technologies that could help reduce delay from the alighting/boarding process, bus design

²⁰ Simulation Modeling and Analysis. Op. Cit., pages 17-25.

²¹ “Issues in Bus Rapid Transit.” Op. Cit., pages 3-4.

²² Simulation Modeling and Analysis. Op. Cit., pages 17-25.

²³ “Bus Rapid Transit Demonstration Program.” Op. Cit., page 5.

features such as low-floor or dual entry doors, and other enhancements such as automated fare collection;

- Signal changes, including signal preference for buses;
- Fare payment strategies, including off-vehicle fare payment, front and rear door payment, self-service or proof-of-payment systems, and prepaid stored-value automatic collection systems such as smart cards; and
- Integration of ITS technologies, such as automatic vehicle location or identification (i.e., AVL/CAD and AVI).

ITS components associated with bus tracking and real-time dispatch were of special interest to the project team since a limited amount of research material quantifying related benefits was found. The limited use of real-time operation control strategies appeared to be an area ripe for BRT simulation. Other ITS systems, such as customer information strategies, were not included in the research because the project team felt that it would be difficult to measure their impact in the model.

3.4.2 Choice of Simulation Model Components

The specification of being selective when choosing which BRT elements to simulate implies secondary functional requirements. First, the end users would need to use discretion in choosing which elements to model. This means that a useful BRT simulation application would need to have a reasonable selection of possible BRT components that a transit agency could simulate even if these components might not be used in all cases. Thus, the BRT simulation model should be built with more elements than any single agency might actually model within the constraints of simulation model complexity described in Section 3.3.

3.4.3 Data Input Requirements

As determined by the BRT simulation model's purpose (see Section 3.1), the user and functional needs should be transit-centric. This functional requirement placed maximum importance on variables related to BRT operation. This suggests development of a model that could be sufficiently validated with typical transit agency field data. Because transit agency field data usually consists of some combination of passenger activity by stop and/or timepoint, point-to-point running times, schedule adherence, and loading profiles, it is readily available to transit agencies. However, this simplicity also presents some potential limitations for validating the model since it limits the data points with which validation can occur. This is discussed further in Section 4. However, the project team felt that any potential limitations would be offset by the fact that most transit agencies regularly collect this type of data. They are comfortable working with these data for service planning purposes, which are not unlike BRT planning.

The focus on a transit-centric model also indicated that the coding of the traffic and transit network and related entities should be minimized to the extent practical to obtain realistic results. General rather than detailed information on roadway and intersection geometry, traffic volumes, and signal system characteristics should be all that is required of the user.

3.4.4 Model Different Rights-of-Way in Same BRT System

From its experience with transit service planning in many major metropolitan areas of the United States, the Multisystems project team pursued the R&D project believing that most BRT implementation in the United States would require using a mix of right-of-way types – busways, exclusive bus lanes, priority lanes, contra-flow lanes, queue jump lanes, and mixed traffic lanes. Most transit agencies do not operate under ideal conditions where the existing infrastructure or space permits the implementation of an ideal BRT system that only uses bus lanes or exclusive rights-of-way. For example, outside of a CBD, a BRT route may have an exclusive bus lane on either an expressway or multi-lane arterial street. But, as the route alignment approaches downtown, the lack of space may require operation in mixed traffic. A good case in point is Ottawa, Canada, one of the most highly touted BRT systems in North America. Its alignment operates on 60% exclusive right-of-way, 30% in priority lanes, and 10% in mixed traffic. The Euclid Corridor project, part of the FTA's BRT Demonstration Program, has been designed to operate 74% on exclusive right-of-way and 26% in mixed traffic lanes.

An informal review of information about existing or planned BRT systems, primarily information about BRT Consortium members available on the BRT Web site²⁴ was performed to identify what mix of rights-of-way was already in use or under development. Unfortunately, this information was not readily available in sufficient detail to develop a composite picture of actual or planned BRT alignments. Nonetheless, in one of the previously cited PATH studies of BRT institutional issues, three of the most highly rated issues were related to rights-of-way.^{25,26}

Given this background, the project team's initial hypothesis of developing a BRT simulation application capable of modeling different right-of-way configurations was deemed an important functional requirement.

3.4.5 Model Operational Control Strategies

According to the literature search, ITS technology is a potentially significant factor in the successful operation of BRT systems. ITS technologies are touted as having significant benefits for bus operations and BRT systems. However, controlled before and after studies measuring actual benefits are not common. The primary transit ITS technology that could have an impact on the performance measures being modeled in the BRT simulation is an AVL/CAD system. This suggests that one requirement of a BRT simulation application should be the ability to model operational control strategies that use information from, and execute control instructions determined by, an AVL/CAD system.

AVL/CAD is the ITS technology most commonly deployed by transit properties. These systems are usually procured initially for operational purposes, such as improving service quality and reliability. Nevertheless, the typical operational control strategy used is schedule adherence. However, many other control strategies, some of which are employed without the use of AVL/CAD, are available. Unfortunately, strategies for using AVL to improve bus system performance are not well understood at this time.

Evidence in the literature indicates that bus operators with AVL generally have not made full or effective use of the AVL capabilities, including to improve passenger information, driver/dispatcher information, schedule adherence, and transfer coordination.... Rather, AVL systems are mostly used for security and service monitoring purposes.²⁷

An ongoing study is being conducted on Portland Tri-Met's Bus Dispatch System (BDS), which uses a GPS-based AVL/CAD system.²⁸ The researchers reported that the BDS deployment has shown measurable – if not dramatic – improvements in performance and reliability as compared to baseline data collected before the system was deployed. This was true even though the system was being used in a passive mode (i.e., operators, dispatchers, and supervisor were simply reacting to reports of the most serious operating problems at any given time). The authors note, however, that active use of the BDS in the future may exploit the full potential of operational control strategies and create significant improvements in operational efficiency and service reliability.

A partial list of control strategies includes schedule adherence, headway maintenance, bus speed adjustments, leap-frogging, stop skipping, and real-time short-turns. Since the range of possible operation

²⁴ The URL for this site is <http://brt.volpe.dot.gov/>.

²⁵ "Institutional Issues of Bus Rapid Transit: The Route from Research to Experience." Op. Cit., pages 13 and 15.

²⁶ Ibid. These issues were opposition to removing or restricting curb lane parking; physical availability of space for rights-of-way; and the potential impact of BRT systems on traffic operations. The rating was based on the study participants' combined ranking of how difficult an issue would be to resolve *and* their perceived importance of the issue.

²⁷ Chira-Chavala, T. et al. "Bus Operations in Santa Clara County, Potential Uses of AVL, and Framework For Evaluating Control Strategies." Institute of Transportation Studies, University of California, Berkeley. California PATH Research Report No. UCB-ITS-PRR-99-25. June 1999: page iv.

²⁸ Strathman, James G. et al. "Automated Bus Dispatching, Operations Control, and Service Reliability: The Initial Tri-Met Experience." Center for Urban Studies, College of Urban and Public Affairs, Portland State University. TRB Paper No.00-0636. October 1999.

control strategies is so broad, modeling them would be an extremely useful endeavor before choosing the bus tracking system that a BRT route would use and exploring the optimal mix of them.

