

# Development of Operational Performance Models for Bus Lane Preferential Treatments

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# **FINAL REPORT**

## **Development of Operational Performance Models for Bus Lane Preferential Treatments**

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## EXECUTIVE SUMMARY

Increasing concern for improving the efficiency of roadways in moving people rather than just vehicles has led to the promotion of giving preferential treatments to buses. Bus lanes and busways are two general types of bus preferential facilities. The use of preferential facilities is generally justified on the grounds that buses can potentially carry more passengers than automobiles. However, when a lane is taken away from the general-purpose traffic and designated as a bus-only or HOV lane, it can create congestion in other lanes, causing protests by motorists. Thus, to maintain the long-term success of preferential facilities, better guidance on conditions that justify bus-only or HOV lanes is needed. Such guidance requires that the expected operational performance of each design alternative be known.

The operational performance of bus facilities may be measured by travel time, speed, capacity, etc. It is affected by a number of factors, including bus headway, vehicle volumes, vehicle mix, free-flow speed, dwell time, bus stop capacity, bus stop location (near-side, mid-block, or far-side), bus stop type (on-line vs. off-line), bus stop spacing, signal control parameters, number of lanes, etc. The CORSIM simulation model was used to estimate the bus and non-bus travel speeds under different conditions of these contributing factors. The simulated data were then used as a substitute for field data in an empirical modeling of relationships between travel speeds and their contributing factors. The estimated speeds then provided input to a decision model for the computation of expected person travel times under a specific set of conditions. The design alternative that provides the lower total average person travel time becomes the recommended design alternative.

The decision models developed in this research allow for the evaluation of a proposed bus lane before implementation, an existing bus lane to be re-evaluated for possible improvements, and should a bus lane become controversial, it can be evaluated objectively. Because such models include a number of design variables, they can be used as a tool to evaluate the effectiveness of design alternatives, for example, the location (near side, far side, or mid-block) of bus stops under prevailing conditions.

For the freeway models the new HOV modeling capability that comes with CORSIM version 5.0 was applied for scenario modeling. Non-linear regression models were developed for predicting the average speeds of HOV lane, mixed lanes adjacent to HOV lane, and mixed-only lanes. The models consider traffic compositions (carpools, vanpools, buses, trucks, and passenger cars), number of lanes, and free-flow speeds. A limited model evaluation was performed by comparing results from a mixed-traffic speed model with those of the Highway Capacity Manual (HCM) and the Bureau of Public Roads (BPR) volume-delay equation. The results are found to be relatively consistent.

For the arterial models a corrected version of CORSIM version 5.0 was used for scenario modeling. Mixed linear and non-linear regression models were developed for average bus and non-bus speeds for bus lane, non-bus lanes, and mixed traffic lanes. The models consider a number of variables, including bus volume, non-bus volume, right-turn volume, bus stop location, bus stop density, use of bus bay, number of bus berths, mean dwell time, green ratio, cycle length, signal offset, and number of lanes. The regression models for arterial bus lanes were evaluated by

comparing the results with those reported in HCM 2000 and the TCRP Report 26. The results were found to be surprisingly close.

### **Freeway Models**

It was observed from the freeway bus speed models developed in this study that:

1. Average speeds can best be described with an exponential distribution. At low volumes, the speeds decrease slowly. At higher volumes, the speeds decrease at an increasing rate. These results are consistent with those of the HCM and the BPR formula.
2. Unless bus volumes are sufficiently high, the impact of bus volumes on average bus-lane speeds is negligible. This suggests that a bus-only lane usually has extra capacity that can be used by other high-occupancy vehicles.
3. When carpools are allowed to share a preferential lane with buses, the preferential lane speed will be impacted, depending on the number of carpools. The decision model developed can be used to determine an appropriate carpool occupancy rate such that the bus speeds are not adversely affected.
4. The CORSIM simulation model produces freeway passenger car equivalence for trucks and buses that closely approximate those in the HCM.
5. The relative impact of different types of vehicles on a mixed-lane freeway was found to come within the range of vehicle equivalent factor reported in the HCM.

### **Arterial Models**

Regression models for bus and non-bus speeds are given in Tables 6-3 and 6-4. The performance of a wealth of bus lane planning and design scenarios may be estimated from these models. A partial examination of the relationships from these models resulted in the following findings:

1. In general, the presence of a bus lane improves bus speeds. The improvements are larger at higher non-bus volumes. When there is a bus lane, bus speeds are not affected by non-bus volumes at low bus volume. At higher bus volumes, bus speeds are slightly affected by non-bus volumes. When buses travel in mixed traffic, their speeds are reduced by increasing non-bus volumes.
2. Non-bus speeds decrease with increasing bus and non-bus volumes. When a bus lane is present, non-bus speeds are not affected by an increase in bus volumes. However, in mixed traffic, non-bus speeds are significantly affected by bus volumes, which suggests that lane separation is beneficial.

3. The location of bus stops can have an impact on bus speeds. At low bus volumes, the difference in bus stop location is less significant. At high bus volumes, far-side bus stops are superior to near-side or mid-block bus stops.
4. Conflicts between buses and right-turning traffic are greatest for near-side bus stops. The effect of right-turn vehicles on bus speeds are negligible for mid-block bus stops at low bus volumes, but are significant at higher bus volumes. Bus speeds are essentially unaffected by right-turn vehicles when the bus stops are located at the far-side.
5. The use of bus bays for far-side bus stops do not have an impact on bus speeds. The use of bus bays for near-side bus stops significantly improves bus speeds.
6. The number of bus berths has the same impact on bus speeds regardless of bus volumes and bus stop locations. Bus speeds significantly improve with increasing number of bus berths.
7. Increasing stop spacing (or reducing stop density) on arterial streets is highly beneficial to both bus speeds and non-bus speeds.
8. Minimizing bus dwell times at bus stop can greatly increase the speed of buses. Accordingly, the use of passes or fare cards, pay-as-you-leave fare collection, prepayment of fare, multi-channel doors, and low-floor at busy bus stops, are potentially beneficial.
9. Cycle length does not have a significant impact on bus and non-bus speeds. On the other hand, the green ratios for arterial through movements have a major impact on bus and non-bus speeds. This is true whether there is a bus lane and/or a bus bay.
10. Since signal offsets are calculated based the speeds of non-bus vehicles, they have no significant impact on bus speeds, regardless of whether there is a bus lane. When a bus lane is present, signal offsets have a significant impact on non-bus speeds. The impact is reduced when buses are mixed with non-bus traffic, suggesting that the presence of buses in the platoon makes progression harder for the non-bus traffic.

## **Recommendations**

This research represents the only known effort that attempts to develop quantitative models for justifying bus lane design alternatives based on the average person travel time for all road users. The scope of the study was constrained by the amount of time required to perform the large number of simulation runs, and to a lesser extent, the available modeling features of the simulator used. Consequently, a number of design alternatives and factors have not been included in this study. Specifically:

1. The freeway simulation models assume that the HOV lane is located on the leftmost lane, that the impact of on- and off-ramp traffic is minimal. Further studies may attempt to

develop models for other configurations of HOV lanes, including the use of the rightmost lane, barrier separation (zero violation rate), and contra-flow lane.

2. The arterial models may incorporate the impact of different signal priority strategies, including queue jumper, that are gaining increasing interest in both traffic and transit communities.

Although the coefficients of the regression models show logical relationships among all the variables considered, the model validation was somewhat limited. Future studies may attempt to further refine and validate the simulated results as more field data and reports become available. The work completed in this research should have laid the groundwork necessary to perform additional studies. Although the models developed in this research are strictly based on the operational efficiency of design alternatives, other important factors such as safety experience must eventually be considered in practice. Studies that look into the safety of various preferential facilities would be beneficial.

# CHAPTER 1

## INTRODUCTION

### **1.1. Background**

Conventional mixed-traffic bus operation accounts for over 99% of total bus route distance in North America (Kittelson, 1999). Buses under this operation share the same right-of-way with other vehicles, thus, suffer from traffic congestion. On average, buses travel at about 60% of the speeds of automobiles using the same roadways due to the cumulative effects of traffic congestion, traffic signals, and passenger boarding. Increasing concern for improving the efficiency of roadways in moving people rather than just vehicles has led to the promotion of giving preferential treatments to buses, since buses can potentially carry a much higher number of passengers than automobiles, thus make more efficient use of the limited roadway space. Accordingly, some urban areas have built special roadways or designated special lanes for use by buses. These preferential facilities aim to improve schedule adherence and reduce travel times and delays for transit users, leading to higher bus capacity, improved bus quality of service, and, ultimately, increased ridership.

The two general types of bus preferential facilities are bus lanes and busways. Bus lanes are a form of exclusive bus facility that is typically found along busy arterial streets. These lanes are reserved primarily for buses, either all day or during specified periods. Depending on local regulations, bus lanes may also be used by other traffic such as by vehicles making turns, or by taxis, carpools, and emergency vehicles. When a bus lane is shared with other high-occupancy vehicles, it becomes a High Occupancy Vehicle (HOV) lane. Busways, on the other hand, are special roadways designed for the exclusive use of buses. They may be used by emergency vehicles, but generally not carpools or taxis. Busways may be constructed at, above, or below grade and may be located either within a separate right-of-way or within a highway corridor.

### **1.2. Problem Statement**

The use of bus preferential facilities is generally justified on the grounds that buses can potentially carry more passengers than automobiles. However, when a lane is taken away from the general-purpose traffic lanes and designated as a bus-only or HOV lane, it can create congestion in other lanes, causing protests by motorists. Such protests are usually exacerbated when a preferential lane is underutilized or perceived to be underutilized, and have led to abandonment of the HOV lane on the Santa Monica freeway in Los Angeles, and more recently, the HOV lanes on I-80 and I-287 in New Jersey (N.J. DOT, 1998). Thus, to maintain the long-term success of preferential facilities, guidance on conditions that justify bus-only or HOV lanes is needed. Such guidance requires that the expected operational performance of each design alternative be known. The operational performance may be measured by travel time, speed, capacity, etc. It is affected by a number of factors, including bus volumes, vehicle volumes, vehicle mix, occupancy rates, dwell time, stop capacity, stop location (near-side, mid-block, or far-side), stop type (on-line vs. off-line), stop density, signal control parameters, number of lanes, etc. The development of quantitative models that relate these contributing factors to performance measures is thus necessary.

### **1.3. Objectives**

This study aims to develop operational performance models that can be applied by transit planners and traffic engineers to help determine the appropriate preferential treatment and design for bus lanes on freeways and arterial streets. Such models allow for the evaluation of a proposed bus lane before implementation, an existing bus lane to be re-evaluated for possible improvements, and should a bus lane become controversial, it can be evaluated objectively. Because such models include a number of design variables, they can be used as a design tool to evaluate the effectiveness of design alternatives, for example, the location (near side, far side, or mid-block) of bus stops under prevailing conditions.

### **1.4. Report Organization**

The rest of this report is organized as follows. Chapter two introduces the essential elements of bus facilities and operations and provides a review of bus preferential treatments. Chapter three reviews existing literature that attempts to justify bus preferential facilities based on both fundamental merit and operational efficiency. Chapter four introduces traffic simulation modeling and describes the general model development process. Chapter five documents the modeling process of freeway performance and decision models as well as the associated results. Chapter six is similar to chapter five but focuses on arterial bus lanes. Finally, Chapter seven concludes this report, summarizes findings, and provides recommendations for further studies.

## **CHAPTER 2**

### **BUS PREFERENTIAL TREATMENTS**

This chapter provides a review of bus preferential treatments. Although the focus of this project is on bus lanes, the review covers all types of preferential treatments for bus services. The essential elements of bus facilities and operations are first introduced, followed by review of the different classes of transit services and the different methods of bus preferential treatments. The last section summarizes literature on the three common types of bus preferential facilities, i.e., bus lanes, busways, and bus rapid transit.

#### **2.1. Bus Transit Elements**

##### **2.1.1. Bus Stop**

A bus stop is an area where one or more buses load and unload passengers. It consists of one or more loading areas called bus berths. A bus stop can be provided in the travel lane (online), where following buses may not pass the stopped bus, or out of the travel lane (offline), where following buses may pass stopped buses. An offline bus stop is generally provided with a specially constructed area called bus bay. Offline bus stops are subject to re-entry delay, which depends on the traffic volume on the travel lane adjacent to the stop and the platooning effect from upstream traffic signals. Some states, such as Florida, have passed laws requiring motorists to yield to buses re-entering a roadway. The re-entry delay varies according to the degree the motorists comply with these laws. To avoid such delay, some bus operators avoid using offline stops on busy streets (Kittelson, 1999).

##### **2.1.2. Bus Stop Location**

Bus stops may be located at the near side or the far side of an intersection. They may also be located at mid-block locations between two intersections. Table 2-1 provides a comparison of the advantages and disadvantages of each bus stop type (TCRP Report 19, 1996).

##### **2.1.3. Bus Stop Spacing**

Bus stop spacing has an impact on access time and line-haul time and, therefore, the demand for transit service. In general, there is a tradeoff between closely spaced, frequent stops and shorter walking distance but longer line-haul time and more sparsely spaced and longer walking distance but shorter line-haul time. Stops in practice are sited to serve major trip generators and attractors in the service area (Kittelson, 1999).

##### **2.1.4. Bus Berth**

A bus berth (or a loading area) is a space for buses to stop and board and discharge passengers. A bus stop may contain one or more bus berths. The most common form of bus berth is a linear bus stop along a street curb. The Transit Capacity and Quality of Service Manual (Kittelson, 1999) indicates that the vehicle capacity of a bus berth is a function of dwell time, dwell time variability, and clearance time, which are discussed below.

**Table 2-1. Comparison of On-Street Bus Stop Locations (TCRP Report 19, 1996).**

Location	Advantages	Disadvantages
Far-Side	<ul style="list-style-type: none"> <li>• Minimizes conflicts between right turning vehicles and buses</li> <li>• Provides additional right turn capacity by making curb lane available for traffic.</li> <li>• Minimizes sight distance problems on intersection approaches</li> <li>• Encourages pedestrians to cross behind the bus</li> <li>• Creates shorter deceleration distances for buses, since the intersection can be used to decelerate</li> <li>• Buses can take advantage of gaps in traffic flow created at signalized intersections</li> </ul>	<ul style="list-style-type: none"> <li>• May result in intersections being blocked during peak periods by stopped buses</li> <li>• May obscure sight distance for crossing vehicles</li> <li>• May increase sight distance problems for crossing pedestrians</li> <li>• Can cause a bus to stop far side after stopping for a red light, interfering with both bus operations and all other traffic</li> <li>• May increase the number of rear-end crashes since drivers do not expect buses to stop again after stopping at a red light</li> <li>• Could result in traffic queued into intersection when a bus stops in the travel lane</li> </ul>
Near-Side	<ul style="list-style-type: none"> <li>• Minimizes interferences when traffic is heavy on the far side of the intersection</li> <li>• Allows passengers to access buses closest to crosswalk</li> <li>• Intersection width available for bus to pull away from the curb</li> <li>• Eliminates potential for double stopping</li> <li>• Allows passengers to board and alight while bus stopped for red light</li> <li>• Allows driver to look for oncoming traffic, including other buses with potential passengers</li> </ul>	<ul style="list-style-type: none"> <li>• Increases conflicts with right turning vehicles</li> <li>• May result in stopped buses obscuring curbside traffic control devices and crossing pedestrians</li> <li>• May cause sight distance to be obscured for side street vehicles stopped to the right of the bus</li> <li>• Increases sight distance problems for crossing pedestrians</li> </ul>
Mid-Block	<ul style="list-style-type: none"> <li>• Minimizes sight distance problems for vehicles and pedestrians</li> <li>• May result in passenger waiting areas experiencing less pedestrian congestion.</li> </ul>	<ul style="list-style-type: none"> <li>• Requires additional distance for no-parking restrictions</li> <li>• Encourages passengers to cross street mid-block (jaywalking)</li> <li>• Increases walking distance for passengers crossing at intersections</li> </ul>

### 2.1.5. Dwell Time

Dwell time is the time required to serve passengers at the busiest door, plus the time required to open and close the doors. It is proportional to the boarding and/or alighting volumes times the service time per passenger (Kittelson, 1999).

### 2.1.6. Dwell Time Variability

The amount of time buses stop at a stop can fluctuate, depending on passenger demand between buses and between routes. The greater the variation in dwell time, the lower the vehicle capacity. Dwell time variability is influenced by the same factors that influence dwell time (Kittelson, 1999).

### **2.1.7. Clearance Time**

Clearance time is measured from the time after a bus closes its doors to the time the following bus opens its doors. During this time the loading area is not available for passenger boarding and alighting. Clearance time can be computed as the average time between one bus leaving a stop and a following bus being able to enter the stop. Part of the clearance time is fixed, consisting of the time for a bus to start up and travel its own length. For online stops, this is the only component of clearance time. For offline stops, the clearance time is increased by the amount of time required to allow a bus to re-enter the traffic stream and accelerate (Kittelsohn, 1999).

## **2.2. Transit Systems Classification**

Transit systems can generally be classified as bus service in mixed traffic, bus service in reserved lane, busway, light rail transit (LRT), and heavy rail rapid transit. This classification is based mainly on right-of-way access, i.e., mixed traffic, shared and limited access (bus lane), shared corridor (busway), and exclusive corridor (LRT and heavy rail). In addition to the above categories, there exists a mixed class of bus transit system called Bus Rapid Transit (BRT)—a broad term referring to bus transit systems that are improved through one or more of the following features (FTA, 1998):

1. Bus lanes: One or more lanes on an arterial street that is reserved for the exclusive or near-exclusive use of buses.
2. Busways: Facilities that dedicate all lanes of a roadway to the exclusive use of buses.
3. Bus signal priority: Extension of green time or actuation of the green light at signalized intersections upon detection of an approaching bus.
4. Traffic management improvements: Low-cost infrastructure elements that can increase the speed and reliability of bus service, including bus turnouts, bus boarding islands, and curb realignments.
5. Faster boarding: Use of ITS technologies such as electronic smart cards or offline fare collection that allows collection of fares upon entering an enclosed bus station or shelter area prior to bus arrivals (passengers can then board through all doors of a stopped bus).

## **2.3. Common Methods of Bus Preferential Treatments**

Three common types of preferential treatments have been used for buses to improve their performance.

### **2.3.1. Exclusive Right-of-Way**

While there are many ways of improving bus services, by far the most important one is physical separation of buses from other vehicles on streets and highways. This separation is important for three major reasons (Vuchic *et al.*, 1994):

1. It allows faster, more reliable, safe and comfortable travel for passengers.
2. Bus separation from general traffic is the only way of achieving speed comparable to that of the automobile, because higher running speed of buses free from congestion can compensate for additional time required for stopping at bus stops.
3. Separate rights-of-way, stations and other infrastructure give the bus service a distinctive image.

### **2.3.2. High Occupancy Vehicle (HOV) Lanes**

Because buses use little capacity, a popular treatment has been to allow carpools and vanpools to use the exclusive bus lanes. These lanes are then referred to as high-occupancy vehicle (HOV) lanes. The main reason for converting exclusive bus lanes to HOV lanes is to fill the gaps that are often perceived by the general public as a sign of under-utilization of facility. Vuchic *et al.* (1994), however, argued against such conversion because it downgrades bus services and benefits its competition. They pointed out that allowing private automobiles into preferential lanes degrades the flow of the truly high occupancy vehicles, buses and vans; increases the friction between vehicles due to an increase in non-uniform vehicle composition; and results in more difficult enforcement control of vehicle classes for entry and use of preferential lanes.

### **2.3.3. Signal Priority**

Another way of improving bus services that is gaining popularity is to give priority to transit vehicles at signalized intersections. Since transit vehicles can hold many more people than passenger cars, giving transit priority can potentially increase the person throughput of an intersection. Skabardonis (2000) divided signal control strategies into passive and active. Passive priority strategies consist of methods for developing signal timing plans (cycle length, green times, and offsets) to favor transit along signal arterials. Active priority strategies involve preemption at specific traffic signals and/or system-wide adjustments to the signal timing plans based on real-time information on traffic conditions and bus arrivals at the intersection.

Abdelfattah (1999) used the TRAF-NETSIM simulation model to identify potential ITS measures that could be used to reduce bus delays. His analysis included three scenarios: (1) normal (existing) traffic operation, (2) one lane is blocked due to a non-recurring incidence, and (3) bus priority at signalized intersections. It was concluded that significant improvements to bus delays could be achieved by using technology for early detection and management of incidents that block lanes and by applying bus priority policy and technology.

Balke *et al.* (2000) developed and tested the concept of using bus position information to predict when in the cycle a bus would arrive at the bus stop and stop line of a signalized intersection and to determine whether a bus needs priority. The strategy used to provide priority was selected based on the estimated arrival time of the bus at the stop line. Priority was provided by using phase extension, phase insertion, and early return strategies without causing the controller to drop from coordination. Implementation of the strategies was accomplished through normal traffic signal controller commands. Hardware-in-the-loop simulation studies were performed to

evaluate the effectiveness of the concept with real traffic signal controllers. The performance of the intelligent bus priority approach was examined at the 0.5, 0.8, and 0.95 volume-to-capacity (v/c) ratios. Significant reductions in bus travel times were found at all three v/c ratios. However, only minor increases in total system stop delay and individual approach stop delays at the 0.5 and 0.8 v/c levels were found using the approach. The results suggested that the approach could be used at moderate traffic levels up to v/c ratios of 0.9 without significantly impacting cross-street delays.

A common signal priority design is through the use of a queue jumper lane, which consists of a short stretch of bus lane combined with traffic signal priority. The idea is to enable buses to bypass waiting queues of traffic and to cut out in front by getting an early green signal. A special bus-only signal may be required. The queue jumper lane can be a right-turn-only lane that permits straight-through movements for buses only, or can be a lane installed between right-turn and straight-through lanes (FTA, 1998).

Nowlin and Fitzpatrick (1997) used a traffic simulation program called TexSIM to study the effects of queue jumper lane on bus operations around a far-side open bus bay. They found that the queue jumper lane provided significant advantages in travel time and speed when traffic volumes exceeded 250 vehicles per hour per lane (vphpl). For traffic volumes below 1,000 vphpl, the advantages in average bus speed when a queue jumper lane was present ranged from approximately 5 km/h to 15 km/h. Field data collected for the study showed that buses saved an average 6.5 seconds at a high-volume intersection.

## **2.4. Bus Lanes**

### **2.4.1. Bus Lane Configurations**

As defined earlier, a bus lane is generally a traffic lane on a freeway or an arterial street that is reserved mainly for the use of buses. Bus lanes can be located either at the curb or in the median. Central lanes are rarely used because of the problem of accommodating loading platforms in the street. With curbside bus lanes right turners are usually permitted. Curbside bus lane operations are subject to illegal parking and standing as well as right-turning vehicles waiting for pedestrians. Solutions to these problems include (Schimek, 2000):

- designating the next lane away from the curb as the bus lane,
- prohibiting right turns at locations, and
- using the lane adjacent to the curb lane as a bus lane and mark a right-turn-only lane next to the curb at intersections with heavy right-turn volumes.

Median lanes are usually part of a wide boulevard and generally separated from the general traffic lanes by a raised curb. Passenger platforms are usually on the right, and can be staggered to reduce the overall width needed. Center platforms can also be used, but they required left-side doors on all vehicles using the median lanes. When the right-of-way is sufficient, median lanes may be designed to permit buses to pass each other. Bus lanes can go either with the general flow of traffic or in the opposing direction of general flow, i.e., contra-flow (Schimek, 2000).

## 2.4.2. Bus Lane Operational Studies

A number of studies have attempted to evaluate the operational performance of bus lanes based on travel time, travel speed, flow rate, capacity, delay, and fuel emission—with travel time and travel speed being the more common measures. The approaches taken in these studies can generally be divided into those that are based on field observations and those on simulation models.

### 2.4.2.1. Field Studies

One of the earlier field studies on travel speed was performed by Rainville *et al.* (1961). The study reported an increase of peak-hour bus speeds of about 1.5 to 2.0 mph when bus lanes were designated. Morin and Reagan (1969) analyzed the delay inflicted upon low-occupancy automobiles when various combinations of buses and “carpool autos” are granted exclusive use of one lane on a freeway. The analysis was applied to demands of 10,000 and 20,000 persons/hour (one-way) for the following four conditions:

1. mixed flow on all lanes,
2. one lane reserved for buses only,
3. lane reserved for all vehicles with two or more occupants, and
4. lane reserved for all vehicles with three or more occupants.

It was found that, on high-demand freeways with four lanes in each direction, use of a reserved lane by buses and carpools of three or more persons would produce average delays to low-occupancy autos 6% to 12% higher than experienced with completely mixed flow.

One of the earlier bus lane demonstration projects was performed in 1973 for a 10-mile arterial on NW 7th Ave (see Figure 2-1) in Miami, Florida (Wattleworth *et al.*, 1976; Michalopoulos, 1978). The 3.5-year demonstration project attempted to develop more efficient people-moving capabilities along the 10-mile corridor to provide fast, peak-period service by express buses. The following three combinations of bus priority treatments were evaluated:

1. a reversible express bus lane,
2. a traffic signal preemption system that allowed express-bus drivers to preempt traffic signals, and
3. a coordinated signal system designed to favor the movement of express buses in the peak-period direction.

The study concluded that express buses could be given priority treatment on urban arterial streets without an adverse impact on the general traffic stream. It was also concluded that a park-and-ride express-bus combination that provides a high level of service could attract automobile riders. The park-and-ride facility was found to be an essential element of the transit service in capturing the bus passengers that would have to use automobiles if the facility had not been provided. In addition, the bus preemption system was found to have little adverse effect on traffic signal operations.

**Figure 2-1. Route for Miami Bus Lane Demonstration Project (Michalopoulos, 1978).**

Erdman and Panuska (1976) performed a study to identify and measure the impact of exclusive bus lanes on urban arterials in Baltimore, Maryland. The arterial had two lanes in each direction. It was found that the exclusive bus lane did not improve transit operations and resulted in a net increase in delay for all travelers on the arterial. This study shows that taking one lane from an arterial that has only two lanes (per direction) could be difficult to justify operationally.

Miese (1977) developed equations for both with-flow and counter-flow configurations of exclusive bus lanes to determine the variation of the resultant emissions with the percentage of diversion for various values of initial speed, number of lanes, and directional split (for counter-flow lanes). Results of the analysis indicated that minimum diversion percentages exist below which carbon monoxide emission rates and total hydrocarbon emissions were greater for the options with exclusive bus lanes.

In 1981, the New York City implemented a dual exclusive bus lane facility on Madison Avenue in midtown Manhattan (Schwartz *et al.*, 1982). The project at the time represents one of the most ambitious transit-priority projects for an urban arterial short of a complete ban of other traffic. The facility operated from 2:00 to 7:00 pm on weekdays and carried 25,000 passengers daily. It shared a roadway with three lanes of mixed traffic and was defined by pavement markings and overhead signs, accompanied by intense enforcement. Initial results indicated that (a) peak-hour bus speed was increased by 83%, (b) peak-hour bus reliability was increased by 57%, (c) peak-hour bus density was reduced by 45%, (d) traffic speed on Madison Avenue was increased by 10%, (e) average speed on parallel avenues was unchanged, and (f) average speed on eastbound cross streets was unchanged and on westbound cross streets was reduced by 6%. Slightly different results from the same project were later reported in an UMTA report by Kuzmyak (1984).

Exclusive bus lanes were first introduced in Singapore in 1974 as an effort to reduce travel times and to improve service reliability of public buses. The lanes were of the with-flow type located next to the curbs. The operational hours of the exclusive bus lane scheme were from 7:30 am to 9:30 am and 4:30 pm to 7:00 pm on weekdays, and 7:30 am to 9:30 am and 11:30 am to 2:00 pm on Saturdays. By mid 1992, the total length of exclusive bus lanes in use reached 70.2 km. A study by Chin (1985) derived the average travel speeds of buses and cars before and after the implementation of the exclusive bus lanes for two stretches of roads. The study found that, as shown in Table 2-2, while the travel speeds of buses improved significantly after the implementation of the scheme, the travel speeds of cars using the two stretches of road suffered a drop. The corresponding changes in fuel consumption rates for buses and cars are shown in Table 2-3. The rate of fuel consumption decreased by a margin of 18.7% to 23.0% for buses, but increased by a margin of 0% to 12.1% for cars. Taking into account the volume of cars and buses affected by the exclusive bus scheme, a comparison of the total fuel consumptions of the morning and evening operational periods was made in Table 2-4 for the two stretches of road. An increase in energy use along the two stretches of roads was found during the morning period of the scheme, that the increase in energy consumption by cars was more than the savings achieved by the buses. However, a net saving of energy use was found for the evening period, resulting a total net energy saved per day of 64.6 GJ (Chin 1985, Fwa and Ang 1996).

**Table 2-2. Average Weekday Journey Speeds Before and After Implementation of Exclusive Bus Lanes.**

Road Stretch	Period	Buses			Cars		
		Volume (vph)	Average Journey Speed		Volume (vph)	Average Journey Speed	
			Before	After		Before	After
A	AM	197	17.5 km/h	23.8 km/h	2853	32.5 km/h	27.8 km/h
	PM	231	17.2 km/h	26.9 km/h	3278	30.0 km/h	26.0 km/h
B	AM	197	18.4 km/h	27.3 km/h	2878	32.5 km/h	24.4 km/h
	PM	231	18.3 km/h	31.2 km/h	2847	30.0 km/h	30.0 km/h

**Table 2-3. Fuel Consumption Before and After Implementation of Exclusive Bus Lanes.**

Road Stretch	Period	Fuel Consumption of Buses (ml/km)			Fuel Consumption of Cars (ml/km)		
		Before	After	% Change	Before	After	% Change
A	AM	494.9	402.2	-18.7%	82.3	90.5	+10.0%
	PM	503.7	387.8	-23.0%	87.9	93.0	+ 5.8%
B	AM	475.1	385.8	-18.8%	85.3	95.6	+12.1%
	PM	476.0	387.2	-18.7%	87.9	87.9	0.0%

**Table 2-4. Fuel and Energy Savings Per Day Due to Exclusive Bus Lanes.**

Road Stretch	A		B	
	AM	PM	AM	PM
Fuel saved by buses (liter)	238.2	435.4	227.9	334.1
Fuel saved by cars (liter)	-304.1	-230.2	-385.4	0.0
Net energy saved (GJ)	-1.1	+8.6	-4.2	+12.4

The effects of bus-bus congestion were examined in a 1986 study of bus priority proposals in New York City (Urbitran Associates, 1986). It was found that delay resulting from bus-bus congestion on Fifth Avenue (with 220 buses per hour, passing difficult) averaged 2.2 minutes per mile in the morning rush hour, and on Sixth Avenue (with 150 buses per hour, passing possible) the delay was insignificant. The bus-bus congestion accounted for about 15% of the total travel time along Fifth Avenue and for less than 1% along Sixth Avenue.

