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Publication Date

2009-09-07

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

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California PATH Research Report
UCB-ITS-PRR-2009-38

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

Final Report for Task Order 6410

September 2009

ISSN 1055-1425

Assessment of the Applicability of Bus Rapid Transit on Conventional Highways — *Case Study Feasibility Analyses Along the Lincoln Boulevard Corridor*

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September 7, 2009

ACKNOWLEDGEMENTS

This work was performed by the California PATH Program and the Department of City and Regional Planning at the University of California at Berkeley, Tongji University in Beijing, China, and the University of California at Los Angeles under the sponsorship of the State of California Business, Transportation and Housing Agency, Department of Transportation (Caltrans), Division of Mass Transportation, Division of Research and Innovation (DR&I) (Interagency Agreement #65A0208). The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California.

The authors thank Elaine Houmani, Wendy Johnsen, Bradley Mizuno, Sebastian Oduni, and Scott Sauer of Caltrans for their support during this research. The authors also want to thank Paul Casey and Benjamin Steers of the Big Blue Bus, City of Santa Monica for their support of this research. The authors would also like to thank Yunus Ghausi, Sin Kim, and Kim Gia Nauyen of the Caltrans District 7 Office in Los Angeles. Finally, the authors would like to very much thank Wei-Bin Zhang, our PATH colleague, for his contributions to this research.

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ABSTRACT

This report presents the results of a performance assessment of the applicability of bus rapid transit on conventional highways in the setting of a site-specific case study along the Lincoln Boulevard corridor in Santa Monica, California. When bus rapid transit systems are implemented on conventional highways, especially on arterials, there are numerous bus priority treatments that can be applied and each has associated with it issues that need to be investigated. In this study, we are investigating concurrent flow curb bus lanes based on the removal of peak period parking along the Lincoln Boulevard corridor. We have focused on traffic and ridership impacts associated with this type of bus rapid transit system implementation.

Key Words: bus rapid transit, bus-only lane, traffic impacts, ridership

EXECUTIVE SUMMARY

This report presents the results of a performance assessment of the applicability of bus rapid transit on conventional highways in the setting of a site-specific case study along the Lincoln Boulevard corridor in Santa Monica, California. When bus rapid transit systems are implemented on conventional highways, especially on arterials, there are numerous bus priority treatments that can be applied and each has associated with it issues that need to be investigated. In this study, we are investigating concurrent flow curb bus lanes based on the removal of peak period parking in the context of the Lincoln Boulevard corridor. We have focused on the traffic and ridership impacts associated with this type of bus rapid transit system implementation.

For the traffic impacts study we have used the VISSIM package as the primary tool with which to simulate the Lincoln Corridor in the context of converting during the morning and afternoon peak periods the curbside parking lane to a bus-only lane over the course of two miles. Both the curbside and adjacent travel lanes were simulated and traffic impacts were accumulated for each of them. VISSIM represented detailed geometric settings, traffic conditions and control, and bus operational characteristics. Initially, the models were calibrated using data collected from the Lincoln Boulevard corridor; and the outputs from the “before” model and the “after” model have been used to evaluate the lane conversion impacts. The outputs include Measures of Effectiveness (MOEs) for both traffic and bus operation status, such as delay, travel time, speed, and queue length for general traffic and buses.

The findings from the simulation runs have been summarized to show which factors or combination of factors would affect the lane conversion impact significantly. Note that the summary will be based on simulation results for the case study site and thus the result is site-specific, however, the factors/combinations discovered to be important should be the ones that need to be studied closely for a site that is considering the lane conversion strategy. The simulation study’s objective was to test and compare different curb lane operational strategies in a simulated environment. Five scenarios were defined:

- Scenario 1: Do Nothing
  No change is made to the existing state, whereas the curb lane remains as a parking lane during the peak periods. This provides a baseline reference scenario with which all other scenarios can be compared.
- Scenario 2: Bus Only Lane
  The curb lane operates as a bus only lane during peak periods. Scenario 2 consists of both the Rapid 3 and Local 3 Lines being allowed to operate in the curb lane during peak periods.
- Scenario 3: Mixed Traffic Lane
  The curb lane operates as a mixed traffic or general purpose lane open to all types of vehicles during peak periods.
- Scenario 4: Special Vehicle Lane for Buses, Taxis, and Charter Buses
  The curb lane operates as a special vehicle lane only open to buses (Rapid 3 and Local 3), taxis, and charter buses during peak periods.
- Scenario 5: Dynamic Dedicated Bus Rapid Transit (BRT) Lane
  The curb lane may dynamically convert from a mixed traffic lane to a bus only lane when a bus appears, and convert from a bus only lane back to a mixed traffic lane when not used by a bus.

The simulation study implemented these five scenarios in the simulation model and derived measures of effectiveness (MOEs) analysis results in terms of delay, travel time and speed for both buses (Rapid 3 and Local 3) and non-buses, and queue length. VISSIM produced these MOEs down to the level of each link within the two-mile corridor and for each 30-minute time period within each three-hour peak period: 7AM-10AM and 4PM-7PM. Over the entire corridor during the peak periods, Tables ES-1 through ES-4 show the simulation findings on a corridor basis across all scenarios so that comparisons relative to the *Do Nothing* (Scenario 1) may be made. Numbers in parentheses are the percentage change in a particular MOE relative to Scenario 1.

As could be observed from the data, with the curb lane converted into a travel lane, the MOEs are all improved compared with the do-nothing scenario, that is, delays decrease across all alternative scenarios, travel times decrease across all alternative scenarios, speeds increase across all alternative scenarios, and queue lengths decrease across all alternative scenarios; however, no single alternative scenario does better than all other alternative scenarios across all MOEs.

Among all scenarios 2 through 5 on a corridor level basis, Scenario 2 has the lowest Rapid 3 and Local 3 bus delay, lowest Rapid 3 and Local 3 travel time and highest Rapid 3 and Local 3 bus speed, and Scenario 3 has the lowest non-bus delay, highest non-bus speed, and shortest queue length. However, Scenarios 4 and 5 give values for delay, travel time, and speed for the Rapid 3 and Local 3 buses that are close to Scenario 2's values; moreover, they are not statistically different from each other in most cases for different MOEs based on a set of statistical tests performed on link level data for scenarios 2, 4, and 5. While Scenario 5, meanwhile, appears to be a good compromise between exclusive bus use and entirely mixed traffic use, it also requires a lot more technology and is considered an experimental scenario and needs more extensive investigation if it is to be seriously considered to be implemented. Another observation is that the travel time and speed gap between the Rapid 3 bus and non-buses decreases considerably, especially for Scenarios 2 and 4.

A primary question we were tasked to answer in this study was to measure the impact on non-bus traffic if a curbside lane with parking privileges were to be converted to a bus only lane during the morning and afternoon peak periods. Among the study's findings is the fact that there is no negative impact on non-bus traffic for each of the bus-only lane scenarios (2, 4, and 5). In fact there are even benefits to non-bus traffic for these three scenarios, just not as large as for Scenario 3, which makes available the curbside lane to all vehicles during the peak periods. Alternatively, Scenario 3 generates benefits for buses – both the Rapid 3 and Local 3 – just considerably smaller than available through Scenarios 2, 4, or 5.

Table ES-1 Average Vehicle Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	2.7	2.4 (-11.1%)	1.7 (-37.0%)	2.3 (-14.8%)	1.8 (-33.3%)
	Rapid 3	4.5	2.8 (-37.8%)	3.9 (-13.3%)	3.2 (-28.9%)	3.0 (-33.3%)
	Local 3	10.8	8.3 (-23.1%)	9.8 (-9.3%)	8.4 (-22.2%)	8.6 (-20.4%)
Northbound (AM Peak)	Non-Bus	1.8	1.7 (-5.6%)	1.2 (-33.3%)	1.7 (-5.6%)	1.3 (-27.8%)
	Rapid 3	4.1	2.5 (-39.0%)	3.3 (-19.5%)	2.5 (-39.0%)	2.6 (-36.6%)
	Local 3	7.5	5.3 (-29.3%)	6.1 (18.7%)	5.4 (-28.0%)	5.4 (-28.0%)

Table ES-2 Average Vehicle Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	6.7	6.5 (-3.0%)	5.8 (-13.4%)	6.3 (-6.0%)	5.9 (-11.9%)
	Rapid 3	9.5	7.8 (-17.9%)	8.9 (-6.3%)	8.2 (-13.7%)	8.0 (-15.8%)
	Local 3	15.8	13.3 (-15.8%)	14.8 (-6.3%)	13.4 (-15.2%)	13.5 (-14.6%)
Northbound (AM Peak)	Non-Bus	4.9	4.7 (-4.1%)	4.2 (-14.3%)	4.7 (-4.1%)	4.3 (-12.2%)
	Rapid 3	7.9	6.3 (-20.3%)	7.2 (-8.9%)	6.3 (-20.3%)	6.5 (-17.7%)
	Local 3	11.3	9.2 (-18.6%)	9.9 (-12.4%)	9.2 (-18.6%)	9.2 (-18.6%)

Table ES-3 Average Vehicle Corridor Speed (mph) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	23.0	23.6 (+2.6%)	26.1 (+13.5%)	24.0 (+4.3%)	25.5 (+10.9%)
	Rapid 3	17.2	20.1 (+16.9%)	17.6 (+2.3%)	19.0 (+10.5%)	19.3 (+12.2%)
	Local 3	9.8	11.5 (+17.3%)	10.4 (+6.1%)	11.4 (+16.3%)	11.3 (+15.3%)
Northbound (AM Peak)	Non-Bus	24.4	25.5 (+4.5%)	27.3 (+11.9%)	25.6 (+4.9%)	27.1 (+11.1%)
	Rapid 3	16.5	18.9 (+14.5%)	17.3 (+4.8%)	19.0 (+15.2%)	18.6 (+12.7%)
	Local 3	10.0	12.4 (+24.0%)	11.4 (+14.0%)	12.3 (+23.0%)	12.4 (+24.0%)

Table ES-4 Average Corridor Queue Length (feet) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	28.1	27.4 (-2.5%)	10.0 (-64.4%)	24.9 (- 11.4%)	12.2 (-56.6%)
Northbound (AM Peak)	19.7	18.2 (-7.6%)	7.4 (-62.4%)	18.3 (-7.1%)	8.9 (-54.8%))

For the ridership impact study, we used multiple regression models, referred to as *Direct Modeling*, to estimate ridership as a function of station environments and transit service features, which provides a fine-grain resolution suitable for studying relationships between built environments, transit services, and ridership. The accessibility of station-area residents to jobs and shops via transit versus auto are sometimes included in such models, thus in this sense, performance attributes of competitive modes are imbedded in the analyses. Direct ridership models generally have small sample sizes since observations consist of transit stations or stops. Thus degree of freedom constraints often limit the number of variables that

can be included as well as their specifications. It is because of these limitations that direct models fall under the rubric of sketch-planning tools. They provide order-of-magnitude insights for testing of various system designs and land-use scenarios. Collected data included ridership from the Rapid 3 along Lincoln Boulevard together with other bus rapid transit lines in Los Angeles County, e.g., numerous Metro Rapid Lines and the Metro Orange Line.

Findings from the model specification and ridership forecasting shows that substantial increases in average daily boardings can be anticipated from the planned service enhancements on the Rapid 3 Line. The adjusted model estimates that average daily boardings across the six Rapid 3 stops along the Lincoln Boulevard corridor will increase by between a factor of 3.5 and a factor of 8.3. The average increase in boardings for the six stops on Rapid Blue Line 3 is estimated to be more than 500%. Such large surges in ridership could be on the high side, again reflecting the more transit-conducive environment of Metro Rapid services in denser, more congested Los Angeles City (that dominated the database). We note that the approximately five-fold average increase in ridership relative to current counts on the Rapid 3 Line is not inconsistent with the differentials in average boardings between the Metro Orange Line stops and other Metropolitan Transportation Authority Metro Rapid stops. While no one has a crystal ball and can predict with any precision what the future ridership will be on the Rapid 3 Line, experiences with dedicated-lane services in Los Angeles County suggest that the impacts will be appreciable.

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1.0 PROJECT OVERVIEW

This report constitutes the final deliverable for PATH Project Task Order 6410 — "Assessing Bus Rapid Transit Implementation on Conventional Highways". The project has examined opportunities for implementing bus rapid transit systems on conventional highways, whether on freeways or arterials by performing a review of the literature of bus lanes and bus rapid transit systems use of conventional highways together with a consideration of California bus rapid transit systems practice, and performing a corridor-specific case study of the Lincoln Boulevard Big Blue Bus (Santa Monica) Rapid 3 Line currently running in mixed flow traffic. The remainder of this section discusses the motivation for, objectives of, and a summary of the contents for the remainder of this final report.

1.1 Motivation

Bus rapid transit (BRT) systems are commonly viewed as an alternative travel mode to help make bus transit more attractive by enhancing customer level of service with an ultimate goal of increasing ridership that contributes to relieving traffic congestion. The elements that comprise any rapid transit system consist of:

- Running Ways;
- Stations;
- Vehicles;
- Intelligent Transportation Systems;
- Fare Collection;
- Service Patterns; and,
- Identity and Branding.

Running ways are the key element of BRT systems around which the other components revolve since running ways serve as the infrastructural foundation around which the other elements function. Moreover, it is the running ways that should allow for rapid and reliable movement of buses with minimum traffic interference to provide a clear sense of presence and permanence. The types of running ways for BRT service can range between mixed flow traffic operation and fully grade-separated busways (Diaz, R.B., et al., 2004), (Kittelson & Associates, Inc., et al., 2007), and (Levinson, H.S., et al., 2003).

An existing mixed flow lane on an arterial represents the most basic form of running way. BRT vehicles can operate with no separation from other vehicle traffic on virtually any arterial street or highway. Increasing levels of segregation begin with operations in mixed arterial traffic, through exclusive arterial lanes (curbside or median), contra-flow freeway bus lanes, normal-flow freeway HOV lanes, grade-separated lanes or exclusive transitways on separate rights-of-way and bus tunnels. Increasing levels of separation from other vehicle traffic add increasing levels of travel time savings and reliability improvement for the operation of BRT services. Fully grade-separated, segregated BRT transitways have the highest cost and highest level of speed, safety and reliability of any BRT running way type.

Because of the incremental nature of bus rapid transit systems deployment, the ease and relatively low cost with which BRT systems can initially be implemented in the setting of mixed flow traffic, and the number of such deployments in the U.S. in general and in California specifically, we are motivated by a desire to focus on the conversion of the running way for a BRT system from mixed traffic flow to one of increasing levels of separation from other vehicle traffic, in particular, to a bus-only lane at curb-side during peak periods.

1.2 Objectives

Of particular importance to consider when implementing bus rapid transit is its deployment on conventional highways including arterials and freeways because of the need to integrate BRT within an existing roadway infrastructure with specific land use patterns. Such integration may require changes including removal of peak period parking to allow for a bus-only travel lane, replacement of conventional traffic signal control systems with transit signal priority systems, or removal of an existing curbside travel lane during peak periods to allow for a bus-only travel lane. Moreover, such changes are likely to have impacts that need to be examined. The overall objective of this project is to identify and assess such impacts resulting from the removal of peak period parking in the context of a site-specific case study along the Lincoln Boulevard corridor in the cities of Santa Monica and Los Angeles.

1.3 Contents of the Report

This is the first of four sections of the report. Section 2 provides a review of bus rapid transit systems on conventional highways from the literature. Section 3 discusses the study of traffic impacts we conducted using modeling and simulation methods; and Section 4 discusses the study of ridership impacts we conducted using transportation planning and analysis methods.

2.0 BUS RAPID TRANSIT RUNNING WAYS: ARTERIAL-RELATED BUS PRIORITY TREATMENTS

There are several types of arterial-related bus priority treatments for Bus Rapid Transit running ways, as follows:

- Mixed traffic flow
- Concurrent flow curb bus lanes
- Concurrent flow inside curb bus lanes
- Contra-flow curb bus lanes
- Median bus lanes
- Bus-only streets

The running way setting for the Lincoln Boulevard bus rapid transit corridor is an arterial street with current bus priority treatment for the *Rapid 3* Line as mixed traffic flow. Bus rapid transit systems generally operate in mixed traffic flow when physical and/or traffic factors preclude bus lanes or busways from being initially implemented. There are tradeoffs with implementing BRT in mixed traffic flow; advantages include low costs and fast implementation with a minimum of construction; however, mixed traffic flow operations can limit bus speeds and service reliability due to the BRT vehicle having to travel in this environment *with other vehicles*; system identity can also suffer without specific actions taken to equip either or both the BRT vehicle and the BRT stop/station with a single unified BRT brand identity. In the *Rapid 3* case, such actions have been taken to provide a brand identity.

There are several examples of BRT systems implemented in California in addition to the Lincoln Boulevard corridor *Rapid 3* Line that currently operate in mixed traffic flow all of which having a distinctively unique brand identity associated with their buses and bus stops, as follows:

- Los Angeles County Metropolitan Transportation Authority's Metro Rapid Lines with the first two lines implemented in 2001 on Wilshire and Ventura Boulevards.
- AC Transit's San Pablo Rapid traveling on State Route 123 (San Pablo Avenue) between San Pablo and Oakland
- Santa Clara Valley Transportation Authority's Rapid Line 522 along the El Camino/Santa Clara Street/Alum Rock Avenue corridor (State Route 82), which

provides service along the east-west length of Santa Clara County between the Eastridge Shopping Center in San Jose and the Palo Alto Transit Center.
- Sacramento County's Regional Transit Line 50 E-Bus on the Stockton Boulevard corridor

Buses will also benefit from customary street and traffic improvements that reduce overall travel delay. The range of transit-related traffic improvements can include grade separations to bypass points of delay; street expansions to improve traffic distribution or to provide bus routing continuity; traffic signal improvements including signal coordination and bus transit signal priority. Other transit-focused enhancements include turn controls that exempt buses, bus stop lengthening, effective enforcement of parking restrictions, and bus stop design improvements.

Of bus lane and bus street priority treatments, normal flow curb bus lanes are the most common; they are generally considered when it is not practical to install other on-street bus service options. They are appropriate for implementation under the following conditions:

- No parking or stopping along the curbs during the time periods that the bus lanes would be in effect
- At least two other moving general traffic lanes in the same direction except in cases on two-way four-lane streets where left turns are not permitted during peak period traffic time periods.
- Curb access for other services to adjacent properties can be readily prohibited during the time periods of bus lane operation; such services can include loading, unloading, deliveries

They are the easiest to implement, have the lowest installation costs because they normally involve only pavement markings and street signs, and have minimum impact on intersecting driveways and street routings. Customarily, such bus lanes have been used to facilitate bus movements in Central Business Districts by separating buses from other traffic; however, such bus lanes are also used along outlying arterials.

Experience in the U.S., however, has shown that they are least effective in terms of travel time saved, image and brand identity, ability to be enforced, and that they may impact curb access requirements such as deliveries. Another disadvantage is that right-hand turns, when allowed may conflict with bus flow; thus efforts should be made to either totally eliminate or at least restrict right-turning movements that would impede BRT service.

Concurrent flow bus lanes can operate at all times or only during peak period times. On one-way and two-way streets, an 11- to 13-foot bus lane should be provided along the curb. When street width and circulation patterns permit and peak bus volumes exceed 90 to 100 buses per peak period hour, dual bus lanes should be considered. Figure 1 depicts four typical concurrent flow bus lane designs for two-way streets. The four designs vary by number of non-bus traffic lanes (one or two) and whether left turns are allowed. For design numbers 1 and 3, no left turns are allowed. Designs 1 and 2 each have a single non-bus traffic lane; designs 3 and 4 each have two non-bus traffic lanes. The width ranges of the right-of-way for each of the four designs are provided at the top of the figure adjacent to each design. Right turns from the bus lane may be prohibited or permitted.

The primary example of a concurrent flow bus lane in California is in San Francisco under the operation of the San Francisco Municipal Railway (Muni) on various streets within the city including:

- Sacramento and Clay Streets, which employ peak-hour curbside lanes that prohibit parking during peak periods.
- Mission Street operates curbside lanes between 7am and 7pm that dedicate a traffic lane to bus-only use, though convert to mixed flow use between 7pm and 7am.
- Third Street between Townsend and Market Streets operates a bus lane throughout the day; taxis are also allowed to travel in the lanes with buses

3.0 LINCOLN BOULEVARD CASE STUDY: TRAFFIC IMPACTS ASSESSMENT

For the Lincoln Boulevard corridor case study, simulation methods were used to quantify the impact, both on the bus-lane and adjacent traffic lane resulting from the lane conversion. The research team built microscopic simulation models using VISSIM[1] to represent detailed geometric settings (for instance, lane configuration), traffic conditions (volume, capacity), traffic control (type, signal timing plan), as well as bus operational characteristics. The models were initially calibrated using data collected from the Lincoln Boulevard case study corridor; and the outputs from the "before" model and the "after" model have been used to evaluate the lane conversion impacts. The outputs will include Measures of Effectiveness (MOEs) for both traffic and bus operation status, such as delay, travel time, speed, and queue length for general traffic and buses, both the Rapid 3 and the Local 3 buses. The models have been used under different traffic settings, such as different volume, capacity, lane configurations, to gain a better understanding of the impacts.

The findings from the simulation runs have been summarized to show which factors or combination of factors would affect the lane conversion impact significantly. Note that the summary will be based on simulation results for the case study site and thus the result is site-specific, however, the factors/combinations discovered to be important should be the ones that need to be studied closely for a site that is considering the lane conversion strategy.

3.1 The Simulation Site, Scenarios, and Data Collection

3.1.1 Simulation Site

The portion of Lincoln Blvd that that is under consideration for lane conversion is approximately 4.1 kilometers (2.5 miles) in length. It extends between Washington and Pico Boulevards. To capture the boundary conditions, as well as possible downstream movement of potential "choke points", the section for the simulation study was extended on both north and south ends of the corridor. More specifically, the total length of the study corridor is

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[1] VISSIM is a microscopic, behavior-based multi-purpose traffic simulation program

approximately eight kilometers (5 miles), and it includes the following three segments:

- North of Pico to Wilshire: approximately 1.5 kilometers (0.9 miles) with eight signalized intersections
- Washington to Pico (where the lane conversion is being considered): approximately 4.1 kilometers (2.5 miles) with 12 signalized intersections
- South of Washington to Jefferson: approximately 2.6 kilometers (1.6 miles) with six signalized intersections

The simulation site belongs to two municipal jurisdictions: City of Los Angeles (Jefferson to Rose) and City of Santa Monica (Rose to Wilshire). See Figures 3.1 through 3.3 for maps of the corridor. Figure 3.1 shows the corridor between Wilshire and Pico Boulevards (north of the lane conversion site) and Pico Boulevard and Rose Ave (part of the lane conversion site). This entire part of the corridor lies within the City of Santa Monica. Figure 3.2 shows the corridor between Rose Avenue and Washington Boulevard (part of the conversion site) and which belongs to the City of Los Angeles. Figure 3.3 shows the corridor between Washington and Jefferson Boulevards (south of the lane conversion site).

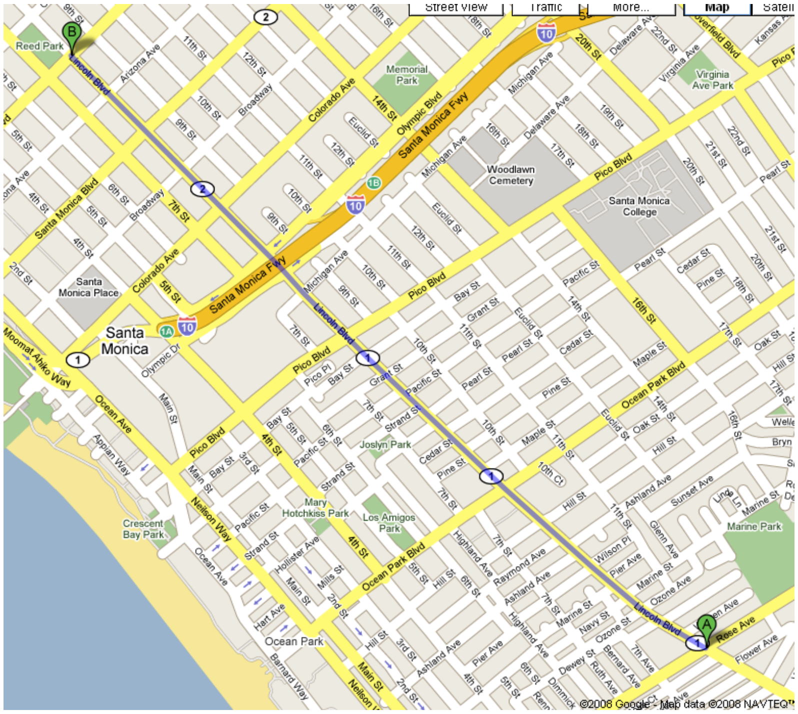


Figure 3.1 Lincoln Boulevard Corridor between Wilshire Boulevard and Rose Avenue

Figure 3.2 Lincoln Boulevard Corridor between Rose Avenue and Washington Boulevard

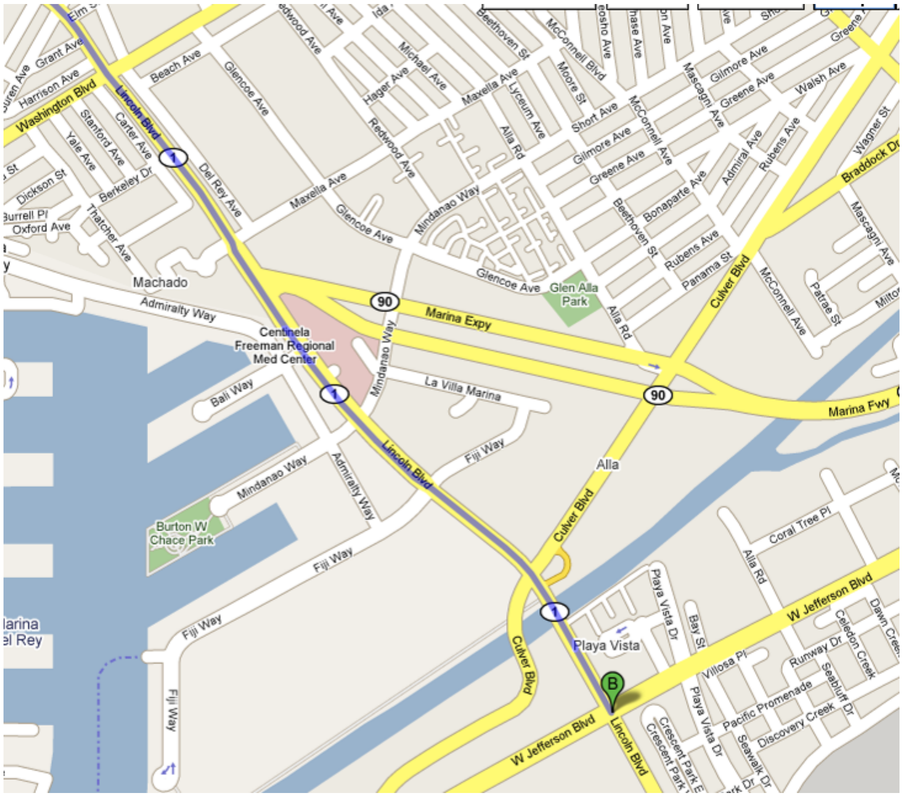


Figure 3.3 Lincoln Boulevard Corridor between Washington and Jefferson Boulevards

3.1.2 Scenarios

The objective of the simulation study was to test and compare different bus curb lane operational strategies in a simulated environment. Six scenarios have been defined:

- Scenario 1: Do Nothing

  No change is made to the existing state, whereas the curb lane remains as a parking lane during the peak periods. This provides a baseline reference scenario with which all other scenarios can be compared.
- Scenario 2: Bus Only Lane During Peak Periods

  The curb lane operates as a bus only lane during peak periods. This scenario was further subdivided into two sub-scenarios, labeled 2 and 2B. Scenario 2 consists of both the Rapid 3 and Local 3 Lines being allowed to operate in the curb lane during peak periods; scenario 2B consists of only the Rapid 3 Line being allowed to operate in the curb lane during peak periods.
- Scenario 3: Mixed Traffic Lane During Peak Periods

  The curb lane operates as a mixed traffic or general purpose lane open to all types of vehicles during peak periods.
- Scenario 4: Special Vehicle Lane for Buses, Taxis, and Charter Buses During Peak Periods

  The curb lane operates as a special vehicle lane only open to buses (Rapid 3 and Local 3), taxis, and charter buses during peak periods.
- Scenario 5: Dynamic Dedicated Bus Rapid Transit (BRT) Lane

  The curb lane may dynamically convert from a mixed traffic lane to a bus only lane when a Rapid 3 appears, and convert from a bus only lane back to a mixed traffic lane when not used by a Rapid 3 bus.