3.4.6 Functional Requirements of Model Output

A simulation model is only useful if it produces results that are easy to understand, easy to interpret, and intuitively appropriate for analyzing and comparing different BRT configurations. (As noted in Section 3.1, simulation is intended for comparing different system configurations, not for producing absolute results.) This includes selecting the proper set of validation measures, since the BRT simulation application developed for this project will necessarily require some validation testing before use in particular transit environments.

Because model credibility can be enhanced by showing animations of the system being studied, it is an essential functional requirement. Animation provides transit planners and managers with the opportunity to see if the model “looks right,” rather than relying on numerical or statistical output.

3.5 Microsimulation Research and Selection of the Software Platform²⁹

The project team originally intended to build the BRT simulation application with a process engineering simulation platform such as Matlab/Simulink®, Modsim®, Prosim®, Simprocess®, Arena®, etc. This was due to the belief that one of these packages would eliminate the perceived overhead demands and resulting constraints of traditional traffic simulation programs. The project team also believed that most of the available traffic microsimulation programs were not designed to support bus planning in general, nor especially at the level of detail required for testing on a specific corridor.

The SMARTTEST traffic microsimulation research project generally showed that this was the case.³⁰ The study found that only 52% of the software packages reviewed supported objects or phenomena needed for a public transportation model; 41% supported easy integration with other models; and 31% could be integrated with GIS and other databases. Of particular interest was the finding that only 26% included measures for transit regularity. Overall, only 6% of the microsimulation models included public transport information. “Traffic efficiency from the designer point of view concerns one type of transport, typically by car, and does not concern other types.”

There was also an expectation that a process engineering platform would afford more flexibility in customizing the application to BRT planning and would support the development of model objects unique to the purpose of the simulation application. For example, an essential model object identified by model users interviewed for SMARTTEST was public transportation stops.³¹

A set of criteria was developed to evaluate the potential simulation platforms. In retrospect, these criteria were in many ways similar to the functional requirements being defined for the transit agency user. They included the following:

- Minimize start-up overhead in terms of cost, training, and data requirements;
- Support the simulation approach and techniques identified in the functional requirements;
- Be easy to use and customizable to the BRT simulation task;
- Have an object-oriented design to allow the development of subroutines for unique model objects;
- Contain a customizable graphical user interface for building and testing the BRT simulation application; and
- Support animation of the model results.

²⁹ Since this SBIR R&D project was not designed to evaluate traffic simulation models, the review of simulation tools only represents the project team’s interpretation of information it had at the time of the research. Therefore, the evaluation of traffic simulation programs is not meant to be exhaustive nor definitive.

³⁰ Algers, Staffan et al. “Review of Micro-Simulation Models.” Simulation Modeling Applied to Road Transport European Scheme Tests (SMARTTEST), Institute for Transport Studies, University of Leeds. August 1997: pages 7-9.

³¹ Ibid., page 22.

The software research, which included reading product literature, talking to technical representatives, and testing demonstration versions of some software packages, showed that none would be appropriate for the R&D effort. Some were too costly, others did not have the ease of use and development flexibility required, and some did not support animation. None had the model object structure needed to include the necessary BRT components, which would have required programming even the most basic model constructs. As indicated by Seneviratne, the ability to microsimulate route and passenger demand characteristics is important since it improves the predictive accuracy of the model when applied to different settings.³²

Therefore, the project team ultimately decided to find a traffic microsimulation package from which the BRT simulation application could be built with a transit-centric focus. Reviews of product literature and the SMARTTEST research narrowed down the search quite quickly. First, many software packages were eliminated because they lacked an animation function. Second, most other products were eliminated because they did not appear to have the ease of use required. In particular, only 7 of the 32 products assessed by the SMARTTEST project had a graphical user interface for network coding.

A demonstration of VISSIM©, one of the packages that had the desired coding interface, was a critical factor in choosing it as the microsimulation platform for this SBIR R&D project. “Although links are used in the simulator, VISSIM does not have a transitional node structure. The lack of nodes provides the user with the flexibility to control traffic operations...”³³ Its user interface for creating the BRT configuration and related traffic network offered the simplicity and flexibility that was determined accessible to transit agency users. While certainly not the only possibility, this choice was supported by two other facts:

- VISSIM© had been rated highly for transit system modeling by the SMARTTEST microsimulation software evaluation commissioned by the European Union; and
- Existing BRT implementation projects, such as the Lane Transit District and the Miami Dade Transit District, both members of the FTA’s BRT Demonstration Program, were using the software for full-fledged modeling and design, and traffic signal priority modeling, respectively.

Finally, from the demonstration described above, the VISSIM© platform was considered ideal for enabling the project team to include the stochastic impacts of traffic directly using microsimulation of traffic at key points in the model. The project team concluded that this would produce more “realistic” results in its BRT simulation application while reducing the demand on the model user.

3.6 Summary of Research

Because the research on potential software platforms pointed toward adopting and creating a BRT application using a traditional microsimulation model, the need to create a highly detailed model architecture was eliminated.

At face value, the dynamic, stochastic, and discrete event modeling approach selected by the project team would apparently lead to a more complicated model application, one which could reduce the simplicity requirement defined in the model purpose. The actual result, however, is that it forced the project team to

³² Seneviratne, P.N., et al. “Scheduling Fixed Route Bus Services Using Simulation.” Microcomputers In Transportation, No date: page 1052.

³³ Bloomberg, Loren and Jim Dale. “A Comparison of the VISSIM and CORSIM Traffic Simulation Models on a Congested Network.” Paper submitted for the 79th annual meeting of the Transportation Research Board. January 1999: page 4.

choose a simulation platform and specify the structure of the BRT application to avoid the barriers of simulation modeling noted in Section 3.1.1. Although not originally envisioned, selective microsimulation of traffic is included to add to the stochastic nature of bus operations.

Finalizing the user and functional requirements was an iterative process that involved selecting the simulation software platform because these two tasks were highly interdependent. Moreover, as Law and Kelton note, “It will often be necessary to use one’s experience or intuition to hypothesize how certain components of a complex system relate, particularly if the system does not currently exist in some form.”³⁴

³⁴ Simulation Modeling and Analysis. Op. Cit., page 309.

4. Develop, Build, and Test Model

Once decisions had been made about the modeling approach and the software platform that would be used, the Multisystems project team began to build a proof-of-concept BRT microsimulation application. The project team faced a balancing act between the functional requirements it had identified (such as the transit-centric focus of the model) and the inherent concern about traffic impacts. Actually developing a proof-of-concept BRT application, even using a traditional traffic microsimulation platform, became an enormous challenge. Often during the process, the team had to refocus itself with a number of the guidelines the research process had produced. The essential guidelines were:

- Do not start out with an excessive amount of model detail since the model can be embellished later if needed; and
- Simulation models are better for comparing alternatives than for determining absolute answers. Simulation is as much an art as it is a science.³⁵

The elements of the model development task changed over the course of the project. This was due primarily to the selection of the VISSIM© traffic microsimulation software, since it already contained many of the model objects needed. Of particular importance was its recently developed transit passenger module.

This task involved:

- Select test corridor;
- Select and develop model components;
- Verify model components; and
- Build and validate the test simulation corridor.