Shalaby (1994) presented an approach that investigates the effect of an urban reserved bus lane on bus travel time on individual segments, i.e., travel times between consecutive bus stops along the bus route. Data were obtained by analysis of videotapes recorded before and after the introduction of exclusive curb bus lanes on a major arterial road in downtown Toronto. The data indicated that time savings were most likely to occur on segments where buses previously experienced considerable congestion, as well as at traffic signals, especially when bus stops were arranged with one on the near side and the next on the far side of their respective intersections. However, these time savings also generated additional ridership, resulting in longer dwell times at stops and a corresponding overall increase in total travel time. Thus, the perception of transit service improvement might have more impacts on ridership change than any substantive change in performance. The results of the study suggested that opportunities for using reserved bus lanes on a more selective basis along a particular route and the need to reconsider whether taxis should be permitted to use these lanes.

Choi and Choi (1995) conducted a study to evaluate the operations before and after the construction of an exclusive bus lane on the interregional freeway from Seoul to Sintanjin (Korea). The study concluded that the bus lane greatly improved bus travel time under oversaturated conditions. The study also found an increase of more than 12% in modal shift from cars to buses as a result of the bus lane. In terms of traffic accidents, although the accident rates were found to decrease, the severity of accidents increased.

#### *2.4.2.2. Simulation Studies*

A number of bus lane studies have applied the simulation approach. Muzyka (1975) used a corridor simulation model called SCOT to predict the effect on bus service and the general traffic performance of implementing candidate bus priority strategies. Numerical values of standard traffic performance measures were determined from computation of network vehicle trajectories. Various bus priority strategies designed to increase bus speeds by providing bus-only lanes were evaluated. It was found that frequency of station stops and red-light signals were the most significant elements affecting bus travel time.

Bowes and Van der Mark (1977) applied the simulation approach to investigate the potential operational capacities under different bus lane operating strategies for downtown Ottawa, Canada. They found that a bus flow rate of 150 to 170 buses per hour could be achieved, depending on the strategy selected. The flow rate could accommodate 8,000 to 9,000 passengers per hour with acceptable loading standards, operating speeds, and existing standard equipment.

Rouphail (1984) performed a study to evaluate the impact of the use of two bus priority techniques on the operation of bus and non-bus traffic using the TRANSYT-7F simulation

model. The strategies studied were (1) contra-flow bus lane on a downtown street, and (2) signal settings based on minimizing passenger instead of vehicle delays. The operational setting reflected actual observations on a Chicago downtown street where a contra-flow bus lane was installed in 1980. It was found that dedicating a lane to bus traffic significantly increased the overall bus speed on the route, that the use of signal priority further enhanced bus operation. Also, the total vehicle-miles of travel for non-bus traffic were found to decrease after the implementation of the bus lane, that some improvements in non-bus traffic operation on the study section could be attributed to that factor.

Shalaby (1999) also used TRANSYT-7F to examine changes in performance measures of through buses and adjacent traffic following the introduction of reserved lanes in an urban arterial. The simulation results showed that the performance of the average bus improved after project implementation, whereas the performance of the adjacent through traffic deteriorated. However, the deterioration exceeded the improvement. The simulations also showed that modifications to left-turn movements would have a minor impact on both bus and adjacent traffic performance, whereas the removal of taxis from the reserved lanes would cause far more performance deterioration to the adjacent traffic than the performance improvement this policy measure would bring to buses.

St. Kevin and Levinson (1997) performed a major operational study under the Transit Cooperative Research Program (TCRP). Using results from a modified version of TRAF-NETSIM, the study analyzed the operation of buses along arterial street bus lanes. The results show how the number of buses per hour, bus stops per mile, bus stop dwell times and service patterns, signal constraints, and traffic volumes in adjacent lanes affect bus lane speeds and capacities. Three types of bus lanes were analyzed:

1. A curb bus lane where passing is impossible or prohibited and where right turns are either permitted or prohibited. The lane may operate in the same direction as other traffic or may operate contra-flow.
2. A curb bus lane where buses can use the adjacent mixed-traffic lane for overtaking or “leap frogging” around stopped buses. Right turns by non-bus traffic may or may not be prohibited from the curb bus lane.
3. Dual bus lanes with non-bus right turns prohibited.

The study concluded with the following findings and recommendations:

1. Bus speeds and capacities depend on how frequently the bus stops are placed, how long the buses stop, traffic conditions along the bus lane or route, and whether buses can pass and overtake each other.
2. Where bus volumes and passenger boardings are heavy, multiple bus berths at stops are essential to provide sufficient capacity and to minimize bus-bus delays.
3. Passenger dwell times at bus stops should be minimized by:

- the use of passes or fare cards, pay-as-you-leave fare collection, and possibly prepayment of fares at busy stops; and
  - the use of wide multi-channel doors, low-floor buses, and sufficient major stops to distribute passenger loads.
4. The variations in dwell times at key bus stops during peak travel periods should be minimized. Local and express bus stops should be separated because they may have widely different dwell times. The provision of bus lanes, bus streets, and busways is desirable to minimize automobile-bus conflicts.
  5. Bus lane speeds can be enhanced by providing alternate skip-stops where alternate groups of buses stop at alternate locations. The main benefit of having the adjacent lane available for buses is the ability to operate skip-stop with alternate groups of buses stopping at alternate locations. This suggests dual bus lanes (normal flow or contra-flow) where block spacing and passenger demands are conducive to skip-stops. Curb bus lane speeds can be enhanced by prohibiting right turns at major boarding and alighting points or by providing far-side bus stops.
  6. Dual bus lanes, with the prohibition of right turns and skip-stop operations, result in a virtual doubling of speeds and, to a lesser extent, route capacities. Where buses must share the adjacent lane with other traffic, the gains in speeds and capacities are less, especially when the adjacent lane operates at or near its capacity.
  7. Bus service and stopping patterns must be tempered by the existing route structure, block spacings, and passenger demand. Over-concentration of passenger boardings would increase dwell times, thereby reducing speeds and capacities. Lengthening the distance between stops throughout the urban area will improve speeds.
  8. Bus speeds are affected by the realities of operations on city streets, where there is much competition for curb space. Other buses, right turns, loading and goods delivery, and dwelling, parked, or parking vehicles will adversely affect bus speeds. Therefore, sound management and effective enforcement of bus lanes is essential.

### **2.4.3. Lymmo—A Bus Lane Example**

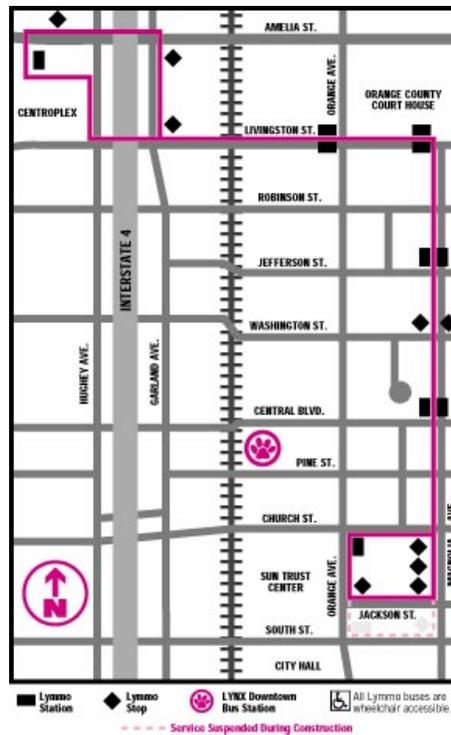
The Lymmo bus lane (see Figure 2-2) in Orlando, Florida was used as a case study in FTA's BRT demonstration project (see Section 2.6.3). Lymmo offers the following service features (Schimek, 2000):

- exclusive lanes for the entire 2.3 mile route (see Figure 2-3)
- signal pre-emption
- stations with large shelters and route information
- automatic vehicle location (AVL)
- next bus arrival information at kiosks
- new low-floor compressed natural gas (CNG) buses
- free fare—no fare collection delay



**Figure 2-2. Lymmo Right-of-way and Station.**

The bus lane service started in 1997 and it replaced an earlier downtown loop circulator called Freebee, which also charged no fare. Lymmo was a substitute for the proposed use of historic trolleys to replace Freebee. The City of Orlando abandoned the trolley idea because it would have had to contribute \$20 million of its own funds. In comparison, the total capital cost for Lymmo of \$21 million was less than half of what the trolley proposal would have cost (Schimek, 2000).



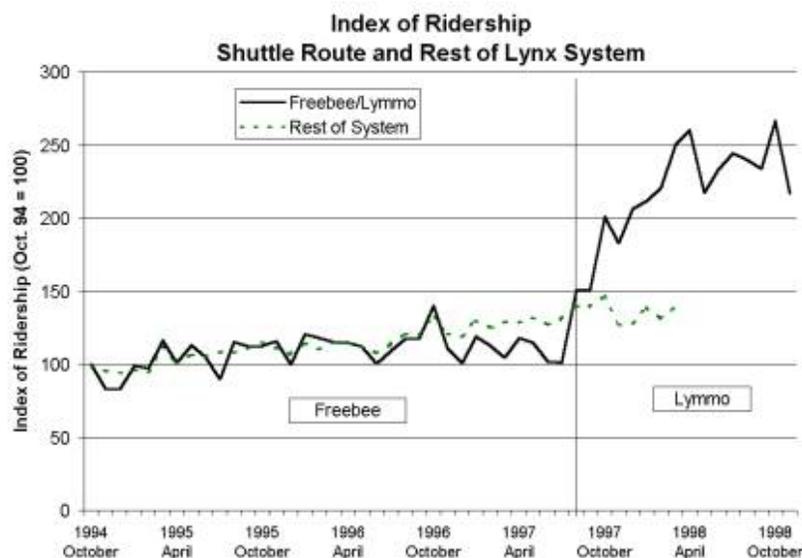
**Figure 2-3. Lymmo Service Route and Stations.**

The exclusive lanes are paved with distinctive pavers. They are separated from general traffic lanes either with a raised median or a double row of raised reflective ceramic pavement markers embedded in the asphalt. The route has loop sections at each end. In the middle segment, the two directions of Lymmo service are on the same street, with one of them being contra-flow to the traffic lanes. On-street parking was eliminated on one side of some streets of the Lymmo route (Schimek, 2000).

Because Lymmo operates in places and directions contrary to other traffic, all bus movements at intersections are controlled by special bus signals. To avoid confusion, these signal heads use lines instead of the standard red, yellow, and green lights. When a bus approaches an intersection, a loop detector in the bus lane triggers the intersection to allow the bus to proceed either in its own signal or at the same time as other traffic is released when no conflicting traffic movements are permitted (Schimek, 2000).

Despite exclusive lanes and signal preemption, scheduled trip speeds were one-third lower on Lymmo than its predecessor. Two contributing were cited: (1) Unlike its predecessor, Lymmo buses stop at each station regardless of demand; and (2) the increased ridership resulted in more dwell time while passengers were boarding. It was suggested that waiting time could be improved to a level below that of Freebee with the use the automated vehicle location (AVL) system by dispatchers to instruct drivers to hold early buses to adjust to the schedule to achieve a more even distribution of headways. It was believed that the bunching problem was less severe for Freebee since it had a short route with average loads well below capacity (Schimek, 2000).

As Figure 2-4 shows, Lymmo’s ridership increased despite a decrease in vehicle speeds. In the year following opening, ridership on Lymmo averaged about twice that of Freebee. Possible sources for increased ridership other than increased service included opening of the new courthouse, better routing, more pleasant service (stations and shelters, passenger information), and aggressive marketing campaign (Schimek, 2000).



**Figure 2-4. Lymmo Ridership Trend.**

## **2.5. Busways**

### **2.5.1. Busway Configurations**

The concept of busways was first introduced in 1960s. They are controlled facilities dedicated to buses and separated from the general traffic. Busways provide fastest speeds if all intersections with roads are grade-separated. At-grade intersections can be used but conflicts with cross traffic can be a problem. If at-grade signalized intersections are used, traffic signal detectors can be installed to give buses a green signal when they arrive at the intersection. There is a danger that cross traffic will ignore traffic signals if they believe there is little traffic on the busway. Busway stations can be designed to have berths for several vehicles to stop simultaneously. A high level of station amenities is generally provided (Schimek, 2000).

Although busways are generally designed for use by public transit vehicles, other vehicles, such as emergency vehicles, passenger vans, carpools, or others, may be permitted to use the facility. However, privately operated carpools and vanpools are usually not permitted. Busways have the following two major advantages over light rail transit (LRT) (Schimek, 2000):

1. Implementation flexibility: Any portion of a busway can be put into service as soon as it is finished.
2. Operational flexibility: Different types of service, such as dedicated, express, and local, can operate on the busway.

### **2.5.2. Busway Operational Studies**

Only a few busway operational studies can be found in the literature. Glazer and Crain (1979) performed an evaluation of the San Bernardino Freeway Express Busway that ran eastward from downtown Los Angeles. The busway included park-and-ride and on-line stations, feeder bus lines, outlying park-and-pool lots, and a supplemental contraflow bus lane in the central business district. It was found that, during the peak hour, the busway lane carried twice the number of passengers as did one adjacent freeway lane. Surveys of bus riders, busway carpoolers, and freeway users (busway nonusers) indicated that most carpoolers would not be carpooling if they could not use the busway. The busway was generally found to be more cost effective than an additional freeway lane. The average savings in out-of-pocket costs, for busway-induced carpoolers and bus riders only, covered two-thirds of the annual (capital and operating) costs of the busway. The authors concluded, however, that most of these conclusions would probably change if congestion on the adjacent freeway was reduced or eliminated.

Nisar and Khan (1992) developed a simulation model to compare LOS of transitway and LRT systems for the Ottawa-Carleton corridor. The results show that the transitway provides faster overall average speed than the LRT system. For various major origin-destination combinations, the overall average speed of the transitway is 1.14 to 1.26 times that of the LRT option. Results of LOS simulation indicate that the transitway provides a superior LOS than does the LRT system in terms of door-to-door travel time, waiting and transferring times for a substantial percentage of riders, frequent service, and availability of seats.

Martinelli (1996) also compared the performance of busways their primary competition, LRT. After considering four most cited advantages of light rail, the author concluded that busways are likely to be a superior mode of transit in most cases.

### 2.5.3. Busway Examples

#### 2.5.3.1. South-Dade Busway, Miami, Florida

The South Dade Busway was included as a case study in the FTA's BRT demonstration project (Schimek, 2000). Opened in 1997, the busway is an eight-mile, two-lane, bus-only roadway constructed in an abandoned railway right-of-way adjacent to the US 1 major arterial (see Figure 2-5). The busway corridor is shared by the following types of transit service:

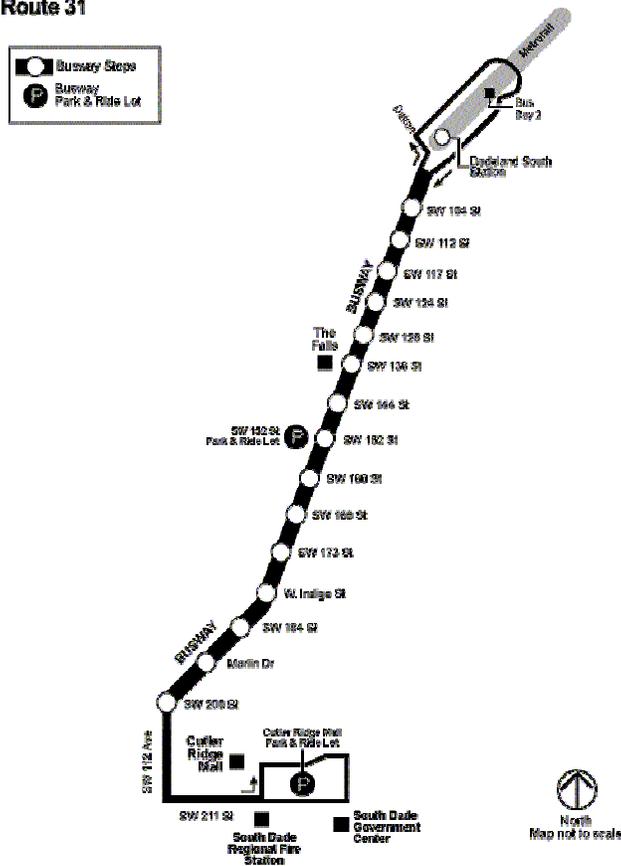
- Local: Runs on the busway only, and makes every stop at all times.
- Limited Stop: Runs the length of the busway and beyond, skips stops nearest Metrorail station during peak periods (Busway Metro Area Express (MAX)).
- Feeder: Collects passengers in neighborhoods and then enters the busway at a mid point (Coral Reef MAX, Saga Bay MAX).
- Crosstown: Pre-existing routes in the corridor that takes advantage of the busway where possible. They enter and exit the busway at middle points and are designed to provide access to many destinations in the region, not just to the center city (Routes 1 and 52).
- Intersecting: Routes in the corridor that intersect with busway routes, sometimes stopping at busway stations (Routes 35, 57 and 70).



**Figure 2-5. South-Dade Busway, Miami.**

The busway has 15 stations in each direction from its southern end at the SW 200th Street, to its northern end at the Dadeland South Metrorail station (see Figure 2-6). The busway stations are located at roughly half-mile intervals, about twice the standard stop spacing for Miami bus routes. Most stations are on the far side of intersections, except at locations where a route turns off the busway, where the stop is placed on the near side. In two locations there are mid-block stops to serve major generators, including a school and a mall. All stations have large shelters, telephones, waste receptacles, and route maps and schedules.

**BUSWAY LOCAL  
Route 31**



**Figure 2-6. South-Dade Busway Service Route and Stations.**

Because the northern portion of the busway has narrow separation between US 1 and the busway, the two intersections at each intersection location was designed to function as one. The signal for the busway traffic is red unless a loop detector senses an approaching bus. If a bus is detected and if parallel US 1 has a green signal, the busway also gets a green. To prevent right-turning vehicles from colliding with busway traffic, right turns from US 1 to side streets are permitted only with a green arrow.

The southern portion of the busway has more separation between the two parallel roads, which were originally signalized as separate intersections. The design resulted in a high number of crashes involving private vehicle drivers who either had not noticed or had ignored the red signal at the busway. As a result, the signal for the busway was synchronized with US 1, which effectively reduced the number of related crashes.

An examination of Route 1 of the busway indicated no significant time savings for transit vehicles using the busway. However, by May 1998, ridership in the corridor increased 49% on weekdays, 130% on Saturdays, and 69% on Sundays. The increase in service provided by the busway in terms of new areas served, more frequent service, and a greater span of service was believed to be the major reason resulting in the increase in ridership. The increase on operating costs was found to be at only half the rate of the increase in vehicle revenue miles.

Siridhara (2000) reported that the narrow space between the busway and U.S. 1 resulted in excessive delays and accidents. He pointed out that results from several studies suggested solutions that included signal-timing adjustments, re-channellizing the geometry of the roadways, and grade separations. He also described an on-going study by the Metro-Dade Transit Agency (MDTA) to improve safety and reduce travel time by considering four possible alternatives for high-priority intersection: (1) a base scenario (no-build), (2) elevated bypass, (3) depressed bypass, and (4) ITS-driven devices and gates.

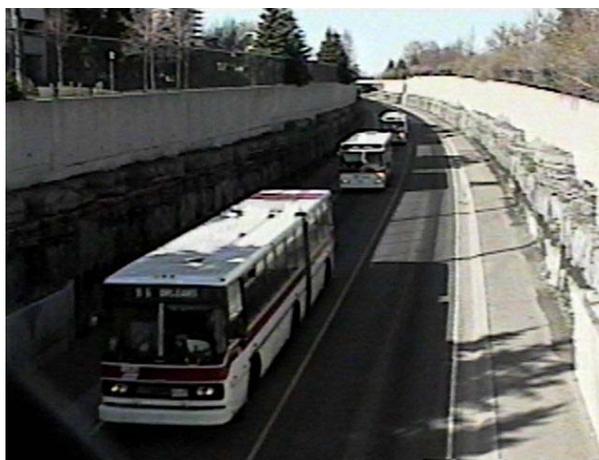
Imada (2000) also described an effort to address the specific signal design need for intersections at a busway. He suggested that the minimum requirements in MUTCD's traffic signal warrants be translated to incorporate the equivalent number of persons when determining the need of a signal at a busway. He proposed three criteria for determining traffic signal warrants at busways, i.e., queue overflows, safe stopping distance, and safe crossing gap.

#### *2.5.3.2. Ottawa Transitway*

Ottawa has one of the world's most extensive systems of exclusive busways that are known to Ottawans as the Transitway. The region consists of 11 rural and urban municipalities with a metropolitan region population of 650,000. Ninety percent of the population resides within the urban areas. Employment is dominated by the federal government, which accounts for 22% of all jobs in the region and half of the 28% of all jobs that are located in the downtown area.

After a detailed study of transit alternatives, the Regional Municipality of Ottawa-Carleton determined that transit would be a key component of the regional plan and that a busway system would be more responsive to the requirements of the area than a rail system. In 1974, it made the decision to construct and operate the busway system (see Figure 2-7) and assigned the responsibility to the Ottawa-Carleton Regional Transit Commission (OC Transpo).

Except in the approaches to bus stations where it widens to four lanes, the Transitway has one lane in each direction. There are 28 stations, including five in the CBD (see Figure 2-8). Stations are heated and have plenty of seating. Other amenities include video monitors with real-time bus information, pay phones, timetables, and direct-dial phones to OC Transpo.



**Figure 2-7. Ottawa Transitway.**

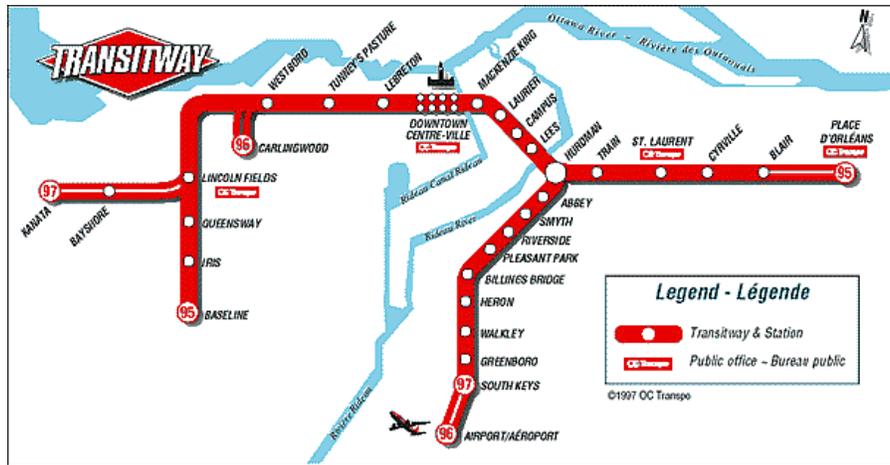


Figure 2-8. Ottawa Transitway and Primary Urban Centers.

With the opening of the final 1.12-mile extension of the Southwest Transitway in 1996, the total Transitway system extends 19.3 miles, with plans for an additional nine miles in the short-term and an additional nine in the longer term. These busways are supported by other bus guideway and support facilities, including bus lanes on general-purpose freeways (approximately ten miles), bus lanes in malls (two, each of approximately one-quarter mile), and surface streets (approximately six miles), for a total bus guideways system of approximately 36 miles.

Daily ridership of 200,000 for the Transitway far exceeds the ridership of all light rail systems, including 42,560 for San Diego, the highest ridership light rail system. It is comparable to the heavy rail systems, such as 261,750 of BART, which is located in a far larger metropolitan area with a far longer guideway system. In terms of ridership per capita, the Ottawa Transitway's 0.4 boardings per capital are over twice Atlanta's value of 0.181, and over seven times the rail average of 0.054.

### 2.5.3.3. Pittsburgh Busways

The Port Authority of Allegheny County (PAAC), through its Port Authority Transit Division (PAT), is the first transit operator in the United States to build and operate exclusive busways. PAT opened the 4.3-mile South Busway in 1977, the 6.8-mile East Busway in 1983, and the 5-mile West Busway in 2000.

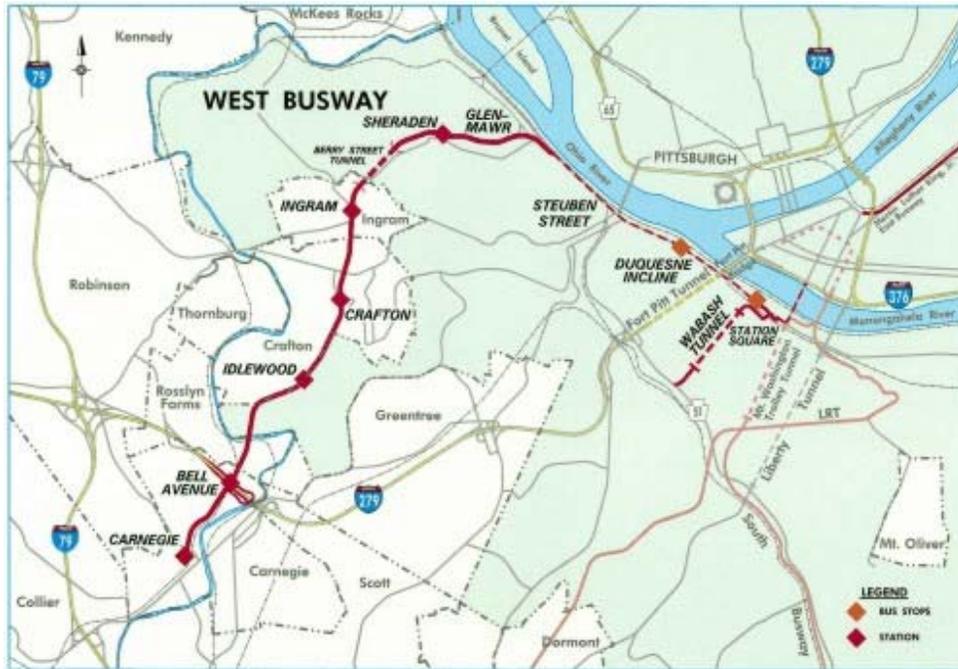
**East Busway.** Due to a seven-mile backup at the peak periods, plans were set to rebuild and repair the Penn Lincoln Parkway. It was estimated that to rebuild the parkway and add a third tube to the tunnel would take seven years. The proposed reconstruction would also severely disrupt traffic, thus, the East Busway (see Figure 2-9) served as a compromise. The busway, which attracts approximately 30,000 riders per day, runs 6.8 miles from the eastern suburbs to downtown Pittsburgh and can be traversed in 15 minutes, compared to 52 minutes for buses on adjacent roadways. Built in 1983 at a cost of \$113 million, the East Busway has six stations along its length, none of which have park-and-ride lots. Eliminating parking lots at the stations cut construction and land acquisition costs, and was made possible because buses pick up passengers in local neighborhoods and then enter the busway, greatly reducing the need for passengers to drive their cars in order to reach transit.



**Figure 2-9. Pittsburgh's East Busway.**

**South Busway.** The 4.3-mile, two-lane exclusive South Busway was opened in 1977 to bypass severe congestion at the Liberty tunnel, a major roadway linking the CBD and the South Hills area. Before the South Busway was opened, buses experienced difficulties in operating on local streets due to the hilly terrain of the South Hills area. In order to avoid steep grades, the South Busway was built parallel to N&W railroad tracks on virtually a flat grade. Buses on the South Busway save from six to 11 minutes over buses before the opening of the busway. Due to the operation of the South Busway, PAT was able to eliminate more than 160 bus trips per day from the congested streets of South Hills. A total of 17 routes uses the busway, including the new service routes added after its opening. The exclusive segment averages approximately 400 bus trips per direction per day. Throughout the early 1990s the South Busway suffered declining passenger levels, due largely to the deteriorating condition of a bridge along the route; this forced buses to take detours which added eight to ten minutes to the trip time. This demonstrates the importance of fast and convenient trips in attracting transit riders.

**West Busway.** The 5-mile West Busway, opened in September 2000, extends from Carnegie to east of the Sheraden Station (see Figure 2-10). Constructed in an abandoned rail right-of-way, the busway connects rapidly growing markets in the corridor between the City of Pittsburgh and the Pittsburgh International Airport. The facility varies in width from two to four lanes, providing a sufficiently wide cross section to allow express buses to pass vehicles stopped at any of the busway's six stations. At least 14 bus routes will use the busway and it was expected to save at least 20 minutes of travel time for morning peak direction trips. Because buses are able to pass other buses that are stopped at stations, two types of bus operation are permitted. The 100 West Busway-All Stops route, similar to light rail operation, travel the length of the busway, stopping at all stations, and leave the busway in the Downtown area to provide central business district circulation.



**Figure 2-10. West Busway Route.**

#### 2.5.3.4. Bogota Busway, Colombia

The Bogota's exclusive busway was completed in 1992. The 10-mile busway is part of a major arterial connecting the south and north parts of town to the city's CBD, the densest employment area of Bogota. Four center lanes—two in each direction—are assigned to high capacity (80-120 passengers) public transit vehicles. This allows faster transit vehicles to overtake the slower ones using the left lane of the busway for each direction. Four additional lanes (two per direction) are assigned to other modes, including taxicabs, private vehicles, and bicycles (Rodriguez *et al.*, 2000).

Small blocks 15 cm in height and 20 cm in length adhered to the pavement separate the busway from the general traffic lanes, preventing cars from entering the bus lanes but allowing buses to exit as needed. Stations are located 500 meters apart. Each station is 100-meter long and is raised 0.3 meter from the ground, and contains four different sections (Rodriguez *et al.*, 2000).