The simulation study has implemented the above six scenarios in the simulation model, and provided MOEs analysis results.

3.1.3 Data Collection

Four types of data have been collected for the simulation study:

- Geometric data such as lane and intersection geometry obtained through Google maps

- Intersection turning volume data from the two cities for the intersections in their respective jurisdictions
- Traffic signal data from the two cities, respectively, and
- Bus schedule and operations data from Big Blue Bus

In addition, drawings from Caltrans District 7 that illustrate parking restrictions were also used in building the simulation model. The intersection turning volume data for different intersections were collected in different years. The most recent are from 2007 (intersections in the City of Santa Monica), and the oldest are from 1997. To bring the volume data to a comparable level, a growth factor of 3% per year is assumed. Furthermore, the turning volume data could not be used directly in VISSIM, since the software only takes origin-destination (OD) demand as input for analysis of a stretch. Thus, a conversion from turning volume data to OD demand data was performed.

3.2 Simulation Network Building

The simulation network building mainly involves the coding of network geometry, traffic demand, and signal controllers.

3.2.1 Network Geometry

In VISSIM, links and connectors are used to model network geometry. Based on the background image from Google Earth map, the geometry layout and lane channelization of the studied stretch of Lincoln Boulevard were modeled into a simulation network.

As illustrated in Figure 3.4, the lane channelization of Scenario 1, also the existing state of Lincoln Boulevard differs from that of other scenarios. In Scenario 1, each direction of the cross section has two lanes and the curb lane is a parking lane not open to traffic during peak periods. While in other scenarios, the curb lane converts to a lane open to particular types of traffic, thus, each direction of the cross section has three lanes. As such, the curb lane is set to be closed to all traffic for Scenario 1, but open to particular types of traffic for all other scenarios.

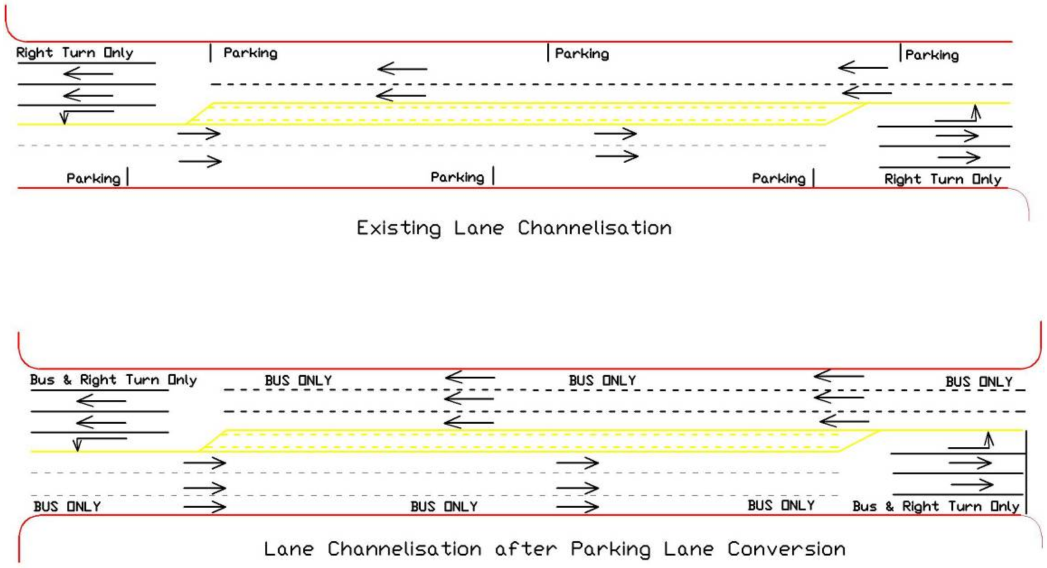


Figure 3.4 Typical Lane Channelization of Lincoln Boulevard

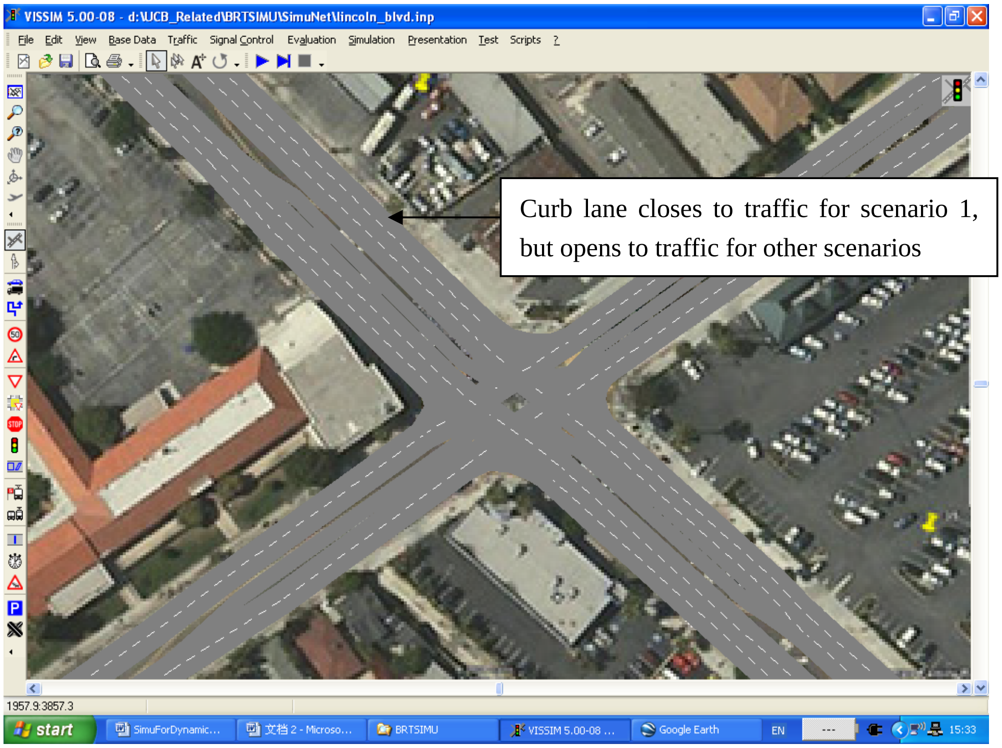
Figure 3.5 is the background map cut from Google Earth. Figure 3.6 shows how the geometric layout and lane channelization are modeled in the VISSIM simulation network.

3.2.2 Traffic Demand Coding

3.2.2.1 Non-Bus Traffic Demand

The data needs for coding of traffic demand is the Origin-Destination (OD) matrix among the inlets and outlets of the corridor. Figure 3.7 shows the OD zone numbers and intersection numbers along Lincoln Boulevard.

Figure 3.5 Background Map Cut from Google Earth (Intersection of Lincoln Blvd-Ocean Park Blvd)



Curb lane closes to traffic for scenario 1, but opens to traffic for other scenarios

Figure 3.6 Geometric Layout and Lane Channelization Modeled in Simulation Network (Intersection of Lincoln Blvd-Ocean Park Blvd)

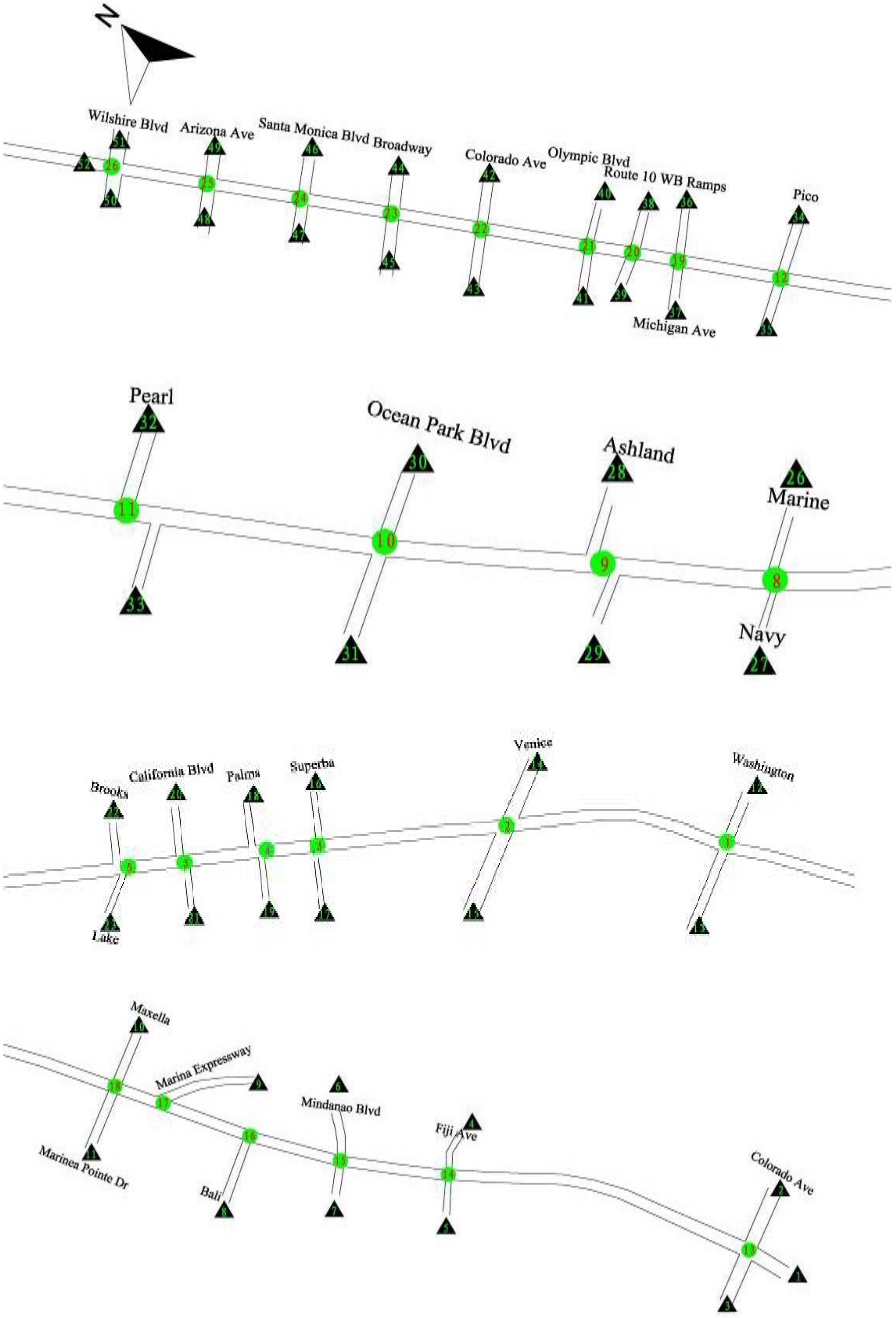
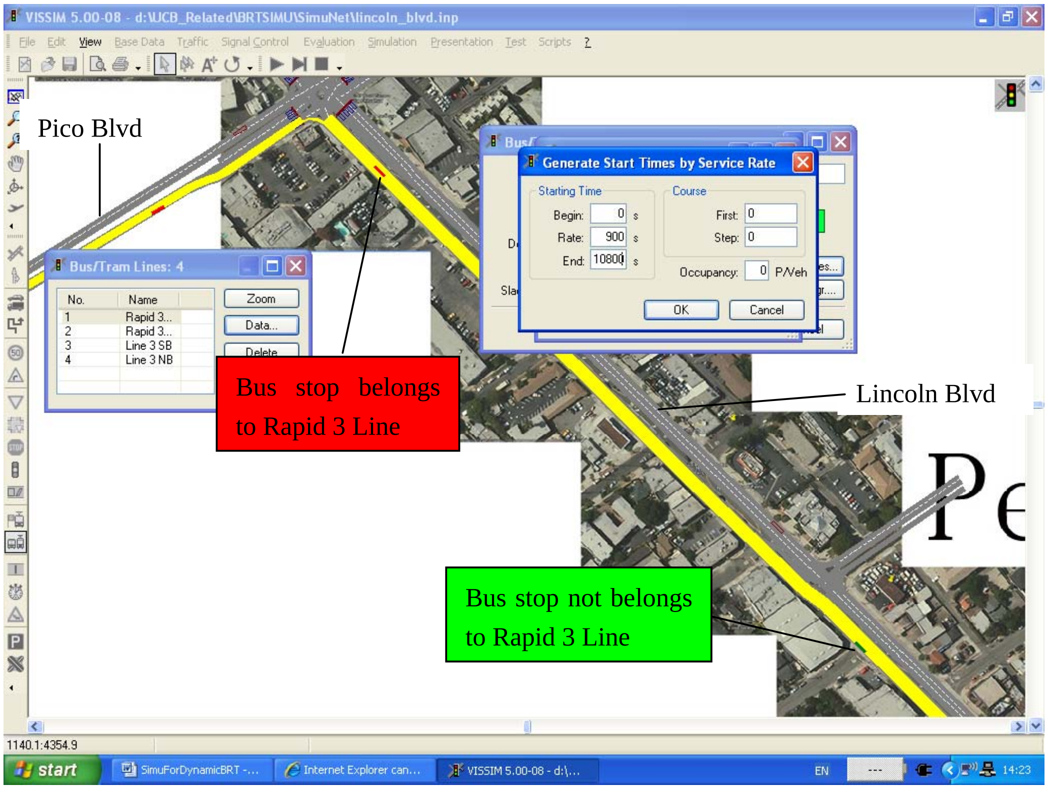


Figure 3.7 OD Zone Numbers and Intersection Numbers along Lincoln Boulevard

3.2.2.2 Bus Traffic Demand

There are two bus routes along Lincoln Boulevard, which are the Rapid 3 and Local 3 Lines. Each line has a departure rate of approximately 15 minutes during commute periods.

In VISSIM, there are three steps to code bus traffic demand. The first step is to place bus stops along the corridor according to their locations. The second step is to define each bus route and then add related bus stops to the route. The third step is to set the departure rate of each route. Figure 3.8 is an illustration of bus traffic demand coding for the Rapid 3 line.



Bus/Tram Lines: 4

No.	Name
1	Rapid 3...
2	Rapid 3...
3	Line 3 SB
4	Line 3 NB

Generate Start Times by Service Rate

Starting Time

Begin: 0 s

Rate: 900 s

End: 10800 s

Course

First: 0

Step: 0

Occupancy: 0 P/Veh

Figure 3.8 Illustration of Bus Traffic Demand Coding of Rapid 3 Line

3.2.3 Signal Controllers Coding

Timing plan(s), detectors deployment, and the positions of signal heads are the major components for coding actuated signal controllers.

VISSIM has a NEMA[2] standard signal controller emulator module, which can simulate fully actuated signal controllers as well as coordinate and semi-actuated coordinate signal controllers. Through a transfer process, other signal controllers like Type 170, ASC/2070 can also be emulated via the VISSIM NEMA module. Figure 3.9 is an illustration of signal controller coding in VISSIM.

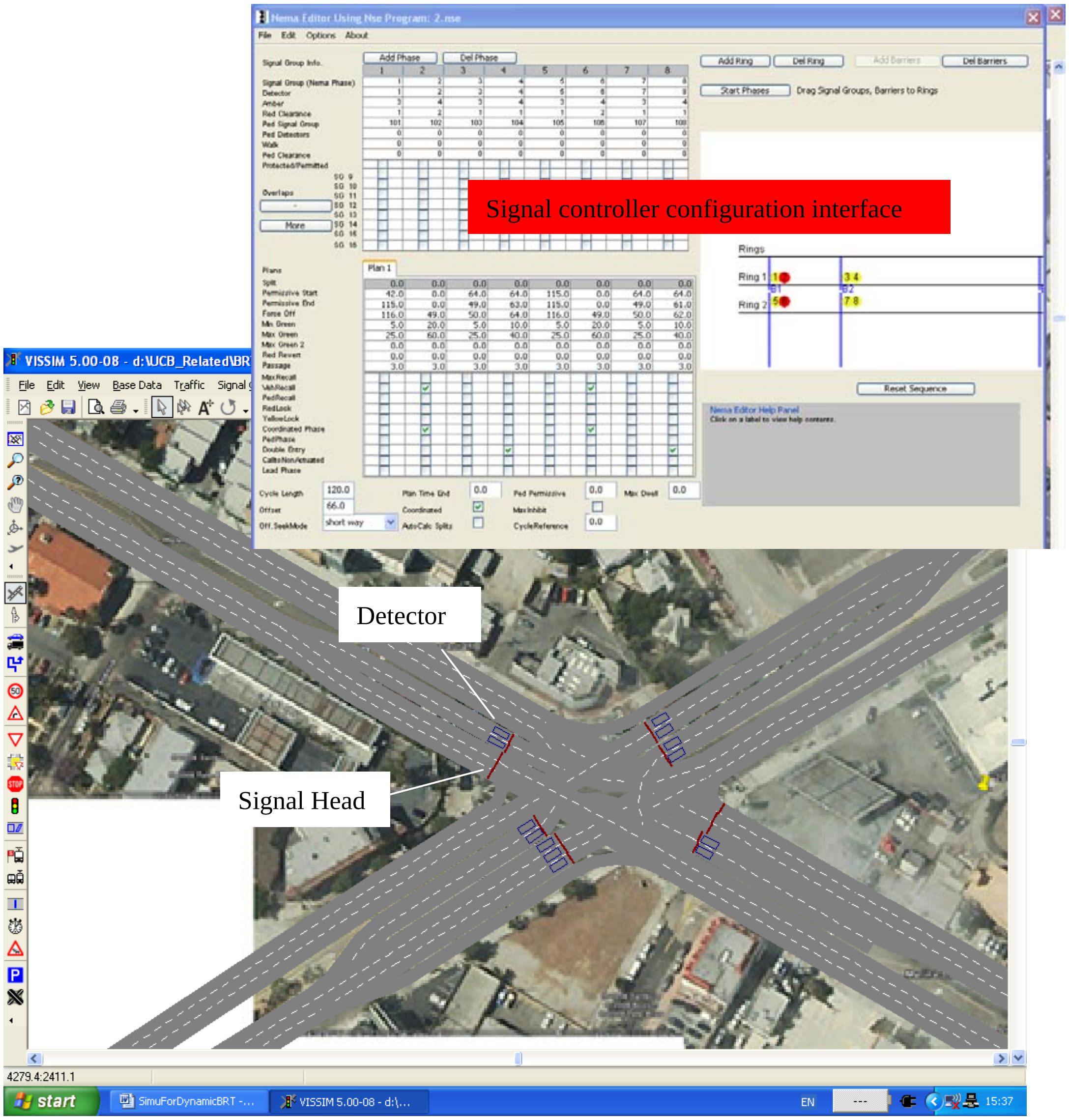


Figure 3.9 Illustration of Signal Controller Coding in VISSIM

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[2] NEMA = National Electrical Manufacturers Association

3.3 Implementation of Scenarios in Simulation

3.3.1 Scenario 1 - Do Nothing (Baseline)

For the existing scenario, except for setting the curb lane closed to all traffic, no additional configuration or setting is needed. Figure 3.10 is a snapshot of the simulation animation of Scenario 1.

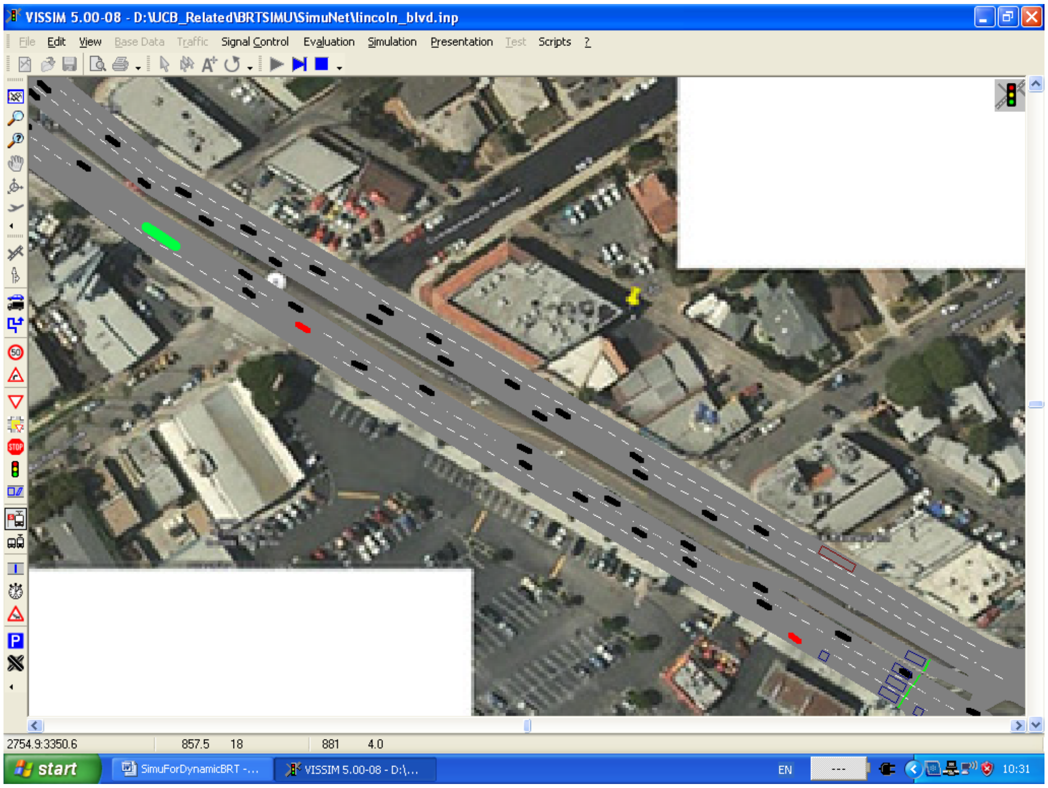

Figure 3.10 A Snapshot of the Simulation Animation of Scenario 1

It can be seen from Figure 3.10 that no vehicle including buses (in green color) travels on the curb lane, but right turn vehicles (in red color) can move to the curb lane when approaching very close to the intersection, and can thus make a needed right turn from the curb lane.

3.3.2 Scenario 2 - Bus Only Lane

For Scenario 2, the curb lane is set to be open to buses but still closed to non-bus vehicles.

Figure 3.11 is a snapshot of the simulation animation for Scenario 2. It can be seen from Figure 3.11 that only buses (in green color) are allowed to travel in the curb lane, right-turning vehicles (in red color) can change lanes to the curb lane when approaching very close to the intersection, and can thus make the right turn from the curb lane.