4.1 Select Test Corridor

One of the first steps in building the BRT simulation application was to select a real bus corridor that would be used as the test corridor. Four criteria were identified for selecting the test corridor:

- The basic geometry of the street network should be suitable for BRT operation. This meant that the average number of lanes and the potential availability of using existing space for BRT operation was required;
- Traffic information, such as the Average Annual Daily Traffic (AADT) volumes on the corridor and the traffic signal timing, would be necessary;
- The test corridor should be served already by a bus route that could be used to validate the simulation. The route would need to have substantial ridership and a service frequency of not less than six buses per hour; and
- Current operating data had to be available for the bus route in the same corridor, consisting of passenger demand and travel times for validating the BRT system.

Selecting the test corridor early in model development was important because the test corridor would need to meet the criteria listed above. It would also have to be appropriate to the functional requirements of the simulation application that had been developed earlier, as described in Section 3.

After considering corridors in several cities where Multisystems is performing bus service planning studies, a corridor in Washington, DC, was chosen as best fitting three of the four criteria. Once the project team was able to obtain the necessary traffic information from the DC Department of Public Works, all of the criteria were met. Also important in this selection was that WMATA officials had already identified the corridor as a potential candidate for BRT development. Moreover, the breadth of the service planning study being conducted meant that the proof-of-concept BRT application might be tested under actual conditions.

³⁵ Simulation Modeling and Analysis. Op. Cit., page 307.

The bus corridor that was selected follows the X2 Metrobus route operated by WMATA. It is comprised of Benning Road from the Minnesota Avenue Metro Station at the edge of Southeast Washington, DC, runs across the Anacostia River to the intersection of Maryland Avenue, Florida Avenue, 16th Street NE and H Street, and then continues on H Street. The east-west path through the city starts in a primarily low-income residential neighborhood and runs through the downtown business area, terminating at Lafayette Park near the White House.

Benning Road is a wide, heavily traveled commuter artery with three full-time travel lanes and a parking lane that becomes a travel lane during the peak periods. East of North Capitol Street, H Street is bordered by a mixed residential and business area and has two travel lanes and a curbside parking lane. Some of the blocks bordering H Street west of North Capitol Street have high-rise office buildings. Most of the route has two travel lanes and one parking lane. Both Benning Road and H Street cross numerous high-volume north-south streets, including 4th and 6th Streets NE, North Capitol Street, and 14th, 15th and 16th Streets NW.

The length of the BRT test corridor is about six miles. It includes approximately 32 bus stops in each direction, with an average spacing of .2 miles (or about 1,000 feet). As is typical for many long, commuter-oriented bus routes, stops near the eastern terminus have very high boarding rates and low alighting rates with that pattern reversing in the downtown area. A major transfer point is 6th Street NE, where the trunk of route 90 crosses H Street. The X2 route operates exclusively with articulated buses that have a standing capacity of 80 riders. The route has high passenger volumes throughout most of the day. Peak headways are approximately seven minutes, and off-peak headways are about 10 minutes.

Although the corridor met the criteria posed above, it is not without limitations vis-à-vis using it as the test corridor for the BRT simulation application. For example, the fact that it crosses several arterials that have higher traffic volumes meant that there could be potential problems with modeling changes to the signal system and using relatively constant traffic flows without regard to cross street impacts.

4.2 Select and Develop Model Components

Once the test corridor had been identified, the Multisystems team could proceed to select components for inclusion in the working BRT application. Components were selected based on three general criteria:

- The number of components would need to be limited in accord with the model building guidelines described in the introduction to this section and in Section 3.3, especially the functional requirement for creating a transit-centric simulation application;
- The components would need to be directly related to the desired output measures identified in Section 3.4; and
- The components would have to be “codable” within the VISSIM© microsimulation software platform, including use of the program’s internal detector and signal programming language, VAP.

The process of integrating these components into the overall simulation application was guided by the specific BRT functional requirements discussed in Section 3.

4.2.1 BRT Right-of-Way

Regular bus routes and BRT systems can and do operate in a variety of rights-of-way. Different sources describe a variety of designs for lane characteristics for bus operations.³⁶⁻³⁷⁻³⁸⁻³⁹ A BRT system may use a combination of exclusive right-of-way and mixed traffic lanes. Exclusive rights-of-way may be

³⁶ “The Bus Transit System: Its Underutilized Potential.” Op. Cit.

³⁷ Federal Transit Administration. “BRT Reference Guide.” <http://brt.volpe.dot.gov/guide/index.html>.

³⁸ Shen, L. David et al. “At-Grade Busway Planning Guide.” National Urban Transit Institute, Lehman Center for Transportation Research, Florida International University. December 1998.

³⁹ Kittelson & Associates, Inc., Texas Transportation Institute, Transport Consulting Limited. “Transit Capacity and Quality of Service Manual.” Transit Cooperative Research Program, Transportation Research Board, National Research Council. January 1999

constructed in dedicated busways, median lanes, or in curbside lanes, with or without physical separation from mixed traffic. In some cases, the right-of-way may operate contra-flow because of the inherent exclusivity this creates. Different combinations of these bus lane characteristics are possible. For example, Montreal's PIC IX BRT uses a median lane operating in a contra-flow direction. Mixed traffic bus lanes can operate either in a curbside lane or adjacent to existing curbside parking.

Because the project team believes curbside lanes and, more particularly, mixed traffic lanes will be a staple of many BRT configurations, it decided to choose this as one of the BRT simulation components. In addition, the project team decided that curbside lanes produce a complex simulation challenge because of the inevitable interaction with traffic lanes. Although having a BRT lane adjacent to an existing curbside parking lane could have been chosen, it was decided that modeling the impact of vehicles using curbside parking would unnecessarily complicate the proof-of-concept BRT simulation application. Besides, as already noted, the X2 route on the H Street test corridor already uses curb parking lanes during peak periods.

Although VISSIM© is exceptionally user-friendly for creating the exact geometry of the street network, the full lane configuration in the test corridor, which was alternately two, three or four lanes, was not coded. This approach was consistent with the functional requirement of limiting the modeling overhead, including detailed coding of the traffic network. Instead, the primary objectives were to configure a BRT corridor that would enable sufficient simulation of traffic as an impedance to BRT operation (and vice versa) and to allow buses in the system to pass each other in the simulated network. The latter objective would be important for modeling a BRT system operating in concert with a local bus route in the same corridor. This configuration is already common on limited stop bus routes.^{40,41} Therefore, only the lane used by the bus and one or two adjacent traffic lanes were included in the test network.

The project team also experimented with VISSIM©'s capability to change the BRT right-of-way from a mixed traffic lane to an exclusive bus lane in the middle of the BRT route. To do this, a short "dummy" link connector was coded in-line at the downstream end of that exclusive lane link. The key to making this work properly is setting a parameter of the connector, which defines the distance upstream (from the connector) where cars would be forced to change lanes in conformance to the lane restriction being imposed. This distance is set at the start of the exclusive lane, the point at which cars are expected to begin merging into the adjacent general travel lane. Beyond the connector at the end of the exclusive segment, the cars were allowed to use all available lanes again.