Ardila and Rodriguez (2000) reported that a recent passenger study counted a flow of more than 35,000 passengers per hour per direction for the exclusive busway. This passenger flow was achieved despite poor operating conditions and a general lack of maintenance without a city busway management and operation authority. Consequently, there was little police control, no systems management, and scarce information for users. These conditions should affect passenger flow negatively, but the Bogota busway carries more passengers than all busways for which data were available. Their analysis suggested that the Bogota busway was able to move high passenger flows due to the following three concurrent and interactive sets of factors:

1. high competition among bus operators provided drivers with an incentive to operate more efficiently,
2. design provides two lanes, allowing for vehicle overtake, as well as stations that enable six or more buses to pick up and discharge passengers simultaneously, and
3. buses move along the busway in platoons of 12 to 16 buses with average 96-second headways.

## **2.6. Bus Rapid Transit (BRT)**

### **2.6.1. BRT Configurations**

As defined in Section 2.2, Bus Rapid Transit (BRT) is a broad term that refers to bus transit systems that are improved through the use of bus lane, bus streets/busways, signal priority, traffic management improvements, and/or faster boarding. In general, BRT can be thought of as coordinated improvements in a transit system's infrastructure, equipment, operations, and technology that give preferential treatment to buses on urban roadways. Conceived as an integrated, well-defined system, BRT provides for significantly faster operating speeds, greater service reliability, and increased convenience, matching the quality of rail transit when implemented in appropriate settings.

The essence of BRT is that bus operating speed and reliability on arterial streets can be improved by reducing or eliminating the various types of delay, including (FTA, 1998):

1. Uncongested moving or free flow operating time: This component can only be reduced if speed limits are raised.
2. Delay due to general congestion: This component can be reduced if general congestion is reduced and/or if buses are given preferential treatment through creation of a reserved lane. Policies requiring general-purpose traffic to yield to buses re-entering the traffic stream from bus stops could also reduce delays associated with general congestion.
3. Delay due to traffic signals: Signal priority treatment of buses at intersections holds the potential to reduce a significant source of delay in bus operations.
4. Delay due to right turns: This type of delay occurs when buses are traveling in the curb lane and a queue of right-turning vehicles blocks the bus from moving forward. This delay may be overcome by relocating bus stops to the far side of the intersection so the bus may be able to bypass the right turning queue in the lane next to the curb lane. Alternately, right turns may be prohibited.
5. Delay due to passenger stops: This includes passenger boarding time, collection of fares, etc. Boarding time can be reduced by improvement of the fare collection process, e.g. pre-payment of fares, self-service fare collection (honor system), greater use of passes, smart cards, etc. and by easing the boarding process with low-floor buses together with

high platforms so that wheelchair-bound passengers could roll on without lifts. This component can also be reduced if stop spacing is increased and the number of stops is reduced. There is a trade-off between stop spacing and convenience to passengers.

BRT is often compared with light rail transit (LRT) because of their similarities. In fact, the fundamental concept of BRT is built on LRT principles, but instead of the required capital investment in trains and track, it utilizes buses in service that is integrated with key components of the existing automobile transportation infrastructure, such as roads and rights-of-way, intersections, and traffic signals. Therefore, BRT is considered more affordable, flexible, and appropriate in scale than LRT for a medium-sized area. In addition, BRT allows for incremental construction and implementation and can be easily tailored to meet the specific transportation needs and opportunities within individual neighborhoods and transportation corridors. BRT can offer many advantages to regular bus service, including service frequency, increased capacity, and speed.

### **2.6.2. Integrated System, Curitiba, Brazil: A Model Bus Rapid Transit**

The Integrated Systems (see Figure 2-11) of Curitiba, Brazil was adopted by the FTA as a model for developing BRT systems in North American (FTA, 1998). Curitiba has one of the most heavily used, yet low-cost, transit systems in the world. It offers many of the features of a subway system, including vehicle movements unimpeded by traffic signals and congestion, fare collection prior to boarding, quick passenger loading and unloading. Around 70% of Curitiba's commuters use transit daily to travel to work. The buses run frequently and reliably, commuters ride them in great numbers, and the stations are convenient, well-designed, comfortable, and attractive.



**Figure 2-11. Curitiba Busway.**

In 1966, in response to travel demands, Curitiba developed a master plan for the city that includes a bus transit network comprised of several different types of bus service. These include (Rubin and Moore, 1997):

1. Express Service: 263 standard, articulated, and double-articulated buses carrying 600,000 passengers per day on approximately 50 miles of dedicated busways operating in five directions to and from the CBD.
2. Feeding Service: 336 buses carrying 350,000 passengers per day on approximately 185 route miles on lines designed to feed passengers to the terminals for the Express buses.
3. Interdistrict Service: 125 buses carrying 200,000 passengers per day on approximately 115 route miles interconnecting the terminals and do not enter the CBD.
4. Direct Service: 161 buses carrying 200,000 passengers per day on approximately 155 route miles that provide limited/express service. This is a faster transportation option for specific trips for which there is sufficient demand to justify the service.
5. Conventional Service: 335 buses carrying 250,000 passengers per day connecting the neighborhoods with the CBD.
6. Special Assistance Service: 28 specially equipped minibuses offering free service for physically and mentally challenged riders
7. Park Service: buses that operate on Sundays and Holidays, using the weekday fleet.
8. Executive Service: downtown circulator and tourist buses.
9. Circular Service: 15 buses carrying 5,000 passengers per day serving the downtown Central Ring area, connecting to Direct and Express buses and stations.

Each type of service is differentiated by different color schemes (red for Express, orange for Feeder, etc.) to allow riders to avoid boarding errors. The first four services (express, feeding, inter-district, and direct) are the products of the integrated transit plan (ITP). These total approximately 235 routes on 500 route miles serving approximately 90% of the urbanized area population, generating approximately 1.8 million unlinked (or 1.2 million linked) passenger trips per day. The remaining 10% of the area is still served by conventional bus service.

The backbone of the Curitiba integrated bus system is composed of the express buses operating on five main arteries leading into the center of the city much as spokes on a wheel lead to its hub. This backbone service, aptly described as Bus Rapid Transit, is characterized by several features that enable Curitiba's bus service to approach the speed, efficiency, and reliability of a subway system:

- integrated planning
- exclusive bus lanes

- signal priority for buses
- pre-boarding fare collection
- level bus boarding from raised platforms in tube stations
- free transfers between lines (single entry)
- large capacity articulated and bi-articulated wide-door buses
- overlapping system of bus services

Buses running in the dedicated and exclusive lanes stop at tube stations (see Figure 2-12). These are modern design cylindrical-shaped, clear-walled stations with turnstiles, steps, and wheelchair lifts. Passengers pay their bus fares as they enter the stations, and wait for buses on raised station platforms. Instead of steps, buses are designed with extra wide doors and ramps, which extend when the doors open to fill the gap between the bus and the station platform. The tube stations serve the dual purpose of providing passengers with shelter from the elements, and facilitating the efficient simultaneous loading and unloading of passengers, including wheelchairs. A typical dwell time of only 15 to 19 seconds is the result of fare payment prior to boarding the bus and same-level boarding from the platform to the bus.



**Figure 2-12. Tube Station.**

The Express portion of the bus system was, in part, designed to operate much like a subway on rubber tires. Known as “Ligherino” (“Lite”), it was specifically conceived to operate in a fast, comfortable, and efficient manner to serve the populace of the entire area at the same fare as the rest of the bus network. Stops were limited for this high-speed, long-distance travel component of the system, with an average distance between major terminal/transfer points of approximately two kilometers and guideway stops approximately every half kilometer. The 88 Ligherino bus stops are tubes, constructed of laminated glass and steel, with fare collection turnstile entrances and exits, where approximately 10–200 riders can await their buses protected from the weather. Tube size is keyed to demand. There are no stairs on the Ligherino buses. The station platform height is the same as that of the bus floor, which, together with fare payment when entering the station, increases boarding/alighting speed by a factor of approximately four (Rubin and Moore, 1997).

The Ligherino buses travel on dedicated rights of way at average speeds of about 21 miles per hour. While this speed is significantly less than the freeway express bus service typical for North America, it provides a significant speed advantage for many travelers in Curitiba, saving as much as 15 minutes on a typical 8–10 miles peak period trip. This vehicle operating speed is only slightly lower than that of the Red Line (projected to be 24 mph) and Blue Line (22 mph) and is faster than most light rail lines in the United States. The North/South Ligherino line carries approximately 15,000 passengers per hour at peak in the peak direction, a figure comparable to that of the Rio de Janeiro Metro—and well in excess of the maximum capacity of the Los Angeles Red Line outside of the CBD (Rubin and Moore, 1997).

Curitiba also uses double-articulated buses on its most heavily utilized line, the Boqueron-Central Ring Line. These buses allow daily ridership as high as 130,000 passengers per line—many times the 40,000 per day ridership of the Blue Line, the most heavily utilized U.S. light rail line, and more than many heavy rail lines.

The cost of the entire Ligherino system was \$45 million—approximately 20% of the estimated cost of a single electric light rail line. A subway system was estimated to cost \$60-70 million per kilometer, while the cost of express bus guideways was \$200,000–\$700,000 per kilometer (Rubin and Moore, 1997).

The popularity of Curitiba's BRT system has affected a modal shift from automobile travel to bus travel, in spite of Curitiba's high income and high rate of car ownership relative to the rest of Brazil. Based on the results from a 1991 traveler survey, it was estimated that service improvements resulting from the introduction of BRT had attracted enough automobile users to public transportation to cause a reduction of about 27 million auto trips per year, saving about 27 million liters of fuel annually. In particular, 28% of direct bus service users previously traveled by car. Compared to eight other Brazilian cities its size, Curitiba uses about 30% less fuel per capita, because of its heavy transit usage. The low rate of ambient air pollution in Curitiba, one of the lowest in Brazil, is attributed to the public transportation system's accounting for around 55% of private trips in the city.

### **2.6.3. BRT Demonstration Projects**

In 1998, the FTA announced a request for participation in a BRT program. The program was designed to encourage transit agencies, local and state governments and metropolitan planning organizations engaging in coordinating infrastructure improvements, technology deployment and operations to consider the benefits of BRT. As part of the program, ten demonstration projects were selected for implementation and the specific project features for each project are summarized below.

#### *2.6.3.1. The Silver Line, Boston, Massachusetts*

The Silver Line project aims to provide improved service between Logan Airport and the Dudley Station in the Roxbury section of Boston with a dedicated lane featuring 60-ft articulated vehicles and alternative-fuel buses with ITS technology. The service runs via downtown Boston,

the South Boston Piers area and the airport, making these major job centers accessible with a one-seat ride.

#### *2.6.3.2. Independence Corridor BRT, Charlotte, North Carolina*

This project includes an exclusive busway in a 29-ft median of Independence Boulevard. Approximately 2.6 miles of the busway already exists. It incorporates a queue jumper at its eastern terminus that allows outbound buses to bypass congested areas. Phase II will add one additional mile in 2004 to incorporate a two-way busway facility with on-line stations. The project features use of low-floor vehicles, installation of AVL with voice annunciators, automatic passenger counters (APC), and real-time passenger information.

#### *2.6.3.3. Euclid Corridor Improvement Program, Cleveland, Ohio*

The Euclid Corridor Transportation Project includes a 5-mile exclusive busway on a landscaped median along the city's main arterial, Euclid Avenue, plus 2.5 miles of mixed traffic lanes with buses operating at the curb lane in mixed traffic. Major project features include:

- Use of electric trolley buses (ETBs) with two left-side and three right-side doors.
- Elimination of on-street parking.
- Relocation of delivery zones.
- Increase of bus station spacing from 500-ft to 1500-ft.
- Significant upgrades of pedestrian and passenger amenities.
- Implementation of traffic signal preemption.
- Use of off-board fare collection.

#### *2.6.3.4. Dulles Corridor BRT, Virginia*

The Dulles Corridor Project is part of a multi-year, multi-phase effort to extend Metrorail to the rapidly growing 22-mile corridor. The BRT project phase, set to start in 2003, would be an intermediate phase that would ultimately lead to the Metrorail extension. BRT would operate on the congestion-free Dulles Airport Access Road and stop at three stations that connect to the planned extension of Metrorail.

#### *2.6.3.5. Pilot East-West Corridor BRT, Eugene, Oregon*

The pilot east-west corridor extends ten miles from the Thurston area in east Springfield to west Eugene. It composes of high-frequency, fast transit service along major corridors with smaller buses providing access from neighborhoods to the BRT lines, nearby shopping and employment. Major system features include:

- exclusive bus lanes, including guided busways,
- ITS applications including transit signal priority and real-time passenger information,
- limited stops with improved facilities,
- barrier-free fare payment systems, and
- park-and-ride lots located along the BRT routes.

#### *2.6.3.6. Hartford-New Britain Busway, Hartford, Connecticut*

The Hartford-New Britain Busway project includes a roadway exclusively dedicated for buses, operating for a 10-mile distance between downtown New Britain and downtown Hartford. It aims to provide a high level of service and amenities, including busway stations, parking at some locations, and other possible ancillary development. ITS applications considered include signal priority, automatic vehicle location (AVL), real-time information, and a smart signal system for grade crossing control.

#### *2.6.3.7. CityExpress!, Honolulu, Hawaii*

The CityExpress! project features limited stop bus service along a 6.6-mile primary urban corridor that runs between the Kalihi Transit Center and the University of Hawaii. The service was expanded in 1999 to include an additional 6.0 miles, with additional transit priority measures and improved express service stations to be added in subsequent phases.

#### *2.6.3.8. South Miami-Dade Busway, Miami, Florida*

This busway project extends the existing South Miami-Dade Busway further south, to the Cities of Homestead and Florida City for a total length of over 11 miles. The proposed design features of the extension are similar to the existing South Miami-Dade Busway (see Section 2.5.3.1).

#### *2.6.3.9. Río Hondo Connector BRT, San Juan, Puerto Rico*

The Río Hondo Connector BRT aims to provide high-speed bus shuttle service between the Tren Urbano rapid transit line and the intermodal transfer facilities. Major project features include:

- construction of a plaza and park-and-ride lot at the end of the Río Hondo Connector—a 2.5-mile limited-access highway with HOV lanes in each direction,
- Non-stop shuttle buses take passengers from the plaza to the Bayamón Centro Tren Urbano station via the new HOV lanes, and
- universal fare payment for shuttle services and parking fees.

#### *2.6.3.10. Line 22 Rapid Transit Corridor, Santa Clara, California*

The Line 22 route is 27-mile corridor that runs on 10-minute headways during weekday peak hours and operates near capacity, with 28,000 riders daily, or 18% of total system ridership. Twenty-four hour service was implemented in January 1998. This BRT project would run articulated buses on the line with the following system features:

- queue jumps,
- bus bulbs at enhanced station areas,
- traffic signal priority,
- route modifications (shortening and straightening),
- fare prepayment using ticket vending machines at stations,

- low-floor buses, and
- AVL and other intelligent transportation system technologies.

#### **2.6.4. Remarks**

The FTA is currently conducting a study, entitled *Implementation Guidelines for Bus Rapid Transit Systems*, under the Transit Cooperation Research Program (TCRP). The project, scheduled for completion in May 2002, will identify the potential range of BRT applications and develop descriptive information and technical guidance tailored to meet the needs of various stakeholders interested in BRT as a means of improving mobility (Zimmerman *et al.*, ongoing.)

## CHAPTER 3 EXISTING WARRANTS

This chapter reviews existing warrants for justifying bus preferential treatments based on both general merits and operational efficiency.

### **3.1. General Justifications and Warrants**

Vuchic *et al.* (1994) cited the following general justifications for providing preferential treatments to buses over private and other vehicles:

1. Favoring public over private facilities is a standard practice. For example, the society pays from its general funds for public schools, parks and other facilities and governments do not support private schools, golf courses, etc.. Transit is the only transportation mode that provides mobility for all citizens and thus contributes to the basic living standard of the entire population.
2. Buses provide much higher passenger capacity than automobiles. They take less travel area per person-kilometer and require lower total cost for transportation than private automobiles. Therefore, buses have inherently much higher productivity and efficiency of transportation whenever there is a sizeable travel demand in a corridor.
3. Buses have far lower negative side effects, such as less pollution and energy consumption per person-km transported.
4. Bus priorities are needed to give transit faster and more reliable service and thus counteract the advantages an individual finds in using the automobile, such as personal convenience and privacy, and extremely low out-of-pocket cost. These advantages are very attractive to the auto users, particularly because they are not charged for any social and environmental impacts which auto travel causes. Transit must offer a comparable set of advantages in order to attract choice riders.
5. Transit can create a more human-based and livable environment than in the cases where all travel is performed by the private automobile only.

The following general warrants for the implementation of exclusive bus lanes were suggested by Parker and Eburah (1973):

1. Give a significant advantage to buses.
2. Not seriously reduce total traffic capacity or cause secondary congestion by developing excessive queues.
3. Yield a net benefit to the community.
4. Not involved excessive expenditure.
5. Be enforceable.
6. Minimize adverse effects on pedestrians, frontage (including loading to shops and other premises) and on the adjacent environment.

7. Where possible, assist the flow of other traffic.
8. Not be subject to undue delay in implementation.
9. Have an economic life.

Warrant 7 recognizes that the separation of buses from the general traffic can decrease turbulences in traffic flow and may improve not only the bus operation, but of the auto traffic in other lanes as well.

### **3.2. Numerical Warrants**

Some numerical warrants can be found the literature. NCHRP Report 155 (1975) suggested a minimum of 60 buses per hour, or 3,000 passengers per hour, to justify an exclusive lane for bus use. A more detailed numerical warrant was developed by Delgoffe (1972) who specified the minimum required buses as a function of congestion level, bus occupancy and number of lanes. As shown in Table 3-1, the minimum number of buses required ranges from 25 to 60, with more number of buses required for more oversaturated roadway conditions, lower bus occupancy rate, lower number of roadway lanes.

**Table 3-1. Minimum Buses per Hour to Justify a Reserved Bus Lane.**

Degree of Saturation	Passengers per bus	Number of lanes from which the bus-only lanes is taken			
		2	3	4	5
Over-saturated Road	50	60	45	40	40
	70	45	30	30	30
	90	35	25	25	25
Non-saturated Road	30	45	40	35	30
	50	50	25	25	25

Vuchic (1981) pointed out that most of the existing warrants for arterial bus lane introduction are biased in favor of autos for several reasons:

- they ignore the greater importance of public transport due to its basic role in the city, greater overall economy, and fewer negative side effects;
- they are based primarily on vehicular, rather than passenger volumes carried by the two modes; and
- they use existing conditions, instead of the relationships of volumes after the bus lane is introduced when some diversion of travel may have occurred.

Because many reasons for bus lane introduction cannot be easily quantified, Vuchic proposed to evaluate bus-lane justification based on the number of persons carried by buses versus those carried by autos, with the most conservative warrant being that a bus lane is justified when buses carry as many people as autos carry per lane in the remaining lanes. Accordingly, the volume of buses required for this warrant is:

$$q_B \geq \frac{q_A}{N-1} x$$

where  $q_A$  and  $q_B$  are hourly volumes of autos (including trucks as passenger-car equivalents) and buses, respectively;  $N$  is the total number of lanes per direction; and  $x$  is the ratio of average auto to bus occupancies. Values of  $x$  vary among locations and during different times of day. Figure 2-1 shows the bus volumes that justify bus lanes for several values of  $N$  and  $X$ . Bus volumes somewhat lower than those shown would already justify reserved lanes for the following reasons:

- Introduction of a bus lane may cause some diversion of travel from auto to bus, so that a lower  $q_A$  and higher  $q_B$  would apply than those for existing conditions.
- It is desirable to favor transit over auto travel because it is an essential service, it is more economical, and has a lower negative impact.
- Permanently reserved lanes have the advantages of better identity, simpler regulatory devices, and less confusion. Thus peak-hour bus lanes can be retained during periods when bus volumes are lower than the diagram shows.

### **Figure 3-1. Minimum Travel Volume for Bus Lane Introduction.**

Webster *et al.* (1976), on the other hand, argued that warrants based on the grounds that buses are entitled to the exclusive use of the first lane when the number of bus riders carried in one lane equals the number of auto occupants in an adjoining traffic lane are not optimal. They suggested another approach that bases the decision on estimated savings in travel time and operating costs from simulation studies and, where possible, real-life studies. Accordingly, they recommended the results from a Transportation Road Research Laboratory (TRRL) simulation study of a with-flow bus lane on a two-lane and a three-lane approach to a signalized intersection. Table 3-2 indicates for two- and three-lane approaches, respectively, the critical bus flows which must be exceeded before an overall benefit is obtained. The benefits in terms of the savings in time and operating costs were calculated for various degrees of saturation of the signalized intersection at different setbacks—defined as the distance between the end of a bus lane to the intersection stop line. A setback allows a bus lane to stop short of an intersection so

that the space (between the bus lane and the stop line) can be used by other vehicles. According to the authors, this helps to maintain the capacity of the intersection, which in turn allow a bus lane to be justified more easily.

**Table 3-2. Calculated Minimum Bus Flows<sup>1</sup> to Justify a With-Flow Bus Lane.**

Approach	Degree of Saturation	Optimum Setback in Meters	No Setback	
			Easy Diversion	Hard Diversion
Two-Lane	0.7	70	100	120
	0.8	60	120	170
	0.9	50	120	180
	0.95	20	100	160
	0.975	10	80	140
Three-Lane	0.7	50	100	100
	0.8	60	130	150
	0.9	50	150	200
	0.95	30	130	200
	0.975	10	100	170

<sup>1</sup> Bus occupancy = 60 passengers.

It can be seen from Table 3-2 that with a setback of optimum length few buses are required to justify a bus lane when the degree of saturation is high. When the degree of saturation is lower, a higher bus flow is required for an overall net benefit to be obtained, but the benefit or the disbenefit in typical cases is so small that other considerations should be overriding. When there is no setback, the chance of obtaining an overall benefit depends on: (a) the ease of diversion and the delaying effect of the diverted traffic on other vehicles, and (b) the flow of bus passengers. With regard to (a) two types of situation were considered: an 'easy' situation in which the diversion is short and the diversion routes have plenty of spare capacity, so that the diverted vehicles do not cause the speed of traffic on the diversion route to fall appreciably; and a 'hard' situation, in which the diversion is lengthy and the diversion routes have little spare capacity, so that congestion increases greatly and the effect on other traffic is severe.

A report prepared by an OECD road research group (1977) suggested that warrants for bus preferential treatments should be based on peak-period travel, with additional considerations given to air quality and energy conservation goals, downtown parking, transportation development policy objectives, as well as the ability of other streets to carry potentially displaced traffic. Based upon these considerations, the group developed a set of warrants for bus preferential treatments on both freeway and arterial facilities, as given in Table 3-3.

The HOV Systems Manual (NCHRP 414, 1998) prescribed the minimum and maximum vehicles for freeway and arterial streets given in Table 3-4. The minimum values were derived to ensure that the number of vehicles using a lane on opening day and during the initial phases of a project is high enough to justify the facility and help build support among users, non-users, and the general public. On the other hand, the maximum values were set to maintain the level of service that provides the travel time savings and reliability of the facility. It is noted that these threshold values are not absolute and should be adjusted for local conditions. For example, the minimum threshold will be lower for a bus-only lane used during the peak hours than for a barrier separated exclusive facility, or for facilities that serve buses with high occupancy rates.

**Table 3-3. Generalized Applicability of Bus Priority Treatments (OECD, 1997).**

Type of Treatment <sup>a</sup>	General Applicability To		“Design Year” Conditions		Related Land Use and Transportation Factors
	Local Bus Service	Limited-Express Bus Service	Range in One-way Peak-Hour Bus Volume	Ranges in Peak-Hours One-Way Bus Passenger Volumes	
1. Buaways on special right-of-way	x	x	40-60	1600-2400	Urban population 750,000, CBD employment - 50,000, 20 million sq. ft. floor space.
2. Buaways within freeway right-of-way		x	40-60	1600-2400	Freeways in corridor congested in peak-hour.
3. Buaways on railroad right-of-Way	x	x	40-60	1600-2400	Not well located in relation to service area. Stations required.
4. Freeway bus lanes normal flow direction		x	60-90	2400-3600	Applicable upstream from lane drop. Bus passenger time saving should exceed other road-user delays.
5. Freeway bus lanes contra-flow		x	40-60	1600-2400	Freeways six or more lanes; where imbalance in traffic volume permits at least LOS D in off-peak travel directions.
6. Bus lane bypass at toll plaza		x	20-30	800-1200	Adequate reservoir on approach to toll station.
7. Exclusive bus access ramp to non-reserve freeway or arterial lane	x	x	10-15	400-600	n/a.
8. Bus by-pass lane at metered freeway ramp		x	10-15	400-600	Alternate surface route available for metered traffic. Express buses leave freeways to make intermediate stops.
9. Bus stops along freeways		x	5-10	50-100 boardings or alightings in peak hour	Generally provide at surface level in conjunction with metered ramp.
10. Bus streets	x	x	20-30	800-1200	Commercially oriented frontage.
11. CBD curb bus lanes-main street	x		20-30	800-1200	Commercially oriented frontage. At least two lanes
12. Curb bus lanes	x		30-40	1200-1600	At least two lanes available for other traffic in same direction.
13. Median turnouts	x	x	60-90	2400-3600	At least two lanes available for other traffic in same direction; ability to separate turn conflict from buses.
14. Contra-flow bus lanes short segments	x		20-30	800-1200	
15. Contra-flow bus lanes extended	x	x	40-60	1000-2400	At least two lanes available for other traffic in opposite direction. Signal spacing greater than 500 ft intervals.
16. Bus turnouts	x		10-15	400-600	Points of major passenger loading on streets with more than 500 peak-hour autos using curb lane.
17. Bus pre-emption of traffic signals	x		10-15	400-600	Wherever not constrained by pedestrian clearance or signal network constraints.
18. Special bus signals and signal phases bus actuated	x		5-10	200-400	At access points to bus lanes, busways or terminals; or where special bus turning movements need to be accommodated.
19. Special bus turn provisions	x		5-10	200-900	Wherever vehicular turn prohibitions are located along bus routes.

a 1- 9: freeway facilities; 10-19: arterial facilities.

It is recognized that the minimum volumes in Table 3-4 are significantly higher than those of Table 3-3. This is because the values in Table 3-4 are justified based on only the number of vehicles served by each alternative, while Table 3-3 take into consideration the average travel time experienced by all road users. The high volumes in Table 3-4 imply that, in general, bus-only preferential treatments are difficult to justify based on bus volumes alone, as there are few candidate freeway facilities, for example, that serve more than 400 buses per hour. This also suggests that an HOV lane that allows carpools and vanpools to share the right of way is more likely to be justified.

**Table 3-4. Operating Threshold Guidelines (NCHRP 414, 1998).**

Facility	Preferential Treatment	Minimum in vphpl	Maximum in vphpl
Freeway	Separate right-of-way, bus only	300-400	800-1,000
	Separate right-of-way, HOV	800-1,000	1,500-1,800
	Exclusive two-directional	400-800	1,200-1,500
	Exclusive reversible	400-800	1,500-1,800
	Concurrent flow	400-800	1,200-1,500
	Contraflow, bus-only	200-400	600-800
	Contraflow, HOV	400-800	1,200-1,500
	HOV bypass lanes	100-200	300-500
Arterial	Bus malls	80-100	200-400
	Right-side bus only	50-80	100-200
	Right-side HOV	200-400	600-800
	Left-side bus-only	50-80	100-200
	Left-side HOV	200-400	600-800
	Center two-way	200-400	600-800
	Center reversible	80-160	400-600
	Contraflow bus only on one-way street	50-80	100-200

## **CHAPTER 4**

### **SIMULATION MODELING**

This chapter introduces the simulation modeling approach. It serves to provide contents that are common to the two subsequent chapters. The existing simulation models are first introduced, followed by the selection of traffic simulator for this study. The final section describes an automated procedure for performing multiple simulation runs.

#### **4.1. Introduction**

Simulation models are designed to “mimic” the behavior of real-world systems by integrating various component behaviors and interactions to produce a detailed, quantitative description of system performance. Traffic simulation, as the name implies, involves simulation modeling that is tailored to applications on traffic systems. Traffic simulation is increasingly becoming a popular and effective tool in the design, evaluation, and operation of complex transportation systems. According to Pursula (1999), the driving forces behind this trend include (1) the advances in traffic theory, computer hardware technology, and programming tools; (2) the development of the general information infrastructure; and (3) the society's demand for more detailed analysis of the consequences of traffic measures and plans.

However, simulation is not always appropriate and it is generally not recommended for problems that can be solved mathematically. Lieberman and Rathi (2000) suggested that simulation modeling should be considered over the mathematical approach when:

1. Mathematical treatment of a problem is infeasible or inadequate due to its temporal or spatial scale, and/or the complexity of the traffic flow process.
2. The assumptions underlying a mathematical formulation (e.g., a linear program) or a heuristic procedure (e.g., those in the Highway Capacity Manual) cast some doubt on the accuracy or applicability of the results.
3. The mathematical formulation represents the dynamic traffic/control environment as a simpler quasi steady-state system.
4. There is a need to view vehicle animation displays to gain an understanding of how the system is behaving in order to explain why the resulting statistics were produced.
5. Congested conditions persist over a significant period of time.

#### **4.2. General Study Approach**

For this study, the simulation approach was selected for two main reasons:

1. It was believed that the complex interactions among the many variables of interest could not be modeled mathematically.

2. It was not feasible to collect field data that would provide a sufficient sample size for calibrating empirical models.

Accordingly, this study uses the simulation approach to generate data from different input scenarios. The simulated output was then used as a substitute for field data in an empirical modeling of statistical relationships between performance and design variables. The overall modeling methodology consists of the following five steps:

1. Select the appropriate measure of effectiveness (MOE) for measuring design effectiveness and the potential contributing factors that are expected to have an impact on the MOE.
2. Develop simulation models to simulate the effects of the contributing factors on the MOE.
3. Establish the empirical relationships between the MOE and the contributing factors.
4. Examine the reasonableness of the empirical models and results.
5. Develop a decision model for determining suitable preferential treatment based on the predicted MOE and occupancy rates.