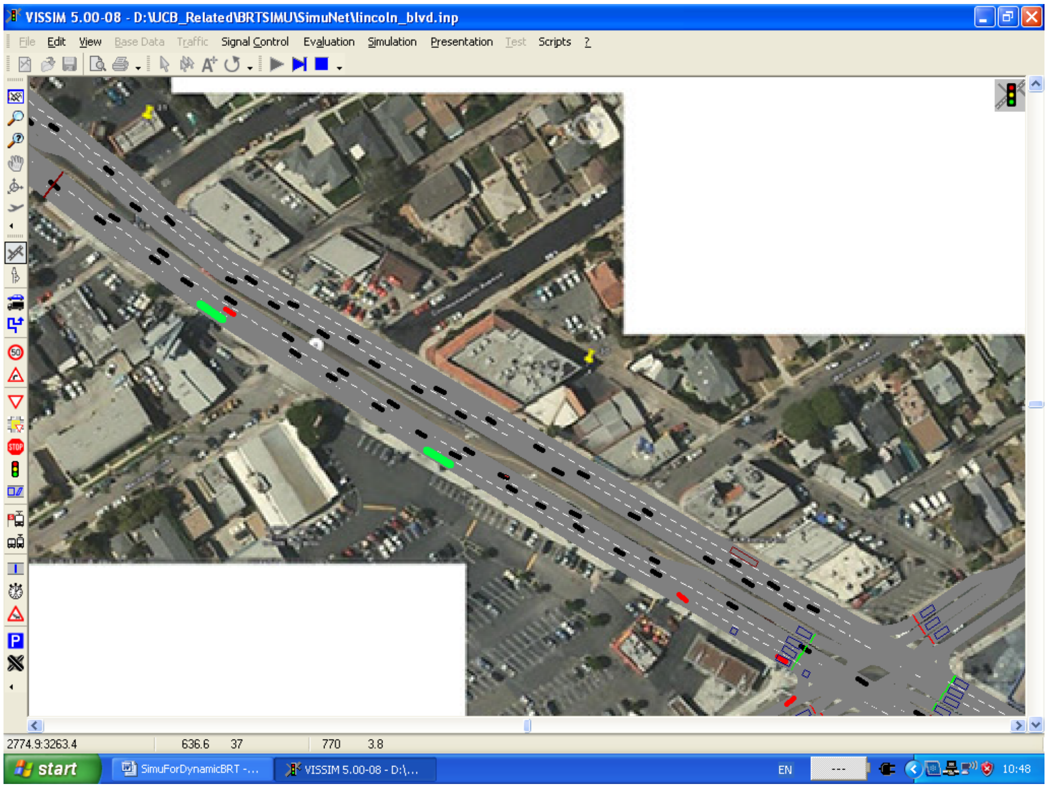

Figure 3.11 Snapshot of the Simulation Animation for Scenario 2

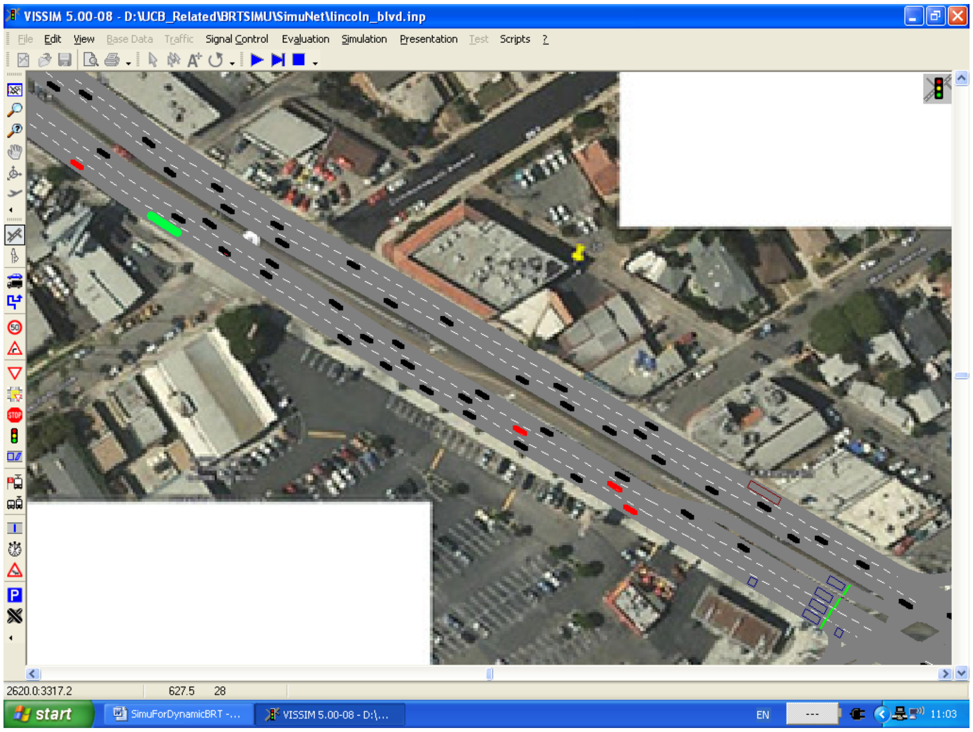

Figure 3.12 Snapshot of the Simulation Animation for Scenario 3

3.3.3 Scenario 3: Mixed Traffic Lane

For Scenario 3, the curb lane is set to be open to all types of vehicles, that is, it is a general purpose traffic lane. Figure 3.12 is a snapshot of the simulation animation of scenario 3. It can be seen from Figure 3.12 that all types of vehicles are allowed on the curb lane.

3.3.4 Scenario 4: Special Lane for Buses, Taxis, and Charter Buses

For Scenario 4, a new vehicle class named *Transit* is defined, which includes the following vehicle types: buses (Rapid 3 plus Local 3 lines), taxis, and special-purpose charter buses. The curb lane is then set to be open to *Transit* vehicles only. Figure 3.13 is a snapshot of the simulation animation for Scenario 4.

It can also be seen from Figure 3.13 that only buses (in green), taxis (in blue) and charter buses (in blue) are allowed to travel on the curb lane of the upstream section.

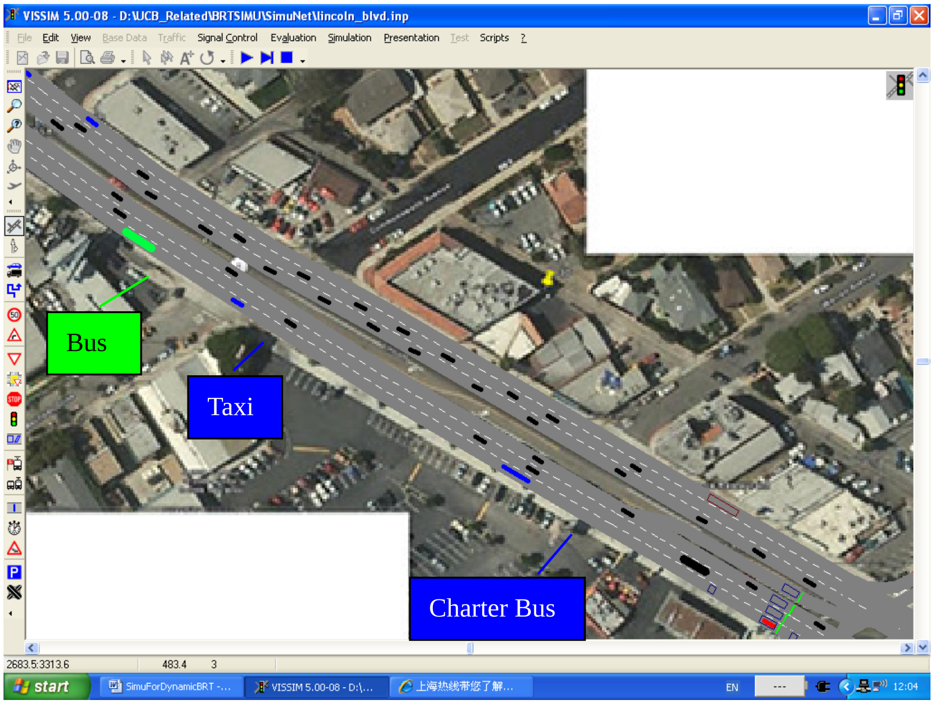

Figure 3.13 Snapshot of the Simulation Animation of Scenario 4

3.3.5. Scenario 5: Dynamic Dedicated Bus Rapid Transit Lane

3.3.5.1. Dynamic BRT Lane Operation Rules

Basically, for a subject link between two intersections, when there is a bus approaching from an upstream link, the curb lane of the subject link will convert from a mixed traffic lane to a bus only lane. Then, the curb lane will convert back from a bus only lane to a mixed traffic lane after the bus leaves the subject link. Figure 3.14 is an illustration of related settings for dynamic BRT lane operation. Below are the rules of the dynamic BRT lane operation:

a. A link consists of an approach section and an upstream section. When the BRT lane operation is triggered, the curb lane of the upstream section will be a bus only lane, the curb lane of the approach section will be a right turn and bus only lane.

b. When a bus is detected by the Bus Approaching Detector (BAD), the accumulated counter number of BAD increases by 1. Then, if currently the curb lane of the subject link is a mixed traffic lane, a new conversion to BRT lane will be triggered and indicator lights along the curb of the subject link will turn on.

c. When a bus is detected by the Bus Departing Detector (BDD), the accumulated counter number of BAD increases by 1. If the accumulated counter number of BDD is equal to that of BAD, which means there is no bus on the curb lane, then the indicator lights of the subject link will turn off. If the accumulated counter number of BDD is less than that of BAD, which means there are one or more buses still in the curb lane, then the indicator lights will remain on. The Dynamic Dedicated BRT lane is very similar to what is referred to in the literature as *Intermittent Bus Lanes* (Viegas, 2007), (Currie, 2008), and (Eichler, 2005). Viegas and Currie discuss implementations of intermittent bus lanes in Lisbon, Portugal and Melbourne, Australia, respectively.

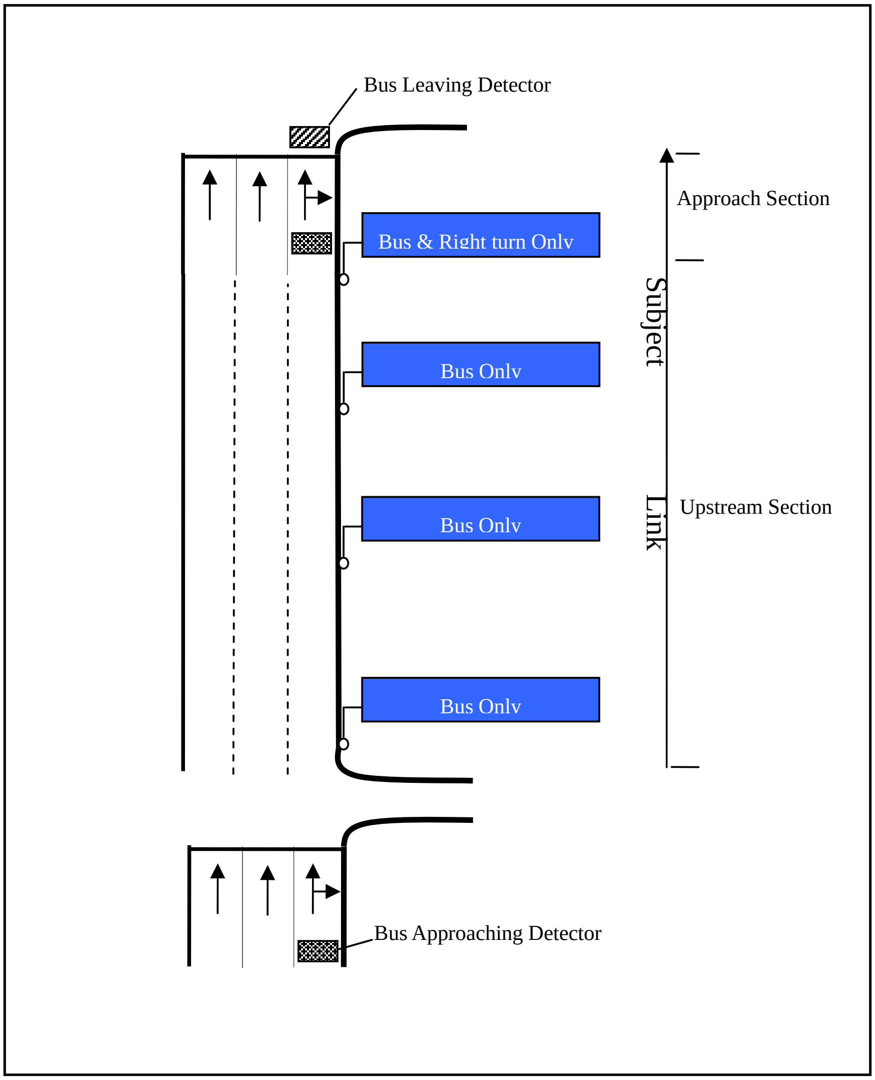

Figure 3.14 Illustration of Related Settings for Dynamic BRT Lane Operation

3.3.5.2 Implementing Dynamic BRT Lane Operation via VISSIM COM Programming

VISSIM provides a COM[3] interface which can be used to realize some additional functions not provided by the standard module. Through COM programming, we can implement dynamic BRT lane operation during the simulation, which is not available in the standard VISSIM module.

Figures 3.15 through 3.18 show major stages for the dynamic BRT lane operation during the simulation, described as follows:

- Figure 3.15 shows the situation when the curb lane is open to all traffic. The vehicles in red are right turning vehicles while those in black are through vehicles.
- Figure 3.16 shows the situation when a bus (in green) has just passed by the Bus Approaching Detector of the subject link, which triggered the curb lane of the subject link converting from a mixed traffic lane to a bus only lane. Since it is the initial period of the lane conversion, there are some non-bus vehicles already on the approach section that may keep traveling on the curb lane.
- Figure 3.17 shows the situation when the curb lane has converted to a bus only lane and all the non-bus vehicles have cleared off the curb lane. It can be seen from this figure that only buses (in green) are allowed on the curb lane and right turning non-bus vehicles (in red) can change to the curb lane of the approach section to make the required turn.
- Figure 3.18 shows the situation when a bus has just passed by the Bus Departing Detector, since there is no other bus on the curb lane of the subject link, thus the curb lane has just converted from a bus only lane back to a mixed traffic lane. It can be seen from the figure that non-bus vehicles have already changed lanes to travel in the curb lane.

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[3] COM = communication

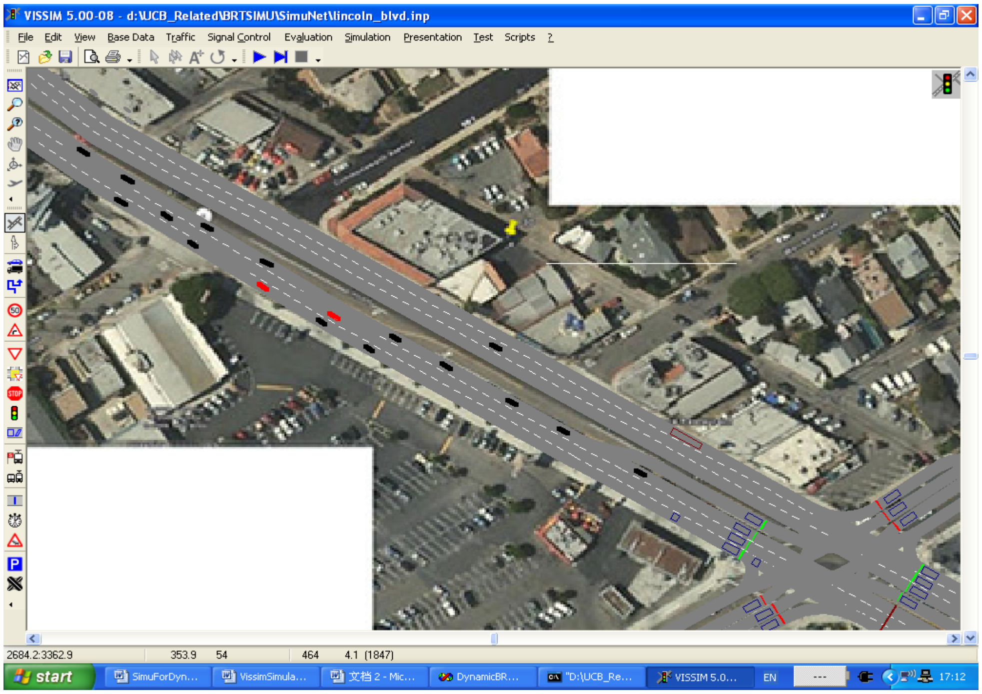
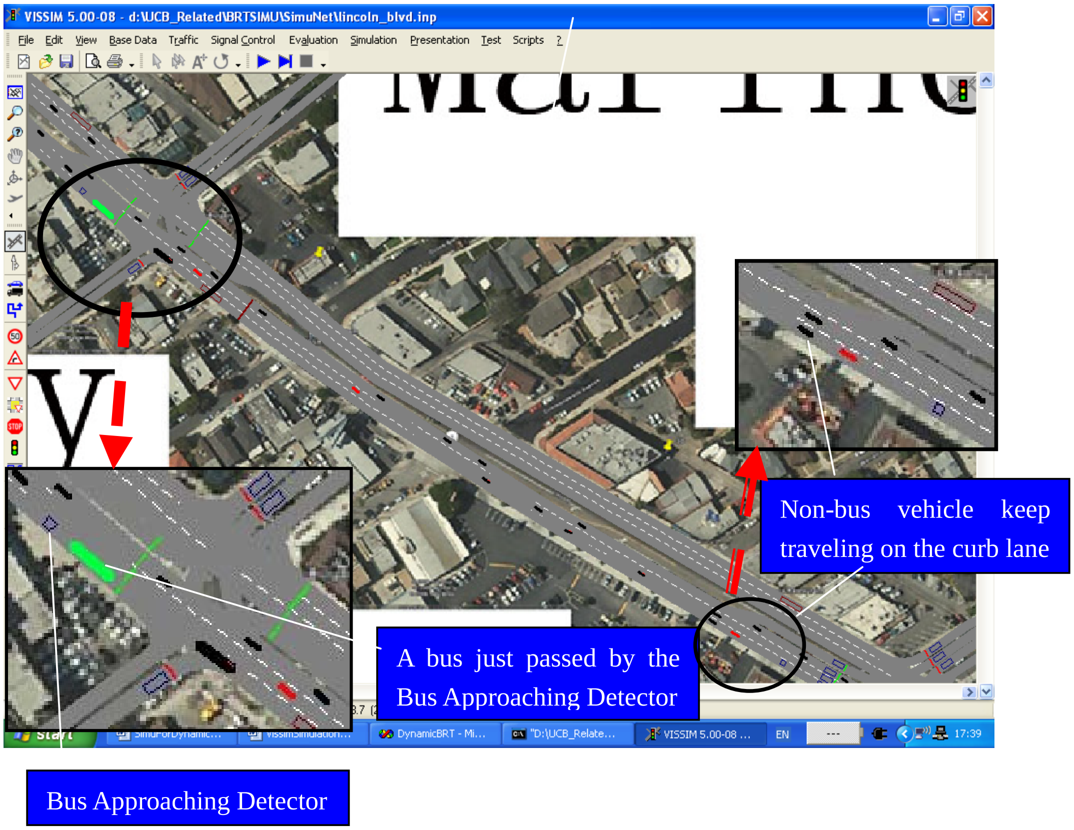


Figure 3.15 Snapshot when the Curb Lane Opens to Mixed Traffic



Non-bus vehicle keep traveling on the curb lane

A bus just passed by the Bus Approaching Detector

Bus Approaching Detector

Figure 3.16 Snapshot after a Bus has just passed the Bus Approaching Detector

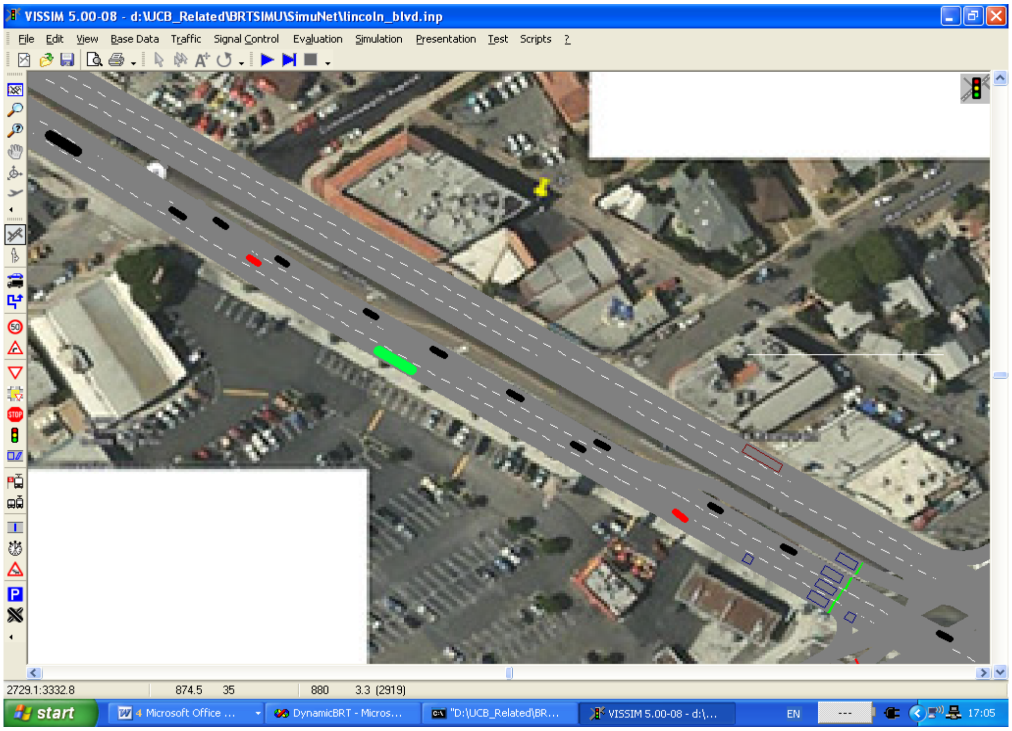


Figure 3.17 Snapshot when the curb lane has Converted to a Bus Only Lane for a while

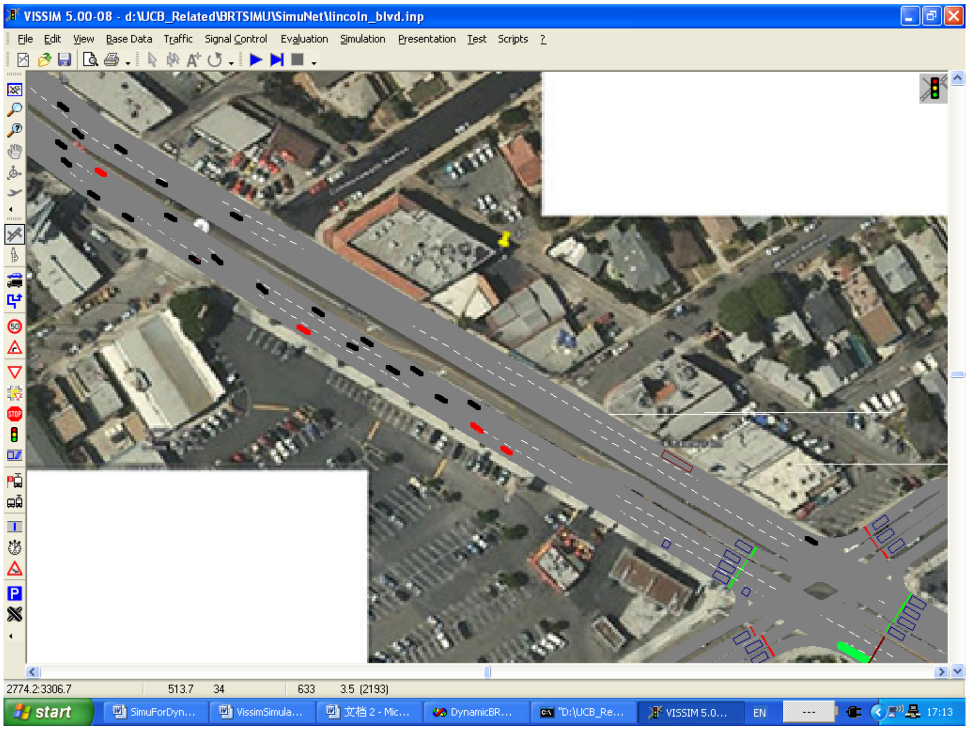


Figure 3.18 Snapshot when a Bus has just passed by the Bus Departing Detector

3.4 Simulation Model Calibration

Scenario 1 as previously defined represents the current traffic situation along the corridor and is used for model calibration. Bus travel times, calculated from bus GPS data, were used as the “ground truth” to calibrate the model. More specifically, GPS data that was obtained from *Big Blue Bus* included arrival and departure times at time points along the Local and Rapid #3 routes; however, because a minimum of two time points were required along the segment coded in the simulation model to calculate travel time, only data from Local #3 buses could be used as the Rapid #3 has only one time point along the coded segment. The two time points along the corridor are at Ocean Park and Washington Boulevards. Traffic demand as well as simulation model parameters were calibrated so the travel times from the simulation model match the travel times resulting from GPS data; the calibrated demand and model parameters were then used in the other scenarios to evaluate the various operating strategies. Calibration was performed for both northbound (NB) and southbound (SB) directions and for AM and PM peak periods and Table 3.1 compares the average travel times from the two sources (GPS data vs. simulation results). All simulated travel times fell within 12% of GPS-observed data; however, more noteworthy is that for NB AM peak and SB PM peak – the travel direction and time period combinations under consideration for lane conversion – errors were within 5% of ground truth.

Table 3.1 Calibration Results: Comparison of Average Bus Travel Times

Direction	Time Period	From GPS Data (seconds)	From Simulation Result (seconds)	Percentage Difference
NB	AM	644.02	671.21	4.2%
SB	AM	498.60	557.72	11.9%
NB	PM	536.28	564.76	5.3%
SB	PM	797.10	760.10	-4.6%

NB = Northbound
SB = Southbound

3.5 Measures of Effectiveness Analysis

Several Measures of Effectiveness (MOEs) were selected and used in determining the traffic impacts – both for non-buses as well as buses – under the various scenarios. Such MOEs consist of

- Delay[4]
- Travel time
- Speed
- Queue length[5]

The MOEs analysis is based on the links between Pico Blvd and Washington Blvd. Table 3.2 gives the numbers and definitions of the links used in the impact analysis evaluation.

Table 3.2 Numbers and Definitions of Links for Evaluation

Direction	Link Number	Start Intersection	End Intersection	Length meters (feet)
Southbound	1	Pico	Ocean Park	903.4 (2,957.3)
	2	Ocean Park	Ashland	331.9 (1,086.5)
	3	Ashland	Marine/Navy	302.2 (989.3)
	4	Marine/Navy	Rose	350.7 (1,148.1)
	5	Rose	Brooks	541.3 (1,772.0)
	6	Brooks	California	151.1 (494.6)
	7	California	Superba	333.2 (1,090.8)
	8	Superba	Venice	488.4 (1,598.8)
	9	Venice	Washington	566.8 (1,855.5)
Northbound	10	Washington	Venice	562.1 (1,840.1)
	11	Venice	Superba	464.6 (1,520.9)
	12	Superba	California	338.1 (1,106.8)
	13	California	Brooks	146.8 (480.6)

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[4] Vehicle delay on a link is defined as the difference between the vehicle's actual travel time and its travel time over this link under free flow conditions. The delay over a 15-minute time interval during a peak period across a particular link is the average of such vehicle delays over all vehicles traveling on this link during this time interval.

[5] Queue length is defined per second; and the queue length on a link is calculated. In a 15-minute time interval, there are 15*60 queue lengths; the average queue is the sum of all these 15*60 queue lengths divided by 15*60.

Direction	Link Number	Start Intersection	End Intersection	Length meters (feet)
	14	Brooks	Rose	509.7 (1,668.6)
	15	Rose	Marine/Navy	343.3 (1,123.8)
	16	Marine/Navy	Ashland	281.5 (921.5)
	17	Ashland	Ocean Park	341.1 (1,116.6)
	18	Ocean Park	Pico	902.0 (2,952.8)

The total simulation time of each run is 3 hours consisting of 6 statistical time intervals each of 30 minutes in length. For southbound, the OD demand during the 4-7 PM peak period is used; for northbound, the OD demand during the 7-10 AM peak period is used.