4.2.2 Dwell Time Components

The operation of a BRT system is affected by a number of dwell time factors that can affect travel time, delay, and reliability. These factors include fare collection strategies, vehicle characteristics such as the number of passenger channels and low floor design, bus stop design, clearance time factors, etc. Bus stop design variables can incorporate bus stop size, bus stop placement either inline or offline (i.e., bus bays that are constructed outside of the travel lane), layout of the passenger area, boarding/alighting height, etc. These elements are largely reflected in the boarding and alighting rates. For example, level boarding with an elevated platform should increase boarding and alighting rates. Elimination of on-board fare collection will increase rates, as can use of Automated Fare Collection (AFC) technologies.

Using VISSIM©'s existing capabilities to microsimulate passenger activity is not straightforward. For each bus stop, the user defines a start time (when the first passenger will arrive at the stop), an end time (when the last passenger will arrive at the stop), and a rate of arrival (which must be expressed as an hourly rate). This last requirement necessitated that field data for passenger arrivals be manipulated in a spreadsheet to fit the required format.

VISSIM© provides an alternative to defining the passenger activity variables. The user can define distributions of dwell time (both normal and empirical distributions) for each stop that then control the

⁴⁰ Orosz, Theodore V., et al. "Limited-Stop Bus Service at New York City Transit." Paper prepared for presentation to the BRT Demonstration Program Consortium's at the Transit Operations Workshop. May 2000.

⁴¹ O'Malley, Kevin. "Western Avenue Express." Fact sheet prepared for the BRT Demonstration Program. May 2000.

behavior of passing buses. The advantage of this approach is that it is considerably faster to define average dwell times. But there are at least three drawbacks to this method. First, the ability to track passenger variables is lost. Second, the opportunity to simulate late buses, increased passenger queues, and the resulting cumulative delay is lost. Finally, the user would need to calculate the distributions using the field data of passenger activity for validating the operational behavior of the route.

Alighting rates are less problematic. These values are set separately for each stop. The user defines the percentage of those on the bus that will get off at each stop, and the percentage at each stop remains constant during the simulation. While this requirement may appear to be restrictive to the simulation, the bus passenger data obtained from WMATA show some consistency with this pattern. It may be necessary, however, to distinguish between peak and non-peak patterns. For both boarding and alighting, the user can specify either a fixed rate or use of a Poisson distribution, which will introduce more variability into the simulation.

The project team decided to use the first technique because it believed that results would be more reliable and would eliminate the need for the additional processing of field data. Since the WMATA field data did not include a bus stop arrival and departure time for each bus trip (as some transit agencies collect), which could have been used to extrapolate boarding and alighting rates, a simple external model was developed to create approximate input values using information from the literature. Table 4.1 shows the boarding and alighting rate model. The model can be easily updated if other rates or adjustment factors are identified. The average adjusted boundary values (A-5 and B-7) were used during the subsequent model validation task. This choice reflected the project team's assessment of the conditions present in the field.

The clearance time, a portion of total dwell time, was set at 12.5 seconds per stop. This was estimated from a number of sources, since no two sources seemed to agree on what defines clearance time. The figure used is similar to the average 11 seconds of lost time per stop for eight BRT systems analyzed in the "At Grade Bus Planning Guide."⁴²

4.2.3 *Transit Stop Spacing*

Because transit stop spacing is considered one of the critical factors in BRT travel time and delay performance, the project team needed to create a workaround in VISSIM© to provide flexibility for creating and testing multiple stop spacing scenarios. (New York City Transit reports that a doubling of stop spacing to create its limited stop routes has improved bus travel times between 14% and 21%.⁴³) The simulation platform allows the user to code multiple routes on a corridor, and individual stops may be programmed with information about which routes service the stop. Passenger route preferences may also be programmed in the bus stop design interface in VISSIM©.

Although routes and individual stops may be activated or deactivated on a case-by-case basis, this required developing individual routes for each desired stop spacing scenario. A minor weakness of the software's default capabilities is that buses on different routes in the same corridor appear to have difficulty passing each other in some circumstances. The reason for this was not identified, but would either need to be accounted for in later versions of the BRT simulation application or fixed in the VISSIM© platform.

⁴² "At-Grade Bus Planning Guide." Op. Cit., page 22.

⁴³ Figures adapted from "Limited-Stop Bus Service at New York City Transit." Op. Cit.

Table 4.1: Boarding/Alighting Rate Model

Rate No.	Source	Direction	High	Avg	Low	Conditions
ALIGHTING RATES						
A-1	Chapter 12 HCM	Alighting	2.5		1.5	Little baggage, few transfers.
A-2	Chapter 12 HCM	"	4.0		2.5	Moderate hand baggage or many transfers.
A-3	Chapter 12 HCM, TCQSM	"	2.0		1.7	Typical values, conventional bus, single door, single coin fare.
A-4	Alighting Rate Boundary Values	"	4.0	2.8	1.5	High value from rate A-2 and low value from A-1. Simple average of high and low values.
A-5	TCQSM Adjusted Boundary Values	Alighting	2.88	1.98	1.08	Boundary values adjusted for heavy 2-Way flow (C-1) and double channel door (C-3).
BOARDING RATES						
B-1	Chapter 12 HCM	Boarding	3.0		2.0	Fare prepayment, with .5 seconds added for standees (per Chap 12 HCM).
B-2	Chapter 12 HCM	"	3.5		2.5	Single coin or token, with .5 seconds added for standees (per Chap 12 HCM).
B-3	Chapter 12 HCM	"	4.5		3.5	Multiple coins cash fare, with .5 seconds added for standees (per Chap 12 HCM)
B-4	Chapter 12 HCM	"	3.5		3.0	Exact fare, standees on bus.
B-5	Chapter 12 HCM	"	3.5		3.1	Conventional bus, 1 door, single coin fare, with .5 seconds added for standees (per Chap 12 HCM).
B-6	Boarding Rate Boundary Values	"	4.5	3.5	2.5	High value from rate B-3 and low value from B-2. Simple average of high and low values.*
B-7	TCQSM Adjusted Boundary Values	Boarding	3.24	2.52	1.80	Boundary values adjusted for heavy 2-Way flow (C-1) and double channel door (C-3).
RATE ADJUSTMENT FACTORS						
C-1	TCQSM-Adjustments	Boarding/Alighting		1.20		Adjust for heavy two-way flow through a single door.
C-2	TCQSM-Adjustments	Boarding/Alighting		0.85		Adjust for low floor bus.
C-3	TCQSM-Adjustments	Boarding/Alighting		0.60		Adjust for double stream door.

*Rate B-1 for prepayment was not included because this fare strategy was not being used.

Separate routes with different stop spacing were created. One route had a one-half-mile spacing, and the other had a three-quarter-mile spacing. The selection of these distances was based on several sources. First, measuring the distance of the stations on the Washington Metro in an area similar to the test corridor showed that the average station spacing was .9 miles. The average station spacing for 18 LRT systems in the U.S. was .67 miles.⁴⁴

4.2.4 *Traffic Signal Parameters and Priority Conditions*

VISSIM© provides two different methods for setting the traffic signal parameters for the corridor. The first is to use fixed time signals with actual or approximated offsets. The advantage of using the fixed time traffic control is the ease with which it can be defined. The major disadvantage of this method is that fixed time control may not be sufficient to simulate traffic operations in a BRT test corridor. It also results in the inability to set up conditional priority. The objective of creating a conditional priority component for the BRT simulation was to limit the number of priority requests granted, thus reducing disruption of mainline signal coordination and the potential impact of reduced green time on cross streets.