### **4.3. Existing Traffic Simulators**

Over the past three decades, a variety of sophisticated simulation models capable of modeling detailed traffic operations have been developed. Chapter two revealed several candidate traffic simulation models for this study and they are briefly introduced as follows.

#### **4.3.1. NETSIM, FRESIM, AND CORSIM**

The NETwork SIMulation (NETSIM) model is a stochastic, microscopic simulation model developed by the U.S. DOT. The current version of NETSIM has been combined with another simulation model called FRESIM (FREeway SIMulation) to produce what is now known as the CORSIM (CORridor SIMulation) model—the most widely used simulation model in the United States. CORSIM represents traffic flow on a roadway system using commonly accepted driver and vehicle behavior models. It can simulate individual transit vehicle operations and control systems on integrated networks containing freeways and surface streets. CORSIM can analyze a wide range of traffic, geometric and control conditions and produces a relatively rich set of performance measures, including travel time, delay, speed, stops, queue time, stop time, queue length and fuel consumption. In addition, CORSIM includes the TRAFVU (TRAF Visualization Utility) program that can dynamically display the actual traffic operations of a simulation mode (ITT Systems and Sciences, 1998).

#### **4.3.2. VISSIM**

VISSIM (VISual SIMulation) is also a stochastic, microscopic simulation model. It was originally developed in the 1970s, with commercial distribution commencing in 1993. Although the model has been applied extensively in Europe, it is relatively new to the U.S. users. VISSIM can analyze a wide range of roadways and transit operations, including general-purpose traffic, buses, HOV, light rail, heavy rail, trucks, pedestrians, and bicyclists. VISSIM can also model ITS components and strategies such as variable message signs (VMS), ramp metering, incident diversion, adaptive signal control, transit signal priority, lane control signals, dynamic lane control signs, etc.

#### **4.3.3. PARAMICS**

PARAMICS (PARAllel MICroscopic Simulation) is a network-level microscopic simulator developed in the 1990s in England. It consists of four components: the Modoller as the core simulation model and Processor, Analyser, and Programmer as the optional components. PARAMICS models individual vehicles in detail for the duration of their entire trip, providing accurate traffic flow and travel time. PARAMICS is particularly suitable for modeling congested road networks and ITS infrastructures, including traffic impact of signals, ramp meters, loop detectors linked to variable speed signs, VMS signing strategies, in-vehicle network state display devices, and in-vehicle messages advising of network problems and re-routing suggestions.

#### **4.3.4. TRANSYT-7F**

TRANSYT-7F is a commonly used macroscopic simulation model for optimizing the timing plans for arterials and networks controlled by traffic signals (Wallace *et al.*, 1998). It simulates the movement of traffic platoons and uses an iterative algorithm to optimize the system cycle length and the splits/offsets at each intersection to minimize the Performance Index (PI), a weighted combination of delays and stops. TRANSYT-7F can be used to develop timing plans to favor buses by coding the bus movements as separate links, and specifying delay and stops weighting factors for the bus links so the signal optimizer would favor the transit vehicles than the rest of the traffic. Because TRANSYT-7F is a macroscopic model that simulates streams of traffic in mathematical abstractions, individual vehicle movements cannot be displayed graphically.

#### **4.3.5. Other Models**

A number of other simulation programs have been developed or used to model bus lane operations. Most of these programs are proprietary and have not gained widespread use in the transit community. One of the earlier programs developed specifically for bus lane modeling was the Bus Lane Algorithm Modeling Program, or BLAMP, for with-flow bus lanes for a single link (Robertson, 1985). The program simulates each second the operation of a bus lane for a given value of its length, setback, flow, cycle time and saturation flow. BLAMP was later improved by Lunes and Willumsen (1988) and resulted in another program called the Bus Lane Interactive Simulation System, or BLISS.

Zargari and Khan (1998) developed a macroscopic model called TRNSIM to investigate travel time, energy and emissions that correspond to bus volume levels on transitway (or busway). TRNSIM treats (a) all physical features of the transitway—in the station areas as well as between stations, (b) the stochastic nature of bus traffic and passenger activity, (c) service characteristics, (d) safety regimes between stations, (e) minimum safe headways in the station area, and (f) queuing of buses. The model accepts as inputs (a) simulation study time period, (b) road characteristics, (c) station characteristics, (d) vehicle characteristics, (e) boarding and alighting passenger information, and (f) traffic characteristics. The outputs of this model for the analysis period include: travel time, average speed, dwell time, total loading and unloading of passengers, vehicle-kilometer, passengers per bus, fuel consumption, and air polluting emissions (i.e., CO, HC, NO<sub>x</sub> and CO<sub>2</sub>).

#### **4.4. Selection of Simulator**

For the purpose of this study, it was first determined that a microscopic simulation model was to be used because of the need to model detailed design features and to visualize traffic animation for model verifications. The CORSIM simulation model was selected for the following reasons:

1. It provides most of the features needed for this project and was readily available to the research team.
2. It is the most widely used and accepted model in the U.S. and the researchers are familiar with the use of the model.
3. Model parameters in CORSIM have been calibrated to the U.S. conditions.
4. It uses the ASCII file format for both input and output files, facilitating the automated execution of multiple simulation runs (see the next section).
5. It allows traffic animation to be visualized.

A modified version of CORSIM Version 5.0 was used in this study. During the development process, a major problem related to improper bus re-entries (from bus bays) was encountered. The problem was fixed by the developer and a corrected version was used.

#### **4.5. Automated Procedure for Multiple Simulation Runs**

In order to determine the appropriate bus lane preferential treatments under various design and traffic conditions, different simulation scenarios must be created by systematically varying the related variables. In addition, because of the stochastic nature of simulation models, each simulation run may produce slightly different results. Thus, to get a reasonably accurate estimate, a number of replications with different random number seeds were performed. Most simulation studies have used between five to ten replications. Due to number of variables involved and the limitation of personal computer power, it was determined that only a minimum number required replications (i.e., five) were to be performed for each scenario. It was also

determined that half an hour of simulation time was sufficiently long to capture the impact of changes in each variable.

Due to the high number of simulation runs, a program was developed to automate the process of creating simulation models and performing multiple simulation runs for various scenarios, and extracting the appropriate simulation output from each run. Accordingly, the program performs multiple simulation runs continuously for different combinations of bus volume, non-bus volume, bus stop spacing, etc., and obtains from each run the simulated performance value. The automated procedure consists of the following steps:

1. Read the input file for the base network.
2. Modify the base input file for a specific scenario.
3. Save as a new input file.
4. Run CORSIM for the specific new input file.
5. Read the CORSIM output file and extract the MOE values for that particular scenario.
6. Repeat steps 2 through 6 for five different random number seeds.
7. Average the MOEs from each of the five replications.
8. Save all MOEs and modified input values to a file.
9. Repeat steps 2-8 until all scenarios are simulated.

This automated procedure allows the complete process to be repeated. This is important because several model fine-tunings were needed during the model development process. Note that in step 4, a shell program called RunCOR developed by Dr. John Leonard of the Georgia Institute of Technology was used to execute CORSIM in the batch mode (i.e., command-line executable). RunCOR allowed CORSIM to be executed without the original TSIS shell program. Although TSIS comes with the “scripting” feature that allows multiple CORSIM runs to be executed continuously, steps 3-8 cannot be included in the script.

## **CHAPTER 5**

### **FREEWAY MODELS**

This chapter presents the process of developing the decision models for high-occupancy lanes on freeways using the simulation approach. It is organized based on the five general methodology steps described in Section 4.2, i.e., variable selection, simulation model development, regression model development, model evaluation, decision model development, and application example.

#### **5.1. Introduction**

A freeway is defined as a divided highway that provides two or more lanes for the uninterrupted flow of traffic in each direction. Operating conditions on a freeway is primarily a result of interactions among vehicles and drivers in the traffic stream and the geometric characteristics. The most common type of freeway preferential lanes involves designating the leftmost lane as a special lane for use by buses. Since bus volumes on freeways are generally not sufficient to warrant the use of an exclusive lane, other high-occupancy vehicles, typically including carpools and vanpools, are allowed to use the preferential lane, or the HOV lane. The decision models to be developed involves only this most general case, i.e., whether the leftmost lane should be designated as a HOV lane, given the expected volumes of different types of vehicles and different geometric conditions, including the number of lanes and free-flow speed (which is a function of geometric conditions).

#### **5.2. Variables Selection**

As indicated in section 4.2, the first step in the model development process is to identify variables to be included in the models. This includes both dependent and independent variables. The dependent variable is the measure of effectiveness (MOE) that is used to assess the performance of each design alternative (i.e., preferential treatment) under different traffic and geometric conditions.

In this study, it was determined that the decision would consider the average person travel time of all road users as the criterion to assess the merit of separating buses from the general traffic. Essentially, the decision model seeks to identify the best design alternative that minimizes the average person travel time of all road users. Accordingly, the average vehicle speed produced by CORSIM was used as the MOE. Given a known travel distance and the average vehicle occupancy rate of each vehicle type, the average travel time per person per mile can be calculated.

The independent variables, on the other hand, include all the variables those that are expected to affect the average speeds and, therefore, the average person travel time. Using the basic-section freeway model in the Highway Capacity Manual (2000) as a reference, variables expected to affect the average person travel time on freeways include passenger car volume, bus volume, truck volume, carpool volume, free-flow speed, and number of freeway lanes.

### 5.3. Simulation Model Development

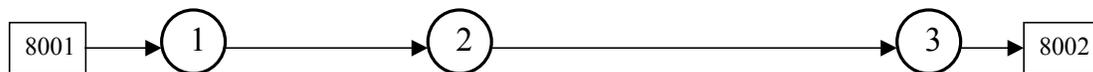
#### 5.3.1. CORSIM Modeling of Freeway HOV Operations

CORSIM first incorporated the capability to model HOV lane(s) in Version 5.0, i.e., the latest version. HOV lane operations are modeled in CORSIM mainly through Record Type 33. CORSIM can model one or more HOV lane of the same type for multiple time periods. The HOV lanes can either be on the left-hand or right-hand side, and can be defined for buses only, carpools only, or both. To model exclusive HOV lane(s) that are barrier or double-line separated, Record Type 19 must be used.

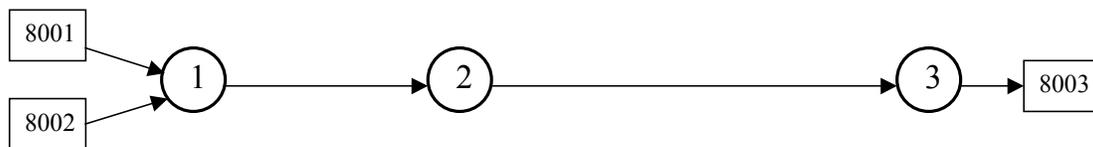
#### 5.3.2. Coding Base Networks

Coding the roadway networks is a major effort in developing traffic simulation models. In this case, the base networks for use in the automated procedure are to be coded. Networks are represented in CORSIM by links and nodes. A link represents a section of roadway and a node is generally used to connect two roadway sections. Figure 5-1 (a) shows the link-node diagram for three-lane and four-lane facilities. Node 8001 is the entry node that is used to specify the entry volume. For five-lane facilities, because the value for entry volume is limited to four digits, the highest link volume that can be specified is 9999 vph. This value cannot meet the capacity of a five-lane facility. To get around this limitation, a second entry link was added. As shown in Figure 5-1 (b), entry link (8001,1) is assigned three lanes and entry link (8002,1) is assigned two lanes. Together, these two links allow the total entry volume to exceed 9999 vph.

For each base network two input files were developed, one with the preferential treatment and one without. Since traffic on the section close to the entry link is generally not stable, especially under heavy entry volume, link (1,2) is included so that the unstable traffic can be excluded and does not affect the final output. The TRAFVU animation was observed to determine the required length of this section. The final outputs were extracted from link (2,3), which has a length of one mile. Figure 5-2 shows a TRAFVU snapshot for two preferential treatments: one with a HOV-lane (top) and one without (bottom). Note that this figure was created only for illustration purposes, that in the actual simulation, the two treatments are simulated separately.

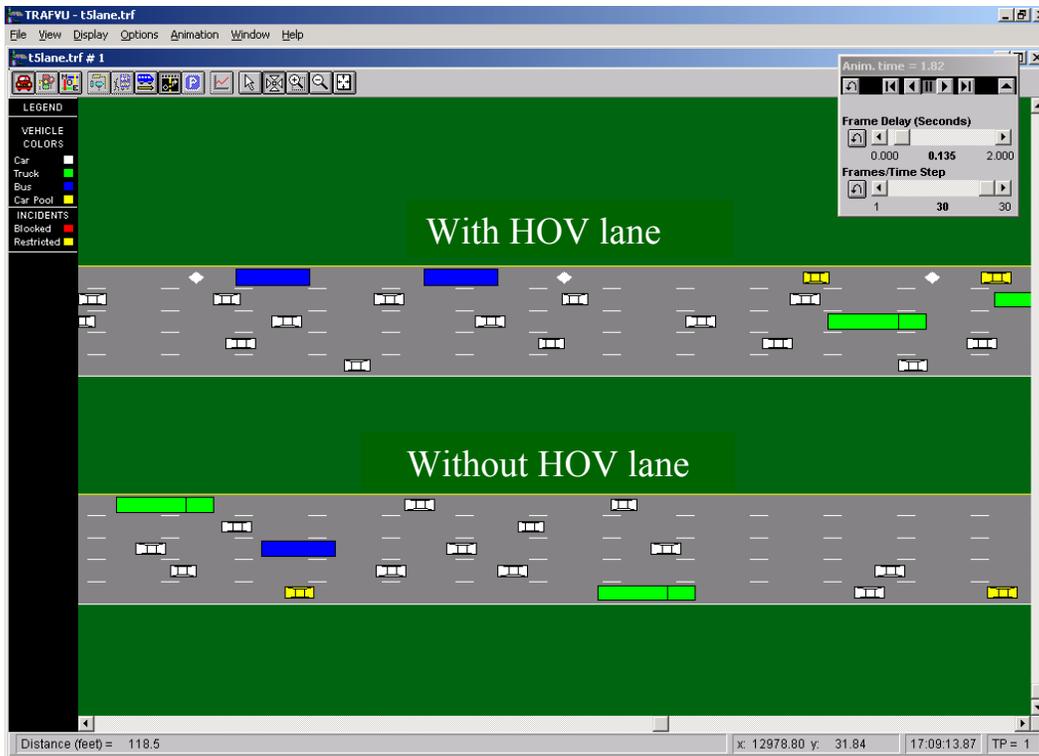


(a) For 3- and 4-Lane Cases



(b) For 5-Lane Case

Figure 5-1. Link-Node Diagrams for Freeway Base Networks.



**Figure 5-2. TRAFVU Animation of Freeway Network.**

### 5.3.3. Simulation Models

A total of six base simulation models were created for 3-, 4-, and 5-lane freeway (per direction) with and without a HOV lane. Using the automated procedure described in Section 4.5, each of these base models was modified systematically to create different simulation scenarios based on different input values for each of the independent variables considered. The values included for each independent variable are listed in Table 5-1. The different inputs resulted in a combination of 9,072 simulation scenarios, or 54,432 scenarios for all six base networks. As mentioned in Section 4.5, because of the stochastic nature of simulation, each scenario must be repeated for a number of random numbers to obtain a more representative output. With five random numbers, the total simulation runs reaches 272,160. Because some of the input combinations result in over-capacity (for example, 6,000 passenger cars and 900 trucks for a three-lane facility), filters were included in the program for the automated procedure to exclude these simulation runs from the output.

**Table 5-1. Independent Variables and Associated Input Values/Options.**

Independent Variable	Input Values
Total volume excluding buses (three lanes)	750, 1500, 3000, 4500, 5400, 6000, 6300, 6600, 6900
No. of passenger cars	Total volume - truck volume - carpool volume
No. of trucks (% of total volume)	0%, 3%, 6%, 9%, 12%, 15%
No. of carpools (% of total volume)	0%, 3%, 6%, 9%, 12%, 15%
No. of buses per hour (headway in second)	40 (60), 90 (40), 180 (20), 300 (12), 450 (8), 600 (6), 720 (5)
Free flow speed	50, 55, 65, 70

## 5.4. Regression Models

The SPSS statistical analysis package was used to develop the regression equations based on the simulated data. Individual variables were first plotted against average speeds to help identify suitable functional forms. Unlike for linear regression, SPSS' non-linear regression procedure does not result in unique model coefficients. The procedure is based on an iterative process that requires a user-specified starting point. Different starting points may result in different model coefficients. Using the coefficient of determination (i.e.,  $R^2$  value) as the principal guide, different starting points were attempted for each model. The following three subsections present the models for estimating the average vehicle speeds of the single HOV lane, the mixed lanes adjacent to the HOV lane, and the all-mixed traffic lanes (i.e., without a preferential lane).

### 5.4.1. Average Speeds of HOV Lane

The regression models for the average speed of the HOV lane,  $S_1$ , for different number of lanes were found to be:

$$S_1 = \begin{cases} FFS \times e^{-\left(\frac{0.812C}{10000}\right)^{0.842}} & \text{for 3-lane facility} & R^2 = 0.824 \\ FFS \times e^{-\left(\frac{0.604C}{10000}\right)^{0.799}} & \text{for 4-lane facility} & R^2 = 0.872 \\ FFS \times e^{-\left(\frac{0.572C}{10000}\right)^{0.878}} & \text{for 5-lane facility} & R^2 = 0.822 \end{cases}$$

where FFS is free-flow speed and C is number of carpools. The exponential function meets the boundary conditions well in that when the total volume is near zero, vehicles will travel near the free-flow speed. The speed will decrease slowly as the total volume increases and continue to decrease in a decreasing rate. It is interesting to note that the number of buses did not show up as a significant factor that affects the average HOV lane speed. This is because only a practical maximum number of buses (720 vph) was used in the simulation. This maximum was not high enough to cause a significant speed reduction in the HOV lane. However, as the model suggested, when carpools are allowed to use the HOV lane, the average HOV lane speed will be reduced.

### 5.4.2. Average Speeds of Mixed Lanes Adjacent to HOV Lane

The regression models for the average speed of the mixed lanes adjacent to the HOV lane,  $S_2$ , for different number of lanes were found to be:

$$S_2 = \begin{cases} FFS \times e^{-\left(\frac{0.014B+0.075C+1.859T+0.818PC}{10000}\right)^{1.999}} & \text{for 3-lane facility} & R^2 = 0.923 \\ FFS \times e^{-\left(\frac{0.051B+0.0002C+1.758T+0.620PC}{10000}\right)^{2.417}} & \text{for 4-lane facility} & R^2 = 0.892 \\ FFS \times e^{-\left(\frac{0.025B+0.00013C+0.544T+0.283PC}{10000}\right)^{1.641}} & \text{for 5-lane facility} & R^2 = 0.982 \end{cases}$$

where B, C, T and PC are number of buses, carpools, trucks, and passenger cars, respectively. The coefficients suggest that a truck has a higher impact than a passenger car on the average travel speed. The relatively small coefficients for buses and carpools suggest that, when the HOV lane is over-capacity, some buses or carpools may use the mixed lanes; however, their impact on the average speed is minor compared to the other vehicles.

### 5.4.3. Average Speeds of All-Mixed Traffic Lanes

The regression models for the average speed of the all-mixed traffic lanes (i.e., no HOV lane),  $S_3$ , for different number of lanes were found to be:

$$S_3 = \begin{cases} FFS \times e^{-\left(\frac{0.925B+1.183T+0.698C+0.689PC}{10000}\right)^{2.478}} & \text{for 3-lane facility} & R^2 = 0.893 \\ FFS \times e^{-\left(\frac{0.933B+1.270T+0.572C+0.646PC}{10000}\right)^{3.362}} & \text{for 4-lane facility} & R^2 = 0.859 \\ FFS \times e^{-\left(\frac{0.735B+1.067T+0.433C+0.444PC}{10000}\right)^{2.906}} & \text{for 5-lane facility} & R^2 = 0.883 \end{cases}$$

where all the variables are as defined previously. The coefficients suggest that one bus has the impact of about 1.5 passenger cars on the average speed. For trucks, the number is increased to about two. These numbers are consistent with those given in the Highway Capacity Manual (HCM) for level terrain. As expected, a carpool has the same impact as a passenger car. The slight difference in their coefficients is due to the regression process and the randomness of simulation.

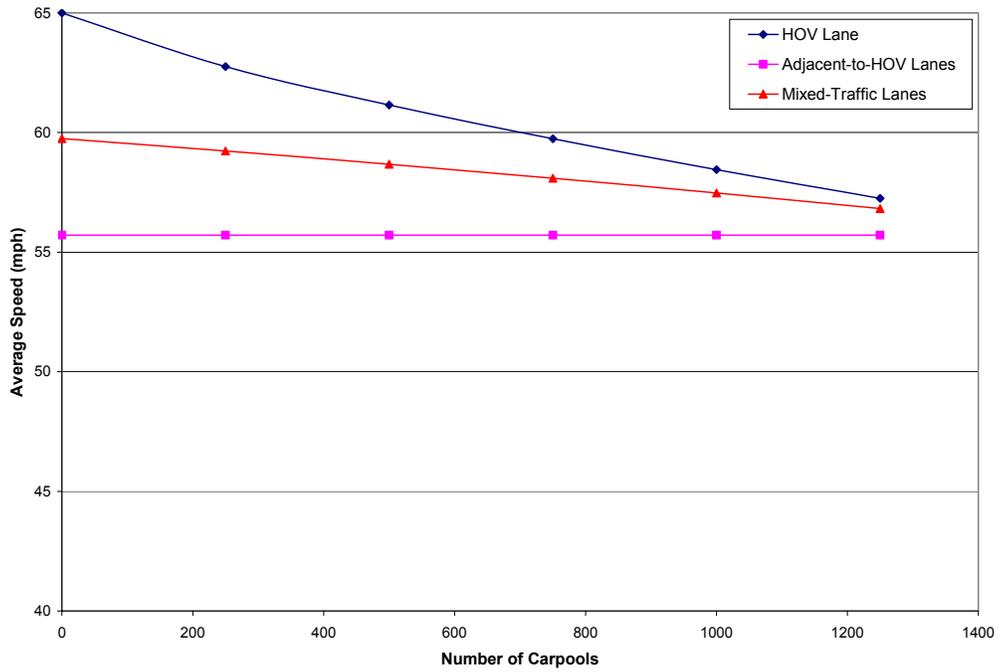
### 5.4.4. Comparisons of Average Speeds

Figures 5-3 to 5-6 plots the regression models developed for the four-lane case as a function of number of carpools, buses, trucks, and passenger cars, respectively. The free-flow speed is assumed to be 65 mph. For each plot, the variables that are not plotted are each assumed to be a constant value, which are indicated as part of the figure title.

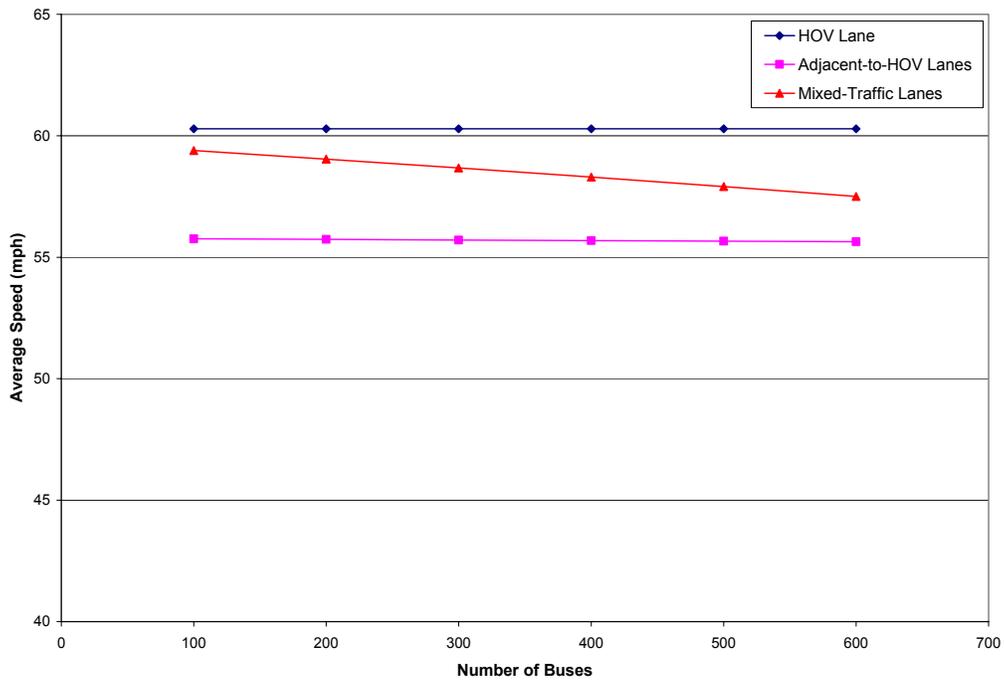
Figure 5-3 shows that an increase in the number of carpools reduces the HOV lane speed. However, the increase in carpools has less impact on the lanes adjacent to the HOV lane. The reduction in speed in this case may be attributed to the increased weaving of carpool vehicles in and out of HOV lanes. As expected, the number of carpools has no impact on the average speed of the all-mixed lanes (i.e., no HOV lane). Figure 5-4 shows that an increase in the number of buses reduces the average speed of the all-mixed lanes, but not the mixed lanes adjacent to the HOV lane, since buses only use the HOV lane.

In Figure 5-5, it can be seen that an increase in the number of trucks will reduce both the mixed lanes adjacent to the HOV lane and all-mixed traffic lanes. However, the impact of trucks is more significant in the presence of HOV facility, since fewer lanes are available for use by trucks. The figure also shows that trucks do not affect the HOV lane since they do not travel on

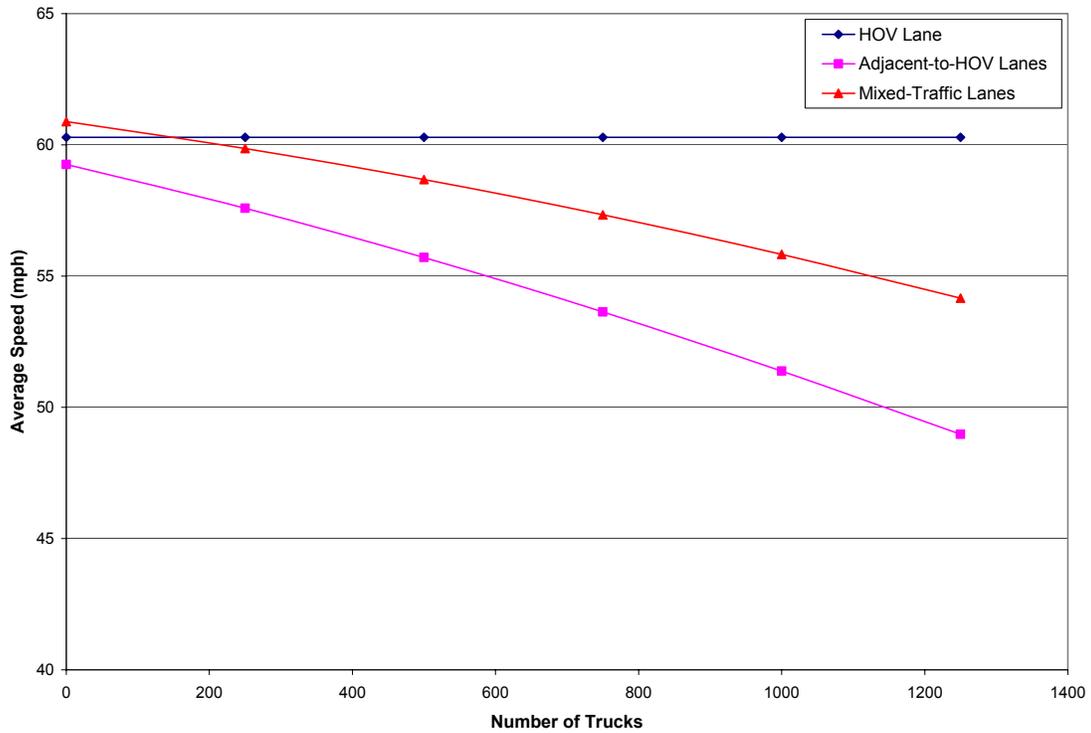
it. Figure 5-6 shows that an increase in the number of passenger cars reduces the average speeds of both the all mixed lanes and mixed-traffic lanes adjacent to HOV lane, but not the HOV lane.



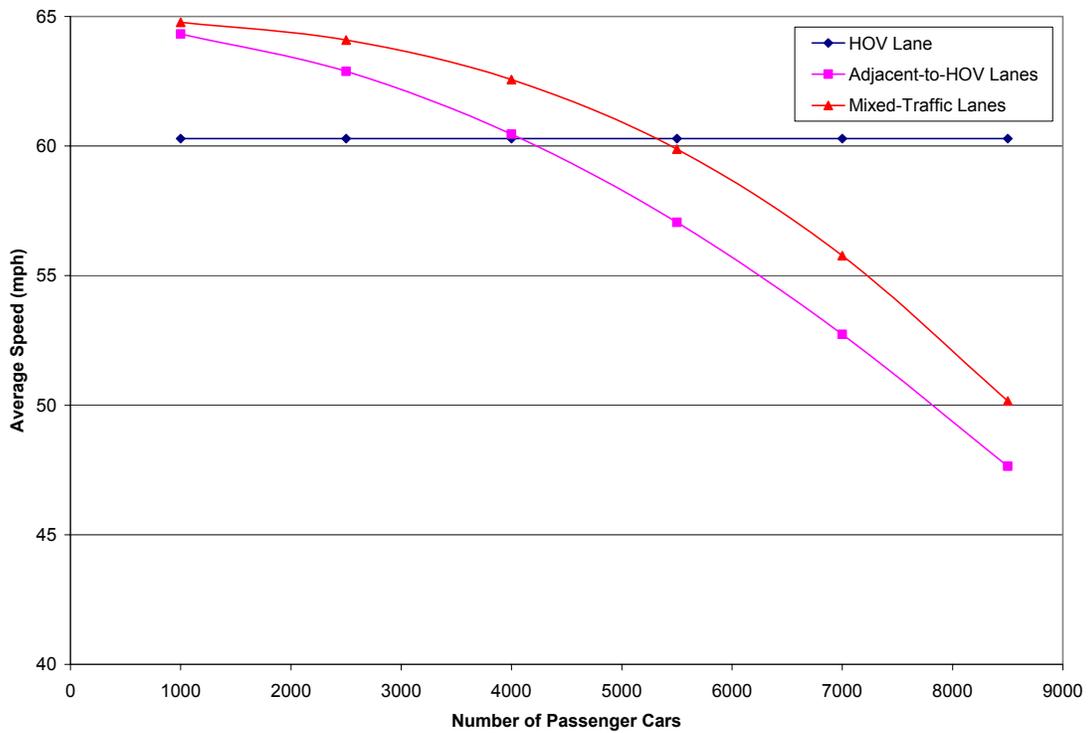
**Figure 5-3. Average Speeds vs. Number of Carpools**  
(Four -Lane; Hourly Volumes: 6000 Passenger Cars, 500 Trucks, and 300 Buses).