Results for the various MOEs have been derived for the 6 time intervals (30 minute time periods) per link for the AM and PM peak periods for all links[6] across each of the scenarios. To display all such results would require approximately 170 figures or tables, an amount which could overwhelm the reader in detail without necessarily contributing to an understanding of the general findings. Moreover, because the links are not uniformly equivalent across characteristics such as length, network geometry, and others, there will be variation from link to link.

To better represent the analysis results and to improve understanding of the findings, we present below in Tables 3.3 through 3.12 the average value for each MOE during the two three-hour peak periods (delay, travel time, speed, and queue length) for non-buses, Rapid 3 buses, and Local 3 buses for each link across the six scenarios. For example, to show all results for the *delay* MOE for non-buses would require 17 tables or figures (one for each link) to display the results for each 30-minute statistical time interval of the simulation for the appropriate 3-hour peak period. Instead, for each link we use the value for the *delay* MOE averaged over the 6 30-minute time periods for both the AM and PM peak periods and

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[6] There are 18 links however on Link 18 (see Table 3.1), the Rapid 3 must leave the bus lane in order to prepare to make a left turn on to Pico Blvd.; so MOEs were not captured for this link. While this affects the total corridor-wide MOEs for the northbound direction (see Table 3.1) in the AM peak, it does not change the general behavior patterns for MOE values for Scenarios 2 through 5 relative to Scenario 1.

present the aggregated results in a single table. In this study, for scenario 4, we assume the percentages of the traffic demand of taxis and charter buses are 2% and 1%, respectively.

3.5.1. Comparative Analysis Across Scenarios

In this section we present and compare the findings from the corridor simulation runs for each measure of effectiveness across the various scenarios.

3.5.1.1 Delay

In this section we discuss the *delay* MOE for non-buses, the Rapid 3 bus and the Local 3 bus.

Non-Buses

Table 3.3 presents the results for each link across all scenarios. Recall that Links 1 through 9 represent the southbound direction of travel during the PM peak and Links 10 through 17 represent the northbound direction of travel during the AM peak. The numbers in parentheses for a given scenario show the percentage change of the non-bus delay MOE for that scenario relative to Scenario 1, the Do Nothing or Baseline Scenario. For example, from Table 3.3 for Link 2, the non-bus delay for Scenarios 2, 3, 4, and 5, *decrease* relative to Scenario 1 by, respectively, 36.8%, 54.4%, 38.6%, and 47.4%.

For more than 80% (14/17) of the links, non-bus delay decreases across Scenarios 2 through 5 relative to Scenario 1. There are, however, a few links with increases in delay for non-buses for particular scenarios.

Typically, one would intuitively expect to observe that delay decreases from Scenario 1 to Scenario 2, Scenario 4, Scenario 5, and finally to Scenario 3 and thus that Scenario 3 would dominate – have the best value for -- the *delay* MOE; we expect this pattern because for Scenarios 2 and 4 there is no change in the number of lanes for non-buses; however buses are removed from the flow of traffic. In Scenarios 5 and 3 an extra lane for non-bus travel is made available either all the time (Scenario 3) or when Rapid 3 and Local 3 buses are not present (Scenario 5). This pattern is generally true on average on a link-by-link basis with a few exceptions (Table 3.3); it is definitely true on a corridor level basis (Tables 3.4 and 3.5).

Figure 3.19 displays more of the full range of such percentage variation for non-bus delay over all links of alternative Scenarios (2, 3, 4, and 5) relative to Scenario 1 (Do Nothing). For example, for Scenario 2 the average percentage change over all links relative to Scenario 1 for non-bus delay is a 16.5% decrease with a range between a 2.8% increase in non-bus delay to a 71.4% decrease in non-bus delay. Analogous figures are provided for each of the other MOEs discussed. We can see from Figure 3.19 how with rare exception across the scenarios the delay MOE decreases relative to Scenario 1.

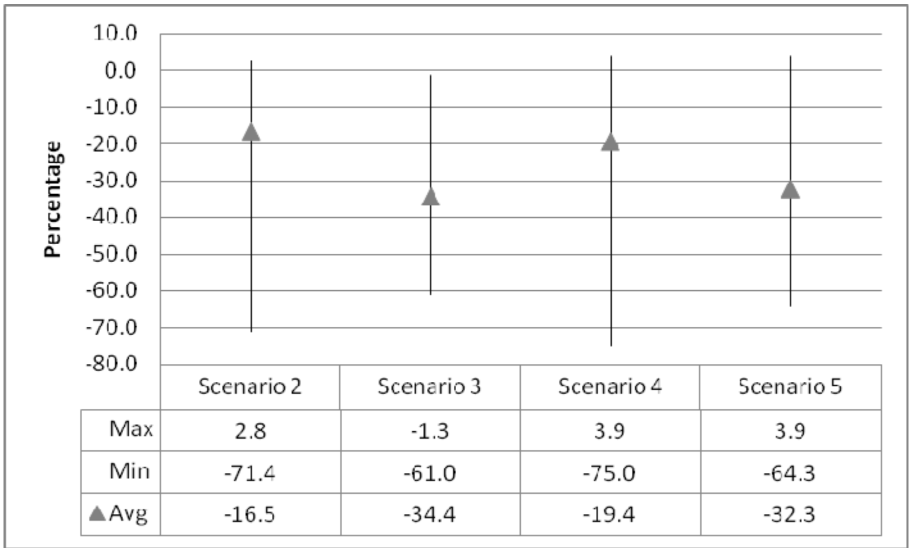
We make the following additional observations from Table 3.3 and Figure 3.19:

- For the corridor as a whole, adding a General Purpose lane (Scenario 3) for use during the peak periods shows the most improvement in delay of Scenarios 2 through 5 relative to the "Do Nothing" baseline (Scenario 1); however, at the individual link level during the peak periods, link variability contributes to other scenarios achieving the delay decreases relative to Scenario 1 surpassing that of Scenario 3.
- Scenario 5 may be viewed as a hybrid scenario between Scenarios 2 and 3 because it allows mixed flow traffic (like Scenario 3) to operate in the curbside lane when no buses (Rapid 3 or Local 3) are present then excludes such traffic (like Scenario 2) when such buses are present. One would then expect simulation results for Scenario 5 to be between those of Scenarios 2 and 3, which is nearly the case across all links. Certainly, this is the case for the overall corridor value relative to Scenarios 2 and 3.

Table 3.3 Average Non-Bus Delay (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	21.1	21.7 (+2.8%)	15.9 (-24.6%)	21.6 (+2.4%)	18.1 (-14.2%)
2	5.7	3.6 (-36.8%)	2.6 (-54.4%)	3.5 (-38.6%)	3.0 (-47.4%)
3	15.8	15.8 (0.0%)	11.6 (-26.6%)	15.8 (0.0%)	11.9 (-24.7%)

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
4	12.4	11.6 (-6.5%)	11.9 (-4.0%)	11.4 (-8.1%)	11.5 (-7.3%)
5	15.5	15.7 (+1.3%)	14.9 (-3.9%)	16.1 (+3.9%)	16.1 (+3.9%)
6	2.8	0.8 (-71.4%)	1.1 (-60.7%)	0.7 (-75.0%)	1.0 (-64.3%)
7	12.4	10.9 (-12.1%)	5.9 (-52.4%)	10.0 (-19.4%)	6.9 (-44.4%)
8	48.0	37.9 (-21.0%)	22.5 (-53.1%)	32.0 (-33.3%)	22.6 (-52.9%)
9	28.0	28.3 (+1.1%)	16.3 (-41.8%)	25.9 (-7.5%)	19.0 (-32.1%)
Northbound (AM Peak Period)					
10	45.8	41.5 (-9.4%)	23.0 (-49.8%)	45.7 (-0.2%)	28.7 (-37.3%)
11	8.0	7.7 (-3.8%)	7.9 (-1.3%)	7.9 (-1.3%)	7.0 (-12.5%)
12	3.6	2.5 (-30.6%)	2.5 (-30.6%)	2.6 (-27.8%)	2.1 (-41.7%)
13	2.9	2.3 (-20.7%)	2.0 (-31.0%)	2.1 (-27.6%)	2.0 (-31.0%)
14	13.9	13.6 (-2.2%)	11.5 (-17.3%)	12.5 (-10.1%)	10.8 (-22.3%)
15	4.1	2.8 (-31.7%)	1.6 (-61.0%)	2.5 (-39.0%)	1.9 (-53.7%)
16	4.6	3.0 (-34.8%)	2.7 (-41.3%)	2.7 (-41.3%)	2.7 (-41.3%)
17	27.4	26.3 (-4.0%)	18.8 (-31.4%)	25.3 (-7.7%)	20.2 (-26.3%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	2.8	-1.3	3.9	3.9
Min	-71.4	-61.0	-75.0	-64.3
▲Avg	-16.5	-34.4	-19.4	-32.3

Figure 3.19 Range in Percentage (%) Variation for *Non-Bus Delay* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.4 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (non-bus) basis. Table 3.5 transforms the results from Table 3.4 by accounting for the total number of vehicles (non-buses) traveling along the corridor during the two peak periods. As expected, we observe that Scenario 3 performs the best of alternative scenarios; however, Scenario 5 performs the closest to Scenario 3 relative to the change in non-bus delay for the corridor as a whole due to the fact that when the Rapid 3 and Local 3 buses are not present, all non-bus vehicles are allowed in the bus lane.

Table 3.4 Average Non-Bus Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	2.7	2.4 (-11.1%)	1.7 (-37.0%)	2.3 (-14.8%)	1.8 (-33.3%)
Northbound (AM Peak)	1.8	1.7 (-5.6%)	1.2 (-33.3%)	1.7 (-5.6%)	1.3 (-27.8%)

Table 3.5 Total Non-Bus Corridor Delay (hours) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	35.3	32.4 (-8.2%)	23.1 (-34.6%)	30.4 (-13.9%)	24.7 (-30.0%)
Northbound (AM Peak)	23.6	21.2 (-10.2%)	15.2 (-35.6%)	21.4 (-9.3%)	16.2 (-31.4%)

Rapid 3 Buses

Rapid 3 bus delay is expected to decrease from Scenario 1 to Scenario 3, then to Scenario 4 and Scenario 5 and finally to Scenario 2. We expect this pattern because for Scenario 3 Rapid 3 buses continue to travel with all other vehicles as in Scenario 1 though with the availability of an additional lane during the peak periods; however, this changes for Scenarios 4, 5, and 2 with Rapid 3 buses traveling only with Local 3 buses for all three scenarios and taxis and chartered buses for Scenario 4. From the simulation data, we found that this is the case for some links but not for all links (Table 3.6); however, it is definitely true on a corridor level basis (Tables 3.7 and 3.8). However, high fluctuation results were also found in two links: Links 6 and 16. What's more surprising is that, for some links, the Rapid 3 bus delay even increases from Scenario 1 to Scenario 3.

We then did further analysis of the simulation process and found that fluctuation of bus arrival times at traffic signals is the main reason for this. Although the bus dispatch time follows the same schedule in each scenario, there are still some variations of the Rapid 3 bus arrival time at each signal. A bus arrives at green time in Scenario 1 may experience much lower delay than in Scenario 3 if it happens to arrive in red time in Scenario 3. Since the statistical time interval length is 30 minutes, there are only three bus arrivals on average within each statistical interval. As such, the discrepancy delay of even one bus may significantly influence the statistical result in that interval. Regardless, in higher congestion level links such as Links 8 and 10, almost every bus may have to stop at the signal, thus other factors, like the lane number and lane operation measures will be more influential to the bus delay.

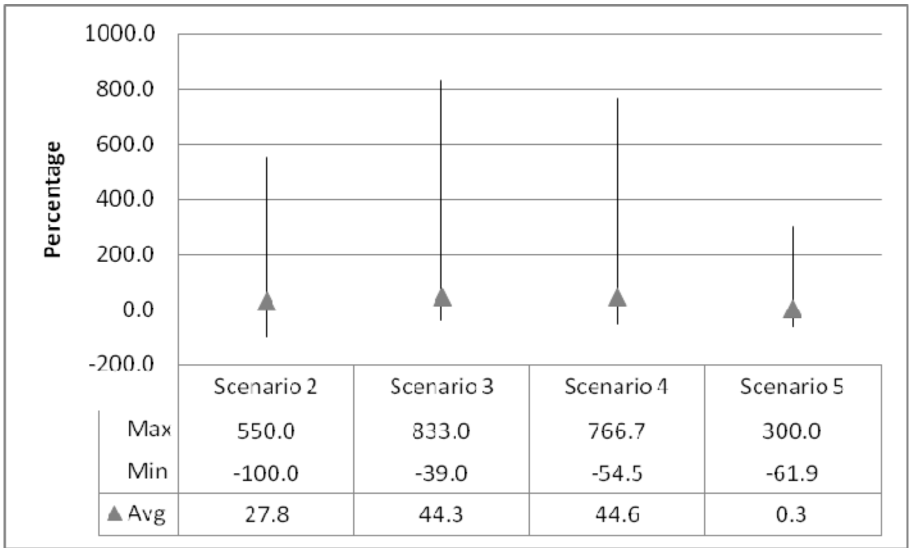
We make the following observations from Table 3.6 and Figure 3.20:

- Approximately 60% of all links across all scenarios show Rapid 3 bus delay decreases
- Scenarios 3 and 5, which allow non-buses to travel in the added curbside lane have the most instances of Rapid 3 bus delay increases across all links
- Figure 3.20a and 3.20b show the percentage change for all scenarios relative to Scenario 1 for all links and for all but Links 6 and 16, respectively. Figure 3.20b removes the effect of the high fluctuation values in Links 6 and 16 and provides a picture of the percentage change for all scenarios relative to Scenario 1 that is more

consistent with expectation. In particular, the average percentage changes for Scenarios 2 through 5 indicate delay *decreases* relative to Scenario 1.

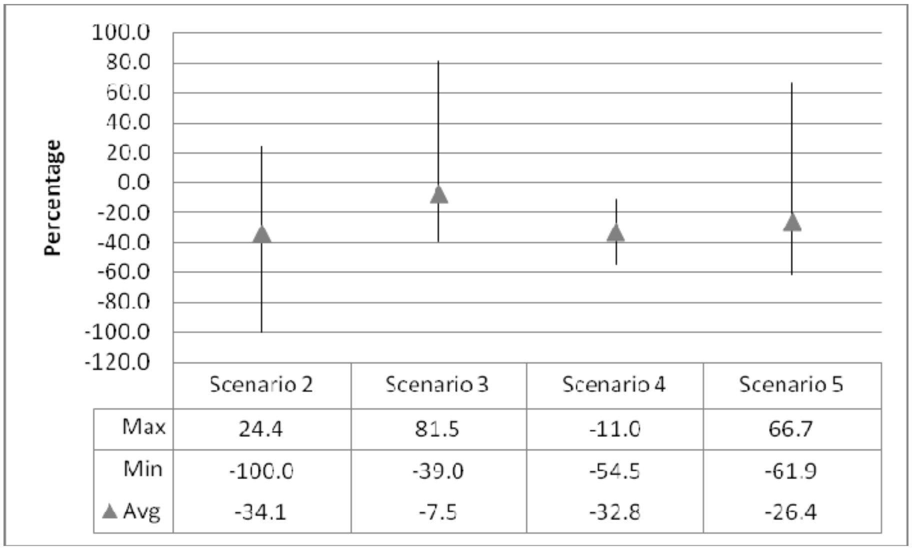
Table 3.6 Average Rapid 3 Bus Delay (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	40.9	31.8 (-22.2%)	43.1 (+5.4%)	35.7 (-12.7%)	36.5 (-10.8%)
2	35.3	26.3 (-25.5%)	32.3 (-8.5%)	31.4 (-11.0%)	29.6 (-16.1%)
3	2.7	3.3 (+22.2%)	4.9 (+81.5%)	1.4 (-48.1%)	4.5 (+66.7%)
4	2.1	0.0 (-100.0%)	1.9 (-9.5%)	1.3 (-38.1%)	0.8 (-61.9%)
5	48.8	27.2 (-44.3%)	38.8 (-20.5%)	36.3 (-25.6%)	29.2 (-40.2%)
6	0.6	3.9 (+550.0%)	5.6 (+833.3%)	3.5 (+483.3%)	2.4 (+300.0%)
7	41.5	26.9 (-35.2%)	37.3 (-10.1%)	30.2 (-27.2%)	30.0 (-27.7%)
8	32.0	6.7 (-79.1%)	19.6 (-38.8%)	15.9 (-50.3%)	14.5 (-54.7%)
9	65.5	41.7 (-36.3%)	50.6 (-22.7%)	38.7 (-40.9%)	33.7 (-48.5%)
Northbound (AM Peak Period)					
10	78.2	35.5 (-54.6%)	49.4 (-36.8%)	35.6 (-54.5%)	36.0 (-54.0%)
11	32.4	25.7 (-20.7%)	32.3 (-0.3%)	24.6 (-24.1%)	22.8 (-29.6%)
12	4.1	5.1 (+24.4%)	2.5 (-39.05)	3.1 (-24.4%)	2.3 (-43.9%)
13	30.3	24.6 (-18.8%)	30.5 (+0.7%)	25.6 (-15.5%)	23.6 (-22.1%)
14	13.9	8.1 (-41.7%)	17.6 (+26.6%)	9.3 (-33.1%)	15.7 (+12.9%)
15	35.3	22.1 (-37.4%)	27.1 (-23.2%)	22.1 (-37.4%)	22.8 (-35.4%)
16	0.3	1.6 (+433.3%)	0.4 (+33.3%)	2.6 (+766.7%)	0.6 (+100.0%)
17	48.7	28.1 (-42.3%)	40.1 (-17.7%)	25.2 (-48.3%)	33.9 (-30.4%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	550.0	833.0	766.7	300.0
Min	-100.0	-39.0	-54.5	-61.9
▲ Avg	27.8	44.3	44.6	0.3

Figure 3.20a Range in Percentage (%) Variation for *Rapid 3 Bus Delay* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	24.4	81.5	-11.0	66.7
Min	-100.0	-39.0	-54.5	-61.9
▲ Avg	-34.1	-7.5	-32.8	-26.4

Figure 3.20b Range in Percentage (%) Variation for *Rapid 3 Bus Delay* for all links except Links 6 and 16 of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing).

Table 3.7 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Rapid 3 bus) basis. Table 3.8 transforms the results from Table 3.7 by accounting for the total number of Rapid 3 buses traveling along the corridor during the two peak periods. For the corridor as a whole for a Rapid 3 bus delay decreases between approximately 29% and 38% for alternative scenarios 2, 4, and 5 in the southbound direction and 37% - 39% for northbound direction; accounting for the number of Rapid 3 buses during each peak period shows a percentage delay reduction range between 31% - 39% for alternative scenarios 2, 4, and 5 southbound and 35% - 40% for the northbound direction, which are considerably more reduction than experienced by Scenario 3.

Table 3.7 Average Rapid 3 Bus Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	4.5	2.8 (-37.8%)	3.9 (-13.3%)	3.2 (-28.9%)	3.0 (-33.3%)
Northbound (AM Peak)	4.1	2.5 (-39.0%)	3.3 (-19.5%)	2.5 (-39.0%)	2.6 (-36.6%)

Table 3.8 Total Rapid 3 Bus Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	9.0	5.5 (-38.9%)	7.7 (-14.4%)	6.2 (-31.1%)	6.0 (-33.3%)
Northbound (AM Peak)	8.1	5.0 (-38.3%)	6.7 (-17.3%)	4.9 (-39.5%)	5.3 (-34.6%)

Local Buses

Local 3 bus delay is expected to follow the same behavior pattern as Rapid 3 bus delay, that is, to decrease from Scenario 1 to Scenario 3, then to Scenario 4 and Scenario 5 and finally to Scenario 2. From the simulation data, we found that again this is the case for some links (Table 3.9); however, it is definitely true on a corridor level basis (Tables 3.10 and 3.11).

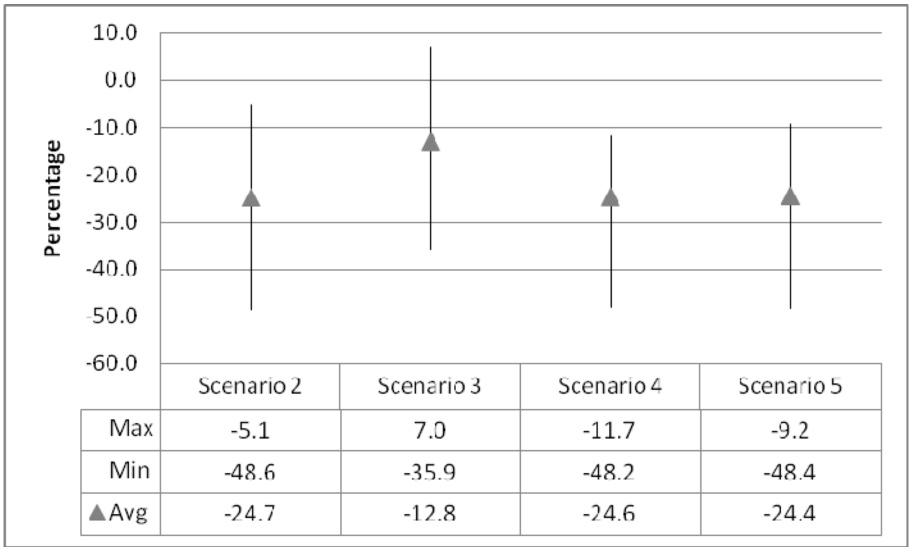
We make the following additional observations from Table 3.9 and Figure 3.21:

- Nearly 90% of all links across all scenarios show Local 3 bus delay decreases
- Scenario 3 is the only scenario to have instances where the Local 3 bus delay increases
- Figure 3.21 indicates very similar behavior among Scenarios 4, 5, and 2, which is to be expected.

Table 3.9 Average Local 3 Bus Delay (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	91.7	73.8 (-19.5%)	91.8 (+0.1%)	80.2 (-12.5%)	77.2 (-15.8%)
2	36.1	27.1 (-24.9%)	31.4 (-13.0%)	28.9 (-19.9%)	27.1 (-24.9%)
3	39.5	28.9 (-26.8%)	32.9 (-16.7%)	29.7 (-24.8%)	28.9 (-26.8%)
4	52.0	39.0 (-25.0%)	46.6 (-10.4%)	37.6 (-27.7%)	37.3 (-28.3%)
5	118.4	97.5 (-17.7%)	108.7 (-8.2%)	99.4 (-16.0%)	95.2 (-19.6%)
6	42.9	32.1 (-25.2%)	39.3 (-8.4%)	30.4 (-29.1%)	31.4 (-26.8%)
7	75.5	60.3 (-20.1%)	70.9 (-6.1%)	60.1 (-20.4%)	60.8 (-19.5%)
8	102.7	66.2 (-35.5%)	85.8 (-16.5%)	66.8 (-35.0%)	76.3 (-25.7%)
9	86.9	74.8 (-13.9%)	81.8 (-5.9%)	68.5 (-21.2%)	78.9 (-9.2%)
Northbound (AM Peak Period)					
10	94.3	48.5 (-48.6%)	62.1 (-34.1%)	54.0 (-42.7%)	51.6 (-45.3%)
11	59.9	51.6 (-13.9%)	55.2 (-7.8%)	50.6 (-15.5%)	49.4 (-17.5%)
12	58.9	46.0 (-21.9%)	48.8 (-17.1%)	46.1 (-21.7%)	46.6 (-20.9%)
13	29.5	28.0 (-5.1%)	29.4 (-0.3%)	25.0 (-15.3%)	23.8 (-19.3%)
14	55.4	46.7 (-15.7%)	59.3 (+7.0%)	48.9 (-11.7%)	47.5 (-14.3%)

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
15	43.4	22.5 (-48.2%)	27.8 (-35.9%)	22.5 (-48.2%)	22.4 (-48.4%)
16	38.5	25.4 (-34.0%)	27.9 (-27.5%)	26.2 (-31.9%)	25.4 (-34.0%)
17	67.9	51.8 (-23.7%)	56.0 (-17.5%)	51.4 (-24.3%)	54.8 (-19.3%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	-5.1	7.0	-11.7	-9.2
Min	-48.6	-35.9	-48.2	-48.4
▲Avg	-24.7	-12.8	-24.6	-24.4

Figure 3.21 Range in Percentage (%) Variation for *Local 3 Bus Delay* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.10 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Local 3 bus) basis. Table 3.11 transforms the results from Table 3.10 by accounting for the total number of Local 3 buses traveling along the corridor during each of the two peak periods. We observe again how alternative scenarios 2, 4, and 5 outperform Scenario 3 in terms of percentage delay reduction for both the southbound and northbound directions.

Table 3.10 Average Local 3 Bus Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	10.8	8.3 (-23.1%)	9.8 (-9.3%)	8.4 (-22.2%)	8.6 (-20.4%)
Northbound (AM Peak)	7.5	5.3 (-29.3%)	6.1 (18.7%)	5.4 (-28.0%)	5.4 (-28.0%)

Table 3.11 Total Local 3 Bus Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	21.2	16.7 (-21.2%)	19.6 (-7.5%)	16.7 (-21.2%)	17.1 (-19.3%)
Northbound (AM Peak)	14.8	10.7 (-27.7%)	12.4 (-16.2%)	11.0 (-25.7%)	10.9 (-26.4%)

3.5.1.2 Travel Time

In this section we present the *travel time* MOE for non-buses, Rapid 3 and Local 3 buses.

Non-Bus

Simulation results are shown in Tables 3.12, 3.13, and 3.14, and in Figure 3.22. The expected behavior pattern for the travel time MOE for non-buses is the same as that for the delay MOE, that is, to decrease from Scenario 1 to Scenario 2, Scenario 4, Scenario 5, and finally to Scenario 3. While this pattern is not true for each of the links in Table 3.12, it is true on a corridor level as shown in Tables 3.13 and 3.14.