The VISSIM© software enables the user to develop customized signal control, including priority measures, using its internal, C-like signal programming language, VAP. Using VAP allows complete control in setting up a corridor's signal system. For each signal, several signal groups are defined (for which the signal indications are controlled by the VAP program). Lane-specific signal heads are then coded and each is tied to one of the signal groups. Since this model focuses on transit operations, many specific features of signal controllers which would be important in a model focused on general traffic operations or exclusively on transit signal priority, are not included. These include signal system features such as gap-out, force-off, phase skip, recall, etc. These usually make the cycle length and phase intervals vary in duration.

More importantly for this project, VAP enables innovative customization of existing signal control functionality. With VAP, the signal parameters are set by coding signal control heads at intersections in combination with vehicle detectors, which together emulate an actuated traffic signal. VAP also allows the user to set up the signal coordination needed when using actuated controls.

Because signal priority is considered an important feature of BRT systems, the project team used VAP to define conditional criteria that would determine whether some form of priority should be given to an approaching transit vehicle. Specifically, VAP was used to simulate green extension and red truncation strategies incorporating two conditions: transit schedule adherence (only lateness) and passenger loads on the approaching transit vehicle. VISSIM© uses model objects named "calling points," a specialized type of detector from which certain types of data can be collected about passing buses. The lateness criterion is based on the VAP delay function, which returns the departure delay of a transit vehicle at the previous stop relative to the schedule. The loading criterion is based on the VAP occupancy function, which returns the number of passengers on a bus. If these conditional criteria are met, the VAP program considers whether to alter the signal timing.

As the simulation is running, if the bus is approaching a green signal and additional green time is needed to clear the bus through the intersection (based on the vehicle's speed), the amount is compared with the green time remaining on that phase. The green is extended to provide the additional green time needed, unless this exceeds a defined maximum extension. If a second priority call occurs later in the same green interval (such as when a bus passing over the calling point is delayed or if a second bus approaches from the opposite direction), the overall extension could be increased up to the maximum.

If the bus is approaching a red signal, the possibility of truncating the cross street red (returning green to the approaching bus early) will be checked. The time needed to end the cross street red (for pedestrian clearance, etc.) is compared with the remaining red time to decide if there is enough time left for the truncation.

⁴⁴ Source: Janes Urban Transport Systems, 1999-2000 edition. Cited in FTA's "BRT Reference Guide" at <http://brt.volpe.dot.gov/guide/stops.html>.

Although the dual condition priority component of the BRT simulation application holds promise, it requires additional development, as described below in verification. For example, the project team worked to develop a feature that would account for offset deviations. This component would correct the offset by incrementally lengthening the green phase of the signal that had previously granted a priority call.

4.2.5 Other BRT System Controls

The project team also developed several other VAP controls to enable more “realistic” simulation of a BRT system. First, the team created a leading green signal for a BRT vehicle waiting in a queue bypass lane. This feature would enable maximizing the benefit of the bypass lane by allowing the waiting bus to start ahead of other traffic and eliminate the need for a short merge lane on the other side of the intersection if the leading green were not used.

VISSIM©’s built-in features effectively limit a transit simulation to travel in one direction. This is due to the nature of the vehicle generator. It creates a new vehicle object based on the desired headway parameter defined by the user adjusted with a random distribution to simulate less than perfect pullout performance. The vehicle generator operates without regard to the operating characteristics of vehicles returning to the route origin. One impact is that a peak vehicle requirement cannot be set. This also precludes tracking the cumulative effects of round trip delay, which is critical to measuring BRT performance in congested corridors.

To overcome this shortcoming, a VAP control was developed that transfers the accumulated travel time and delay values to the next scheduled vehicle to establish continuity for bi-directional travel. It works using a gating signal where buses enter the route from the vehicle generator. The control tracks how many buses have entered the route versus how many have returned. Detectors then track statistics at the two counters associated with the gating signal. Using this setup, a newly generated bus is held unless the difference between the two is less than the parameter set as the number of buses available, thus simulating late running buses. A VAP program controls the signal.

4.2.6 Operational Control Strategies

As explained in Section 3, the development of operational controls for BRT systems is an important component for improving service reliability, assuming the BRT system has an AVL/CAD or similar system that can track and monitor bus operations in real-time. VISSIM© has a basic feature that allows the user to set a default schedule adherence parameter for each bus stop. It works by simply holding a bus if it is running ahead of schedule after boarding and alighting have completed.

Although this is a useful and easy-to-program feature, it is limited to adjusting bus routes based on buses running ahead of schedule. This type of schedule adherence strategy is already being applied informally by some transit agencies equipped with AVL/CAD, although it is not dependent on schedule adherence at the stop, since many such systems notify bus operators if they are running ahead or behind schedule anywhere along the route. In addition, the VISSIM© feature is dependent on the scheduled departure time set for each bus stop (defined relative to the start of the first bus trip for the route, i.e., the offset). In transit systems that are not currently meeting their schedules, a decision would need to be made when setting up the simulation as to whether the offset/schedule should be taken from the written schedule or first measured using field data and then applied.

A headway maintenance strategy is potentially more useful for heavily congested corridors, where schedules are difficult to maintain and where a BRT system would be operating at relatively short headways (less than 10 minutes, maximum). A headway maintenance component of the BRT simulation application, specifically vehicle holding, was developed by coding a VAP-controlled gating signal at bus stops. The control held the bus at that location if its headway to the bus ahead of it was less than the minimum time desired. This measurement is based on the time the previous bus was released by the gating signal from the stop.

An additional component to this VAP routine inspects the current headways at any gating signals immediately upstream and downstream. If it has been too long since a bus was released from an upstream control, the next bus is held to avoid creating a long headway behind it that the following bus it would be

unlikely to recover. Similarly, if it has been too long since a bus was released from the downstream control, the bus is held to help avoid too short a headway in front of it. In both cases, if the headway at the gated stop ahead or behind goes beyond a maximum, the bus is no longer held since there has most likely been a breakdown in operations.

All the time parameters are set in the VAP routines. The disadvantage of this approach to simulating the impact of headway maintenance is the coding time required to implement it in the model. Signal heads and detectors must be coded for each gated stop, and VISSIM© must be configured to pass the data between VAP programs. (Implementation is more difficult if bus stops are inline rather than in offline bus bays because the stop signal heads and detectors must be programmed to only control buses and not other vehicles.

4.2.7 *Intermittent Delays*

Recognizing the many sources of delay in the operation of a bus route, both random and predictable, it was necessary to introduce additional bus delays into the BRT simulation application not covered in other model components. The objective was to replicate operational variability that is likely to occur on any given bus route, not just a BRT system. To accomplish this, “phantom” transit stops were coded to add delay time based on a user-defined empirical distribution (excluding passenger loading or other dwell time components normally built into the bus stop object). Using bus stops in this way along the transit route was developed for simulating a variety of random events, such as brief lane-specific delays to buses from right turning vehicles, driveway traffic, on-street parking access/egress, bus lane violations, etc. General traffic is not affected by these impedance objects, but modeling the impacts on general traffic is not the aim of this model.