**Figure 5-4. Average Speeds vs. Number of Buses**  
(Four -Lane; Hourly Volumes: 6000 Passenger Cars, 500 Trucks, and 500 Carpools).



**Figure 5-5. Average Speeds vs. Number of Trucks (Four -Lane; Hourly Volumes: 6000 Passenger Cars, 500 Carpools, and 300 Buses).**



**Figure 5-6. Average Speeds vs. Number of Passenger Cars (Four -Lane; Hourly Volumes: 500 Trucks, 500 Carpools, and 300 Buses).**

## 5.5. Model Evaluation

Ideally, calibrated regression models should be evaluated by field data. However, in many cases, available study sites are either too limited and/or data cannot be easily collected. Even if some data are collected, they are likely to be insufficient to draw conclusions on the validity of the models. In this study, models are evaluated by comparing their output with those reported in the literature.

Figure 5-7 shows a comparison of the modeled average speeds for mixed-traffic lanes ( $S_3$ ) with those predicted by the HCM for basic freeway section and the Bureau of Public Roads (BPR) volume-delay function. The input conditions are 4-lane, FFS = 65 mph, and all passenger cars. The figure shows that the speeds predicted by the model are very much in agreement with those predicted by the BPR function. Unlike the 1985 HCM, the 2000 HCM uses a constant speed for v/c ratios below a certain threshold (up to about v/c = 0.7). While it is well known that freeway speeds do not drop significantly under free-flow condition, it is only a matter of convenience to assume that the speeds are a constant. In fact, freeway speeds do drop continuously with increasing traffic. This is reflected in the CORSIM simulation model, the BPR function, the 1985 HCM, as well as the data collected from the field (see Figure 5-8).

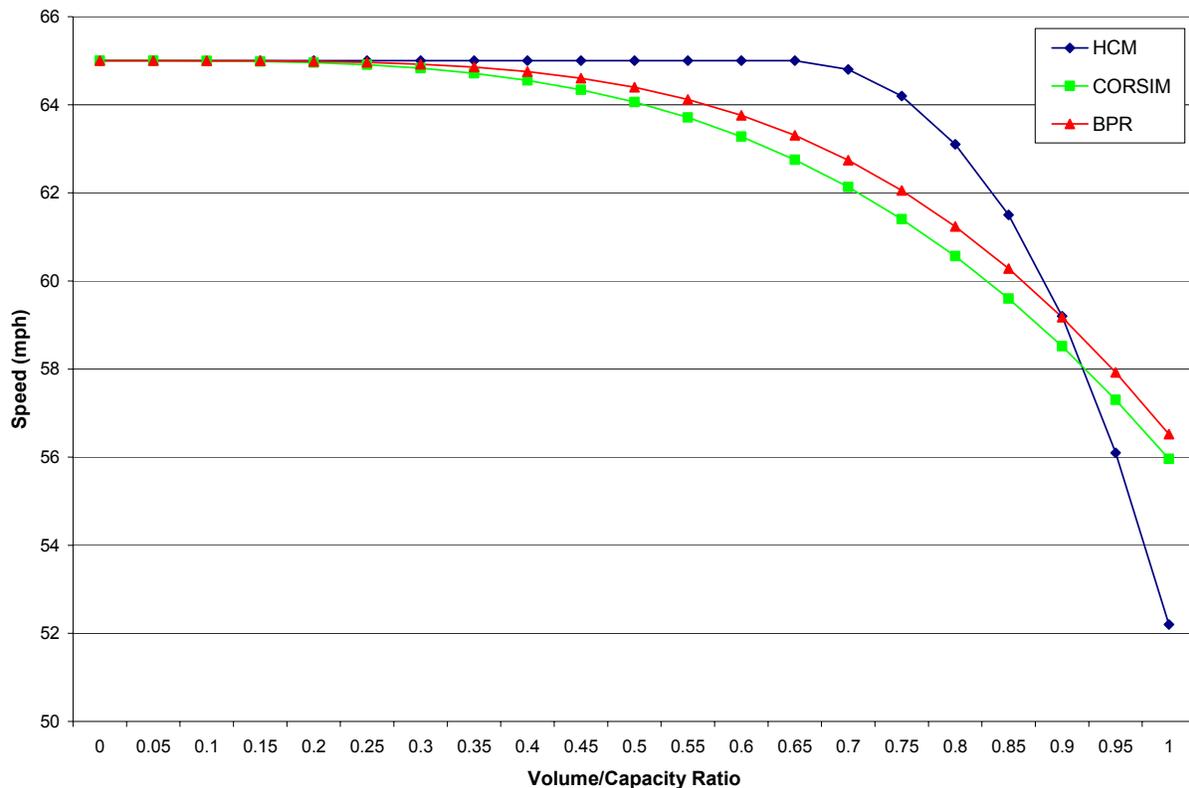
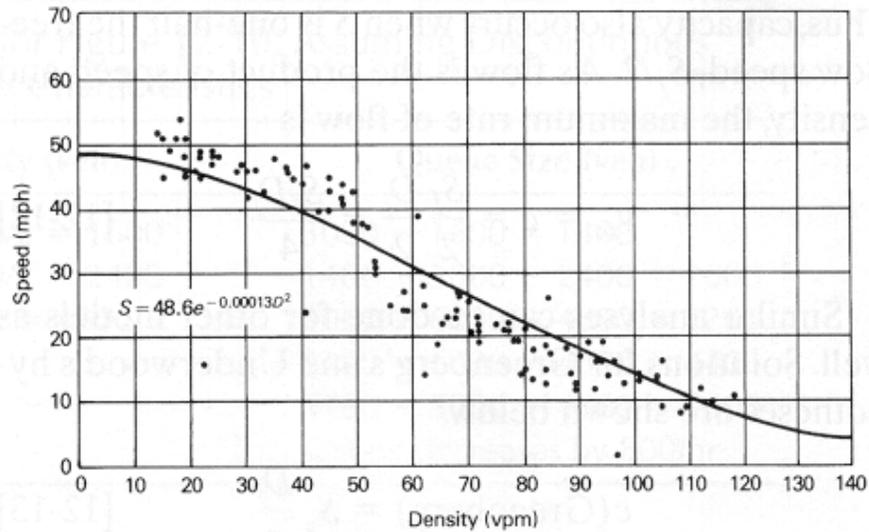


Figure 5-7. Comparison of Speeds for Five-Lane Facility.



**Figure 5-8. Decreasing Speed with Increasing Density (Volume).**

### **5.6. Decision Model**

The objective of the decision models is to minimize the travel time of all road users of all modes by comparing the person travel times associated with the different design alternatives. The basic decision rule is that a separated lane, either bus-only or HOV, is justified when the resulting person travel time is less than that of a non-separated facility.

The person travel time (PTT) in seconds per mile for the preferential facility can be computed by using the average speeds of the HOV lane ( $S_1$ ) and the non-HOV lanes ( $S_2$ ) that were estimated from the regression models, as follows:

$$PTT_{separated} = \frac{3600 \times \left( \frac{B \times BO + C \times CO}{S_1} + \frac{PC \times PCO + T \times TO}{S_2} \right)}{B \times BO + C \times CO + PC \times PCO + T \times TO}$$

where BO, CO, PCO, and TO are the occupancy rate for buses, carpools, passenger cars, and trucks, respectively, and other variables are as defined previously. Because the occupancy rate for carpools is part of the equation, the decision model may be used to set policy on the minimum carpool occupancy rate.

The person travel time in seconds per mile per person for the non-separated facility is simply computed as follows:

$$PTT_{mixed} = \frac{3600}{S_3}$$

where  $S_3$  is the average speed of all lanes. This equation assumes that all vehicles travel at about the same speed in the mixed-lane case. This assumption is needed because CORSIM does not

allow differential speeds to be specified for different vehicle types. In reality, when there are no preferential treatments, trucks and buses generally travel at slightly lower speeds than passenger cars, with the speed differential diminishing at higher degrees of saturation, as passenger-car speeds begin to be constrained by increasing traffic friction.

### 5.7. Application Example

The application of the decision model is straightforward. For example, given the following information:

- ✓ Five-lane freeway (per direction)
- ✓ Free flow speed = 65 mph
- ✓ Number of passenger cars per hour = 9000
- ✓ Number of carpools per hour = 500
- ✓ Number of trucks per hour = 1500
- ✓ Number of buses per hour = 200
- ✓ Occupancy rate for passenger cars = 1.3
- ✓ Occupancy rate for carpools = 3.5
- ✓ Occupancy rate for trucks = 1.2
- ✓ Occupancy rate for buses = 50

*Step1. Compute average HOV lane speed ( $S_1$ ) and average mixed adjacent lane speed ( $S_2$ ):*

$$S_1 = 65 \times e^{-\left(\frac{0.572 \times 500}{10000}\right)^{0.878}} = 62 \text{ mph}$$

$$S_2 = 65 \times e^{-\left(\frac{0.025 \times 200 + 0.00013 \times 500 + 0.544 \times 1500 + 0.283 \times 9000}{10000}\right)^{1.641}} = 55 \text{ mph}$$

*Step2. Compute average all-mixed-traffic lane speed ( $S_3$ ):*

$$S_3 = 65 \times e^{-\left(\frac{0.735 \times 200 + 1.067 \times 1500 + 0.433 \times 500 + 0.444 \times 9000}{10000}\right)^{2.906}} = 52 \text{ mph}$$

*Step 3. Compute average person travel time for “with bus lane” ( $PPT_{separated}$ ) and “without bus lane” ( $PPT_{mixed}$ ) design alternatives:*

$$PPT_{separated} = \frac{3600 \times \left( \frac{200 \times 50}{62} + \frac{9000 \times 1.3 + 1500 \times 1.2}{55} \right)}{200 \times 50 + 500 \times 3.5 + 9000 \times 1.3 + 1500 \times 1.2} = 62 \text{ seconds / person}$$

$$PPT_{mixed} = \frac{3600}{52} = 70 \text{ seconds / person}$$

Step 4. Decision: Since  $PPT_{mixed} > PPT_{separated}$ , a bus lane is justified.

## **CHAPTER 6**

### **ARTERIAL MODELS**

This chapter presents the process of developing the decision models for bus lanes on arterial streets using the simulation approach. Like for the previous chapter on freeway models, it is organized based on the five general steps described in Section 4.2, i.e., variable selection, simulation model development, regression model development, model evaluation, decision model development, and application example.

#### **6.1. Introduction**

Arterials are signalized streets that are designed primarily to serve through traffic. Accordingly, the HCM (2000) bases its assessment of arterial level of service on the travel speed of through vehicles. The number of lanes of an arterial typically ranges from 2 to 4 per direction. Unlike for freeways, which are mainly affected by traffic characteristics, the performance of an arterial street is mainly affected by signal density, intersection delay, and progression. Buses on arterial generally suffer additional delay since progression is usually set for vehicles rather than buses. This provides the incentive for installing bus-only lanes and bus signal priority on arterials in order to reduce the total person travel time and improve bus ridership (or reduced single-occupancy vehicles to ease congestion). Arterial bus lane(s) is generally designed for one lane, although in rare occasions two lanes may be used. The most common type of bus lanes is one that uses the curb lane. This chapter documents the process of developing regression and decision models for determining appropriate bus lane design.

#### **6.2. Variables Selection**

As in the case of freeway models, average speed is used as the MOE for determining the quality of traffic flow on arterial streets. The use of travel speed is consistent with the HCM, which uses travel speed as a major measure of arterial level of service. As mentioned, travel speed allows the travel time to be calculated, given a specific distance. The importance of bus travel times and speeds are well described in TCRP Report 26 (St Jacques and Levinson, 1997), as follows:

“Bus travel times and speeds are important to the transit passenger, transit operator, traffic engineer and transportation planner. The transit passenger wants a quick and dependable trip. The transit operator (or service planner) measures and analyzes bus speeds to set, monitor, and refine schedules; estimate vehicle requirements; and plan new routes and services. The traffic engineer uses bus speeds to assess the impacts of traffic control and bus priority treatments. The transportation planner uses speeds to quantify congestion and provide input into the transit demand and modeling process”

The independent variables include both qualitative and quantitative variables that affect bus and passenger car travel speeds. Table 6-1 provides a list of variables selected for modeling and analysis. The selection of these variables is obviously restricted to only those that can be modeled by CORSIM. Note that for simplicity, the signal offset, defined as the difference in seconds between the green initiation time of the upstream intersection and that of the

downstream intersection, is treated as a qualitative variable, i.e., whether an offset is provided or not. When an offset is not provided (i.e., offset = 0), the signals of both upstream and downstream intersections for the progressive movement will turn green at the same time. When an offset is provided, the number of seconds is calculated as the distance divided by the vehicle free-flow speed.

**Table 6-1. Independent Variables for Arterial Models.**

<b>Independent Variables</b>	<b>Variable Type</b>
Bus lane	Qualitative
Bus bay	Qualitative
Bus stop location	Qualitative
Signal offset (sec)	Qualitative
Number of passenger cars per hour per lane (pcphpl)	Quantitative
Right turn percentage	Quantitative
Number of buses per hour (headway in second)	Quantitative
Mean dwell time (sec)	Quantitative
Number of bus berths	Quantitative
Green ratio	Quantitative
Cycle length (sec)	Quantitative
Stop spacing (ft)	Quantitative
Number of lanes	Quantitative

### **6.3. Simulation Model Development**

#### **6.3.1. CORSIM Modeling of Arterial Bus Operations**

Unlike for the freeway HOV operations, the modeling of arterial bus operations is a relatively old feature in CORSIM. The Record Types used in the CORSIM input files for bus operations included those numbered from 185 to 189. CORSIM allows up to 25 bus routes and 99 bus stations within a network. For each route, a user specifies the mean headway. For each station, a user may specify the route number, distance from stop line, stop capacity (i.e., number of bus berths, mean dwell time, type of station—up to six types, each representing different dwell times), and whether there is a bus bay. If there is not a bus bay, other vehicles following the bus will wait behind the bus or switch lanes if there are gaps in the adjacent lane. If a station is at capacity, an arriving bus will wait for an available space before entering the station. In a station with a bus bay, a bus coming out of the bay will wait for a gap before merging into the travel lane. If the bus bay is located within 20 feet of the downstream stop line, the program will treat it as a right-turn pocket when no bus is being served at the station (ITT Systems and Sciences, 1998; Wong, 1990).

#### **6.3.2. Coding Base Networks**

Figure 6-1 shows the link-node diagram for the base network for arterial streets. Again, the 8000 series nodes are the entry nodes that are used to specify the entry volumes. Links (7,2), (2,5), (8,3), and (3,6) are the side streets specifically created to generate turning-movement traffic. Node 2 and node 3 are signalized intersections. Bus stops are placed in arterial represented by

links (1,2), (2,3) and (3,4), and located besides the curb lane. The free-flow speed is assumed 40 mph throughout the network. The final outputs were extracted from link (2,3). Different base networks were created for arterial with and without a bus lane, bus stop locations, and intersection spacing. The number of stops is one per block and a stop can be located at near-side, mid-block, or far-side. The signal timings are kept the same at both intersections and are two-phase, fixed-time. Figure 6-2 shows a TRAFVU snapshot for an arterial street with an exclusive bus lane and bus bay.

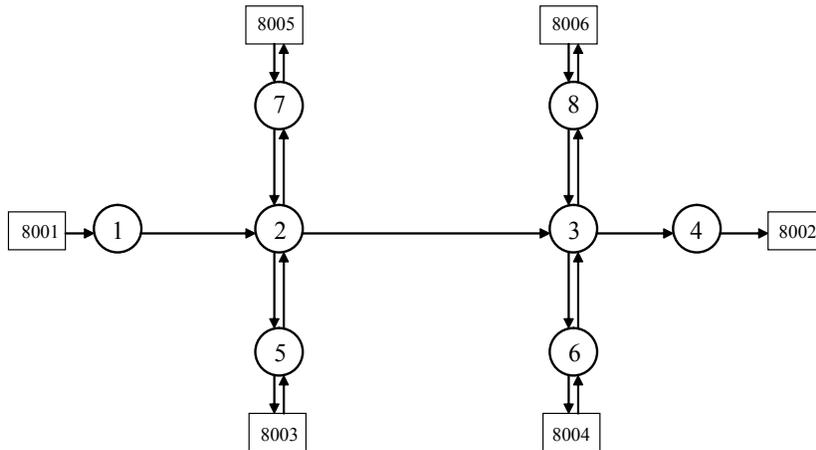


Figure 6-1. Link-Node Diagrams for Arterial Base Networks.

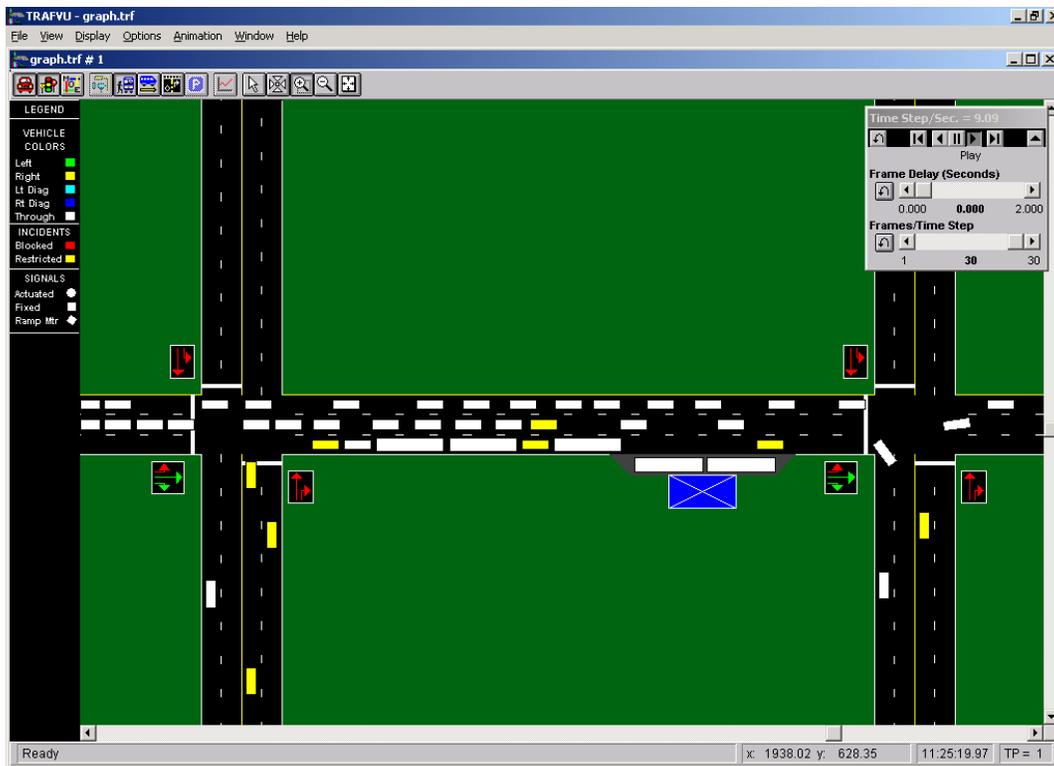


Figure 6-2. TRAFVU Animation of Arterial Network.

### 6.3.3. Simulation Models

Once the CORSIM base files were developed, the values for the independent variables were systematically changed using the automated procedure described in Section 4.5 to obtain the simulated results from different traffic, geometric, and control scenarios. The values used for each independent variable are listed in Table 6-2. The ranges of values selected reflect those that are typical of downtown arterials, where bus lanes are likely to be justified. The different inputs resulted in a combination of 1,399,680 simulation scenarios. As for the freeway models, each scenario was replicated five times based on five different random number seeds, resulting in a total of 6,998,400 simulation runs. Again, filters were included in the automated procedure to exclude from the output simulation runs that involved over-capacity.

**Table 6-2. Independent Variables and Associated Input Values/Options.**

Independent Variable	Input Values
Bus lane	With/without bus lane
Bus bay	With/without bus bay
Bus stop location	Near-side, mid-block, far-side
Signal offset (sec)	With/without offset
Number of passenger cars per hour per lane (pcphpl)	900, 2200, 3000, 3800, 4500
Right turn percentage	0%, 10%, 20%
Number of buses per hour (headway in second)	40 (90), 120 (30), 200 (18), 300 (12)
Mean dwell time (sec)	15, 30, 45, 60
Number of bus berths	1, 2, 3
Green ratio	0.5, 0.65, 0.80
Cycle length (sec)	60, 90, 120
Stop spacing (ft)	400, 700, 1000
Number of lanes	2, 3, 4

### 6.4. Regression Models

SPSS was again used to model the statistical relationships between average speeds and various independent variables. Individual variables were first plotted against average speeds to help identify suitable functional forms. The plots show that, in general, the variables for traffic volumes exhibits a non-linear trend while the non-volume variables (e.g., green ratio) show a linear trend. Various non-linear models were fitted before a final form was selected. Four basic models for a combination of bus and non-bus speeds and with and without a bus lane were identified. The basic model for bus speed (BS) with a bus lane is as below:

$$BS = \beta_0 + \beta_4 e^{\left( \frac{\beta_5 RV + \beta_6 Bus \times Dwell^{\beta_7}}{10000 + 10000 \times BB} \right)^{\beta_8}} + \beta_9 Dwell + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes$$

where

- RV = number of right-turn vehicles per hour,
- Bus = number of buses per hour,
- Dwell = mean dwell time in seconds,

BB = number of bus berths,  
 GC = green ratio,  
 Cycle = cycle length,  
 Lanes = number of lanes, and  
 $\beta_i$  = model coefficients.

Note that the coefficient numbering is discontinuous in this equation in order for the coefficients to be consistent with those of the following model for non-bus speed (NBS) with bus lane:

$$NBS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000}\right)^{\beta_3}} + \beta_4 e^{-\left(\frac{\beta_3 RV + \beta_6 Bus \times Dwell^{\beta_7}}{10000 + 10000 \times BB}\right)^{\beta_8}} + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes$$

where TV is number of through non-bus vehicles and all the other variables are as defined previously. The model for bus speed in mixed traffic (without bus lane) is given below:

$$BS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV + \beta_3 RV + \beta_4 Bus \times Dwell^{\beta_5}}{10000 + 10000 + 10000 \times BB}\right)^{\beta_6}} + \beta_7 Dwell + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes$$

where all the variables are as defined previously. The model for non-bus speed (NBS) when there is not a bus lane is given below:

$$NBS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV + \beta_3 RV + \beta_4 Bus \times Dwell^{\beta_5}}{10000 + 10000 + 10000 \times BB}\right)^{\beta_6}} + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes$$

where all the variables are as defined previously.

Tables 6-3 and 6-4 give the final model coefficients for arterial streets with and without a bus lane, respectively. For ease of reference, the corresponding formulas are given below each table again. Each table consists of a total of 24 speed models, including 12 for non-bus speeds and 12 for bus speeds. The coefficients for bus and non-bus speed models are given separately for each combination of the qualitative variables given in Table 6-1. For the models associated with arterials with a bus lane, the coefficients of determination ( $R^2$ ) of a majority of the models exceeds 0.7, with over one third of them exceeding 0.8. The models associated with the mixed-traffic alternative (i.e., without a bus lane) have lower  $R^2$  values, with only half of them exceeding 0.6. This difference reflects the higher speed differentials (i.e., higher variance) that exist between buses and non-buses that travel in mixed-traffic facilities.

## **6.5. Sample Plots and Discussion**

This section provides some sample plots from the speed models developed. Because of the many variables involved, there exists a large number of different ways of plotting the relationships. Only a select number of plots are included. It should be obvious that these plots, shown in Figures 6-3 through 6-20, should be treated as examples, rather than the only available relationships from the regression models. It is noted that, in each of the plots, the variables that are not mentioned are assumed to resume the values or options listed in Table 6-5

**Table 6-3. Model Coefficients for Arterial Streets with a Preferential Bus Lane.**

				Coefficients of Variables														
Bay	Stop	Offset	Speed	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	$\beta_5$	$\beta_6$	$\beta_7$	$\beta_8$	$\beta_9$	$\beta_{10}$	$\beta_{11}$	$\beta_{12}$	$\beta_{13}$	$R^2$
Y	Near	Y	Non-Bus	-55.34	33.96	1.39	1.13	18.89	14.61	6.72	0.76	3.09	-	41.26	-0.011	-0.50	3.60	0.63
			Bus	-5.00	-	-	-	14.88	0.71	19.34	0.49	3.62	-0.12	10.93	-0.011	-0.39	-0.08	0.78
		N	Non-Bus	-43.58	14.85	5.94	1.46	19.25	9.46	5.69	0.76	2.79	-	47.19	0.007	-0.31	2.17	0.68
			Bus	-5.29	-	-	-	14.82	0.68	17.38	0.53	3.81	-0.10	11.30	-0.016	-0.39	-0.09	0.78
	Mid	Y	Non-Bus	-17.53	5.11	11.30	37.44	14.17	17.69	2.35	0.95	1.83	-	36.83	-0.001	-0.59	3.02	0.72
			Bus	5.41	-	-	-	6.45	0.42	12.96	0.64	7.73	-0.10	4.57	-0.005	-0.41	-0.04	0.87
		N	Non-Bus	-28.92	8.17	10.77	4.24	14.54	9.46	4.73	0.61	1.27	-	44.75	0.016	-0.37	1.66	0.80
			Bus	6.38	-	-	-	5.45	0.32	12.52	0.66	9.67	-0.09	4.81	-0.011	-0.41	-0.05	0.86
	Far	Y	Non-Bus	-16.84	5.07	11.36	11.46	12.88	16.03	7.97	0.73	4.14	-	37.88	-0.008	-0.55	2.79	0.70
			Bus	6.33	-	-	-	5.70	1.09	19.50	0.53	4.59	-0.11	6.33	-0.008	-0.47	-0.05	0.85
		N	Non-Bus	-27.01	12.34	8.82	2.43	8.43	13.63	8.02	0.71	4.66	-	46.07	0.012	-0.36	1.27	0.78
			Bus	6.39	-	-	-	5.55	1.05	18.29	0.55	4.81	-0.10	6.69	-0.015	-0.46	-0.06	0.83
N	Near	Y	Non-Bus	-18.94	1.28	31.23	2.70	17.30	40.48	5.57	0.88	4.95	-	33.15	-0.014	-0.49	3.75	0.56
			Bus	0.70	-	-	-	10.66	9.62	21.65	0.51	2.40	-0.13	8.95	-0.009	-0.33	-0.05	0.70
		N	Non-Bus	-13.38	8.77	10.13	0.59	10.78	31.37	4.01	0.97	3.96	-	31.46	-0.007	-1.31	2.29	0.59
			Bus	1.40	-	-	-	9.42	9.97	21.63	0.53	2.58	-0.12	9.36	-0.014	-0.32	-0.06	0.70
	Mid	Y	Non-Bus	-21.07	5.09	9.68	3.49	16.87	26.63	3.59	0.90	1.44	-	35.55	-0.002	-0.56	4.11	0.63
			Bus	5.33	-	-	-	6.20	5.81	10.38	0.69	3.55	-0.11	4.49	-0.003	-0.36	-0.13	0.84
		N	Non-Bus	-25.44	5.67	10.96	5.52	12.67	15.61	2.71	0.91	1.49	-	38.20	0.010	-0.37	2.77	0.68
			Bus	5.73	-	-	-	5.73	6.04	9.53	0.72	3.86	-0.10	4.88	-0.009	-0.36	-0.12	0.82
	Far	Y	Non-Bus	-25.85	5.33	11.44	27.84	24.24	11.05	3.35	0.78	1.11	-	36.15	-0.011	-0.67	3.27	0.70
			Bus	7.44	-	-	-	4.86	0.72	16.83	0.57	4.76	-0.11	6.05	-0.007	-0.48	-0.04	0.86
		N	Non-Bus	-23.62	8.98	10.53	3.69	10.96	15.39	13.47	0.48	1.41	-	42.15	0.007	-0.44	1.75	0.75
			Bus	7.66	-	-	-	4.62	0.87	16.76	0.58	4.89	-0.10	6.43	-0.014	-0.47	-0.04	0.85

Formulas:

$$Bus\ Speed = \beta_0 + \beta_4 e^{\left(\frac{\beta_5 RV + \beta_6 Bus \times Dwell^{\beta_7}}{10000 + 10000 \times BB}\right)^{\beta_8}} + \beta_9 Dwell + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes$$

$$Non-Bus\ Speed = \beta_0 + \beta_1 e^{\left(\frac{\beta_2 TV}{10000}\right)^{\beta_3}} + \beta_4 e^{\left(\frac{\beta_5 RV + \beta_6 Bus \times Dwell^{\beta_7}}{10000 + 10000 \times BB}\right)^{\beta_8}} + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes$$