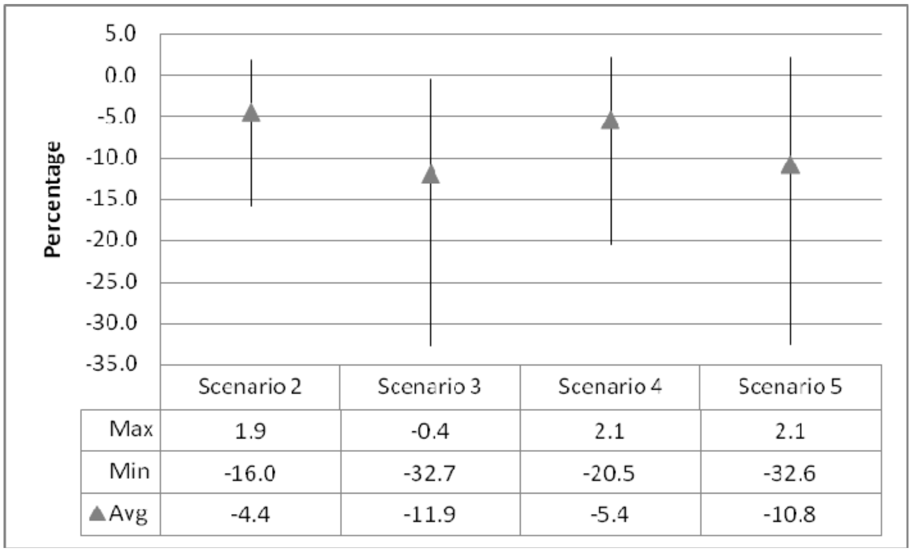
We make the following observations from Table 3.12 and Figure 3.22:

- More than ¾ of all links (13/17) across all scenarios show non bus delay decreases

- Scenario 3 is the only scenario to record delay reductions for all links
- Figure 3.22 indicates very similar behavior among Scenarios 4, 5, and 2, which is to be expected.

Table 3.12 Average Non Bus Travel Time (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	75.5	76.9 (+1.9%)	71.1 (-5.8%)	76.8 (+1.7%)	73.3 (-2.9%)
2	26.4	23.9 (-9.5%)	22.9 (-13.3%)	23.8 (-9.8%)	23.3 (-11.7%)
3	33.8	34.2 (+1.2%)	30.1 (-10.9%)	34.3 (+1.5%)	30.3 (-10.4%)
4	34.2	33.5 (-2.0%)	33.6 (-1.8%)	33.2 (-2.9%)	33.3 (-2.6%)
5	48.1	48.7 (+1.2%)	47.9 (-0.4%)	49.1 (+2.1%)	49.1 (+2.1%)
6	11.9	10.0 (-16.0%)	10.3 (-13.4%)	10.0 (-16.0%)	10.3 (-13.4%)
7	32.8	31.3 (-4.6%)	26.3 (-19.8%)	30.4 (-7.3%)	27.3 (-16.8%)
8	77.7	67.7 (-12.9%)	52.3 (-32.7%)	61.8 (-20.5%)	52.4 (-32.6%)
9	62.7	63.0 (+0.5%)	50.9 (-18.8%)	60.5 (-3.5%)	53.6 (-14.5%)
Northbound (AM Peak Period)					
10	80.9	75.8 (-6.3%)	57.3 (-29.2%)	79.9 (-1.2%)	63.0 (-22.1%)
11	37.0	36.1 (-2.4%)	36.3 (-1.9%)	36.3 (-1.9%)	35.3 (-4.6%)
12	25.0	23.1 (-7.6%)	23.2 (-7.2%)	23.3 (-6.8%)	22.8 (-8.8%)
13	11.5	11.3 (-1.7%)	11.0 (-4.3%)	11.1 (-3.5%)	11.0 (-4.3%)
14	45.1	44.7 (-0.9%)	42.6 (-5.5%)	43.6 (-3.3%)	41.9 (-7.1%)
15	25.3	23.8 (-5.9%)	22.6 (-10.7%)	23.5 (-7.1%)	22.9 (-9.5%)
16	22.0	20.2 (-8.2%)	19.8 (-10.0%)	19.9 (-9.5%)	19.8 (-10.0%)
17	47.7	47.1 (-1.3%)	39.6 (-17.0%)	46.1 (-3.4%)	41.0 (-14.0%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	1.9	-0.4	2.1	2.1
Min	-16.0	-32.7	-20.5	-32.6
▲Avg	-4.4	-11.9	-5.4	-10.8

Figure 3.22 Range in Percentage (%) Variation for *Non Bus Travel Time* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.13 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (non-bus) basis. Table 3.14 transforms the results from Table 3.13 by accounting for the total number of non-buses traveling along the corridor during the two peak periods. As expected, we observe that Scenario 3 performs the best of alternative scenarios; however, Scenario 5 performs the closest to Scenario 3 relative to the change in non-bus delay for the corridor as a whole due to the fact that when the Rapid 3 and Local 3 buses are not present, all non-bus vehicles are allowed in the bus lane.

Table 3.13 Average Non-Bus Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	6.7	6.5 (-3.0%)	5.8 (-13.4%)	6.3 (-6.0%)	5.9 (-11.9%)
Northbound (AM Peak)	4.9	4.7 (-4.1%)	4.2 (-14.3%)	4.7 (-4.1%)	4.3 (-12.2%)

Table 3.14 Total Non-Bus Corridor Travel Time (hours) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	89.2	87.5 (-1.9%)	78.2 (-12.3%)	85.5 (-4.1%)	79.8 (-10.5%)
Northbound (AM Peak)	65.3	62.5 (-4.3%)	56.5 (-13.5%)	62.7 (-4.0%)	57.5 (-11.9%)

Rapid 3 Bus

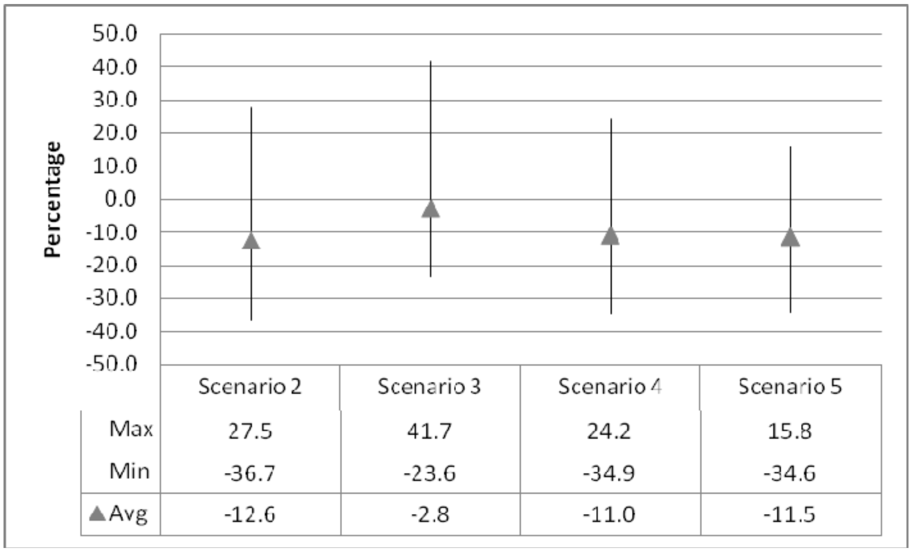
Simulation results are shown in Tables 3.15, 3.16, and 3.17, and in Figure 3.23. The expected behavior pattern for the travel time MOE for Rapid 3 buses is the same as that for the delay MOE for Rapid 3 buses, that is, to decrease from Scenario 1 to Scenario 3, Scenario 4, Scenario 5, and finally to Scenario 2. While this pattern is not true for each of the links in Table 3.15, it is true on a corridor level basis as shown in Tables 3.16 and 3.17.

We make the following observations from Table 3.15 and Figure 3.23:

- Approximately 60% of all links (10/17) across all scenarios show Rapid 3 bus delay decreases
- No scenario records travel time decreases for all links; however, Scenarios 2, 4, and 5 have the fewest instances of travel time increases compared to Scenario 3.
- Figure 3.23 indicates very similar behavior among Scenarios 2, 4, and 5, which is to be expected. There is very little variation among the average percentage reduction in travel time for these three scenarios: 12.6%, 11.0%, and 11.5% for Scenarios 2, 4, and 5, respectively

Table 3.15 Average Rapid Bus Travel Time (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	108.6	99.4 (-8.5%)	110.8 (+2.0%)	103.4 (-4.8%)	104.2 (-4.1%)
2	61.0	52.0 (-14.8%)	58.1 (-4.8%)	57.2 (-6.2%)	55.4 (-9.2%)
3	25.1	25.7 (+2.4%)	27.4 (+9.2%)	23.8 (-5.2%)	26.9 (+7.2%)
4	28.7	26.6 (-7.3%)	28.5 (-0.7%)	27.9 (-2.8%)	27.4 (-4.5%)
5	89.5	67.9 (-24.1%)	79.5 (-11.2%)	77.0 (-14.0%)	69.9 (-21.9%)
6	12.0	15.3 (+27.5%)	17.0 (+41.7%)	14.9 (+24.2%)	13.9 (+15.8%)
7	67.0	52.3 (-21.9%)	62.7 (-6.4%)	55.6 (-17.0%)	55.4 (-17.3%)
8	68.9	43.6 (-36.7%)	56.5 (-18.0%)	52.8 (-23.4%)	51.4 (-25.4%)
9	108.4	84.6 (-22.0%)	93.4 (-13.8%)	81.6 (-24.7%)	76.6 (-29.3%)
Northbound (AM Peak Period)					
10	122.0	79.3 (-35.0%)	93.2 (-23.6%)	79.4 (-34.9%)	79.8 (-34.6%)
11	68.3	61.6 (-9.8%)	68.2 (-0.1%)	60.5 (-11.4%)	58.7 (-14.1%)
12	30.6	31.6 (+3.3%)	29.0 (-5.2%)	29.5 (-3.6%)	28.7 (-6.2%)
13	41.2	35.5 (-13.8%)	41.4 (+0.5%)	36.5 (-11.4%)	34.5 (-16.3%)
14	52.6	46.8 (-11.0%)	56.3 (+7.0%)	48.0 (-8.7%)	54.4 (+3.4%)
15	61.8	48.6 (-21.4%)	53.6 (-13.3%)	48.6 (-21.4%)	49.4 (-20.1%)
16	21.9	23.3 (+6.4%)	22.1 (+0.9%)	24.2 (+10.5%)	22.2 (+1.4%)
17	74.2	53.6 (-27.8%)	65.4 (-11.9%)	50.7 (-31.7%)	59.4 (-19.9%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	27.5	41.7	24.2	15.8
Min	-36.7	-23.6	-34.9	-34.6
▲Avg	-12.6	-2.8	-11.0	-11.5

Figure 3.23 Range in Percentage (%) Variation for Rapid *3 Bus Travel Time* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.16 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Rapid 3 bus) basis. Table 3.17 transforms the results from Table 3.16 by accounting for the total number of Rapid 3 buses traveling along the corridor during the two peak periods. For the corridor as a whole for a Rapid 3 bus, delay decreases between approximately 14% and 18% for alternative scenarios 2, 4, and 5 in the southbound direction and 18% - 20% for northbound direction; accounting for the number of Rapid 3 buses during each peak period shows a percentage delay reduction range between 16% - 19% for alternative scenarios 2, 4, and 5 southbound and 18% - 20% for the northbound direction, which are considerably greater percentage reduction than experienced by Scenario 3.

Table 3.16 Average Rapid 3 Bus Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	9.5	7.8 (-17.9%)	8.9 (-6.3%)	8.2 (-13.7%)	8.0 (-15.8%)
Northbound (AM Peak)	7.9	6.3 (-20.3%)	7.2 (-8.9%)	6.3 (-20.3%)	6.5 (-17.7%)

Table 3.17 Total Rapid 3 Bus Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	19.0	15.4 (-18.9%)	17.5 (-7.9%)	16.0 (-15.8%)	16.0 (-15.8%)
Northbound (AM Peak)	15.8	12.7 (-19.6%)	14.3 (-9.5%)	12.6 (-20.3%)	12.9 (-18.4%)

Local 3 Bus

Local 3 bus travel time is expected to follow the same behavior pattern as Rapid 3 bus travel time, that is, to decrease from Scenario 1 to Scenario 3, then to Scenario 4 and Scenario 5 and finally to Scenario 2. From the simulation data, we found that again this is the case for some links (Table 3.18); however, it is definitely true on a corridor level basis (Tables 3.19 and 3.20).

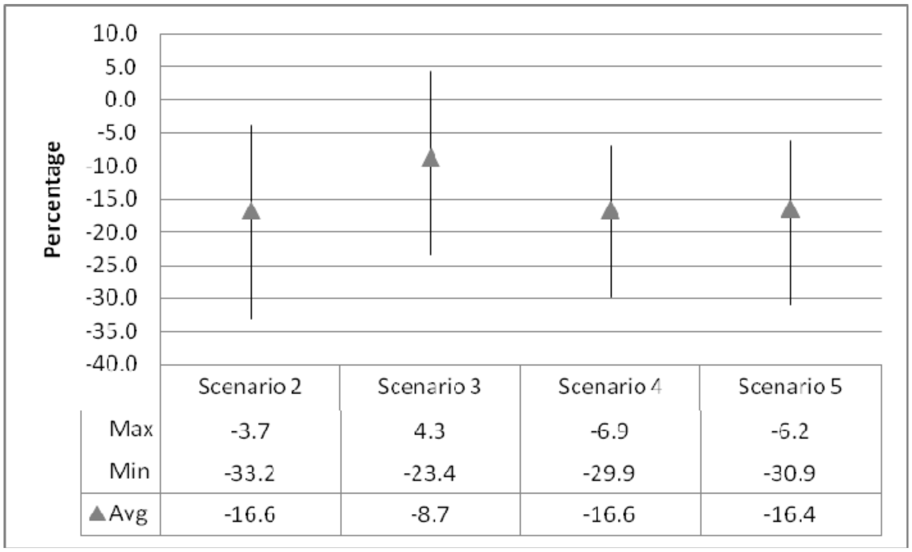
We make the following additional observations from Table 3.18 and Figure 3.24:

- Nearly 90% of all links across all scenarios show Local 3 bus travel time decreases
- Scenario 3 is the only scenario to have instances where the Local 3 bus delay increases
- Figure 3.24 indicates very similar behavior among Scenarios 2, 4, and 5, which is to

be expected. The average percentage reductions in travel time across all links for these scenarios are, respectively, 16.6%, 16.6%, and 16.4%.

Table 3.18 Average Local Bus Travel Time (seconds) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	159.3 (%)	141.4 (-11.2%)	159.4 (+0.1%)	147.8 (-7.2%)	144.8 (-9.1%)
2	61.9 (%)	52.9 (-14.5%)	57.2 (-7.6%)	54.7 (-11.6%)	52.9 (-14.5%)
3	61.9 (%)	51.3 (-17.1%)	55.3 (-10.7%)	52.2 (-15.7%)	51.3 (-17.1%)
4	78.6 (%)	65.5 (-16.7%)	73.2 (-6.9%)	64.1 (-18.4%)	63.9 (-18.7%)
5	159.1 (%)	138.2 (-13.1%)	149.3 (-6.2%)	140.1 (-11.9%)	135.9 (-14.6%)
6	54.3 (%)	43.5 (-19.9%)	50.6 (-6.8%)	41.8 (-23.0%)	42.7 (-21.4%)
7	100.9 (%)	85.8 (-15.0%)	96.4 (-4.5%)	85.6 (-15.2%)	86.3 (-14.5%)
8	139.6 (%)	103.1 (-26.1%)	122.7 (-12.1%)	103.7 (-25.7%)	113.3 (-18.8%)
9	129.7 (%)	117.7 (-9.3%)	124.7 (-3.9%)	111.3 (-14.2%)	121.7 (-6.2%)
Northbound (AM Peak Period)					
10	138.1 (%)	92.3 (-33.2%)	105.8 (-23.4%)	97.8 (-29.2%)	95.4 (-30.9%)
11	95.8 (%)	87.5 (-8.7%)	91.1 (-4.9%)	86.4 (-9.8%)	85.3 (-11.0%)
12	85.3 (%)	72.4 (-15.1%)	75.2 (-11.8%)	72.5 (-15.0%)	73.1 (-14.3%)
13	40.5 (%)	39.0 (-3.7%)	40.4 (-0.2%)	36.0 (-11.1%)	34.7 (-14.3%)
14	94.1 (%)	85.4 (-9.2%)	98.1 (+4.3%)	87.6 (-6.9%)	86.2 (-8.4%)
15	69.9 (%)	49.0 (-29.9%)	54.3 (-22.3%)	49.0 (-29.9%)	49.0 (-29.9%)
16	60.2 (%)	47.1 (-21.8%)	49.6 (-17.6%)	47.9 (-20.4%)	47.1 (-21.8%)
17	93.3 (%)	77.3 (-17.1%)	81.4 (-12.8%)	76.9 (-17.6%)	80.2 (-14.0%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	-3.7	4.3	-6.9	-6.2
Min	-33.2	-23.4	-29.9	-30.9
▲Avg	-16.6	-8.7	-16.6	-16.4

Figure 3.24 Range in Percentage (%) Variation for Local *3 Bus Travel Time* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.19 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Local 3 bus) basis. Table 3.20 transforms the results from Table 3.19 by accounting for the total number of Local 3 buses traveling along the corridor during the two peak periods. We observe again how alternative scenarios 2, 4, and 5 outperform Scenario 3 in terms of percentage travel time reduction for both the southbound and northbound directions.

Table 3.19 Average Local 3 Bus Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	15.8	13.3 (-15.8%)	14.8 (-6.3%)	13.4 (-15.2%)	13.5 (-14.6%)
Northbound (AM Peak)	11.3	9.2 (-18.6%)	9.9 (-12.4%)	9.2 (-18.6%)	9.2 (-18.6%)

Table 3.20 Total Local 3 Bus Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	31.1	26.6 (-14.5%)	29.6 (-4.8%)	26.7 (-14.1%)	27.1 (-12.9%)
Northbound (AM Peak)	22.4	18.3 (-18.3%)	20.2 (-9.8%)	18.8 (-16.1%)	18.7 (-16.5%)

3.5.1.3 Speed

In this section we present the simulation results for the *speed* MOE for non-buses, Rapid 3 and Local 3 buses. Each scenario's speed was calculated as a weighted average of the link-level speeds for that scenario with each link's weight equal to the proportion of that link's length over the entire corridor.

Non-Buses

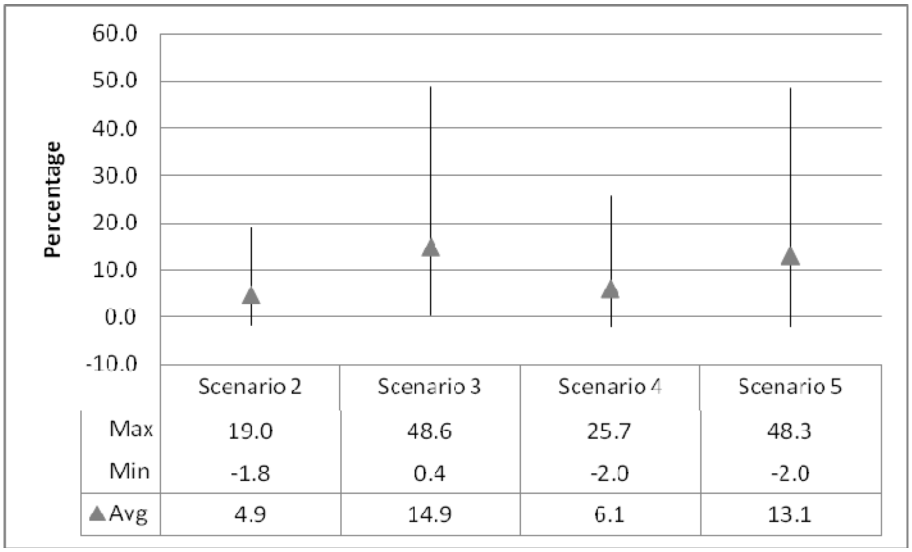
Tables 3.21 and 3.22, and Figure 3.25 show the simulation findings for the *speed* MOE for non-buses. Table 3.21 shows the value of non-bus speed for each link (overall 30-minute time periods during the peak periods) together with the percentage changes exhibited in parentheses. It is expected that non-bus speeds would increase the most for Scenarios 3 and 5 because for each of these scenarios additional lane space is provided for non-buses and for most links this is true as well as being true for the average corridor-wide speed (Table 3.22).

We make the following additional observations:

- Approximately 76% of all links across all scenarios show non-bus speed increases
- At worst, non-bus speeds decrease at most 2.0% (Link 5, Scenarios 4 and 5)
- Figure 3.25 shows for each scenario the percentage change in speed for non-buses compared with Scenario 1. The figure depicts that the speed changes are overwhelmingly increases and that the magnitude of speed decreases are very small.

Table 3.21 Average Non-Bus Speed (mph) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	26.7	26.2 (-1.8%)	28.4 (6.2%)	26.3 (-1.7%)	27.5 (3.0%)
2	28.1	31.0 (10.5%)	32.3 (15.3%)	31.1 (10.9%)	31.8 (13.3%)
3	20.0	19.7 (-1.2%)	22.4 (12.3%)	19.7 (-1.5%)	22.3 (11.6%)
4	22.9	23.4 (2.1%)	23.3 (1.8%)	23.6 (3.0%)	23.5 (2.7%)
5	25.1	24.8 (-1.2%)	25.2 (0.4%)	24.6 (-2.0%)	24.6 (-2.0%)
6	28.3	33.7 (19.0%)	32.7 (15.5%)	33.7 (19.0%)	32.7 (15.5%)
7	22.7	23.8 (4.8%)	28.3 (24.7%)	24.5 (7.9%)	27.2 (20.1%)
8	14.0	16.1 (14.8%)	20.8 (48.6%)	17.6 (25.7%)	20.8 (48.3%)
9	20.2	20.1 (-0.5%)	24.9 (23.2%)	20.9 (3.6%)	23.6 (17.0%)
Northbound (AM Peak Period)					
10	15.5	16.6 (6.7%)	21.9 (41.2%)	15.7 (1.3%)	19.9 (28.4%)
11	28.0	28.7 (2.5%)	28.6 (1.9%)	28.6 (1.9%)	29.4 (4.8%)
12	30.2	32.7 (8.2%)	32.5 (7.8%)	32.4 (7.3%)	33.1 (9.6%)
13	28.5	29.0 (1.8%)	29.8 (4.5%)	29.5 (3.6%)	29.8 (4.5%)
14	25.2	25.5 (0.9%)	26.7 (5.9%)	26.1 (3.4%)	27.2 (7.6%)
15	30.3	32.2 (6.3%)	33.9 (11.9%)	32.6 (7.7%)	33.5 (10.5%)
16	28.6	31.1 (8.9%)	31.7 (11.1%)	31.6 (10.6%)	31.7 (11.1%)
17	16.0	16.2 (1.3%)	19.2 (20.5%)	16.5 (3.5%)	18.6 (16.3%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	19.0	48.6	25.7	48.3
Min	-1.8	0.4	-2.0	-2.0
▲Avg	4.9	14.9	6.1	13.1

Figure 3.25 Range in Percentage (%) Variation for *Non-Bus Speed* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.22 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (non-bus) basis. As expected, we observe that Scenario 3 performs the best of alternative scenarios; however, Scenario 5 performs the closest to Scenario 3 relative to the increase in non-bus speed for the corridor as a whole since when the Rapid 3 and Local 3 buses are not present, all non-bus vehicles are allowed access to the bus lane.