4.2.8 *Traffic Impact Simulation*

Although the functional requirements directed the R&D work toward a transit-centric simulation model, some aspects of traffic are necessary to create the impedance that a transit bus would face under a range of operating conditions. This was accomplished by creating traffic lanes in addition to the lane a bus would operate in primarily.

At the head of the traffic links in the BRT corridor, an incoming traffic volume is set and modified by stochastic distribution to vary the simulated volumes in a way similar to variations in actual traffic flows. In VISSIM©, multiple traffic links can be used along the corridor if the changes in traffic volume are known. So for the BRT simulation application, the most recent AADT volumes by segment along the H Street corridor were manipulated to develop approximate peak, directional volumes, which were loaded on links of the mainline network. Other changes in traffic volume can be applied by coding a routing decision point with a defined percentage of the traffic that would be routed off the network.

The traffic volume is applied to a user-defined traffic composition that determines the percentage of the various standard vehicle classes (i.e., 95% cars and 5% trucks). Probabilistic distributions for speed, acceleration/deceleration, and other vehicle characteristics are determined by the user for each vehicle class using default distributions provided in VISSIM©.

4.3 Model Verification

Verification is the first formal step in testing a simulation model. Verification is distinct from validation in that there is no attempt to model a real-world system and confirm whether the program results match field data. During the first step in the project team’s verification, the correctness of individual model components were evaluated. Then, combinations of components were tested together to determine if the pieces work as expected alone and with other parts of the model.

Law and Kelton define verification as determining whether a simulation program works as intended, thus checking how well the model’s functional requirements were translated into code.⁴⁵ The authors suggest eight techniques that a model designer can use during verification. For the BRT simulation application

⁴⁵ Simulation Modeling and Analysis. Op. Cit., page 299.

project, the Multisystems team used a hybrid of those approaches. These included running the model components under simplified conditions to check the reasonableness of the output; tracing values during a simulation run for individual program variables; and visually inspecting the animation produced by VISSIM©. This involved a combination of “debugging” (uncovering and correcting errors in the program coding) and refining the approach to implementing the components of the conceptual model to achieve more reasonable results. In some cases it required identifying potential alternative approaches to coding and simulating BRT features.

The initial verification effort involved developing a scaled-down trial network with which the performance could be observed with animation run in real-time. The observation focused on questions of face validity. For example, did the model generate the correct number of buses, did the traffic volumes look reasonable, were signals operating as expected, or did unreasonable bus queues develop at bus stops? The basic techniques for generating vehicles, operating traffic signals, and producing the desired traffic flows were developed in this simplified setting. Some of the initial techniques for simulating BRT operational strategies were also identified.

The next step was to expand the verification process into working with a somewhat more complex and extended network that modeled a more realistic BRT route, in terms of length, passenger activity, traffic volumes, traffic signal, and other input. This configuration of the simulation was the precursor to, and intended for, eventual use in the validation process. At this point, evaluating the model’s performance extended beyond viewing the animation results to assessing selected model output measures. These included output speeds and dwell times. By systematically varying selected input variables listed below, while holding other input conditions constant based on a verification matrix, the expected response of both the animation and output measures was checked against the reasonably anticipated response.

The verification scenarios included changing the following variables:

- The amount of green time allotted to the main corridor at signalized intersections;
- The speed profile of transit vehicles;
- Passenger stop arrival rates; and
- Individually introducing six of the BRT components on a limited scale.

As a final step in the verification, the inputs listed above were changed in different combinations to represent “traffic congestion” and “bus bunching” scenarios. Tables 4.2 and 4.3 show the verification matrix that was used for testing a sequence of key input variables during the model verification simulation runs.

Examining the results of verification runs for each test case showed that the components of the model performed appropriately under these basic conditions. That is, the output speeds and dwell times changed in the expected direction and magnitude with the parameter input changes. The one exception was the test of conditional priority, where the bus speed was reduced rather than improved. This model component will thus require further development and was not included during validation due to time constraints.

Verification was particularly challenging for this project because, although VISSIM© provides excellent tools for setting up basic transit operations, the BRT features of the R&D simulation application required additional effort. This involved a combination of innovative use of the modeling tools and objects available in VISSIM, and use of the VAP programming language.

Table 4.2: Parameter Variation for Model Verification

Test Name		Test Variable Values			
		Green %	Traffic Volume	Speed Range	Pax Arrival Rates
Baseline		50	500	30/40	20
Green %	Hi	75	500	30/40	20
	Lo	25	500	30/40	20
Volume	Hi	50	700	30/40	20
	Lo	50	300	30/40	20
Speed Range	Hi	50	500	20/50	20
	Lo	50	500	35/35	20
Pax Arrival Rate	Hi	50	500	30/40	60
	Lo	50	500	30/40	10
Scenarios					
Traffic Congestion		25	700	20/50	20
Bus Bunching		50	500	30/40	“Spike” of demand variation over time at selected stops
BRT Alternatives					
Exclusive ROW		add one exclusive segment including transitions			
Reducing Dwell Time		increase boarding rate for a stop			
Varying Stop Spacing		change route to double stop spacing			
Headway Maintenance		add headway VAP controls for stops in a stretch			
Queue Bypass Lanes		add for one signal, w lane and advance green			
Conditional Priority		set calling points and VAP thresholds for 1 signal			

4.4 Build And Validate Full BRT Corridor Test Model

This section describes the construction and validation of the BRT simulation application using both existing VISSIM© capabilities and features developed or refined by the project team. In reality, building the application, verification, and validation were intertwined during the project since an R&D effort of this sort is inevitably an iterative process. For example, the final level of detail in some model components was driven in part by the demands of validation. Likewise, the scope of the validation was reduced because of the time and difficulty that some steps would have added to construction of the model. Indeed, it is possible that new verification runs would have been necessary to broaden the validation task.

This section describes the BRT simulation application. It is important to note that two key decisions were made before building the full model. First, since the one-way distance of the H Street test corridor was about six miles, the project team determined that the validation would be easier to work with, and cause and effect would be isolated, if the BRT system was only simulated in the peak direction. Second, to reduce the impact of variability caused by using schedule and field data across different time periods, the simulation was limited to the AM peak. Tradeoffs encountered during model construction and validation are highlighted.

4.4.1 Building the Simulation Model Application

The first step in building the model was to create the traffic and transit network components discussed above. The general layout of the H Street corridor was obtained from the street file provided by WMATA. A GIS program was used to extract a scale copy of the corridor for importing into VISSIM©. The GIS map served as the template for using VISSIM©'s graphical user interface network tool to trace (code) the transit and traffic network. The GIS map also served as a background for the simulation animations. The most important factor was that the network be scaled properly so that any input or output related to distance, such as vehicle travel time and speed, would be accurate.

During this step, two basic model objects of VISSIM© were used: (1) links, representing segments of lanes; and (2) connectors, the object that connects links to one another. Although VISSIM© allows for creating highly detailed network geometry, the functional requirements of the BRT simulation application discussed in Section 3 did not require the accuracy needed in a full-fledged traffic microsimulation. This made the process considerably faster since many fewer objects and variables had to be put into the network.