**Table 6-4. Model Coefficients for Arterial Streets without a Bus Lane (Mixed Traffic).**

				Coefficients of Variables												
Bay	Stop	Offset	Speed	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	$\beta_5$	$\beta_6$	$\beta_7$	$\beta_8$	$\beta_9$	$\beta_{10}$	$\beta_{11}$	R <sup>2</sup>
Y	N e a r	Y	Non-Bus	-23.03	22.18	3.81	4.47	7.03	0.85	2.89	-	42.51	-0.026	-0.40	1.44	0.44
			Bus	-2.32	11.43	2.54	2.49	15.32	0.57	1.25	-0.08	11.25	-0.007	-0.38	-0.03	0.57
		N	Non-Bus	-29.74	26.24	3.27	3.17	5.83	0.86	2.12	-	44.00	-0.017	-0.31	1.03	0.48
			Bus	-0.64	6.67	3.38	3.63	15.65	0.63	2.17	-0.07	12.13	-0.009	-0.35	-0.02	0.57
	M i d	Y	Non-Bus	-13.13	17.21	6.06	6.68	3.84	0.98	4.42	-	32.41	-0.016	-0.13	1.87	0.49
			Bus	5.17	3.76	4.73	3.20	4.51	0.96	4.26	-0.07	6.88	-0.005	-0.37	-0.03	0.69
		N	Non-Bus	-15.42	14.23	7.02	4.95	3.89	0.97	4.43	-	35.45	-0.007	-0.05	1.27	0.52
			Bus	4.97	3.60	5.04	2.91	4.31	0.97	4.51	-0.07	7.27	-0.008	-0.36	-0.04	0.68
	F a r	Y	Non-Bus	-15.77	20.84	6.60	10.40	3.25	0.92	2.05	-	37.76	-0.019	-0.53	2.74	0.60
			Bus	-0.11	9.70	1.72	1.90	7.96	0.64	1.88	-0.08	8.27	-0.008	-0.42	-0.06	0.73
		N	Non-Bus	-18.53	15.69	7.96	7.62	2.14	1.01	2.57	-	42.25	-0.005	-0.38	1.76	0.68
			Bus	0.88	8.00	2.50	1.92	6.19	0.74	1.76	-0.07	8.93	-0.011	-0.40	-0.05	0.72
N	N e a r	Y	Non-Bus	-19.47	28.34	6.45	11.97	4.82	1.02	2.07	-	30.69	-0.016	-0.26	2.08	0.45
			Bus	-3.86	22.64	6.15	8.61	7.65	0.96	0.64	-0.05	8.65	-0.007	-0.32	0.06	0.51
		N	Non-Bus	-19.81	23.68	6.41	10.84	4.48	1.04	2.18	-	31.73	-0.014	-0.22	1.70	0.47
			Bus	-1.42	10.98	5.50	7.60	3.92	1.12	1.46	-0.03	9.58	-0.009	-0.31	0.04	0.52
	M i d	Y	Non-Bus	-11.02	19.92	7.65	11.13	1.74	1.26	2.93	-	22.37	-0.011	-0.04	2.39	0.48
			Bus	4.41	6.07	5.77	5.65	1.88	1.31	2.25	-0.06	5.20	-0.005	-0.29	0.03	0.65
		N	Non-Bus	-12.87	12.17	7.84	9.66	1.52	1.30	2.63	-	25.14	-0.007	0.00	1.88	0.50
			Bus	4.17	6.15	5.70	5.72	1.27	1.42	2.10	-0.05	5.48	-0.008	-0.29	0.02	0.64
	F a r	Y	Non-Bus	-18.29	29.92	10.36	14.69	1.63	1.06	0.98	-	30.65	-0.018	-0.58	3.93	0.60
			Bus	2.41	6.65	4.80	2.00	6.28	0.80	2.23	-0.08	8.24	-0.008	-0.40	0.25	0.75
		N	Non-Bus	-20.08	17.60	9.12	6.36	0.93	1.14	1.99	-	35.34	-0.008	-0.48	2.93	0.66
			Bus	2.21	6.01	5.47	1.72	5.38	0.85	2.48	-0.07	8.99	-0.010	-0.39	0.21	0.75

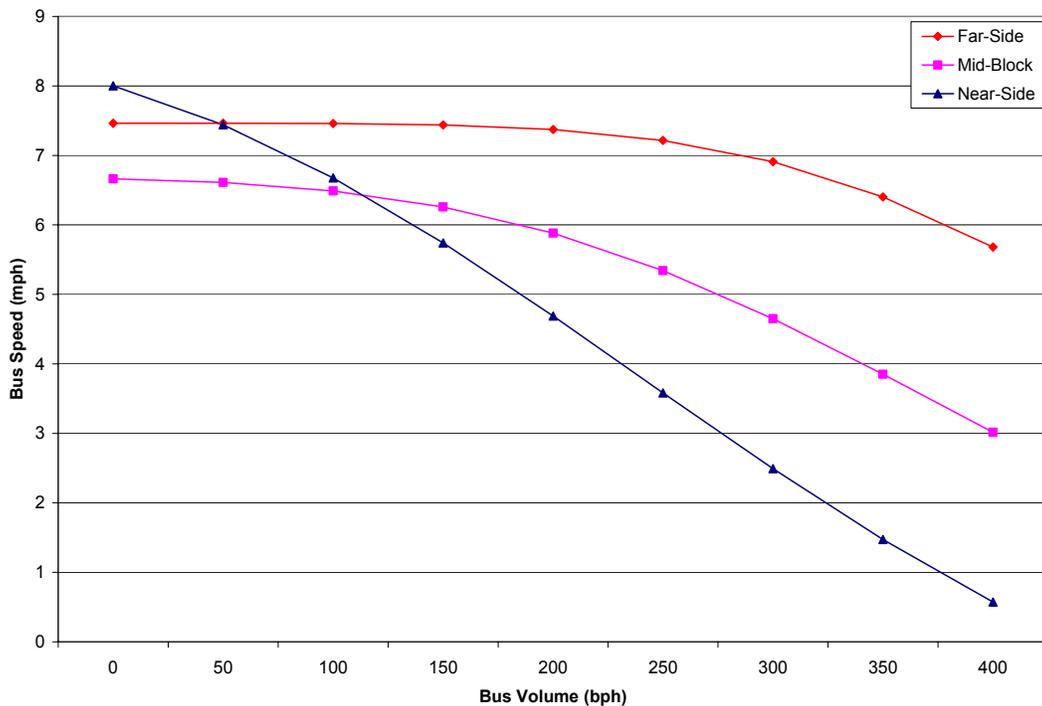
Formulas:

$$Bus\ Speed = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000} + \frac{\beta_3 RV}{10000} + \frac{\beta_4 Bus \times Dwell^{\beta_5}}{10000 \times BB}\right)^{\beta_6}} + \beta_7 Dwell + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes$$

$$Non\ -\ Bus\ Speed = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000} + \frac{\beta_3 RV}{10000} + \frac{\beta_4 Bus \times Dwell^{\beta_5}}{10000 \times BB}\right)^{\beta_6}} + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes$$

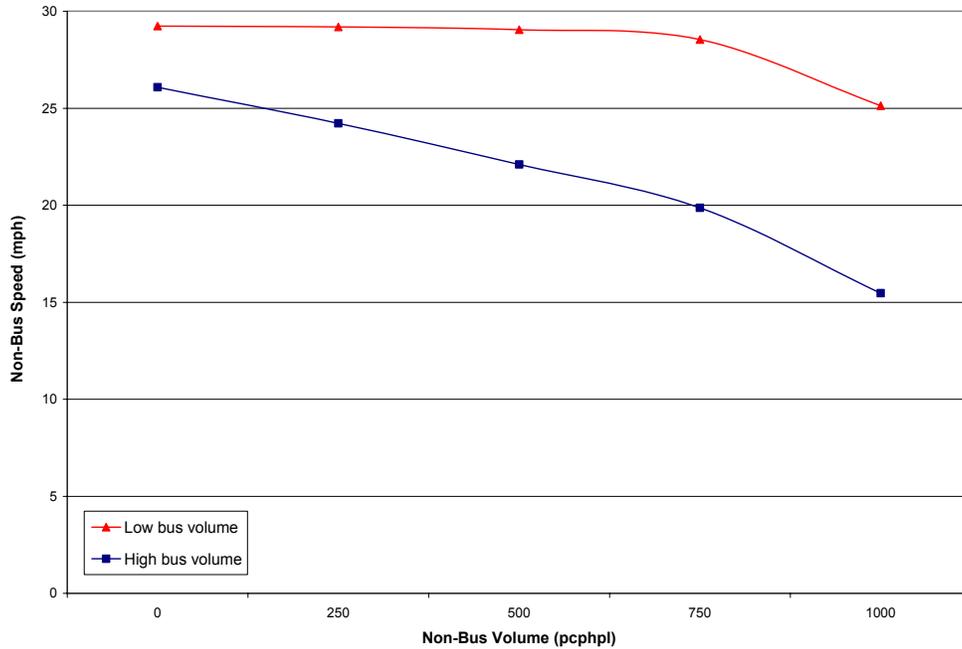
**Table 6-5. Default Input Values or Options for Plots.**

Independent Variable	Default for Graphs
Bus lane	With Bus Lane
Bus bay	With bus bay
Bus stop location	Near-side
Signal offset (sec)	Without offset
Number of passenger cars per hour per lane (pcphpl)	650
Right turn volume (pcph)	200
Number of buses per hour	75
Mean dwell time (sec)	40
Number of bus berths	2
Green ratio	0.65
Cycle length (sec)	90
Stop spacing (ft)	700
Number of lanes	3

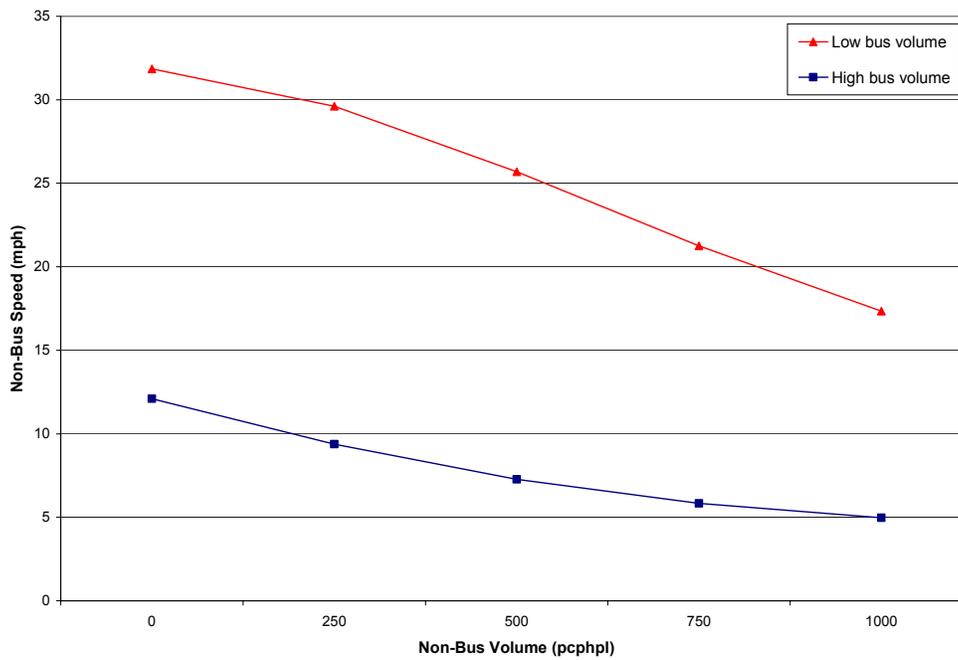


**Figure 6-3. Effect of Bus Volume on Bus Speeds (with Bus Lane and without Bus Bay).**

**Observations:** Bus speeds are reduced by increasing bus volumes. The impact of bus volumes on bus speeds is much stronger for near-side bus stops than for far-side or mid-block bus stops. Near-side bus stops are superior to far-side and mid-block bus stops only at very low bus volumes.



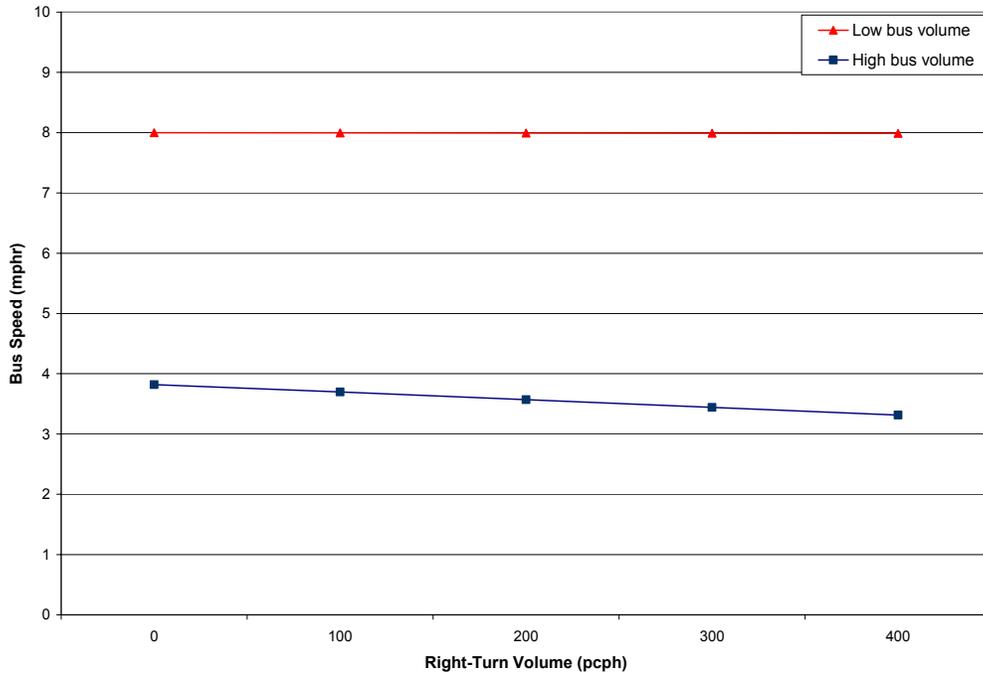
(a) with bus lane



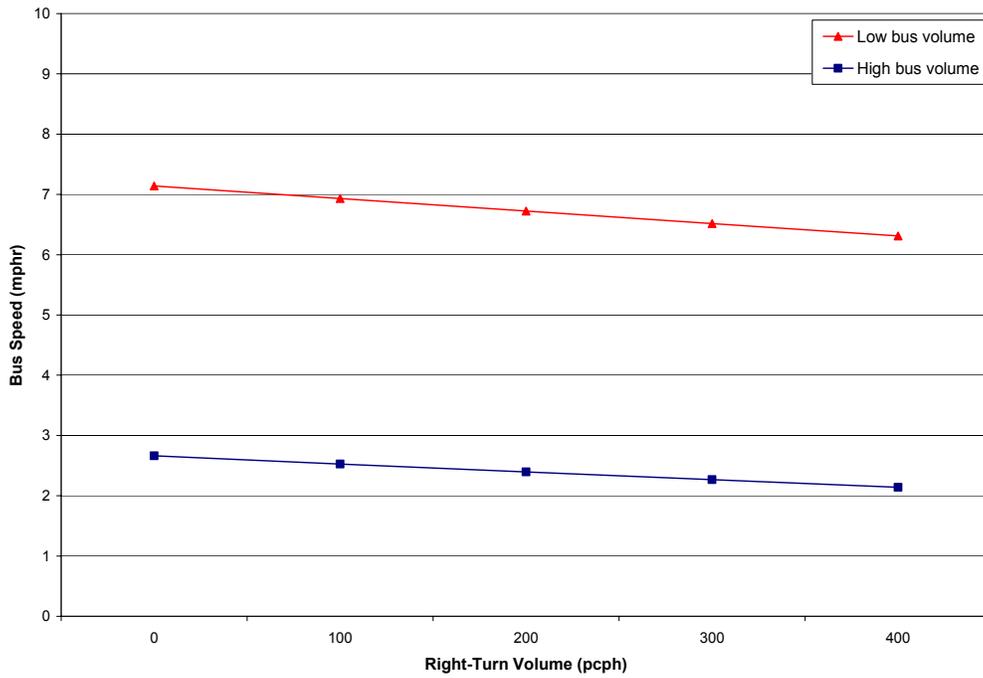
(b) without bus lane

**Figure 6-4. Effect of Bus Lane on Non-Bus Speeds.**

**Observations:** In general, non-bus speeds decrease with increasing non-bus volumes and increasing bus volumes. Non-bus speeds are significantly affected when there is a presence of high bus volumes without a bus lane. Non-bus speeds are improved by the presence of a bus lane at both low and high bus volumes.



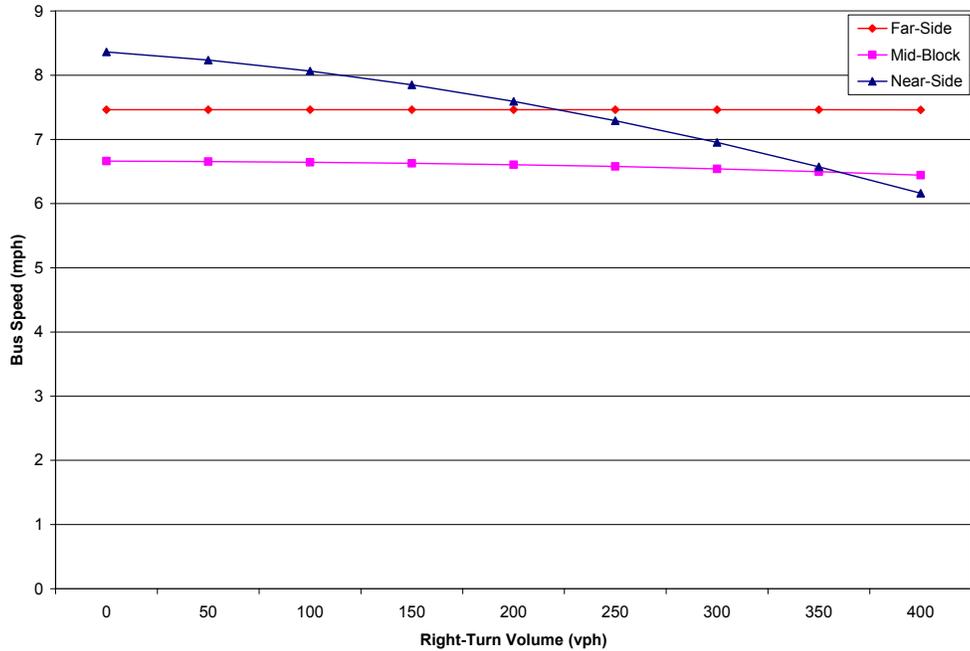
(a) with bus lane



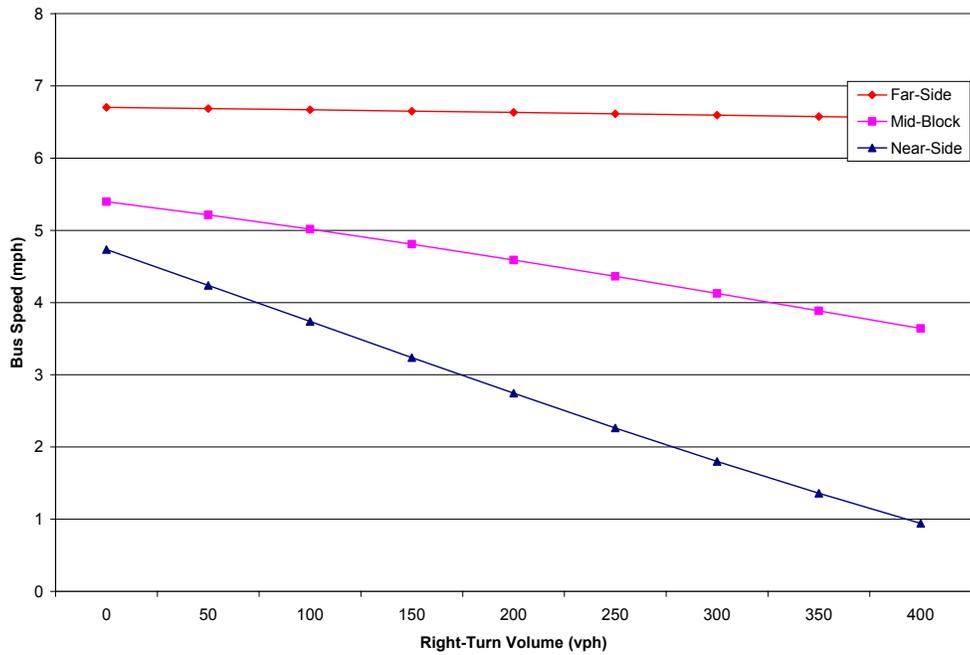
(b) without bus lane

**Figure 6-5. Effect of Right-Turn Volume (with Bus Bay and Near-Side Stop).**

**Observations:** Increasing right-turn vehicles reduced bus speeds. When there is a bus lane, bus speeds are relatively unaffected by right-turn volumes at low bus volumes.



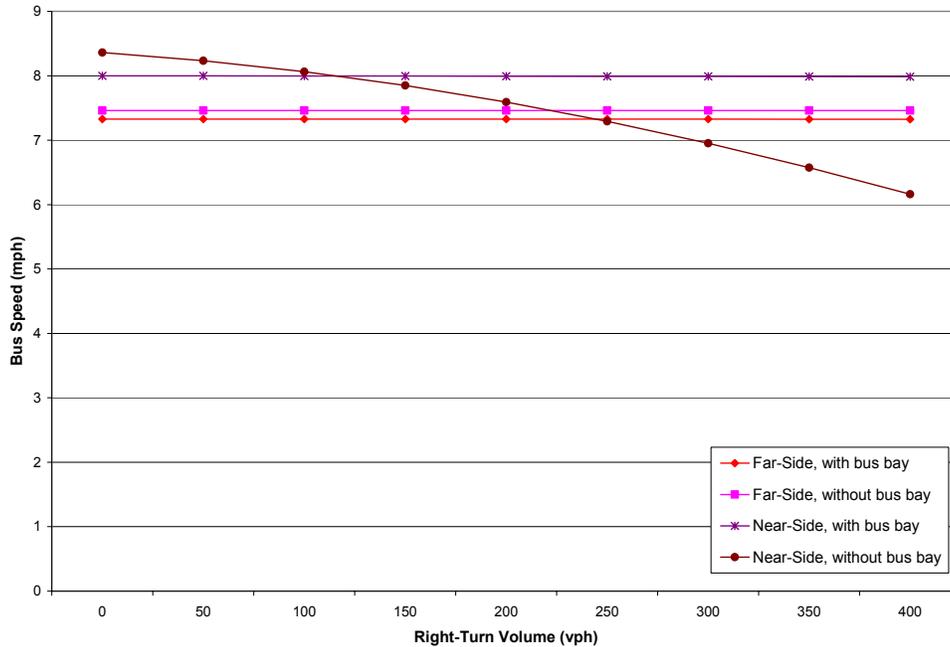
(a) low bus volume



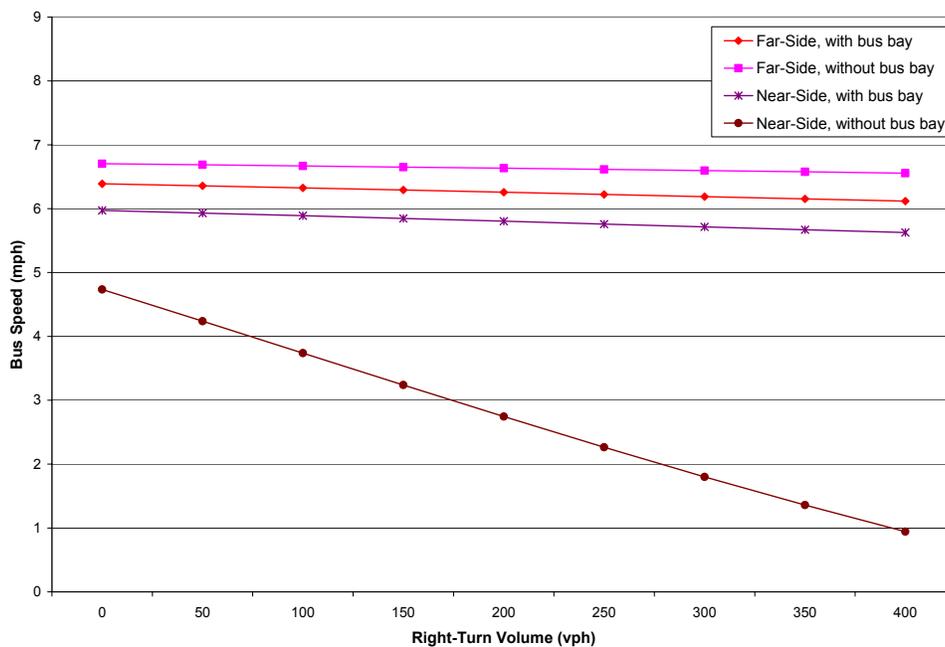
(b) high bus volume

**Figure 6-6. Effect of Right-Turn Volume (with Bus Lane and without Bus Bay).**

**Observations:** The conflicts between buses and right-turning traffic are greatest for near-side bus stops. The effect of right-turn vehicles on bus speeds are negligible for mid-block bus stops at low bus volumes, but are significant at higher bus volumes. Bus speeds are essentially unaffected by right-turn vehicles when the bus stops are located at the far-side.



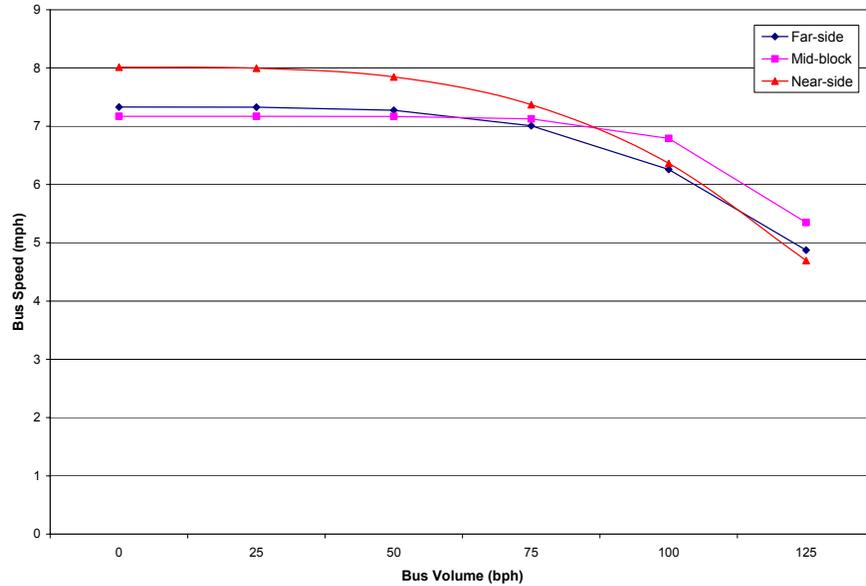
(a) low bus volume



(b) high bus volume

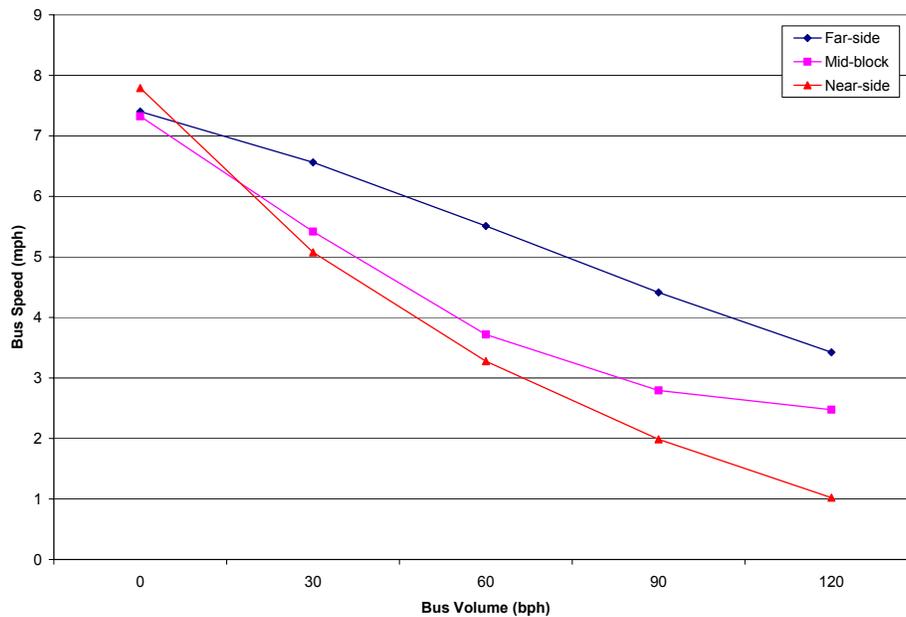
**Figure 6-7. Effect of Bus Bay (with Bus Lane).**

**Observations:** Nears-side bus stops without a bus bay are affected by right-turn vehicles at both low and high bus volumes. The effect is the largest at high bus and right-turn volumes. Far-side bus stops are relatively unaffected by the presence of a bus bay, even under high bus volumes. This suggests a bus bay is much more useful for near-side bus stops than for far-side bus stops.



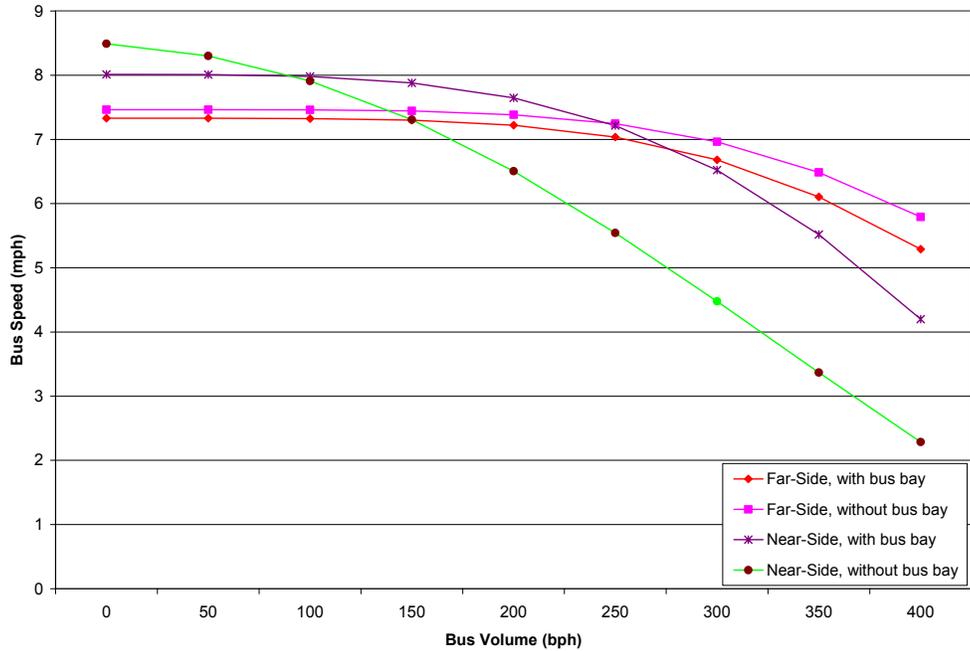
**Figure 6-8. Effect of Stop Location on Bus Speeds (with Bus Lane and Bus Bay).**

**Observations:** Bus speeds generally decrease with increasing bus volumes. At low bus volumes, bus speeds are relatively unaffected by bus volumes. At higher bus volumes, bus volumes reduce bus speeds at an increasing rate.