Table 3.22 Average Non-Bus Corridor Speed (mph) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	23.0	23.6 (+2.6%)	26.1 (+13.5%)	24.0 (+4.3%)	25.5 (+10.9%)
Northbound (AM Peak)	24.4	25.5 (+4.5%)	27.3 (+11.9%)	25.6 (+4.9%)	27.1 (+11.1%)

Rapid 3 Bus

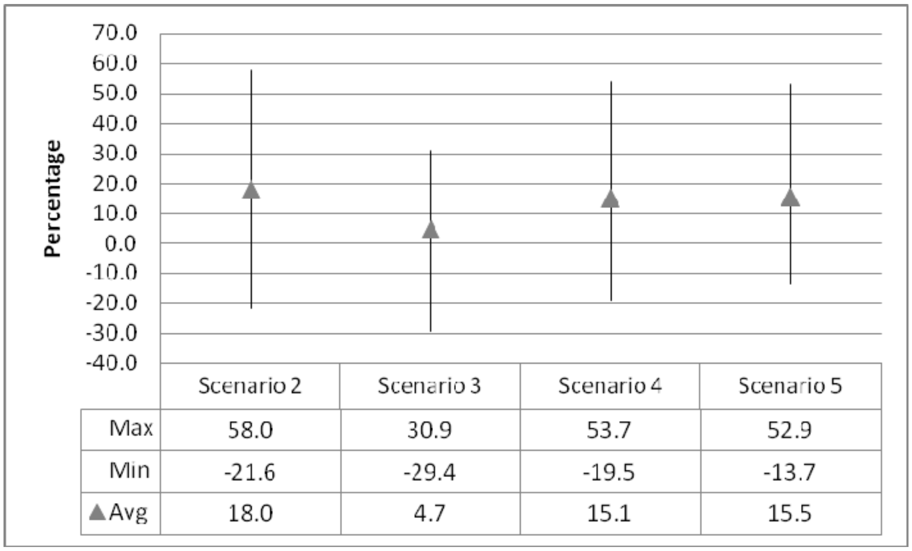
The next measure of effectiveness examined was speed with respect to Rapid 3 buses. Tables 3.23 and 3.24, and Figure 3.26 show the simulation findings for the speed MOE for Rapid 3 buses. As previously described, Table 3.23 shows the value of Rapid 3 bus speeds for each link (overall 30-minute time periods during the peak periods) together with the percentage changes exhibited in parentheses. It is expected that Rapid 3 bus speeds would increase the most for Scenarios 2, 4, and 5 because for each of these scenarios exclusive additional lane space is provided for Rapid 3 buses and for most links this is true. Moreover, it is certainly true for the average corridor-wide speeds for Rapid 3 buses (Table 3.24). We make the following additional observations:

- Approximately 60% of all links across all scenarios show bus speed increases
- At worst, Rapid 3 bus speeds decrease at most 29.4% (Link 6, Scenario 3)

Table 3.23 Average Rapid 3 Bus Speed (mph) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	18.6	20.3 (9.3%)	18.2 (-2.0%)	19.5 (5.0%)	19.4 (4.2%)
2	12.1	14.2 (17.3%)	12.8 (5.0%)	13.0 (6.6%)	13.4 (10.1%)
3	26.9	26.2 (-2.3%)	24.6 (-8.4%)	28.3 (5.5%)	25.1 (-6.7%)
4	27.3	29.4 (7.9%)	27.5 (0.7%)	28.1 (2.9%)	28.6 (4.7%)
5	13.5	17.8 (31.8%)	15.2 (12.6%)	15.7 (16.2%)	17.3 (28.0%)
6	28.1	22.0 (-21.6%)	19.8 (-29.4%)	22.6 (-19.5%)	24.3 (-13.7%)
7	11.1	14.2 (28.1%)	11.9 (6.9%)	13.4 (20.5%)	13.4 (20.9%)
8	15.8	25.0 (58.0%)	19.3 (21.9%)	20.6 (30.5%)	21.2 (34.0%)
9	11.7	15.0 (28.1%)	13.5 (16.1%)	15.5 (32.8%)	16.5 (41.5%)
Northbound (AM Peak Period)					
10	10.3	15.8 (53.8%)	13.5 (30.9%)	15.8 (53.7%)	15.7 (52.9%)
11	15.2	16.8 (10.9%)	15.2 (0.1%)	17.1 (12.9%)	17.7 (16.4%)
12	24.7	23.9 (-3.2%)	26.0 (5.5%)	25.6 (3.7%)	26.3 (6.6%)

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
13	8.0	9.2 (16.1%)	7.9 (-0.5%)	9.0 (12.9%)	9.5 (19.4%)
14	21.6	24.3 (12.4%)	20.2 (-6.6%)	23.7 (9.6%)	20.9 (-3.3%)
15	12.4	15.8 (27.2%)	14.3 (15.3%)	15.8 (27.2%)	15.5 (25.1%)
16	28.7	27.0 (-6.0%)	28.4 (-0.9%)	26.0 (-9.5%)	28.3 (-1.4%)
17	10.3	14.2 (38.4%)	11.6 (13.5%)	15.0 (46.4%)	12.8 (24.9%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	58.0	30.9	53.7	52.9
Min	-21.6	-29.4	-19.5	-13.7
▲Avg	18.0	4.7	15.1	15.5

Figure 3.26 Range in Percentage (%) Variation for *Rapid* 3 *Bus Speed* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.24 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Rapid 3 bus) basis. For the corridor as a whole for a Rapid 3 bus, speed increases between approximately 11% and 17% for alternative scenarios 2, 4, and 5 in the southbound direction and approximately 13% and 15% for the northbound direction;

Table 3.24 Average Rapid 3 Bus Corridor Speed (mph) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	17.2	20.1 (+16.9%)	17.6 (+2.3%)	19.0 (+10.5%)	19.3 (+12.2%)
Northbound (AM Peak)	16.5	18.9 (+14.5%)	17.3 (+4.8%)	19.0 (+15.2%)	18.6 (+12.7%)

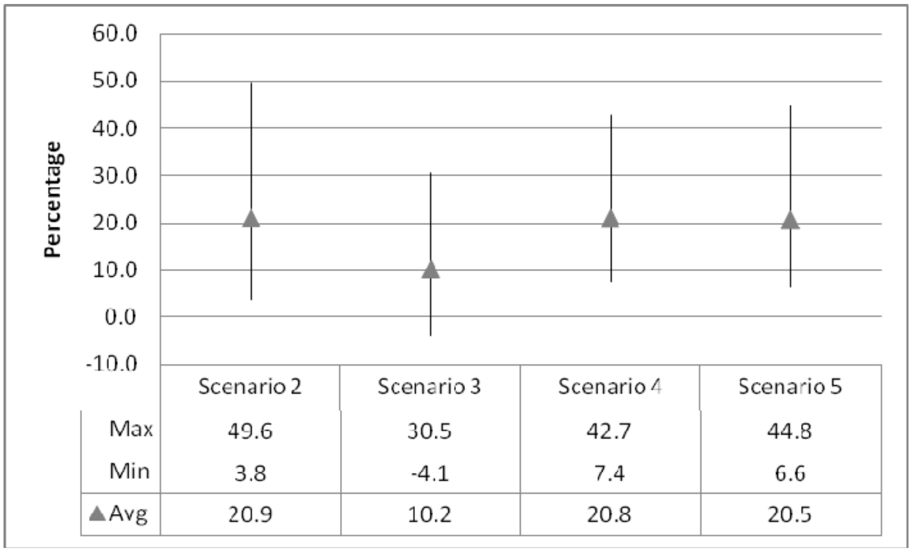
Local 3 Buses

The next measure of effectiveness examined was speed for Local 3 buses. Tables 3.25 and 3.26, and Figure 3.27 show the simulation findings for the speed MOE for Local 3 buses. As previously described, Table 3.25 shows the value of Local 3 bus speed for each link (overall 30-minute time periods during the peak periods) together with the percentage changes exhibited in parentheses. It is expected that Local 3 bus speeds would increase the most for Scenarios 2, 4, and 5 because for each of these scenarios semi-exclusive lane space is provided for Local 3 buses and for all links this is true. Moreover, it is certainly true for the average corridor-wide speeds for Local 3 buses (Table 3.26). We make the following additional observations:

- Approximately 90% of all links across all scenarios show bus speed increases
- At worst, Local 3 bus speeds decrease at most 4.1% (Link 14, Scenario 3)
- Figure 3.27 shows how rare, if ever, Local 3 bus speed decreases and this occurs for Scenario 3 as expected.

Table 3.25 Average Local 3 Bus Speed (mph) per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	12.7	14.3 (12.7%)	12.6 (-0.1%)	13.6 (7.8%)	13.9 (10.0%)
2	12.0	14.0 (17.0%)	13.0 (8.2%)	13.5 (13.2%)	14.0 (17.0%)
3	10.9	13.1 (20.7%)	12.2 (11.9%)	12.9 (18.6%)	13.1 (20.7%)
4	10.0	12.0 (20.0%)	10.7 (7.4%)	12.2 (22.6%)	12.2 (23.0%)
5	7.6	8.7 (15.1%)	8.1 (6.6%)	8.6 (13.6%)	8.9 (17.1%)
6	6.2	7.8 (24.8%)	6.7 (7.3%)	8.1 (29.9%)	7.9 (27.2%)
7	7.4	8.7 (17.6%)	7.7 (4.7%)	8.7 (17.9%)	8.6 (16.9%)
8	7.8	10.6 (35.4%)	8.9 (13.8%)	10.5 (34.6%)	9.6 (23.2%)
9	9.8	10.7 (10.2%)	10.1 (4.0%)	11.4 (16.5%)	10.4 (6.6%)
Northbound (AM Peak Period)					
10	9.1	13.6 (49.6%)	11.9 (30.5%)	12.8 (41.2%)	13.2 (44.8%)
11	10.8	11.9 (9.5%)	11.4 (5.2%)	12.0 (10.9%)	12.2 (12.3%)
12	8.8	10.4 (17.8%)	10.0 (13.4%)	10.4 (17.7%)	10.3 (16.7%)
13	8.1	8.4 (3.8%)	8.1 (0.2%)	9.1 (12.5%)	9.4 (16.7%)
14	12.1	13.3 (10.2%)	11.6 (-4.1%)	13.0 (7.4%)	13.2 (9.2%)
15	11.0	15.6 (42.7%)	14.1 (28.7%)	15.6 (42.7%)	15.6 (42.7%)
16	10.4	13.3 (27.8%)	12.7 (21.4%)	13.1 (25.7%)	13.3 (27.8%)
17	8.2	9.8 (20.7%)	9.4 (14.6%)	9.9 (21.3%)	9.5 (16.3%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	49.6	30.5	42.7	44.8
Min	3.8	-4.1	7.4	6.6
▲Avg	20.9	10.2	20.8	20.5

Figure 3.27 Range in Percentage (%) Variation for *Local 3 Bus Speed* over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.26 shows the average delay for the entire corridor length (southbound and northbound) on an individual vehicle (Local 3 bus) basis for each of the two peak periods. We observe again how alternative scenarios 2, 4, and 5 outperform Scenario 3 in terms of percentage travel time reduction for both the southbound and northbound directions with a range in average speed increases for scenarios 2, 4, and 5 of approximately 15% to 17% (southbound) and 23% to 24% (northbound). For Scenario 3, the average percentage speed increase is approximately 6% (southbound) and 14% (northbound).

Table 3.26 Average Local 3 Bus Corridor Speed (mph) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	9.8	11.5 (+17.3%)	10.4 (+6.1%)	11.4 (+16.3%)	11.3 (+15.3%)
Northbound (AM Peak)	10.0	12.4 (+24.0%)	11.4 (+14.0%)	12.3 (+23.0%)	12.4 (+24.0%)

3.5.1.4 Queue Length

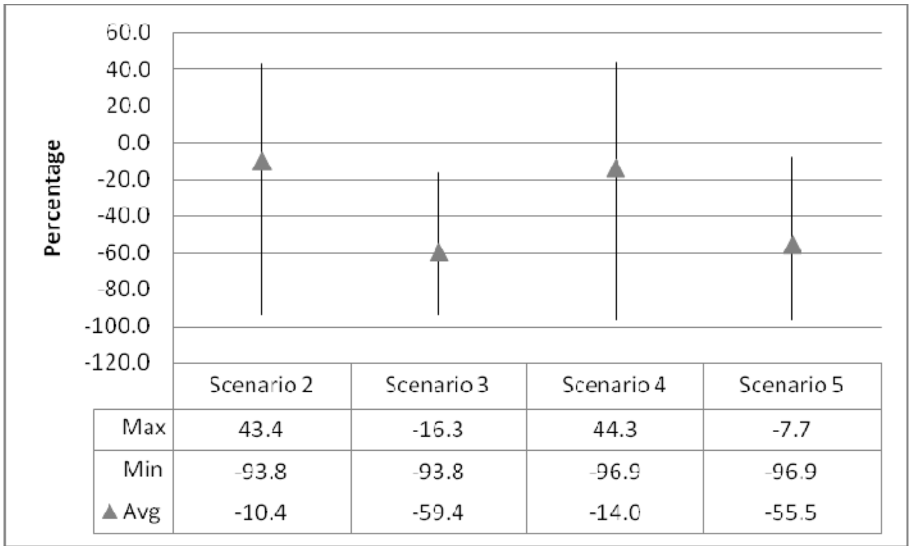
The next measure of effectiveness examined was queue length. Tables 3.27 and 3.28, and Figure 3.28 show the simulation findings for the queue length MOE. It is expected that queue lengths would decrease the most for Scenarios 3 and 5 because for each of these additional lane space is provided for non-buses and for most links this is true and is also true on average over all links. We make the following observations from Table 3.27 and Figure 3.28:

- More than 50% of all links across all scenarios show queue length decreases
- Scenarios 3 and 5 have queue length decreases across all links

Table 3.27 Average Queue Length per Corridor Link over Peak Periods

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak Period)					
1	28.2	31.3 (+11.0%)	13.7 (-51.4%)	32.5 (+15.2%)	17.2 (-39.0%)
2	4.9	3.8 (-22.4%)	1.2 (-75.5%)	3.8 (-22.4%)	1.6 (-67.3%)
3	27.6	30.1 (+9.1%)	11.7 (-57.6%)	29.5 (+6.9%)	13.7 (-50.4%)
4	16.8	17.5 (+4.2%)	11.2 (-33.3%)	16.9 (+0.6%)	10.8 (-35.7%)
5	22.1	31.7 (+43.4%)	15.3 (-30.8%)	31.9 (+44.3%)	20.4 (-7.7%)
6	3.2	0.2 (-93.8%)	0.2 (-93.8%)	0.1 (-96.9%)	0.1 (-96.9%)
7	16.5	16.0 (-3.0%)	4.5 (-72.7%)	14.5 (-12.1%)	5.7 (-65.5%)
8	90.9	70.2 (-22.8%)	20.2 (-77.8%)	56.1 (-38.3%)	24.1 (-73.5%)
9	43.1	46.1 (+7.0%)	12.0 (-72.2%)	38.4 (-10.9%)	16.0 (-62.9%)
Northbound (AM Peak Period)					
10	67.7	60.8 (-10.2%)	18.0 (-73.4%)	68.7 (+1.5%)	27.7 (-59.1%)
11	8.0	9.7 (+21.3%)	6.7 (-16.3%)	9.7 (+21.3%)	5.8 (-27.5%)

Link #	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
12	1.5	0.8 (-46.7%)	0.9 (-40.0%)	1.5 (0.0%)	0.7 (-53.3%)
13	2.9	2.6 (-10.3%)	1.3 (-55.2%)	2.2 (-24.1%)	1.2 (-58.6%)
14	18.2	21.4 (+17.6%)	10.7 (-41.2%)	17.5 (-3.8%)	10.5 (-42.3%)
15	3.8	2.8 (-26.3%)	0.5 (-86.8%)	2.0 (-47.4%)	0.8 (-78.9%)
16	4.0	2.3 (-42.5%)	1.2 (-70.0%)	1.8 (-55.0%)	1.2 (-70.0%)
17	51.7	45.4 (-12.2%)	19.6 (-62.1%)	42.9 (-17.0%)	23.4 (-54.7%)



	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Max	43.4	-16.3	44.3	-7.7
Min	-93.8	-93.8	-96.9	-96.9
▲ Avg	-10.4	-59.4	-14.0	-55.5

Figure 3.28 Range in Percentage (%) Variation for Queue Length over all links of Alternative Scenarios (2, 3, 4, 5) Relative to Scenario 1 (Do Nothing)

Table 3.28 shows the average queue length for the entire corridor length (southbound and northbound) for each of the two peak periods. We observe how alternative scenarios 3 and 5 outperform Scenarios 2 and 4 in terms of percentage queue length reduction for both the southbound and northbound directions with a range in average queue length decreases for scenarios 3 and 5 of approximately 57% to 64% (southbound) and 55% to 62% (northbound). For Scenarios 2 and 4, the average percentage queue length decrease ranges between approximately 3% to 11% (southbound) and 7% to 8% (northbound).

Table 3.28 Average Corridor Queue Length (feet) over Peak Periods

Direction (Time Period)	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	28.1	27.4 (-2.5%)	10.0 (-64.4%)	24.9 (- 11.4%)	12.2 (-56.6%)
Northbound (AM Peak)	19.7	18.2 (-7.6%)	7.4 (-62.4%)	18.3 (-7.1%)	8.9 (-54.8%))

3.5.2 Major Corridor-wide Findings

Based on the simulation results, the performance of each scenario averaged over all the links is summarized in Tables 3.28 through 3.31 for queue length, delay, travel time, and speed, respectively. Tables 3.32 and 3.33 account for the number of vehicles (non-buses and buses) and show the total value for delay and travel time across all alternative scenarios. As could be observed from the data, with the curb lane converted into a travel lane, the MOEs are all improved compared with the do-nothing scenario, that is, delays decrease across all alternative scenarios, travel times decrease across all alternative scenarios, speeds increase across all alternative scenarios, and queue lengths decrease across all alternative scenarios; however, no single alternative scenario does better than all other alternative scenarios across all MOEs.

Among scenarios 2 through 5 on a corridor level basis, Scenario 2 has the lowest Rapid 3 and Local 3 bus delay, lowest Rapid 3 and Local 3 travel time and highest Rapid 3 and Local 3 bus speed, and Scenario 3 has the lowest non-bus delay, lowest non-bus travel time, highest non-bus speed, and shortest queue length. These corridor-wide findings are shown in Table 3.30 and graphically in Figures 3.31 and 3.32 for the travel time MOE and in Table 3.29 and graphically in Figures 3.29 and 3.30 for the delay MOE. However, Scenarios 4 and 5 give values for delay, travel time, and speed for the Rapid 3 and Local 3 buses that are close to Scenario 2's values. In fact they are not statistically different from each other in most cases based on a set of non-parametric statistical tests[7] that we conducted on data shown in Tables 3.3, 3.6, 3.9, 3.12, 3.15, 3.18, 3.21, 3.23, and 3.25 for scenarios 2, 4, and 5.

Scenario 5, meanwhile, appears to be a good compromise between exclusive bus use and entirely mixed traffic use, however, it also requires a lot more technology (e.g. a warning signal, either in the pavement or on the roadside, to communicate to vehicles that a bus is approaching), and is considered an experimental scenario and needs more extensive investigation if it is to be seriously considered to be implemented.

Table 3.29 Average Vehicle Corridor Delay (minutes) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	2.7	2.4 (-11.1%)	1.7 (-37.0%)	2.3 (-14.8%)	1.8 (-33.3%)
	Rapid 3	4.5	2.8 (-37.8%)	3.9 (-13.3%)	3.2 (-28.9%)	3.0 (-33.3%)
	Local 3	10.8	8.3 (-23.1%)	9.8 (-9.3%)	8.4 (-22.2%)	8.6 (-20.4%)
Northbound (AM Peak)	Non-Bus	1.8	1.7 (-5.6%)	1.2 (-33.3%)	1.7 (-5.6%)	1.3 (-27.8%)
	Rapid 3	4.1	2.5 (-39.0%)	3.3 (-19.5%)	2.5 (-39.0%)	2.6 (-36.6%)
	Local 3	7.5	5.3 (-29.3%)	6.1 (18.7%)	5.4 (-28.0%)	5.4 (-28.0%)

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[7] We used the Mann-Whitney and Kruskal-Wallis tests, which are each nonparametric tests for the significance of the difference between the distributions of independent samples; two such samples for the Mann-Whitney test and three or more samples for the Kruskal-Wallis test.

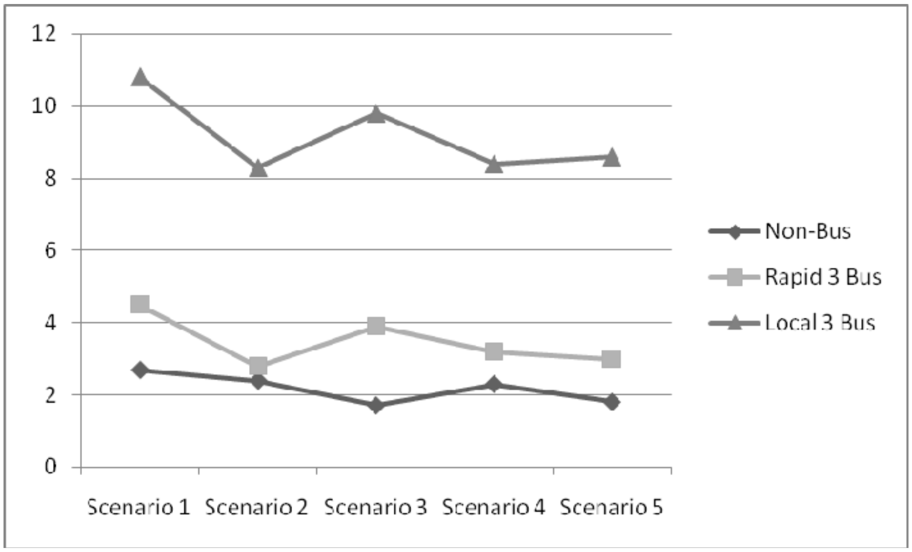

Figure 3.29 Southbound Corridor Delay Across Scenarios

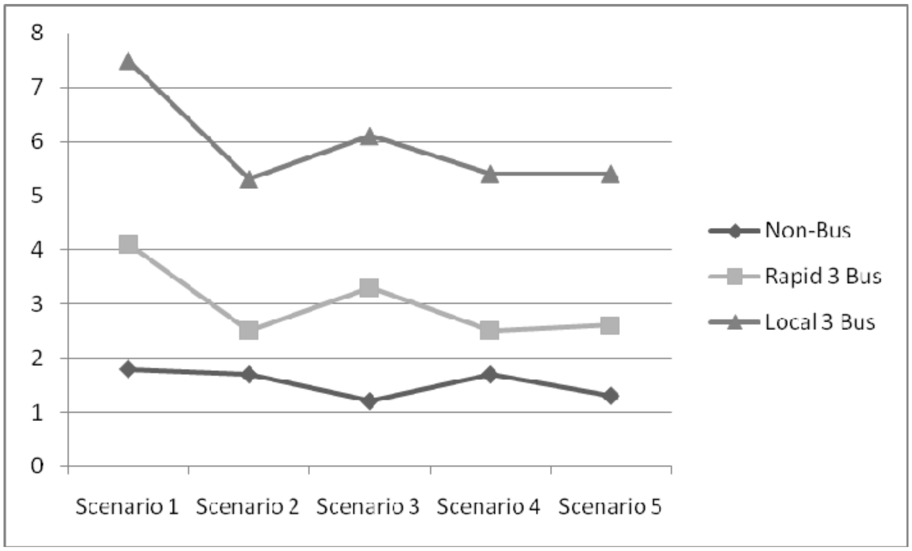

Figure 3.30 Northbound Corridor Delay Across Scenarios

Table 3.30 Average Vehicle Corridor Travel Time (minutes) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	6.7	6.5 (-3.0%)	5.8 (-13.4%)	6.3 (-6.0%)	5.9 (-11.9%)
	Rapid 3	9.5	7.8 (-17.9%)	8.9 (-6.3%)	8.2 (-13.7%)	8.0 (-15.8%)
	Local 3	15.8	13.3 (-15.8%)	14.8 (-6.3%)	13.4 (-15.2%)	13.5 (-14.6%)
Northbound (AM Peak)	Non-Bus	4.9	4.7 (-4.1%)	4.2 (-14.3%)	4.7 (-4.1%)	4.3 (-12.2%)
	Rapid 3	7.9	6.3 (-20.3%)	7.2 (-8.9%)	6.3 (-20.3%)	6.5 (-17.7%)
	Local 3	11.3	9.2 (-18.6%)	9.9 (-12.4%)	9.2 (-18.6%)	9.2 (-18.6%)

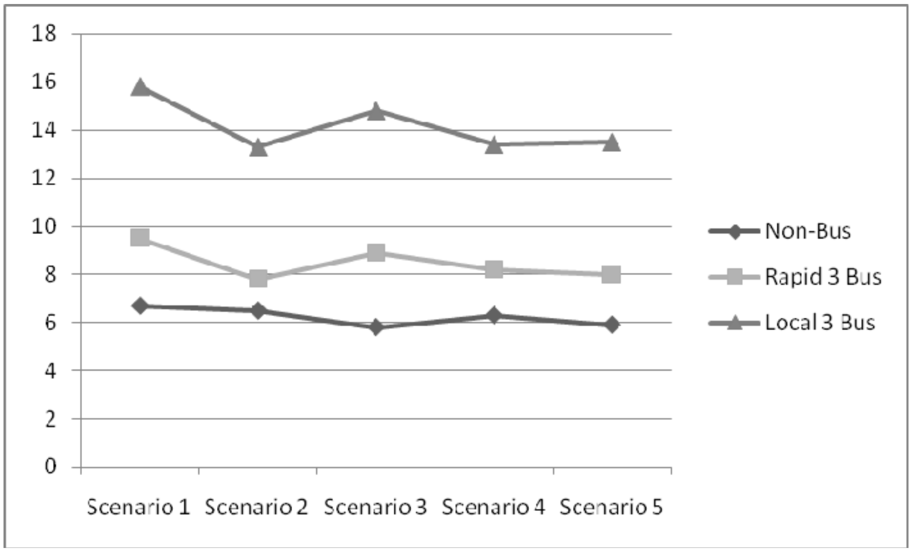

Figure 3.31 Southbound Corridor Travel Time Across Scenarios

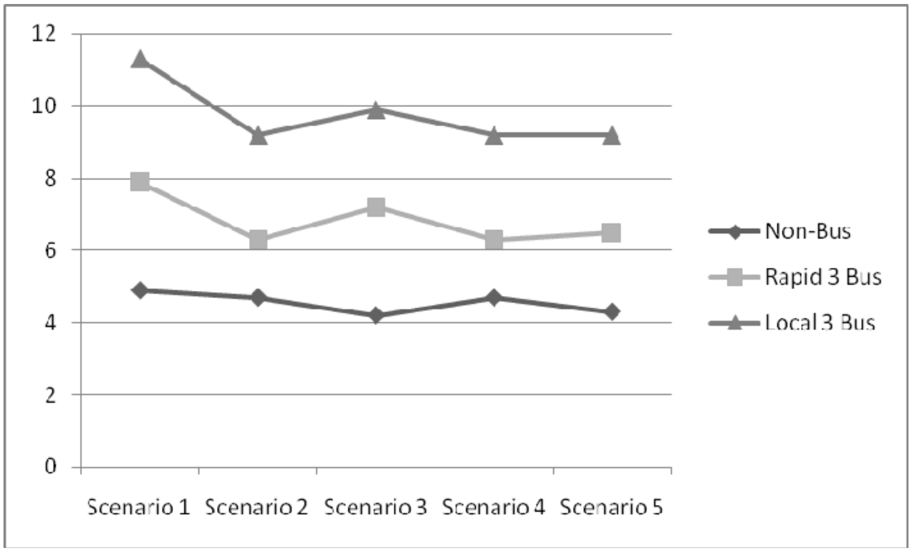

Figure 3.32 Northbound Corridor Travel Time Across Scenarios

Table 3.31 Average Vehicle Corridor Speed (mph) over Peak Periods

Direction (Time Period)	Vehicle Type	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	23.0	23.6 (+2.6%)	26.1 (+13.5%)	24.0 (+4.3%)	25.5 (+10.9%)
	Rapid 3	17.2	20.1 (+16.9%)	17.6 (+2.3%)	19.0 (+10.5%)	19.3 (+12.2%)
	Local 3	9.8	11.5 (+17.3%)	10.4 (+6.1%)	11.4 (+16.3%)	11.3 (+15.3%)
Northbound (AM Peak)	Non-Bus	24.4	25.5 (+4.5%)	27.3 (+11.9%)	25.6 (+4.9%)	27.1 (+11.1%)
	Rapid 3	16.5	18.9 (+14.5%)	17.3 (+4.8%)	19.0 (+15.2%)	18.6 (+12.7%)
	Local 3	10.0	12.4 (+24.0%)	11.4 (+14.0%)	12.3 (+23.0%)	12.4 (+24.0%)

Table 3.32 Total Corridor Delay over Peak Periods

Direction (Time Period)	Vehicle Type	Units	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	Hours	35.3	32.4 (-8.2%)	23.1 (-34.6%)	30.4 (-13.9%)	24.7 (-30.0%)
	Rapid 3	Minutes	9.0	5.5 (-38.9%)	7.7 (-14.4%)	6.2 (-31.1%)	6.0 (-33.3%)
	Local 3	Minutes	21.2	16.7 (-21.2%)	19.6 (-7.5%)	16.7 (-21.2%)	17.1 (-19.3%)
Northbound (AM Peak)	Non-Bus	Hours	23.6	21.2 (-10.2%)	15.2 (-35.6%)	21.4 (-9.3%)	16.2 (-31.4%)
	Rapid 3	Minutes	8.1	5.0 (-38.3%)	6.7 (-17.3%)	4.9 (-39.5%)	5.3 (-34.6%)
	Local 3	Minutes	14.8	10.7 (-27.7%)	12.4 (-16.2%)	11.0 (-25.7%)	10.9 (-26.4%)

Table 3.33 Total Corridor Travel Time over Peak Periods

Direction (Time Period)	Vehicle Type	Units	Scenario 1 (Do Nothing)	Scenario 2 (Rapid 3 + Local 3)	Scenario 3 (General Purpose)	Scenario 4 (Bus + Taxi)	Scenario 5 (Dynamic Dedicated BRT)
Southbound (PM Peak)	Non-Bus	Hours	89.2	87.5 (-1.9%)	78.2 (-12.3%)	85.5 (-4.1%)	79.8 (-10.5%)
	Rapid 3	Minutes	19.0	15.4 (-18.9%)	17.5 (-7.9%)	16.0 (-15.8%)	16.0 (-15.8%)
	Local 3	Minutes	31.1	26.6 (-14.5%)	29.6 (-4.8%)	26.7 (-14.1%)	27.1 (-12.9%)
Northbound (AM Peak)	Non-Bus	Hours	65.3	62.5 (-4.3%)	56.5 (-13.5%)	62.7 (-4.0%)	57.5 (-11.9%)
	Rapid 3	Minutes	15.8	12.7 (-19.6%)	14.3 (-9.5%)	12.6 (-20.3%)	12.9 (-18.4%)
	Local 3	Minutes	22.4	18.3 (-18.3%)	20.2 (-9.8%)	18.8 (-16.1%)	18.7 (-16.5%)

3.6 Recommendations and Conclusions

The decision to choose among the alternative scenarios

- Bus/HOV (Scenarios 2 or 4)
- General Purpose Lane (Scenario 3)
- Hybrid (Scenario 5)

mostly depends on *how much* the different values of MOEs really make a difference. To determine that, a Level of Service (LOS) comparison for both general traffic and transit (instead of comparing the exact numbers) is made next.