Second, after summarizing and formatting the field data provided by WMATA, passenger boarding and alighting activity was coded into the model at both the time point and bus stop levels. Actual WMATA schedule data was also prepared at this time and put into the model. WMATA had provided passenger boardings and alightings, vehicle travel time, and vehicle arrival time by stop and timepoint for the X2 route operating in the H Street corridor. The ride check was a 100% sample of schedule trips randomly collected mostly between March 27 and March 31, 1998. The data summarized to the timepoint level also included the scheduled arrive time at that point. WMATA also provided a complete weekday schedule of the X2's 4 AM to 2 AM service span consisting of 245 total one-way trips. For the test simulation, 27 trips between 5:58 AM and 9:30 AM were duplicated in the westbound, or A.M. peak direction.

Third, traffic volumes provided by the Washington, DC, Department of Public Works (DPW) for the H Street corridor were analyzed and prepared for the model. The traffic data was limited to the bi-directional AADT on each segment along the corridor. Two hourly point traffic counts were used to scale the data appropriately to the AM peak direction. No information on traffic entering and exiting at each intersection was available at the time. While ignoring small differences in volume along the corridor, large changes in volume between adjacent arterial segments were noted and coded accordingly. All told, some of the volume changes were large enough to warrant creating four points where traffic volumes were changed in the simulation network.

In addition to the traffic volumes, the DPW also provided the traffic signal parameters for the 11 busiest intersections in the corridor. The signalization data included the systems offsets so that the proper signal coordination could be simulated. For other intersections, relative traffic flows were used to assign green time, based on information that the standard cycle length was 80 seconds. Since the project team had been told that the signals had been "optimized," trial and error adjustments were used (where no signal data existed) to simulate smooth signal coordination.

To code the correct amount of traffic, links were loaded with the volumes identified above. To change volumes, vehicle were added or subtracted from the network to arrive at the correct volume for each interval. Traffic volume mostly drops inbound along the corridor. To duplicate this phenomenon, a percentage of cars were subtracted at four places. Near the end of the corridor, in the heart of downtown Washington, traffic volumes increase again.

The BRT configuration and traffic network were enhanced to collect information needed for analysis of the simulation results. VISSIM© allows the user to define time segments that initiate the collection of vehicle travel times and other statistics over any particular time segment. The time segments created for the BRT simulation application were placed to correspond with the time point intervals used to summarize the WMATA field data so that the two data sources would be comparable. Overall, the time expended in configuring the network to produce the desired output was minimal. This is because most of the output measures of interest to the project team's BRT application are derived from data that can be automatically collected in text files by toggling various model variables during model runtime.

4.4.2 Model Validation

Law and Kelton note that "the most definitive test of a simulation model's validity is establishing that its output data closely resembles the output data that would be expected from the actual [proposed] system." Law and Kelton also note that the nature of the output processes of nearly all real-world systems and simulations seems to preclude classical statistical tests. Instead, they "believe that it is more useful to ask whether or not the differences between the system and the model are significant enough to affect any conclusions derived from the model." Finally, they note that most practitioners follow what they call the inspection approach. Under the inspection approach, "one or more statistics from the real-world observations and corresponding statistics from the model output data" are computed, and then compared without the use of a formal statistical procedure. They suggest using the sample mean and sample variance for this purpose.⁴⁶ The project team used the sample standard deviation because it is generally easier to interpret and explain. The coefficient of variation was also used because it normalizes output and makes comparisons possible.

The ideal model validation articulated by the authors quoted above would be difficult to implement fully in a transit simulation. The method assumes a tight correspondence between the system and the simulation. Due to data limitations, simulated travel times between time points and arrival times at time points are the only direct basis of comparison with the historical data. Fortunately, other measures such as headway reliability can also be computed from the simulation and field data to increase the number of comparison measures. Nevertheless, a one-to-one correspondence between all possible simulation outputs and historical data would be very unlikely.

The project team decided that a more realistic standard was to average travel times for trips that took place under reasonably similar circumstances. Because the validation focused on the inbound AM peak, the output values (e.g., travel times) for the 27 trips in each of the 10 simulation runs were averaged for each validation series. In the end, the validation rested on average travel times by time point segment and variability of travel times by segment.

4.4.3 Validation Results

Two formal validation series of 10 runs each were performed. Each of the individual runs involved the simulation of 27 trips, corresponding to trips scheduled during the AM peak from approximately 6 AM to 9:30 AM. The trips in the simulation ran west-bound beginning at the Minnesota Avenue Metro Station on the Green Line and ending at 16th and Madison Streets near Lafayette Square.

The most important output of the model was a record of travel times for transit vehicles along several different segments of the corridor. As noted earlier, the travel times were important because they were the best field data that had been obtained from WMATA. As noted before, time points in the model were coded to corresponded to the timepoints that had been used by WMATA in summarizing its data.

In the first validation, the travel times from the model correlated well with the historic data. Table 4-2 shows average travel times for transit vehicles over six time segments and over the entire route from the simulation and historic data. Most of the simulation averages for the individual segments differ by 30 seconds to one minute, or 10% to 15%, from the historic averages (the others differ by less). The simulation average for the entire route differs by only 2% from the historic average.

⁴⁶ Simulation Modeling and Analysis. Op. Cit., pages 307-311.

Table 4.2: First Validation Run - Travel Time Statistics by Travel Time Segment, Simulation and Actual Compared

Travel Time Segment	Simulation			Actual			Sim COV / Actual COV
	Average (Minutes)	Standard Deviation (Minutes)	COV	Average (Minutes)	Standard Deviation (Minutes)	COV	
1	10.9	0.6	0.05	10.7	1.9	0.18	29%
2	5.9	0.4	0.07	6.9	1.5	0.22	33%
3	5.0	0.2	0.04	5.4	1.4	0.26	16%
4	5.7	0.4	0.07	5.1	1.1	0.21	32%
5	4.9	0.3	0.06	4.4	1.4	0.32	20%
6	5.9	0.1	0.02	6.9	2.0	0.28	7%
Total	38.7	0.6	0.02	39.5	4.4	0.11	15%

Although the simulation travel time averages were reasonably accurate representations of the historic data in the first validation run, the variability of the simulation travel times were not. Unlike the historic transit vehicles, those in the first simulation were seldom early or late. Table 4-2 also shows two measures of variability, the standard deviation and the coefficient of variation (COV) for both the simulation and historic data. The latter measure normalizes the data sets so that they can be compared directly without regard to the length of a segment. The historic travel times for the individual segments have a standard deviation that ranges from one to two minutes, and the travel time for the entire route has a standard deviation of about four and one-half minutes. In contrast, most of the averaged simulation travel times had standard deviations of less than 30 seconds. The COV reflects this pattern.

The lack of variability in travel times in the first validation series represented a significant weakness in the model. One of the purposes of the model was to simulate the extremes of realistic circumstances – especially those in which everything goes wrong. Without realistic variability, the model would be unlikely to capture scenarios (e.g., an early bus that is followed by a late bus that is further delayed by traffic) that produce cumulative impacts. The project team hypothesized that the lack of variability in the model was caused in part by an absence of intermittent delay in the model. The most common sources of such delay for a transit vehicle would be right-turning vehicles and stopped or illegally parked vehicles. We focused on right-turning vehicles.