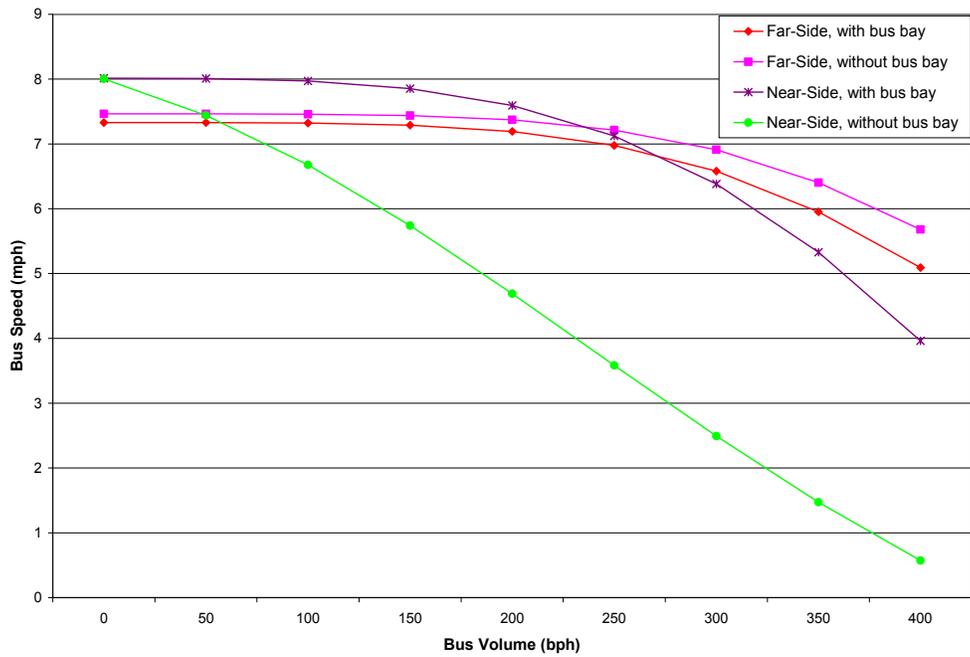


**Figure 6-9. Stop Location on Bus Speeds (without Bus Lane and without Bus Bay).**

**Observations:** When bus lanes and bus bays are not present, bus speeds decrease with increasing bus volumes for all bus stop locations. Bus speeds are more vulnerable to increasing bus volumes for near-side bus stops than for far-side bus stops. At low bus volumes differences in the performance of bus stop locations are less significant. At high bus volumes, far-side bus stops are superior to near-side or mid-block bus stops.



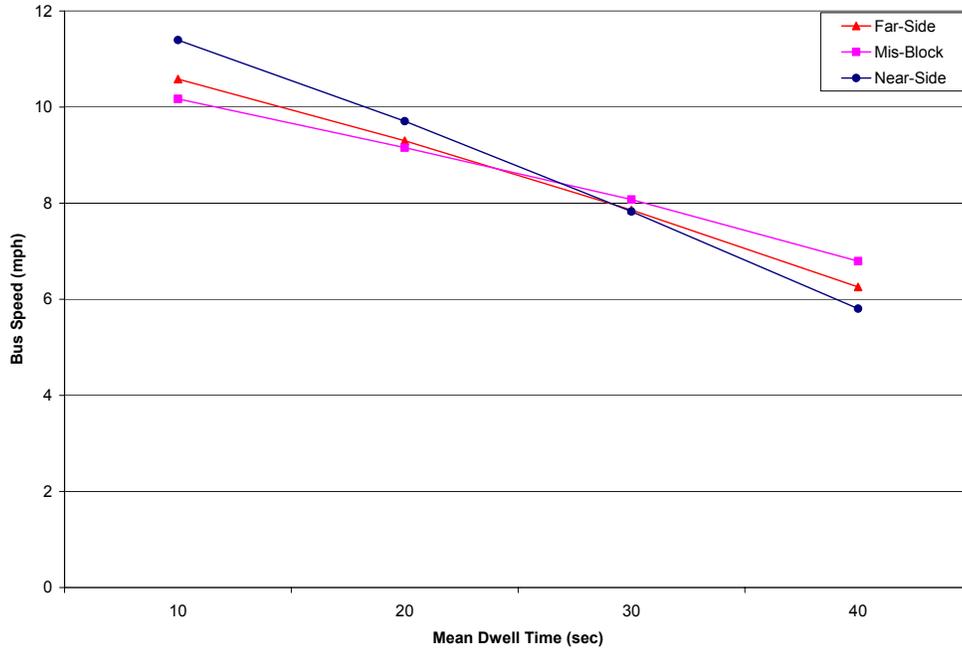
(a) low right-turn volume



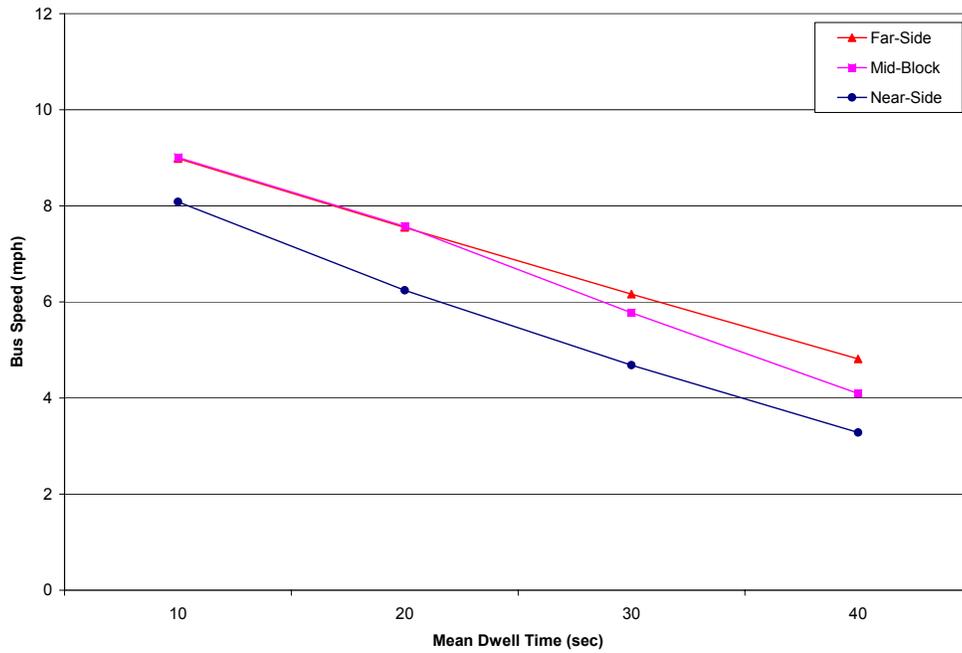
(b) high right-turn volume

**Figure 6-10. Effect of Bus Bays on Bus Speeds (with Bus Lane).**

**Observations:** The use of bus bays for far-side bus stops does not have an impact on bus speeds, but the use of bus bays for near-side bus stops significantly improve bus speeds.



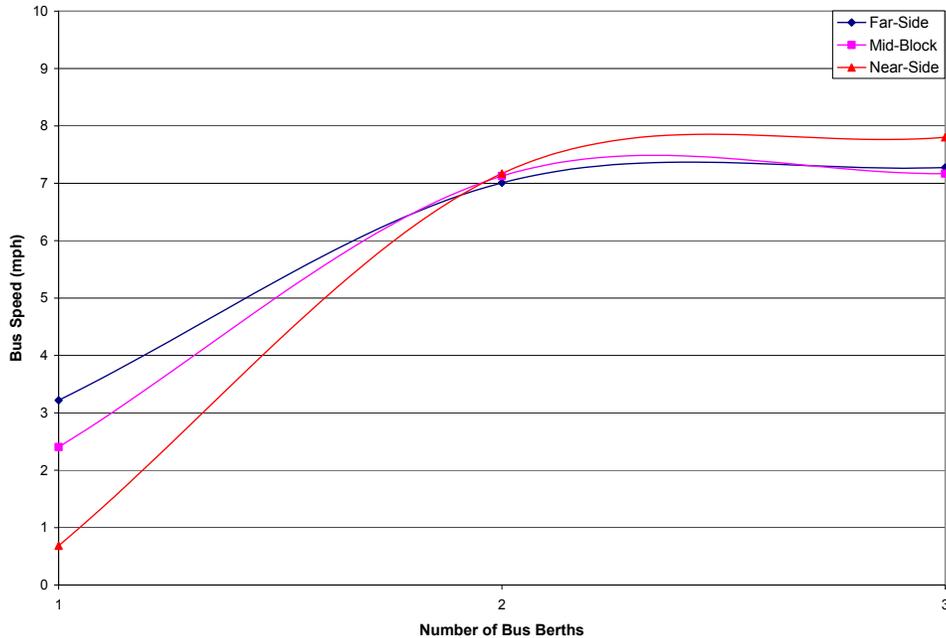
(a) with bus lane



(b) without bus lane

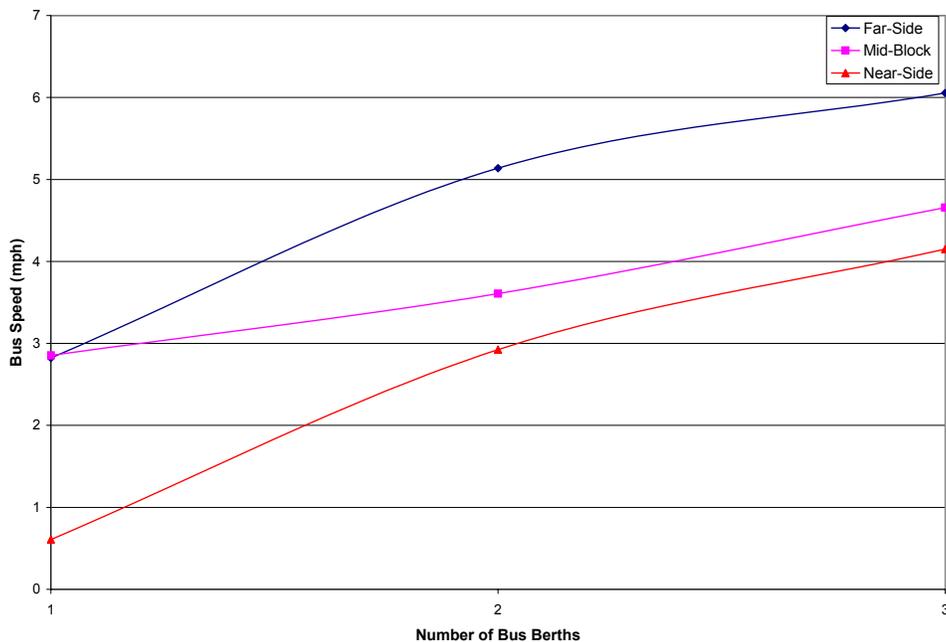
**Figure 6-11. Effect of Mean Dwell Time on Bus Speeds (with Bus Bay, Near-Side).**

**Observations:** Bus speeds are significantly reduced by increasing mean dwell times regardless of whether there is a bus lane and where the bus stop is located.



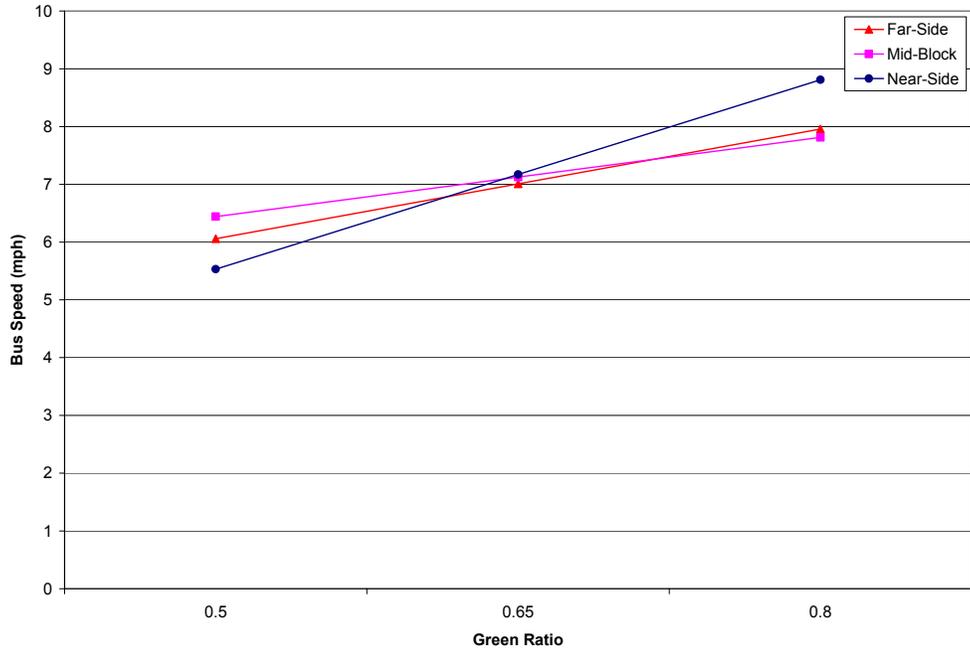
**Figure 6-12. Effect of Bus Berths on Bus Speeds (With Bus Lane and Bus Bay).**

**Observations:** When bus lane and bus bay are present, bus speeds generally improve with increasing number of bus berths. However, the increase is more significant when the number of bus berths is increased from one to two than from two to three (for the given bus volumes)

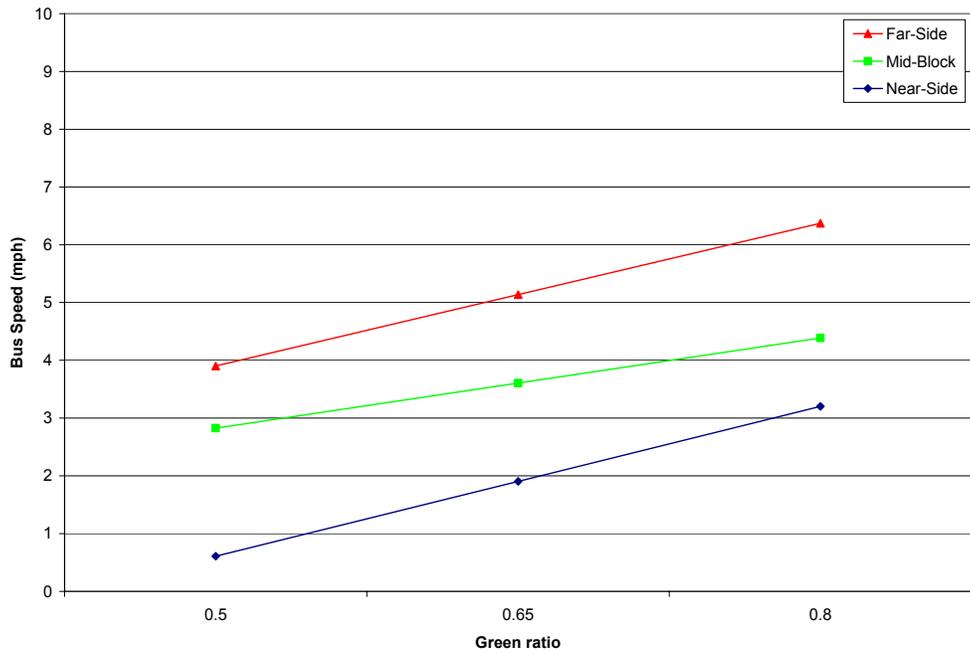


**Figure 6-13. Effect of Bus Berths on Bus Speeds (without Bus Lane and Bus Bay).**

**Observations:** When bus lane and bus bay are not present, bus speeds generally improve with increasing number of bus berths regardless of bus stop locations and bus volumes.



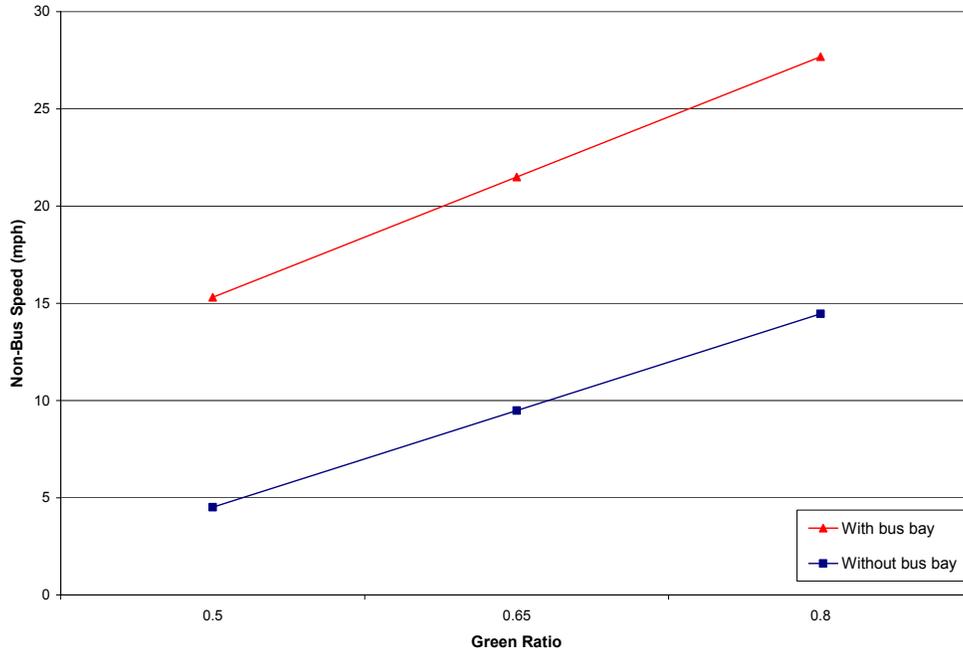
(a) with bus lane



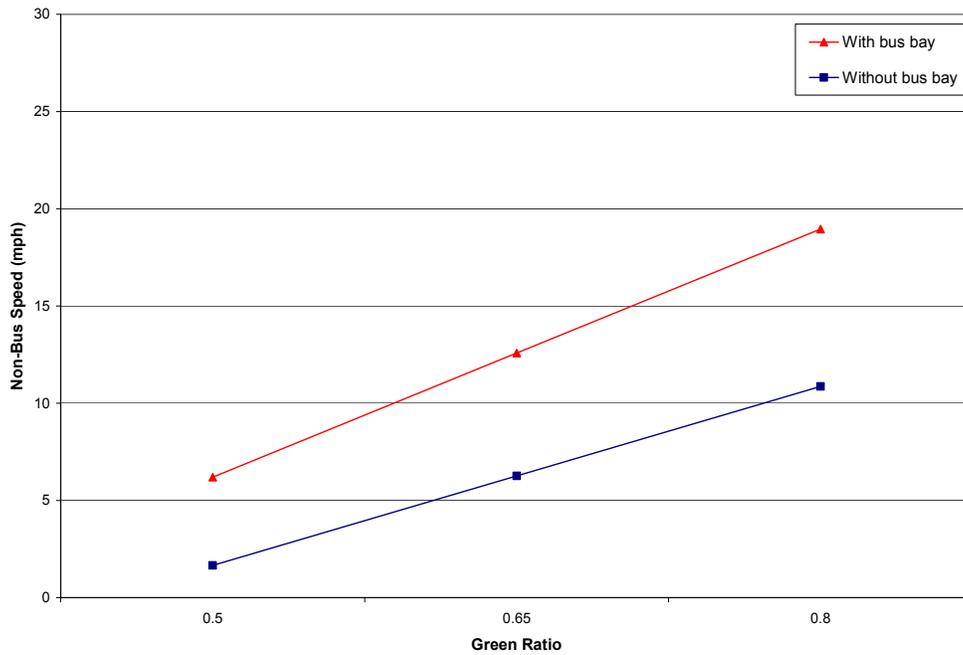
(b) without bus lane

**Figure 6-14. Effect of Green Ratio on Bus Speeds (with Bus Bay).**

**Observations:** Bus speeds improve significantly with increasing green ratios for arterial through movements regardless of bus stop locations and whether there is a bus lane.



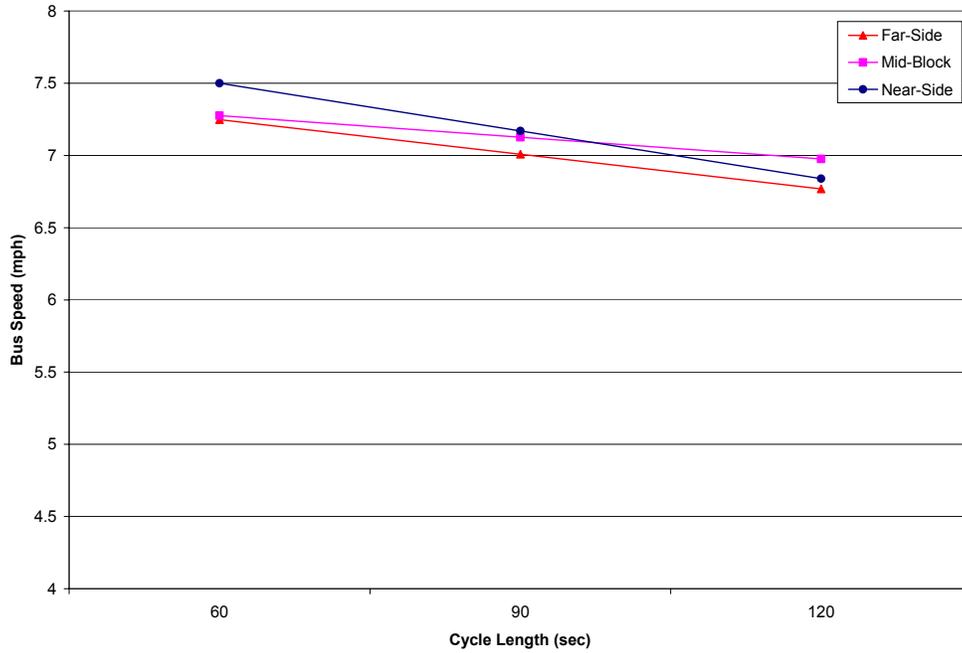
(a) with bus lane



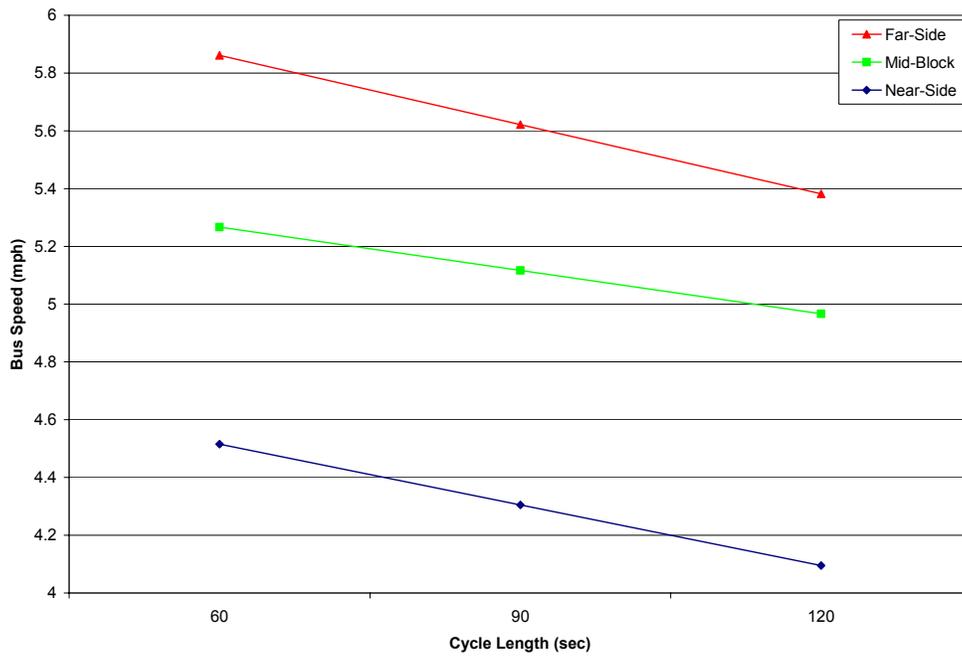
(b) without bus lane

**Figure 6-15. Effect of Green Ratio on Non-Bus Speeds (with Near-Side Stop).**

**Observations:** Non-bus speeds are significantly improved by increasing green ratios regardless of whether there is a bus lane and/or a bus bay.



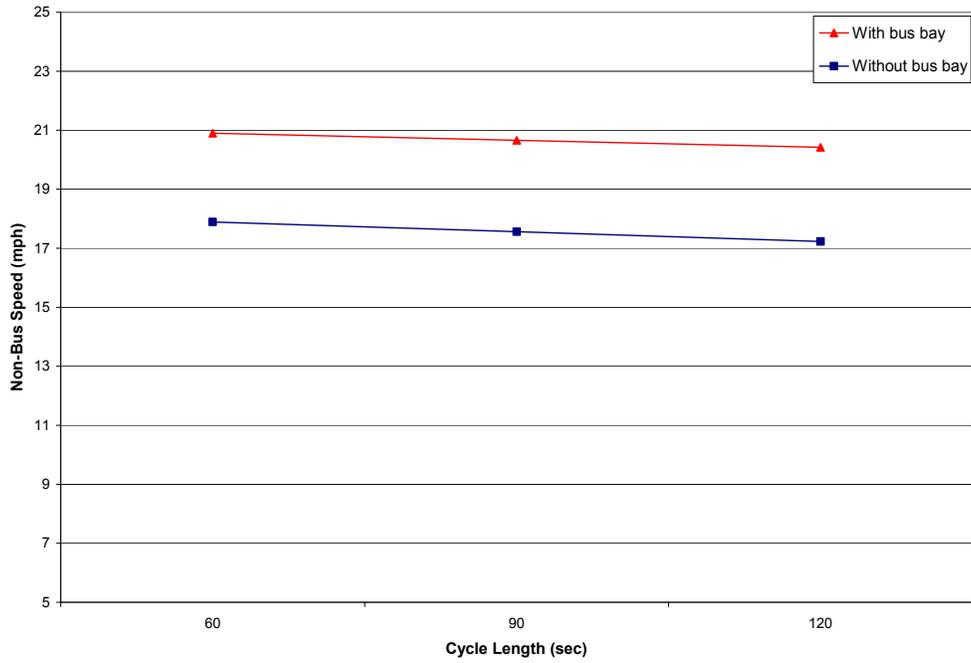
(a) with bus lane



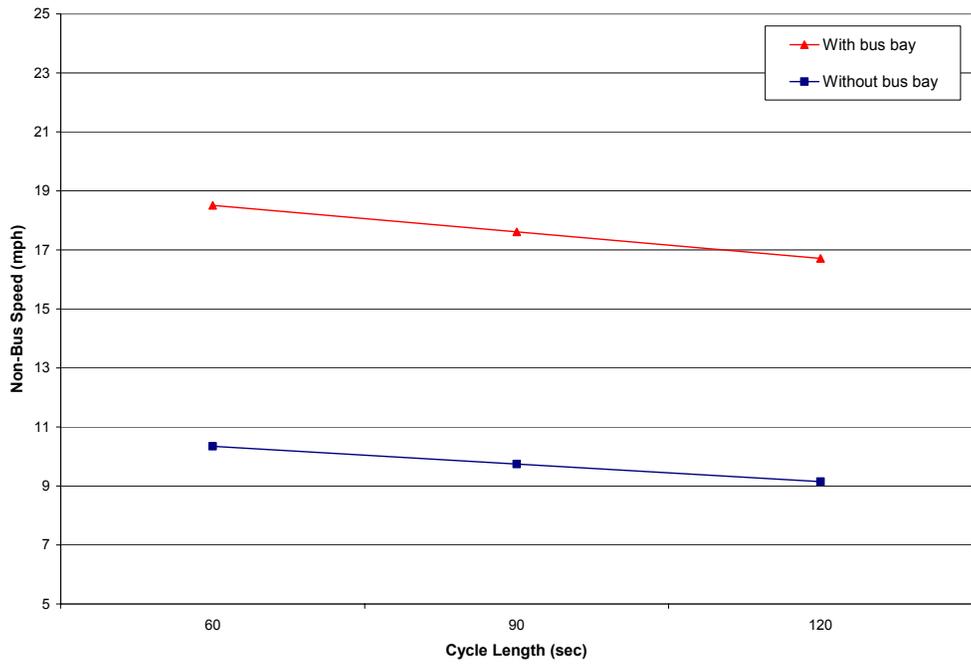
(b) without bus lane

**Figure 6-16. Effect of Cycle Length on Bus Speeds (with Bus Bay).**

**Observations:** Increasing cycle length reduces bus speeds. The impact is similar for near-side and far-side bus stops, and with or without lane separation.