The LOS for an arterial is based on its average travel speed (Transportation Research Board, 1994). For Lincoln Blvd, which is an urban arterial, divided, with some parking at curbside, the appropriate LOS values are the following:

Arterial LOS Values

LOS	**Speed (mph)**
A	**>= 30**
B	**>= 24**
C	**>= 18**
D	**>= 14**
E	**>= 10**
F	**< 10**

Based on these LOS values and findings from Table 3.31 (and a weighted average of southbound and northbound speeds), the LOS ratings resulting from the five scenarios are shown in Table 3.34.

Table 3.34 LOS Values Comparison Across Scenarios

Measures of Effectiveness	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Average Non-Bus Speed (mph)	***23.7***	***24.6***	***26.7***	***24.8***	***26.3***
Non-Bus LOS	***C***	***B***	***B***	***B***	***B***

From Table 3.34, Scenarios 2, 4, and 5 provide the same LOS for non-bus traffic as Scenario 3 does, while providing better service (in terms of reduced bus delay and increased bus speed) to buses. Thus Scenarios 2, 4, and 5 appear to be better than Scenario 3; moreover, there is another issue as it relates to Scenario 3 that needs to be considered:

- Possible impact of generated traffic, that is, diverted traffic (trips shifted in time, route and destination), and induced vehicle travel (shifts from other modes, longer trips and new vehicle trips). With the LOS improved along Lincoln Boulevard for Scenario 3 relative to Scenario 1 more traffic will likely be attracted to the curbside lane especially from the off-peak to the peak periods; and such growth in traffic could result in deteriorated LOS again over time and thus would continue to favor the alternative bus-only scenarios (Litman, 2009), and (Cervero, 2002). The amount of traffic generated by a road project varies depending on site-specific conditions. Generated traffic usually accumulates over several years and under typical urban conditions, more than half of added capacity is filled within five years of project completion by additional vehicle trips that would not otherwise occur, with additional but slower growth in later years (Litman, 2009).

Because Scenario 5 would require an investment of substantial technology and extensive investigation if it is to be seriously considered for implementation, in the short term we recommend that Scenarios 2 and 4 be pursued.

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4.0 LINCOLN BOULEVARD CASE STUDY: RIDERSHIP IMPACTS ASSESSMENT

Direct modeling of transit ridership has emerged as an alternative to traditional four-step travel-demand modeling for corridor and station-levels analyses (Cervero, 2006). Direct models estimate ridership as a function of station environments and transit service features rather than using mode-choice results from large-scale models. This provides a fine-grain resolution suitable for studying relationships between built environments, transit services, and ridership. Moreover, the amount of resources needed to code a network, set up a regional travel model, and then do a mode choice analysis favored a sketch planning approach like a direct ridership model.

Because *direct models* predict demand for a specific node or location versus the origin-destination attributes of a trip, some variables normally found in mode-choice models, such as comparative travel times and prices of transit versus auto, are noticeably absent. The comparative accessibility of station-area residents to jobs and shops via transit versus auto are sometimes included in direct models, thus in this sense, performance attributes of competitive modes are imbedded in the analyses.

Direct ridership models generally have small sample sizes since observations consist of transit stations or stops. Thus degree of freedom constraints often limit the number of variables that can be included as well as their specifications (e.g., inclusion of interactive terms). It is because of these limitations that direct models fall under the rubric of sketch-planning tools. They provide order-of-magnitude insights for testing of various system designs and land-use scenarios.

To date, direct modeling has been used to estimate station- and corridor-level ridership for rail transit investments and expansion proposals in areas as diverse as Charlotte-Mecklenburg County (NC), St. Louis (MO), the East Bay of the San Francisco Bay Area, and Boise (ID) (Cervero, 1998; Cervero, 2004; Fehr and Peers, 2005). For a host of reasons, including fiscal constraints and development densities that are too low for rail investments, more and more U.S. cities and regions are turning to Bus Rapid Transit (BRT) as a cost-effective alternative to rail transit. As far as we know from the literature, no direct ridership model has been estimated to date for a BRT proposal.

The remaining sections of this chapter present a Direct Ridership Model developed to estimate ridership levels for a proposed dedicated bus-only lane Big Blue Bus BRT service in Santa Monica, California along the Lincoln Boulevard corridor. The section is divided into the following remaining sections. First, we discuss the sample frame used to conduct the analysis as well as candidate variables that were considered for entry into the Direct Ridership Model. This is followed by a presentation of a best-fitting regression model that conforms with travel-demand theory, yields interpretable and statistically significant results, and demonstrates a capacity to produce ridership estimates for existing Big Blue Bus (BBB) patronage that are reasonably accurate. The final section of the chapter uses the validated model to estimate ridership for six BBB bus stops that are being considered for a significant upgrade in BRT services – notably, the creation of a dedicated, bus-only operating lane.

4.1 Modeling Approach and Sample

Limited real-world experiences with Bus Rapid Transit in the U.S. constrain the ability to draw upon empirical experiences to inform ridership estimates. While foreign cities like Curitiba, Brazil and Bogota, Colombia have accumulated considerable experience with dedicated-lane BRT operations, vast cultural, socio-economic, and institutional differences with the U.S. limit the use of empirical evidence from such settings.

Fortunately one of the most proactive regions of the U.S. in advancing BRT services has been Southern California. The Metropolitan Transportation Authority (MTA) phased in the Metro Rapid Program between June 2000 and December 2000 with the goal of improving bus speeds within urbanized Los Angeles County. Four pilot routes -- along Wilshire Boulevard (720), Broadway (745), Vermont Avenue (754) and Ventura Boulevard (750) – used Next Bus technology at most stops to inform waiting customers of estimated bus arrival times. Metro Rapid buses consist exclusively of low-floor buses and have their own distinctive color scheme and markings. Other features include transit signal prioritization, frequent headways, and comparatively long spacings between bus stops.

A new stage in BRT services was reached in October 2005 when MTA's Metro Orange Line opened. The Orange Line is one of the first "full-service" BRT systems in the United States, featuring a dedicated busway (running on a disused rail corridor), high-capacity articulated buses, "rail-like" stations (incorporating level boarding and off-board fare payment) and headway-based schedules. The 14-mile route connects the western terminus of the Red Line subway at North Hollywood with Warner Center, the third largest employment center in Los Angeles County. As of late 2008, Southern California's Metro Rapid Program consisted of 28 routes in total providing 450 directional miles of service. MTA operates all but two of the routes. The Santa Monica Big Blue Bus operates Rapid 3 Line along Lincoln Boulevard and Rapid 7 connecting downtown Santa Monica and the Rimpau Transit Center in Los Angeles along Pico Boulevard. The Rapid 3 line is under consideration for conversion to higher end BRT services with a dedicated bus lane, and is the subject of the ridership forecasts presented in this section.

4.1.1 Sample Selection

In order to obtain a sample of sufficient size to draw statistically reliable inferences, 50 MTA bus stop locations were sampled across 20 different Metro Rapid lines. Each location had a stop on each side of a road, meaning ridership as well as service-level data were compiled for both stops at each location. Additionally, in order to account for characteristics of BBB's own operating environment and to incorporate data for the BRT corridor of interest, data were compiled for six bus stop locations of the Rapid 3 Line. Lastly, to reflect the relationships between services and ridership for "high end" BRT services, data for 13 Orange Line stops were also compiled. Figure 4.1 shows the locations of the 69 total bus stop locations that constituted the sample frame for our Direct Ridership modeling. Average daily ridership data were obtained for each stop for October 2008. Accordingly, data for explanatory variables were obtained for time periods as close as possible to the October

2008 date.

4.1.2 Model Specification and Variables

Direct Ridership models estimate boardings (and/or exits) at a stop or station for a defined period of time (e.g., daily) as a function of three key sets of variables related to each stop or station:

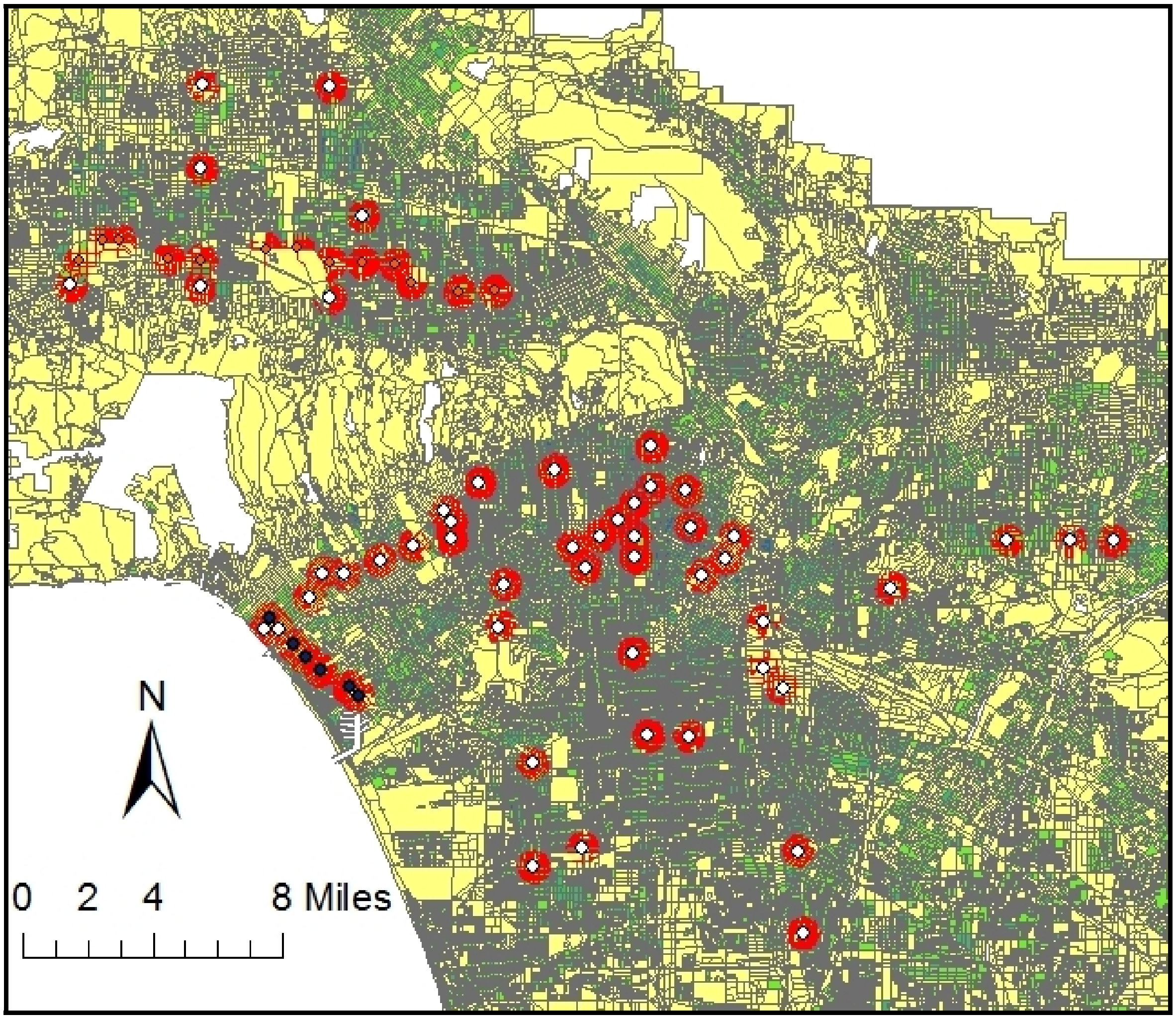

Figure 4.1 Locations of 69 BRT bus stop observations used for estimating Direct Ridership Model: 50 Metro Rapid stops, 13 Orange Lines stops, and 6 Rapid 3 stops

(1) *Service Attributes* – e.g., frequency of buses (headways, buses per hour), operating speeds, feeder bus connections (number of lines or buses), dedicated lane

(0-1 variable), vehicle brand/marketing (0-1 variable), etc.;

(2) *Location and Neighborhood Attributes* – e.g., population and employment densities, mixed land use measures (0-1 scale), median household incomes and vehicle ownership levels (as proxies for levels of "transit dependence"), distance to nearest stop (as a proxy for catchment size), accessibility levels (e.g., number of jobs that can be reached within 30 minutes over transit network in peak periods), terminal station (0-1 variable), street density (e.g., directional miles of street divided by land area), connectivity indices (e.g., links/nodes of street network), etc.; and

(3) *Bus Stop/Site Attributes* – e.g., bus shelters (0-1), Next Bus passenger information (0-1), bus benches (0-1), far-side bus stops (0-1), park-and-ride lots (0-1, or number of spaces), bus bulbs (0-1), etc.

Often, service attributes like bus headways do not vary within bus lines though they can and often do vary across lines. Travel-demand theory holds that transit riders, particularly choice users, are more sensitive to service quality and operating features than other factors. Accordingly we expected some measures of a bus stop's service quality to enter the Direct Ridership model. Other attributes of the operations, like fare levels, are usually so similar across passengers who board buses at each stop that they are not of use for Direct Ridership models. The one service-related variable that we felt would significantly enter the model was whether a stop received an exclusive-lane service. No factor can begin to make bus-transit more time-competitive with the private car than operating in a bus-only lane. Accordingly, the 13 Orange Line bus stops were "dummy-coded" (binary 0-1 variable) to denote their qualitatively higher service levels than the other bus stops in the data base.

Location variables aim to capture attributes of the immediate operating environment, such as nearby densities and distances to nearest stop. The farther a bus stop is from the next nearest stop, for instance, typically the stop's geographical catchment area increases in size. Being a terminal station often boosts ridership even more since end-line stations also serve big catchments[8]. If stops with large catchment average high population densities, boardings at the stop should go up even more. And if nearby residents average relatively low incomes and car ownership rates, then boarding can be expected to further rise. Factors like dense street networks with high connectivity (i.e., link-to-node ratios) can bump up ridership, at the margin, by expediting pedestrian flows to stops. One issue pertains to the appropriate size of the geographic buffer drawn around bus stops to capture neighborhood attributes. In keeping with other research on the walkability to transit, we opted to create ½ mile buffers around stops. Overlaying these buffers onto census tract polygons allowed variables like population density within ½ mile of a stop to be estimated using GIS techniques.

Lastly, some of the bus-stop attribute variables – such as the presence of bus shelters or far-side bus stops – are binary (0-1) and thus are used in the models as dummy variables. These variables largely represent passenger amenities and relative to variables that traditional mode choice theory holds influences utility are thought to have fairly marginal influences on ridership levels. While the presence of a bench at a bus stop might be appreciated by a waiting customer, its presence or absence is unlikely to cause or deter people from making a transit trip. In light of the relatively small sample size, we were prepared for such variables not to enter the best-fitting model.

One other possibility we allowed for in Direct Ridership modeling was interactive terms – specifically, the interaction between operating on a bus-only lane and other factors, like urban densities. That is, does the combination of having an exclusive bus lane and high nearby densities give a proportionally bigger boost in ridership than the sum of these two individual influences? Accordingly, we created a number of variables to capture the interaction between the presence of bus-only services with other predictors like population densities and feeder bus connections.

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[8] A **catchment area** is the area and population from which a city or individual service attracts visitors or customers. For example, a school catchment area is the geographic area from which students are eligible to attend a local school.

In all, the numbers of candidate variables available for model entry were: (1) Service Attributes – 9 variables[9]; (2) Location and Neighborhood Attributes – 6 variables[10]; and (3) Bus Stop/Site Attributes – 8 variables[11]. The general modeling approach involved including variables that traditional travel-demand theory holds are significant predictors of transit ridership – namely, some measures of service quality (e.g., number of daily buses, number of feeder connections), location (e.g., distance to the nearest bus stop), and neighborhood density. Once a best-fitting "core" model was developed, we then stepped in other variables related to bus-stop attributes (e.g., bus shelters, far-side bus stops) to see if they provided marginal explanatory benefits to the core model. Lastly, we sought to introduce interactive terms and capture boosts in ridership from combining dedicated-lane services with other predictors. Only interactive terms that marginally improved the predictive power of the model were added. In all cases, variables were only included if the signs on coefficients met a prior expectations and the t statistics were reasonably significant, preferably with probability values less than 0.05.

While good statistical fits were important in estimating a Direct Ridership Model, since the chief purpose of this analysis was to estimate ridership for a proposed high-quality, dedicated bus-lane service on the Rapid 3 Line, the ultimate litmus test was whether the model yielded ridership estimates that were reasonably close to actual daily ridership in October 2008. What ended up as the Direct Ridership Model with the best overall statistical fit (i.e., the highest R-Square statistic and significant, interpretable coefficients) did not however provide the best predictive accuracy of the six Rapid 3 Line bus stops. The model that is presented in the next section did and was thus used to estimate future ridership

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[9] Daily buses in each direction; daily hours of service; number of feeder buses, bus lines, rail trains, and rail lines (for perpendicular and parallel connections); dedicated-lane service (0-1).

[10] Computed within ½ mile buffers of each station: population density (2000 census); employment density (2000 census); total urban (population + employment) density; street density; connectivity index (links/nodes). Also, distance to the nearest stop. While terminal station status (0-1) has been successfully used in Direct Ridership Models of rail services (Cervero, 2006), bus networks tend to be dense and interconnected thus terminal status was not considered for modeling BRT demand.

[11] Parking lot (0-1); parking capacity (number of spaces); benches (0-1); schedule information (0-1); Next Bus (0-1); cover/shelter (0-1); farside bus stop (0-1); bus branding/logo (0-1).

associated with converting the existing Rapid 3 Line service to a high-end, dedicated-bus lane service.

4.2 Direct Model for Estimating Bus Rapid Transit Ridership

Ordinary least squares (OLS) regression was used to estimate a Direct Ridership Model. Since a number of BRT bus stops in the data base share the same bus line, we also attempted Hierarchical Linear Model (HLM) estimates to account for the nested nature of the data. In theory, HLM accounts for the statistical non-independence of bus stops that share the same bus lines. Although interclass correlations suggested significant nesting of bus stops within bus lines, the HLM models yielded results with poorer fits than OLS and did not produce satisfactory estimates of actual ridership on the Rapid Blue 3 line. Accordingly, OLS results are presented in this section.

As noted earlier, the best-fitting OLS multiple regression did not produce the best estimates of ridership for the six Rapid Blue Line 3 stops. This was due in part to the fact that the other 63 stops in the database were for MTA Metro Rapid lines, which generally serves much denser, more transit-dependent settings and accordingly have considerably higher ridership than found on the Rapid Blue lines, which is revealed in Table 4.1. The higher ridership was partly picked up through the constant term in the OLS regression model, a term that “scales” estimates of the dependent variable – i.e., average number of daily boarding. To remove this influence, we opted to run the regression equation through the origin, thus eliminating the constant term. While this did not yield the best-fitting regression line, it did yield a model that produced the most accurate estimates of actual ridership on the six Rapid 3 Line stops.

Table 4.2 presents descriptive statistics for the dependent variable (average daily boardings) and seven explanatory variables that entered into the Direct Ridership Model (Interactive variables that entered the model are not presented in Table 4.2.). Among predictor variables, the largest variation (standard deviation/mean) was with the number of feeder rail trains (only 3 of the 63 Metro Rapid stops had rail connections) and in park-and-ride capacity (10 of the 69 bus stops had nearby parking lots). Bus service frequency varied least across the 69 bus-stop observations.

Table 4.1 Comparison of Average Daily Ridership Among BRT Services in Los Angeles County

		Average Daily Ridership (October 2008)			
	Number (stops)	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Rapid 3 Line	6	80	189	134.6	44.1
Metro Orange Line	13	678	8703	2152.9	2168.2
Other Metro Rapid Lines	50	0	2612	449.7	413.1

Table 4.2 Descriptive Statistics for Dependent Variable and Independent Variables that enter the Direct Ridership Model

(All values are for bus stop observations)

	Minimum	Maximum	Mean	Std. Deviation	Coefficient of Variation
***Dependent Variable**:* Average Number Daily Boardings	0	8703	743.9	1194.9	1.61
***Independent Variables**:*					
Number of daily buses (each direction)	40	185	88.6	40.9	0.46
Number of perpendicular daily feeder bus lines	0	7	1.56	1.29	0.83
Number of perpendicular daily feeder buses	0	225	73.7	67.8	0.92
Number of perpendicular daily rail feeder trains	0	100	5.49	22.31	4.06
Park-&-Ride Lot Capacity (number of spaces)	0	1205	76.2	231.6	3.04
Population density (people within 1/2-mile buffer)	19.4	53488.8	13809.5	9300.5	0.67
Total density (population + employment within ½ mile buffer)	6238.0	115808.4	24746.6	18409.1	0.74

The best performing multiple regression model for directly measuring BRT ridership is presented in Table 4.3. From the summary statistics, a model with good overall statistical fit was obtained: 96 percent of the variation in average daily boardings across the 69 bus stop locations was explained by the nine variables in the model. As noted, the regression surface was run through the origin, thus no constant term appears in the model.

The Direct Ridership model results conform to expectations. All of the service quality variables positively contribute to ridership. As Metro Rapid bus service frequency increases, so does ridership – each Metro Rapid bus arriving at a bus stop increases average daily boardings at that stop by 2.4 passengers (or stated another way, the average number of boardings per bus at a stop was 2.4 passengers). Daily boardings also increased with the intensity of both bus and rail-train feeder services (though the feeder bus variable was not statistically significant, yet it was retained in the model to improve the prediction accuracy for the six Rapid 3 stops). Also notably significant were the two interactive terms for bus service quality: BRT and Feeder Bus as well as BRT and Feeder Rail. Based on the beta weight (standardized regression coefficient), the combination of dedicated-lane services and rail connections had the strongest predictive power of any variable in the model (reflecting the ridership boost received at two Orange Line stops served by rail). For example, the model results indicate that each feeder train that arrives increases average daily ridership by 7.5 passengers. However, if the daily train connects to a stop with a dedicated-lane Metro Rapid service, it increases average daily ridership by another 52.3 passengers, for a total of nearly 60 passengers.

Table 4.3 Direct Ridership Model for BRT in Los Angeles County

(No-Constant model, estimated using OLS for 69 Bus Stop Locations in Los Angeles County)

	Coefficient	Std. Error	Beta	t statistic	Significance Level
Service Attributes					
Number of Daily Metro Rapid Buses (each direction)	2.436	.849	.170	2.869	.006
Number of perpendicular daily feeder buses (each direction)	.758	.551	.054	1.374	.174
Number of Perpendicular Daily Rail feeder trains	7.467	2.001	.122	3.731	.000
Neighborhood Attribute					
Population density (1/2-mile buffer)	.011	.004	.135	2.582	.012
***Interactive Terms**:*					
BRT & Feeder Bus: Dedicated Lane (0-1) * Number of perpendicular daily feeder bus lines	190.333	54.499	.169	3.492	.001
BRT & Feeder Rail: Dedicated Lane (0-1) * Number of Perpendicular Daily Rail feeder trains	52.369	4.030	.450	12.996	.000
BRT & Parking Capacity: Dedicated Lane (0-1) * Park-&-Ride Lot Capacity	.475	.267	.076	1.782	.080
BRT and Total Density: Dedicate Lane (0-1) * (Population + Employment density within 1/2-mile buffer)	.046	.011	.223	4.164	.000
Rapid Blue and Population Density: Rapid Blue 3 (0-1) *Population Density (1/2-mile buffer)	-.012	.010	-.033	-1.226	.225
Summary Statistics: R Square = .960 F Statistic (prob.) = 159.9 (.000) N = 69					

The only neighborhood variable that entered the model was population density within ½ mile of a bus stop. Metro Rapid stops surrounded by denser residential areas averaged higher ridership, controlling for other factors. Two interactive variables modified this relationship. If the Metro Rapid stop had a dedicated-lane service, the combination of both population and employment densities further boosted ridership. In the case of the six Rapid 3 Line stops, however, nearby population densities served to lower ridership (relative to the influences of population densities around the 63 MTA Metro Rapid bus stops). We note that this latter interactive term was not statistically significant however it was retained in the model for purposes of improving the fit for predicting ridership on the Rapid 3 Line.

The only bus-stop attribute that entered the model was the capacity of Park & Ride lots for Metro Rapid stops with dedicated-lane bus services. As shown in Table 4.3, this interactive term has a positive coefficient indicating that bundling high-quality BRT services with parking-lot capacity boosted ridership in Los Angeles County.

4.3 Prediction Accuracy of the Direct Ridership Model

Overall, the Direct Ridership Model's prediction of October 2008 average daily boardings corresponded fairly closely to actual boardings. This is reflected by both the high R-Square statistic in Table 4.3 (R^2 = .96) as well as the plot in Figure 4.2. The 45-degree angle of the data points (plotting predicted values on the vertical axis and actual boardings on the horizontal axis) reveals high prediction accuracy.