Right-turning vehicles impede transit vehicles (and other vehicles) when they cannot make a right turn immediately, forcing the bus to decelerate or stop. Right-turning vehicles may be waiting for a gap in traffic or pedestrian flow before turning. Right-turning vehicles were not included in the first simulation application for two reasons. First, as noted before, the model was kept simple by not coding the generation of cross-traffic at each intersection. Second, we lacked data on turning movements at each intersection.

Following this hypothesis, intermittent right-turning vehicles were modeled by creating 18 control objects near intersections, which were designed to delay transit vehicles in approximately the same way as a right-turning vehicle. The distribution of delay for each of the 18 locations was defined so the bus was delayed half the time for anywhere from 10 to 30 seconds, and progressed unimpeded the rest of the time.

The results of the second validation suggest that this technique was somewhat successful. Table 4.3 shows the same travel time statistics recomputed for the second validation and again compared to historic data. The COV numbers based on the simulation data indicate much more variability in travel time (though still less than appears in the historic data). Specifically, the COV numbers from the simulation compared to those from WMATA indicate about 70% of the variability. It should be noted that the average travel times from the second validation are somewhat less comparable to the field data than from

those of the first validation. Still, this second validation series provides a more satisfactory base model that can then be tested against scenarios reflecting BRT improvements.

The results shown in Tables 4.2 and 4.3 imply that the scaled-down network used in the simulation lacks the variability observed in the corridor. Thus, other inputs that capture the types of random delays that a bus would experience would be needed in a second build of the application. Order-of-magnitude data on turning movements might need to be estimated, for example. Alternatively, the approach of simulating phantom delays may be sufficient when estimated by transit and traffic professionals who are familiar with local conditions.

Table 4.3: Second Validation: Travel Time Statistics by Travel Time Segment Simulation and Actual Compared

Travel Time Segment	Simulation			Actual			Sim COV / Actual COV
	Average (Minutes)	Standard Deviation (Minutes)	COV	Average (Minutes)	Standard Deviation (Minutes)	COV	
1	11.0	1.7	0.15	10.7	1.9	0.18	86%
2	5.5	1.0	0.18	6.9	1.5	0.22	83%
3	3.9	0.7	0.18	5.4	1.4	0.26	70%
4	7.2	1.1	0.16	5.1	1.1	0.21	73%
5	3.3	0.7	0.21	4.4	1.4	0.32	66%
6	5.1	0.7	0.13	6.9	2.0	0.28	46%
Total	36.4	3.4	0.09	39.5	4.4	0.11	84%

4.5 BRT Test Scenario

Given that the results from the second model validation appear reasonable, the next step is to use the model to simulate the impact of implementing various BRT strategies that could impact bus travel speeds and variability of service. Due to limitations in time and resources, our scenario testing was limited. However, the project team tested a scenario that included improved boarding and alighting times, similar to that which a BRT system might achieve by changing its fare system or aspects of vehicle design.

The inputs for this test scenario are shown versus the base model in Table 4.4, and the results are given in Table 4.5. As can be seen in Table 4.5, the simulation model implies that a 34% to 44% improvement in boarding and alighting times can lead to 10% faster travel times overall. More importantly, perhaps, the improvement seems to indicate that variability in travel time can be reduced by around 29%.

Table 4.4: Model Inputs

	BRT Scenario	Base Model	% Change
Boarding Time	2.52 sec/pax	4.52 sec/pax	-44%
Alighting Time	1.98 sec/pax	3.00 sec/pax	-34%

Table 4.5 BRT Scenario vs. Base Model

	BRT Scenario			Base Model		
Travel Time Segment	Average (Minutes)	Standard Deviation (Minutes)	COV	Average (Minutes)	Standard Deviation (Minutes)	COV
1	9.3	1.2	0.13	11.0	1.7	0.15
2	4.6	0.7	0.14	5.5	1.0	0.18
3	3.6	0.6	0.17	3.9	0.7	0.18
4	6.4	0.9	0.13	7.2	1.1	0.16
5	3.0	0.6	0.19	3.3	0.7	0.21
6	5.0	0.7	0.14	5.1	0.7	0.13
Total	32.4	2.4	0.07	36.4	3.4	0.09

Further testing of scenarios can easily be accomplished with this the BRT simulation application because it contains the BRT components described in Section 4.2.

5. Future Development of the SBIR BRT Simulation Application

Given the successful results of this R&D effort, the project team looks forward to making a number of improvements to the BRT simulation application.

- Incorporate other performance measures: The capabilities of VISSIM© coupled with enhancements made by the project team will allow a much greater range of validation and output measures to be produced, analyzed, and compared. Producing components of delay, constituents of dwell time, and order-of-magnitude impacts on traffic is feasible.
- Further component verification: As the BRT simulation application develops, some of the components will need to go through verification testing again. In particular, the dual condition signal priority routine would be a key element for refinement and testing.
- Stochastic variables: Create random distributions from the transit agency field data to replace default distributions provided by VISSIM© or use reliable distributions from other transit properties where appropriate.
- Boarding/alighting rates: Extend the research on boarding and alighting rates to include a more substantial range of values and adjustment factors that can be selected by the user.
- Full test scenarios: Develop and run simulations on test scenarios that include a range of BRT options. Provide results that show which components have the largest benefits in travel time, delay reduction, and service reliability.
- Incorporate other BRT model components: The project team developed a host of simulation features that were not included in the validation. For example, incorporate the VAP control that facilitates more realistic round trip modeling of a BRT system.
- Operation control strategies: Because AVL/CAD systems are becoming so common, and few automated or semi-automated control strategies are being practiced, build on the headway maintenance features developed for this project.
- The user front end: While VISSIM©'s menu driven user interface is easy to navigate, some changes require repetition of simple parameter changes to change a BRT scenario. The development of a user front end would enable batch changes to the input text file would be a tremendous enhancement. The fact that the text file is not in a typical delimited or fixed column format would make this an interesting challenge.
- The user back end: Running simulations in the BRT model generates loads of data. The project team made some strides in automating the processing and analysis data from two different output files. It would be very useful to create and customize a user back end, most likely using a standard database tool, to facilitate cleaning, summarizing, and analyzing output data easier if not transparent for the user.

6. Summary of Potential Commercial Applications and Possible Use by the Federal Government

Considering the federal government's support for BRT system development, many transit agencies and planning organizations are or will be exploring the potential of BRT. For those transit agencies that are planning BRT-like transit enhancements, the BRT simulation application developed with this SBIR Phase 1 grant will be useful for them as well. Thus, transit agencies may be interested in purchasing a fully developed product that allows them to address full-fledged BRT systems, and to model individual bus service improvement strategies that have merit on their own. The project team determined that using a traditional traffic microsimulation product that meets the functional requirements identified for a BRT simulation application provide considerable flexibility in design and warrants further product development.

The BRT simulation application developed with SBIR funds could have direct application to the FTA's efforts to demonstrate BRT systems. It addresses many of the essential features of BRT and can provide systemwide or location specific analyses. The particular transit-centric application of the model portends to provide a rapid modeling and sensitivity environment for the FTA's consortium members.