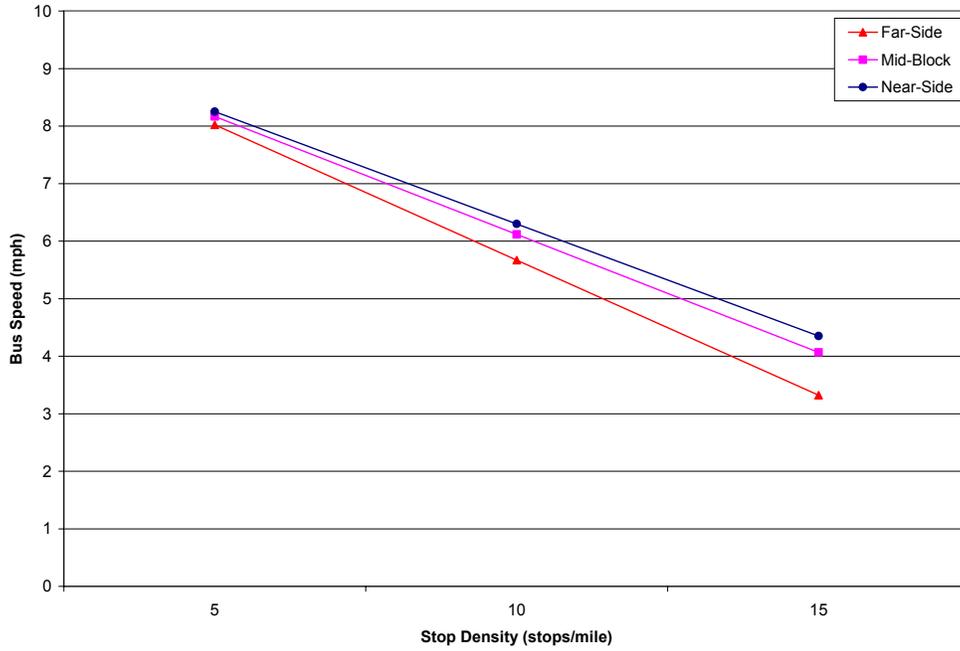
(a) with bus lane



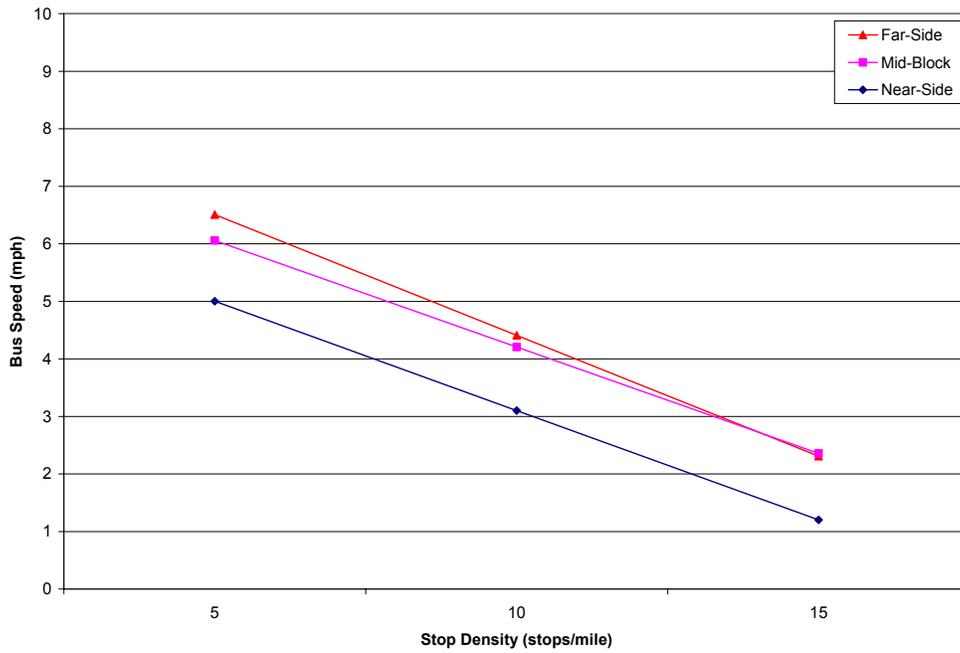
(b) without bus lane

**Figure 6-17. Effect of Cycle Length on Non-Bus Speeds (Near-Side Stops).**

**Observations:** Increasing cycle length has only a minor impact on non-bus speeds, with the mixed-traffic facilities having a slightly larger impact.



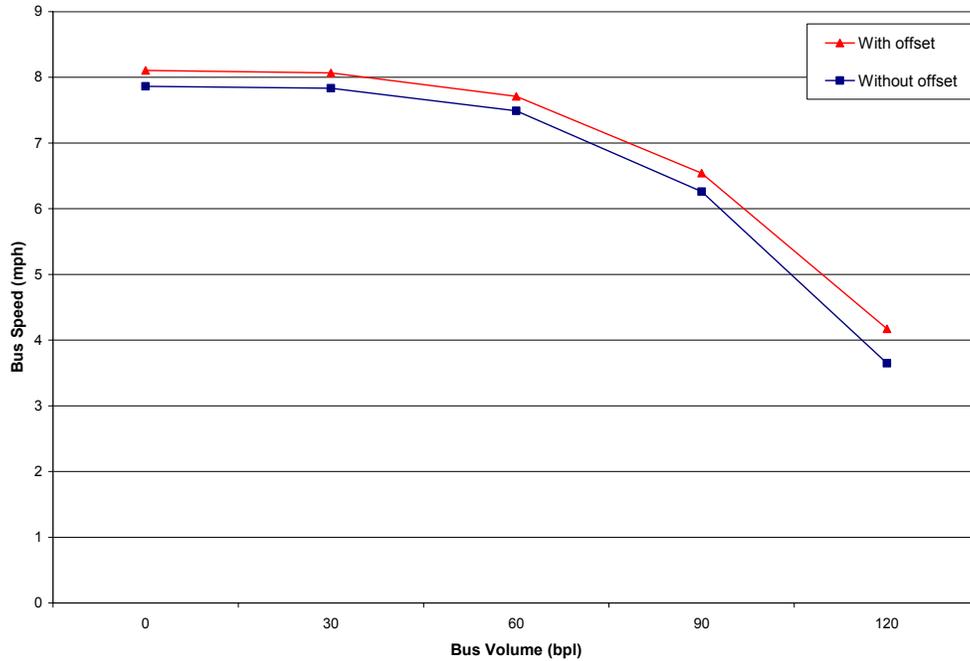
(a) with bus lane



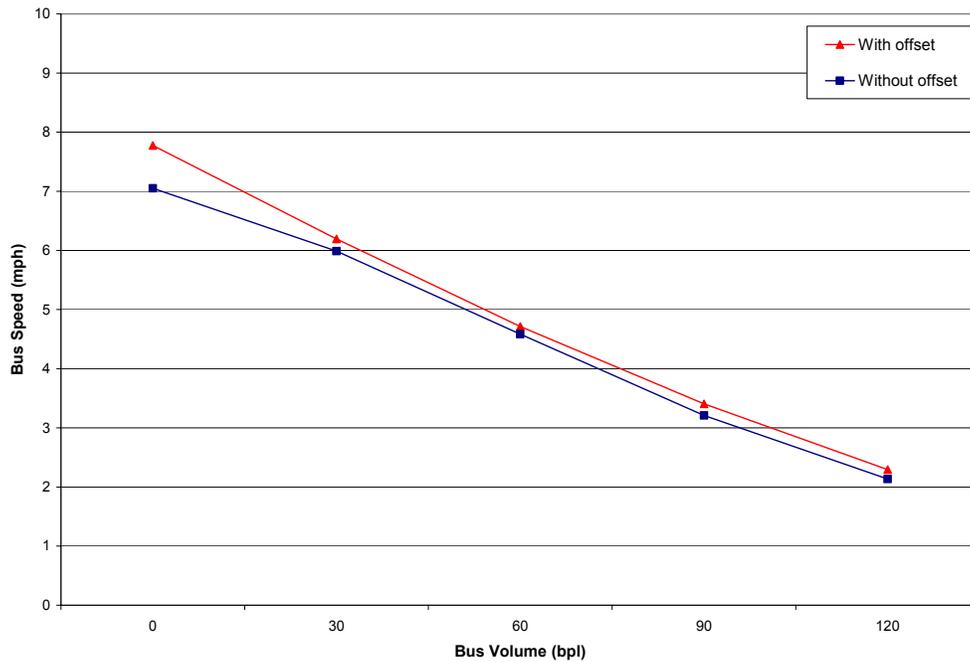
(b) without bus lane

**Figure 6-18. Effect of Stop Density on Bus Speeds (with Bus Bay).**

**Observations:** Bus speeds are significantly reduced by increasing bus stop densities regardless of bus stop locations and lane separation.



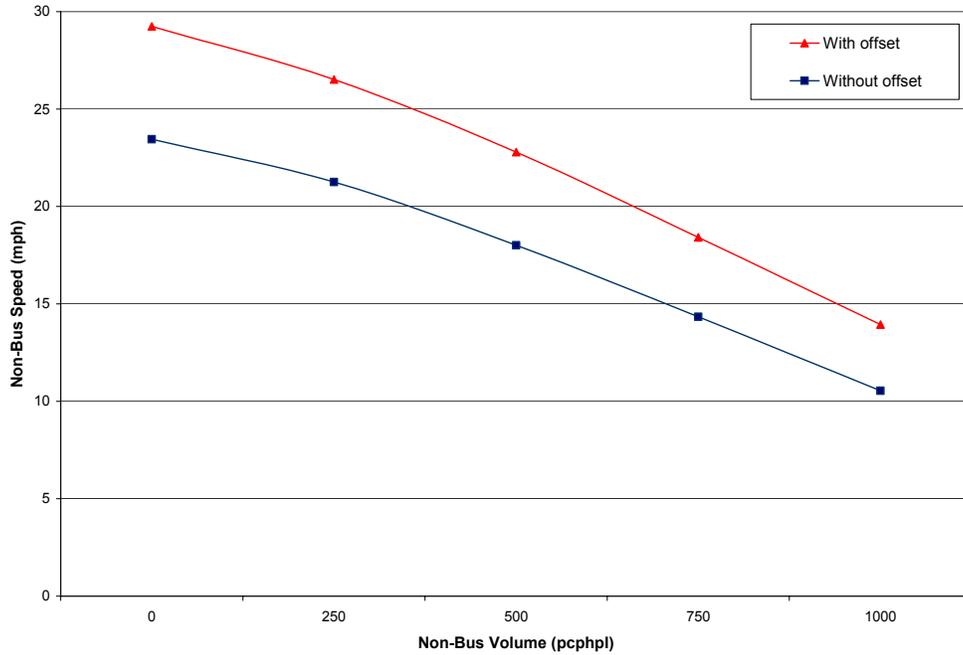
(a) with bus lane



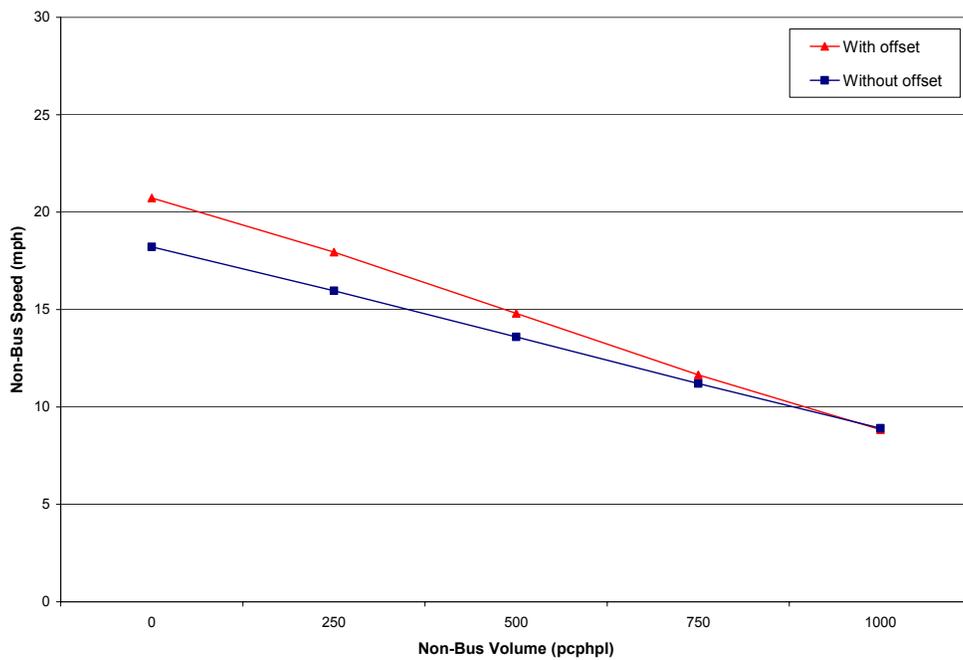
(b) without bus lane

**Figure 6-19. Effect of Signal Offsets on Bus Speeds (with Bus Bay, Near-Side Stops).**

**Observations:** Signal offsets do not have a significant impact on bus speeds regardless of whether there is a bus lane.



(a) with bus lane



(b) without bus lane

**Figure 6-20. Effect of Signal Offsets on Non-Bus Speeds (with Bus Bay, Near-Side Stops).**

**Observations:** When there is a bus lane, signal offsets have a significant impact on non-bus speeds. The impact is reduced when buses are mixed with non-bus traffic, suggesting that the presence of buses in the platoon makes progression harder for the non-bus traffic.

## 6.6. Model Evaluation

Figures 6-3 through 6-20 have shown that the models produce logical relationships for all the variables examined. Figure 6-21 shows a comparison of the modeled speeds with a graph reported (Exhibit 27-22) in the 2000 Highway Capacity Manual (HCM 2000) for two different stop densities. The curves are plotted for bus speeds (with bus lane) against the volume-to-capacity ratio ( $v/c$ ). The input conditions are:

- ✓ Three-lane arterial street, single bus lane
- ✓ Far-side bus stop with bus bay
- ✓ Dwell time = 30 seconds
- ✓ Number of bus berths = 2
- ✓ Cycle length = 90 seconds
- ✓ Green ratio = 0.5

For the computation of  $v/c$  ratios, the bus lane capacity was estimated using the maximum bus flow rates in the simulated data set. The figure shows that, overall, the estimates from CORSIM simulation are comparable to those of the HCM. For stop density equals to 6 stops per mile, CORSIM's estimates are slightly lower than those of the HCM. For stop density equals to 10 stops per mile, CORSIM's estimates are slightly higher than those of the HCM at low lower  $v/c$  ratios, but slightly lower at higher  $v/c$  ratios.

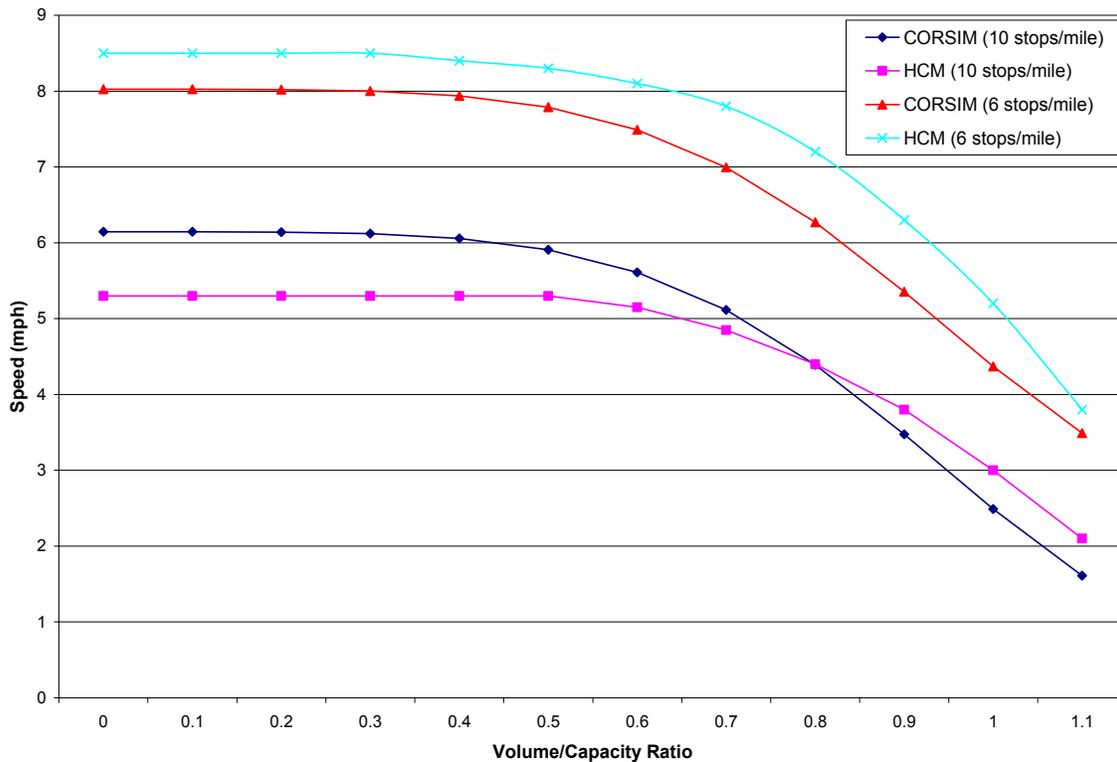


Figure 6-21. Comparison of Modeled Speeds with HCM's.

Table 6-6 provides a comparison of the modeled bus speeds (the last row) with those measured at three bus lane sites, as reported in TCRP Report 26 (St Jacques and Levinson, 1997). The average bus speeds, given in ranges, were found to be comparable for two of the sites (Geary Street and Madison Street) and slightly on the low side for one site (Louisiana Street).

**Table 6-6. Comparisons with Real-World Data.**

Item	Geary Street San Francisco	Louisiana Street Houston	Madison Street Chicago
Bus Stops Per Mile	8	16	7
Buses Per Hour	16-20	84-102	26-48
Average Dwell Time	41-58 seconds	21-36 seconds	13-37 seconds
Average Bus Speeds (Measured)	3.9-5.1 mph	4.4-6.0 mph	6.2-7.8 mph
Average Bus Speeds (Modeled)	4.0-5.7 mph	3.2-5.0 mph	6.1-8.5 mph

### **6.7. Decision Models**

As for the freeway models, the objective of the arterial decision models is to also minimize the travel time of all road users of bus and non-bus vehicles by comparing the person travel times associated with the different design alternatives. The person travel time (PTT) in seconds per mile for both preferential facilities and non-preferential facilities can be computed using the average speeds of buses (BS) and the non-buses (NBS) that were estimated from the regression models, as follows:

$$PTT_{separated} = \frac{3600 \times \left( \frac{B \times BO}{BS} + \frac{(TV + RV) \times NBO}{NBS} \right)}{B \times BO + (TV + RV) \times NBO}$$

where

- TV = through non-bus volume in vehicles per hour per lane (pcphpl),
- RV = right-turn non-bus volume in non-bus vehicles per hour per lane (pcphpl),
- B = bus volume in buses per hour (bph),
- NBO = average non-bus occupancy rate, and
- BO = average bus occupancy rate.

The FRESIM submodel of CORSIM reports separate speeds for HOV lanes. The NETSIM submodel of CORSIM, on the other hand, reports separate speeds for buses regardless of whether there is a bus lane. Thus the equation for  $PTT_{mixed}$  is the same as  $PTT_{separated}$ . The decision rule is that an arterial bus lane is warranted if  $PTT_{separated}$  is less than  $PTT_{mixed}$ .

### **6.8. Application Example**

Given the following input conditions:

- ✓ Three-lane arterial street (per direction)
- ✓ Number of total through vehicles = 1600 vph
- ✓ Number of right-turning vehicles = 150 vph
- ✓ Number of buses = 75 bph

- ✓ Cycle length = 90 seconds
- ✓ G/C ratio = 0.65
- ✓ Mean dwell time = 20 seconds
- ✓ Number of bus berth = 2
- ✓ Bus stop spacing = 700 feet
- ✓ Occupancy rate for passenger cars = 1.3
- ✓ Occupancy rate for carpools = 3.5
- ✓ Occupancy rate for trucks = 1.2
- ✓ Occupancy rate for buses = 50

Step 1. Compute bus speed (BS) and non-bus speed (NBS) for arterial with bus lane (from Table 6.3):

$$BS = 6.33 + 5.70e^{-\left(\frac{1.09 \times 150}{10000} + \frac{19.5 \times 75 \times 20^{0.53}}{10000 \times 2}\right)^{4.59}} - 0.11 \times 20 + 6.33 \times 0.65 - 0.008 \times 90 - 0.47 \times 2 - 0.05 \times 3$$

$$= 9.3 \text{ mph}$$

$$NBS = -16.84 + 5.07e^{-\left(\frac{11.36 \times 1600}{2 \times 10000}\right)^{11.46}} + 12.88e^{-\left(\frac{16.03 \times 150}{10000} + \frac{7.97 \times 75 \times 20^{0.73}}{10000 \times 2}\right)^{4.14}} + 37.88 \times 0.65 - 0.008 \times 90 - 0.55 \times 2 + 2.79 \times 3$$

$$= 26.9 \text{ mph}$$

Step 2. Compute bus speed (BS) and non-bus speed (NBS) for arterial without bus lane (from Table 6.4):

$$BS = -0.11 + 9.70e^{-\left(\frac{1.72 \times 1600}{3 \times 10000} + \frac{1.90 \times 150}{10000} + \frac{7.96 \times 75 \times 20^{0.64}}{10000 \times 2}\right)^{1.88}} - 0.08 \times 20 + 8.27 \times 0.65 - 0.008 \times 90 - 0.42 \times 2 - 0.06 \times 3$$

$$= 8.0 \text{ mph}$$

$$NBS = -15.77 + 20.84e^{-\left(\frac{6.60 \times 1600}{3 \times 10000} + \frac{10.40 \times 150}{10000} + \frac{3.25 \times 75 \times 20^{0.92}}{10000 \times 2}\right)^{2.05}} + 37.76 \times 0.65 - 0.019 \times 90 - 0.53 \times 2 + 2.74 \times 3$$

$$= 24.1 \text{ mph}$$

Step 3. Compute average person travel time for “with bus lane” ( $PPT_{separated}$ ) and “without bus lane” ( $PPT_{mixed}$ ) design alternatives:

$$PPT_{separated} = \frac{3600 \times \left( \frac{75 \times 50}{9.3} + \frac{(1600 + 150) \times 1.3}{30.1} \right)}{75 \times 50 + (1600 + 150) \times 1.3} = 292 \text{ seconds / person}$$

$$PPT_{mixed} = \frac{3600 \times \left( \frac{75 \times 50}{8.0} + \frac{(1600 + 150) \times 1.3}{24.1} \right)}{75 \times 50 + (1600 + 150) \times 1.3} = 336 \text{ seconds / person}$$

Step 4. Decision: Since  $PPT_{mixed} > PPT_{separated}$ , a bus lane is justified.

## CHAPTER 7 SUMMARY, FINDINGS, AND RECOMMENDATIONS

### **7.1. Summary**

Increasing concern for improving the efficiency of roadways in moving people rather than just vehicles has led to the promotion of giving preferential treatments to buses. Bus lanes and busways are two general types of bus preferential facilities. The use of preferential facilities is generally justified on the grounds that buses can potentially carry more passengers than automobiles. However, when a lane is taken away from the general-purpose traffic and designated as a bus-only or HOV lane, it can create congestion in other lanes, causing protests by motorists. Thus, to maintain the long-term success of preferential facilities, better guidance on conditions that justify bus-only or HOV lanes is needed. Such guidance requires that the expected operational performance of each design alternative be known.

The operational performance of bus facilities may be measured by travel time, speed, capacity, etc. It is affected by a number of factors, including bus headway, vehicle volumes, vehicle mix, free-flow speed, dwell time, bus stop capacity, bus stop location (near-side, mid-block, or far-side), bus stop type (on-line vs. off-line), bus stop spacing, signal control parameters, number of lanes, etc. The CORSIM simulation model was used to estimate the bus and non-bus travel speeds under different conditions of these contributing factors. The simulated data were then used as a substitute for field data in an empirical modeling of relationships between travel speeds and their contributing factors. The estimated speeds then provided input to a decision model for the computation of expected person travel times under a specific set of conditions. The design alternative that provides the lower total average person travel time becomes the recommended design alternative.

The decision models developed in this research allow for the evaluation of a proposed bus lane before implementation, an existing bus lane to be re-evaluated for possible improvements, and should a bus lane become controversial, it can be evaluated objectively. Because such models include a number of design variables, they can be used as a tool to evaluate the effectiveness of design alternatives, for example, the location (near side, far side, or mid-block) of bus stops under prevailing conditions.

For the freeway models the new HOV modeling capability that comes with CORSIM version 5.0 was applied for scenario modeling. Non-linear regression models were developed for predicting the average speeds of HOV lane, mixed lanes adjacent to HOV lane, and mixed-only lanes. The models consider traffic compositions (carpools, vanpools, buses, trucks, and passenger cars), number of lanes, and free-flow speeds. A limited model evaluation was performed by comparing results from a mixed-traffic speed model with those of the Highway Capacity Manual (HCM) and the Bureau of Public Roads (BPR) volume-delay equation. The results are found to be relatively consistent.

For the arterial models a corrected version of CORSIM version 5.0 was used for scenario modeling. Mixed linear and non-linear regression models were developed for average bus and non-bus speeds for bus lane, non-bus lanes, and mixed traffic lanes. The models consider a

number of variables, including bus volume, non-bus volume, right-turn volume, bus stop location, bus stop density, use of bus bay, number of bus berths, mean dwell time, green ratio, cycle length, signal offset, and number of lanes. The regression models for arterial bus lanes were evaluated by comparing the results with those reported in HCM 2000 and the TCRP Report 26. The results were found to be surprisingly close.

## **7.2. Findings**

### **7.2.1. Freeway HOV Lanes**

It was observed from the freeway bus speed models developed in this study that:

1. Average speeds can best be described with an exponential distribution. At low volumes, the speeds decrease slowly. At higher volumes, the speeds decrease at an increasing rate. These results are consistent with those of the HCM and the BPR formula.
2. Unless bus volumes are sufficiently high, the impact of bus volumes on average bus-lane speeds is negligible. This suggests that a bus-only lane usually has extra capacity that can be used by other high-occupancy vehicles.
3. When carpools are allowed to share a preferential lane with buses, the preferential lane speed will be impacted, depending on the number of carpools. The decision model developed can be used to determine an appropriate carpool occupancy rate such that the bus speeds are not adversely affected.
4. The CORSIM simulation model produces freeway passenger car equivalence for trucks and buses that closely approximate those in the HCM.
5. The relative impact of different types of vehicles on a mixed-lane freeway was found to come within the range of vehicle equivalent factor reported in the HCM.

### **7.2.2. Arterial Bus Lanes**

Regression models for bus and non-bus speeds are given in Tables 6-3 and 6-4. The performance of a wealth of bus lane planning and design scenarios may be estimated from these models. A partial examination of the relationships from these models resulted in the following findings:

1. In general, the presence of a bus lane improves bus speeds. The improvements are larger at higher non-bus volumes. When there is a bus lane, bus speeds are not affected by non-bus volumes at low bus volume. At higher bus volumes, bus speeds are slightly affected by non-bus volumes. When buses travel in mixed traffic, their speeds are reduced by increasing non-bus volumes.
2. Non-bus speeds decrease with increasing bus and non-bus volumes. When a bus lane is present, non-bus speeds are not affected by an increase in bus volumes. However, in

mixed traffic, non-bus speeds are significantly affected by bus volumes, which suggests that lane separation is beneficial.

3. The location of bus stops can have an impact on bus speeds. At low bus volumes, the difference in bus stop location is less significant. At high bus volumes, far-side bus stops are superior to near-side or mid-block bus stops.
4. Conflicts between buses and right-turning traffic are greatest for near-side bus stops. The effect of right-turn vehicles on bus speeds are negligible for mid-block bus stops at low bus volumes, but are significant at higher bus volumes. Bus speeds are essentially unaffected by right-turn vehicles when the bus stops are located at the far-side.
5. The use of bus bays for far-side bus stops do not have an impact on bus speeds. The use of bus bays for near-side bus stops significantly improves bus speeds.
6. The number of bus berths has the same impact on bus speeds regardless of bus volumes and bus stop locations. Bus speeds significantly improve with increasing number of bus berths.
7. Increasing stop spacing (or reducing stop density) on arterial streets is highly beneficial to both bus speeds and non-bus speeds.
8. Minimizing bus dwell times at bus stop can greatly increase the speed of buses. Accordingly, the use of passes or fare cards, pay-as-you-leave fare collection, prepayment of fare, multi-channel doors, and low-floor at busy bus stops, are potentially beneficial.
9. Cycle length does not have a significant impact on bus and non-bus speeds. On the other hand, the green ratios for arterial through movements have a major impact on bus and non-bus speeds. This is true whether there is a bus lane and/or a bus bay.
10. Since signal offsets are calculated based the speeds of non-bus vehicles, they have no significant impact on bus speeds, regardless of whether there is a bus lane. When a bus lane is present, signal offsets have a significant impact on non-bus speeds. The impact is reduced when buses are mixed with non-bus traffic, suggesting that the presence of buses in the platoon makes progression harder for the non-bus traffic.

### **7.3. Recommendations**

This research represents the only known effort that attempts to develop quantitative models for justifying bus lane design alternatives based on the average person travel time for all road users. The scope of the study was constrained by the amount of time required to perform the large number of simulation runs, and to a lesser extent, the available modeling features of the simulator used. Consequently, a number of design alternatives and factors have not been included in this study. Specifically:

3. The freeway simulation models assume that the HOV lane is located on the leftmost lane, that the impact of on- and off-ramp traffic is minimal. Further studies may attempt to develop models for other configurations of HOV lanes, including the use of the rightmost lane, barrier separation (zero violation rate), and contra-flow lane.
4. The arterial models may incorporate the impact of different signal priority strategies, including queue jumper, that are gaining increasing interest in both traffic and transit communities.

Although the coefficients of the regression models show logical relationships among all the variables considered, the model validation was somewhat limited. Future studies may attempt to further refine and validate the simulated results as more field data and reports become available. The work completed in this research should have laid the groundwork necessary to perform additional studies. Although the models developed in this research are strictly based on the operational efficiency of design alternatives, other important factors such as safety experience must eventually be considered in practice. Studies that look into the safety of various preferential facilities would be beneficial.

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