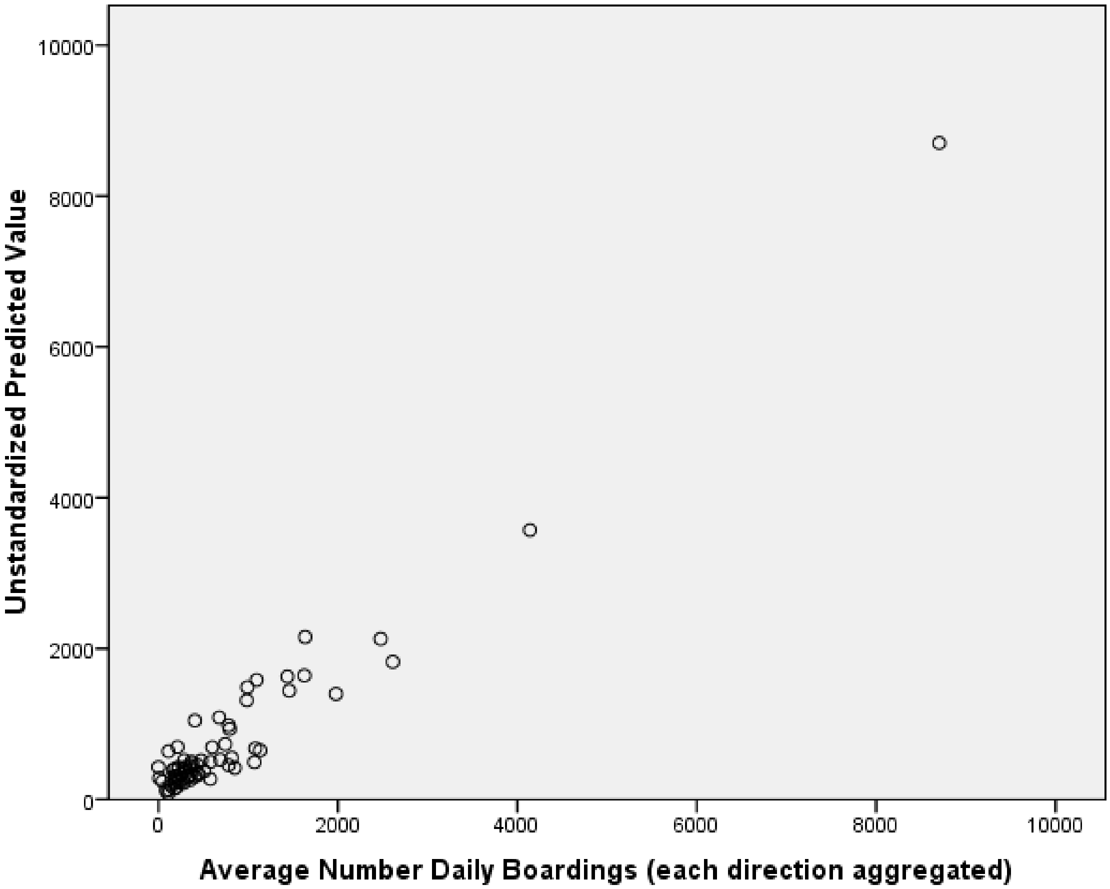


Figure 4.2 A Plot of Predicted Boardings (Vertical Axis) and Actual Boardings (Horizontal Axis) for 69 Metro Rapid Bus Stops

While the overall model predicted Metro Rapid ridership fairly closely, its performance in estimating average daily boardings on the six Rapid 3 Line stops was less accurate. Table 4.4 and Figure 4.3 show that the model over-estimated daily boardings for three of the stops (by between 14.3% and 35.8%) and under-estimated boardings for three other stops (by 17.7% to 27.4%). As noted before, this likely reflects the dominance of MTA Metro Rapid bus stops, which serve in qualitatively different operating environments than in Santa Monica. While it would have been preferable to have included more observations from the Santa Monica Big Blue Bus service to better capture local conditions, the absence of other Metro Rapid operations in the city precluded this, prompting us to rely on the next best thing available – data on nearby MTA Metro Rapid bus services.

An effective and commonly used approach in travel-demand forecasting to neutralize the prediction error for forecasting purposes is to employ a K Factor. The K Factor explicitly accounts for the error in the future prediction by using the ratio of actual ridership to predicted ridership. The last column of Table 4.4 shows the computed K Factors. One can multiply forecasts by this term to adjust the estimate to account for past prediction errors. In the case of the Rapid Blue stop at Pico Blvd. and Lincoln Blvd., the model predicted 158 average daily boardings while the actual number was 201. To account for this under-prediction, further forecasts can be adjusted up by 27.3%.

Table 4.4 Comparison of Actual and Predicted Average Daily Boardings for October 2008, Six Rapid 3 Line Stops

	Average Daily Boardings			
Rapid Blue Line 3 Stop	**Actual**	**Prediction**	**Error %**	**K-Factor**
Pico Blvd & Lincoln Blvd	**201**	**157.88**	-21.45	**1.273**
Ocean Park Blvd & Lincoln Blvd	**112**	**128.06**	14.34	**0.875**
Rose Ave & Lincoln Blvd	**108**	**78.45**	-27.36	**1.377**
California Ave & Lincoln Blvd	**85**	**115.46**	35.83	**0.736**
Venice Blvd & Lincoln Blvd	**177**	**213.20**	20.45	**0.830**
Washington Blvd & Lincoln Blvd	**174**	**143.26**	-17.66	**1.215**

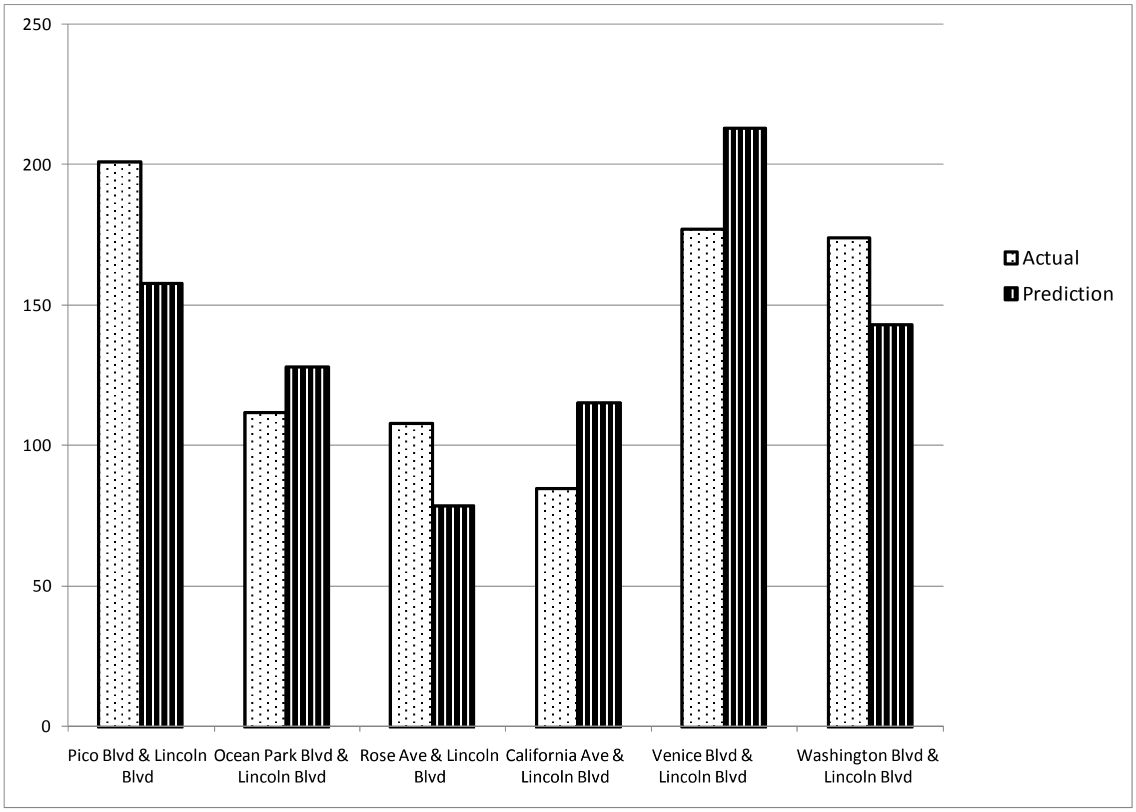


Figure 4.3 Plot of Actual and Predicted Average Daily Boardings for October 2008, Six Rapid 3 Line Stops

4.4 Forecasted Daily Ridership for Six Rapid 3 Line Stops

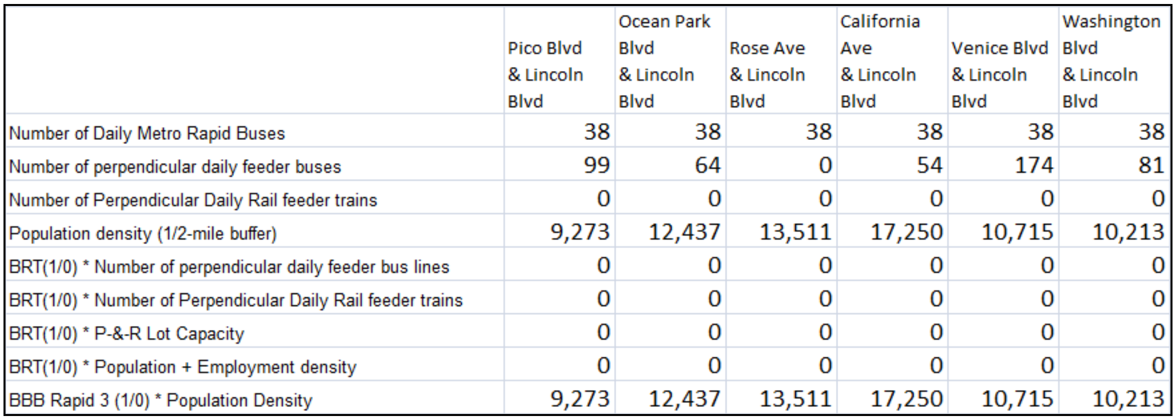
Rapid Blue Line 3 is slated for a dedicated-lane BRT service and other enhancements. This concluding section uses the Direct Ridership Model along with the K-Factor adjustments and other assumptions to arrive at estimated averaged daily boardings of the upgraded services in 2010.

The ridership estimates involved using the equations presented in Table 4.3 to estimate ridership based on the values for the four interactive terms related to dedicated-lane BRT services being adjusted. Normally, this would involve involved “switching” the value of the dedicated-lane dummy variable from “0” to “1” (and multiplying this by the other values in the interactive model – namely numbers of daily feeder bus lines, number of daily rail feeder trains, Park-&-Ride capacity, and total density). However the Direct Ridership model was estimated based on MTA’s Orange-Line BRT operations, which is a high-end BRT service with an exclusive lane on a former rail-way right-of-way that is fully separated from other traffic. The Rapid 3 Line upgrade will have a curbside dedicated lane and will thus unlikely enjoy the same speed advantages of an Orange Line type of service due to side friction of cars in adjacent lanes, interlopers (e.g., delivery trucks) who might occasionally intrude on the lane, and other impedances. Accordingly, operating speeds and conditions on the Rapid 3 Line upgrade are expected to lie somewhere midway between the existing Local 3 Line service and the Metro Orange Line. Accordingly, values of 0.5 instead of 1.0 were used for BRT interactive terms in the Direct Ridership model to reflect the intermediate-level of dedicated-lane services that are expected.

Table 4.5 shows the existing input values for the nine explanatory variables in the Direct Ridership model for the six stops on Rapid 3 Line. Of note, the entries for the BRT variable that denoted the presence of dedicated-lane service are 0. Table 4.6 reflects the service improvements slated for Rapid 3 Line. The table shows that the anticipated daily number of buses coming through each stop will increase from the present value of 38 to either 42 or 51. Two other rows of values change in Table 4.6 to capture other factors that can be expected to influence ridership. Notably, the combination of dedicated-lane BRT services (coded as 0.5) and feeder bus lines (as distinguished from feeder buses themselves) changes the coding to non-zero values for five of the six stops; and the combination of dedicated-lane BRT services and higher densities adds value-entries to the next to last row in Table 4.6.

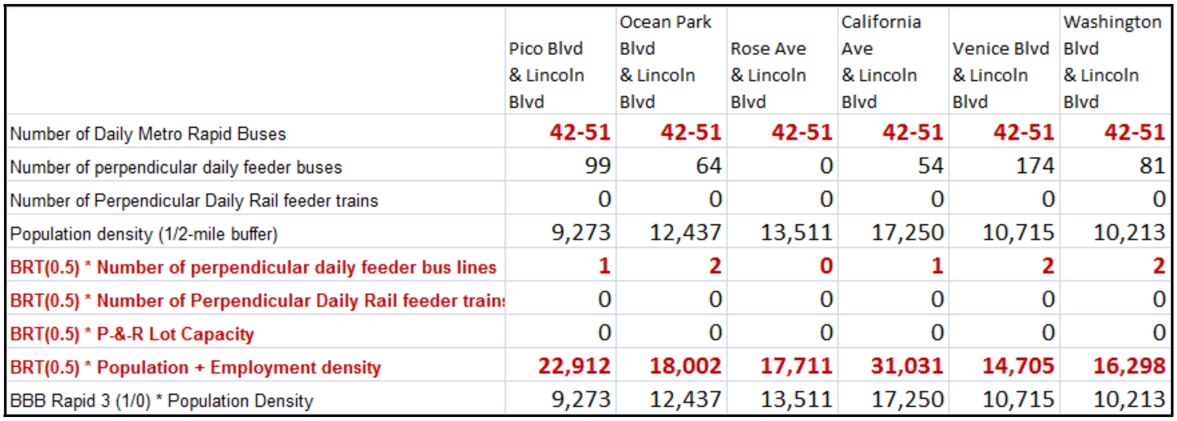
The predictions of future average daily boardings for the enhanced Rapid 3 Line were obtained by inputting the values in Table 4.6 into the model presented in Table 4.3 and multiplying the estimates by the K-Factor in Table 4.4. Since two levels of new services are being considered possible (i.e., 42 daily buses and 51 daily buses), two sets of forecasts were produced. These are shown in both Table 4.7 and Figure 4.4.

Table 4.5 Existing Conditions of Six Stops on Rapid 3 Line (October 2008).



	Pico Blvd & Lincoln Blvd	Ocean Park Blvd & Lincoln Blvd	Rose Ave & Lincoln Blvd	California Ave & Lincoln Blvd	Venice Blvd & Lincoln Blvd	Washington Blvd & Lincoln Blvd
Number of Daily Metro Rapid Buses	38	38	38	38	38	38
Number of perpendicular daily feeder buses	99	64	0	54	174	81
Number of Perpendicular Daily Rail feeder trains	0	0	0	0	0	0
Population density (1/2-mile buffer)	9,273	12,437	13,511	17,250	10,715	10,213
BRT(1/0) * Number of perpendicular daily feeder bus lines	0	0	0	0	0	0
BRT(1/0) * Number of Perpendicular Daily Rail feeder trains	0	0	0	0	0	0
BRT(1/0) * P-&-R Lot Capacity	0	0	0	0	0	0
BRT(1/0) * Population + Employment density	0	0	0	0	0	0
BBB Rapid 3 (1/0) * Population Density	9,273	12,437	13,511	17,250	10,715	10,213

Table 4.6 Future BRT Scenario for Six Stops on Rapid Blue Line 3



	Pico Blvd & Lincoln Blvd	Ocean Park Blvd & Lincoln Blvd	Rose Ave & Lincoln Blvd	California Ave & Lincoln Blvd	Venice Blvd & Lincoln Blvd	Washington Blvd & Lincoln Blvd
Number of Daily Metro Rapid Buses	**42-51**	**42-51**	**42-51**	**42-51**	**42-51**	**42-51**
Number of perpendicular daily feeder buses	99	64	0	54	174	81
Number of Perpendicular Daily Rail feeder trains	0	0	0	0	0	0
Population density (1/2-mile buffer)	9,273	12,437	13,511	17,250	10,715	10,213
BRT(0.5) * Number of perpendicular daily feeder bus lines	**1**	**2**	**0**	**1**	**2**	**2**
BRT(0.5) * Number of Perpendicular Daily Rail feeder train	0	0	0	0	0	0
BRT(0.5) * P-&-R Lot Capacity	0	0	0	0	0	0
BRT(0.5) * Population + Employment density	**22,912**	**18,002**	**17,711**	**31,031**	**14,705**	**16,298**
BBB Rapid 3 (1/0) * Population Density	9,273	12,437	13,511	17,250	10,715	10,213

Table 4.7 Forecasted Ridership for Six Stops on the Planned Dedicated-Lane Rapid 3 Line

	Actual (38 Buses)	Prediction 1 (42 BRT Buses)	Prediction 2 (51 BRT Buses)
Pico Blvd & Lincoln Blvd	**201**	**1008**	**1036**
Ocean Park Blvd & Lincoln Blvd	**112**	**651**	**670**
Rose Ave & Lincoln Blvd	**108**	**685**	**715**
California Ave & Lincoln Blvd	**85**	**690**	**706**
Venice Blvd & Lincoln Blvd	**177**	**625**	**643**
Washington Blvd & Lincoln Blvd	**174**	**874**	**901**

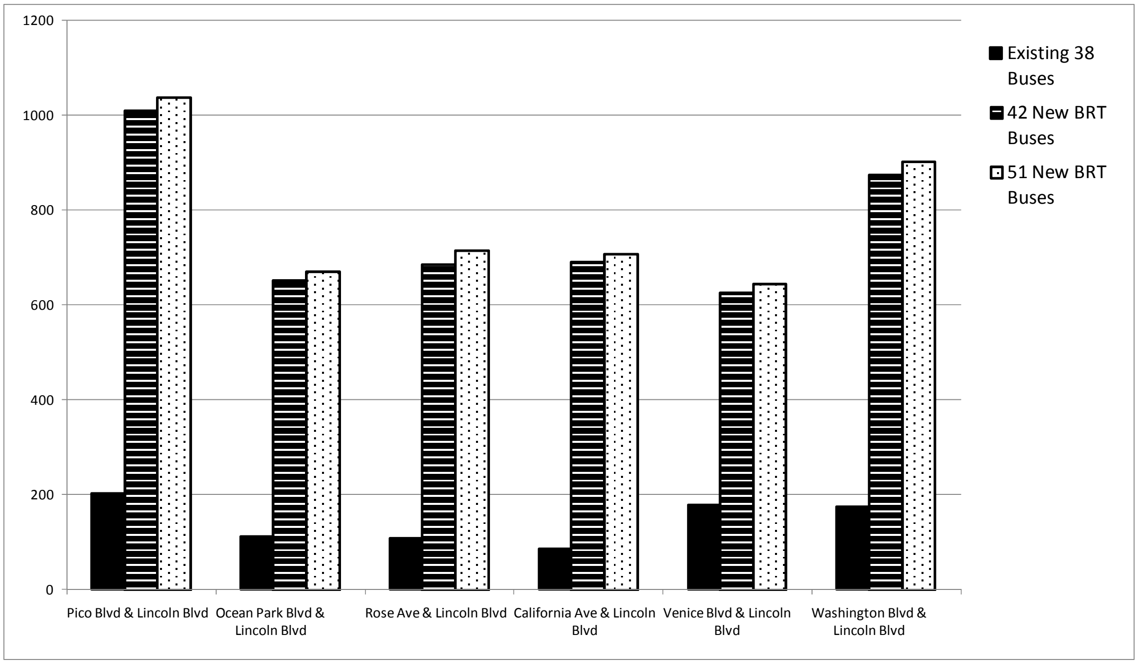
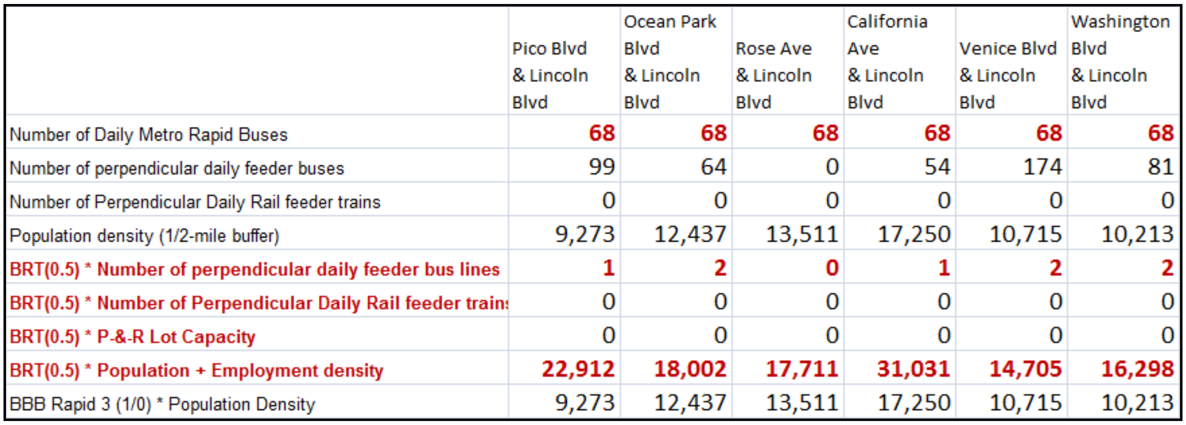


Figure 4.4 Comparison of Forecasted Ridership for Six Stops on the Planned Dedicated-Lane Rapid 3 Line

Clearly, substantial increases in average daily boardings can be anticipated from the planned service enhancements on the Rapid 3 Line. The adjusted model estimates that average daily boardings across the six stops will increase by between a factor of 3.5 (Venice & Lincoln bus stop) and a factor of 8.3 (California & Lincoln bus stop). The average increase in boardings for the six stops on Rapid Blue Line 3 is estimated to be more than 500%. Such surges in ridership could be on the high side, again reflecting the more transit-conducive environment of Metro Rapid services in denser, more congested Los Angeles City (that dominated the database). We note that the approximately five-fold average increase in ridership relative to current counts on the Rapid 3 Line is not, however, inconsistent with the differentials in average boardings between the Orange Line stops and other MTA Metro Rapid stops (as shown previously in Table 4.1). While no one has a crystal ball and can predict with any precision what the future ridership will be on the Rapid 3 Line, experiences with dedicated-lane services in Los Angeles County suggest that the impacts will be appreciable.

The ridership forecasts discussed so far pertain to the Rapid 3 Line. However 68 existing buses from other BBB bus lines (Local 3 Line) that operate on Lincoln Boulevard will also used the 2-mile stretch of dedicated bus lane and stop at the six bus stops. Assuming these 68 buses will operate as BRT on this 2-mile stretch of dedicated lane (and thus not make any other stops), then they will further add daily riders to each stop. Table 4.8 shows the input data used to forecast ridership for these 68 buses. The second column of Table 4.9 shows the projected average daily boardings associated with the 68 existing Lincoln Boulevard buses that will stop at the six dedicated-lane bus stops. These estimates should be interpreted with caution since the Direct Ridership Model was estimated based on BRT experiences of Metro Rapid buses that operate on BRT corridors, not regular buses that use the dedicated lane for a portion of its services. Our guess is that the forecasts for these 68 existing regular buses are on the high side (since the bulk of services will be in non-dedicated lane operations and thus experience ridership patterns associated with regular, mixed-traffic bus services). The final two columns forecasts total average daily boardings for each of the six stops by summing the forecasts for the Rapid 3 Line (for 42 and 51 bus scenarios) with the estimates for the 68 existing regular buses that will operate on the dedicated lane for the 2-mile stretch of Lincoln Boulevard. The total forecasted average daily boardings for all six bus stops and all services combined are in the range 9,460 to 9,600.

Table 4.8 Inputs for Existing 68 Buses that will operate as BRT Services for Six Stops on Lincoln Boulevard



	Pico Blvd & Lincoln Blvd	Ocean Park Blvd & Lincoln Blvd	Rose Ave & Lincoln Blvd	California Ave & Lincoln Blvd	Venice Blvd & Lincoln Blvd	Washington Blvd & Lincoln Blvd
Number of Daily Metro Rapid Buses	**68**	**68**	**68**	**68**	**68**	**68**
Number of perpendicular daily feeder buses	99	64	0	54	174	81
Number of Perpendicular Daily Rail feeder trains	0	0	0	0	0	0
Population density (1/2-mile buffer)	9,273	12,437	13,511	17,250	10,715	10,213
BRT(0.5) * Number of perpendicular daily feeder bus lines	**1**	**2**	**0**	**1**	**2**	**2**
BRT(0.5) * Number of Perpendicular Daily Rail feeder trains	0	0	0	0	0	0
BRT(0.5) * P-&-R Lot Capacity	0	0	0	0	0	0
BRT(0.5) * Population + Employment density	**22,912**	**18,002**	**17,711**	**31,031**	**14,705**	**16,298**
BBB Rapid 3 (1/0) * Population Density	9,273	12,437	13,511	17,250	10,715	10,213

Table 4.9 Forecasted Ridership for Six Stops for Existing 68 Buses on Lincoln Boulevard as well as Total Including New Rapid Blue Line 3 Services

	Existing 68 Buses on Lincoln Blvd. as BRT	New Rapid Blue Line 3		Total: Existing 68 Buses & New Rapid Blue Line 3 Services	
		42 Bus Scenario	51 Bus Scenario	42 Bus Scenario	51 Bus Scenario
Pico Blvd & Lincoln Blvd	**1089**	**1008**	**1036**	**2097**	**2125**
Ocean Park Blvd & Lincoln Blvd	**706**	**651**	**670**	**1352**	**1376**
Rose Ave & Lincoln Blvd	**771**	**685**	**715**	**1456**	**1486**
California Ave & Lincoln Blvd	**736**	**690**	**706**	**1426**	**1442**
Venice Blvd & Lincoln Blvd	**677**	**625**	**643**	**1302**	**1330**
Washington Blvd & Lincoln Blvd	**951**	**874**	**901**	**1825**	**1852**

4.5 Conclusions

In closing, the state of practice in BRT ridership forecasting is still in its infancy. Many unknowns could influence future transit ridership in Santa Monica and elsewhere, including factors outside the sphere of ridership modeling, such as the price of gasoline or unemployment levels, especially in these nearly unprecedented economic times. The safest course when facing such uncertainty is to monitor trends and continually re-adjust ridership estimates. Ridership on the Rapid 3 Line and other Metro Rapid services should be closely monitored over time and modeling adjustments made to account for unfolding trends. As more experiences with dedicated-lane BRT services are recorded in Los Angeles County and elsewhere, it should be possible to fine-tune Direct Ridership Models so as to achieve more accurate forecasts in coming years.

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