IMPACT OF EXCLUSIVE BUS LANES ON TRAFFIC PERFORMANCE IN URBAN AREAS

by

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Dedication

This thesis is dedicated to my parents, uncle, sister, and brother. It is also dedicated to those who provided feedback through reading, improving or editing this work. With their continuous support, I am able to achieve my goals.

Abstract

In recent years, increased traffic congestion and shortage of available funds to build new roads have created a challenging situation. One of the possible solutions to this challenge is to manage the transportation infrastructure to operate at its maximum capacity. Sharjah, United Arab Emirates, has recently started its public transportation system, which is still under development. With the anticipated growth rates within the urban areas of Sharjah, there is a need for an efficient public transportation system. One of the possible approaches to improve the bus transit system performance in Sharjah is exclusive bus lanes (XBLs). Implementing XBL has been recognized as an effective strategy in the field of urban traffic congestion mitigation. This thesis provides a parametric study to investigate the impact of XBLs on urban road network performance under different traffic conditions using micro-simulation software, VISSIM, which is utilized to simulate different traffic scenarios. This thesis considers different traffic parameters such as demand-to-capacity ratio D/C, traffic turning percentages (through and left), bus headway, and bus direction. Results show that the XBLs are effective at D/C ratio of 0.80 or more. They also indicated that as the percentage of vehicles taking left turns decreases, the improvement percentage of the buses' travel time, intersection delay, and average speed increase and vice versa. XBLs were effective for the buses turning left for D/C ratio of 1.15 of the main road. The bus headway of 10 minutes had the least improvement percentages of the buses intersection delay for all D/C ratios while the bus headway of 15 minutes had the best improvement percentage of the buses' intersection delay for D/C ratios of 0.95 or less. The bus mode share that achieves the most benefit of the XBL is in the range of (10% - 15%) and (27% - 29%) for D/C ratios of 0.95 and 1.15, respectively. Furthermore, the performance of vehicles in adjacent lanes sacrificed after the implementation of XBLs for all D/C ratios and the average deterioration percentages of vehicles' travel time, intersection delay, and average speed are -5%, -11%, and -5%, respectively.

Search Terms: Exclusive bus lane, Travel time, Delay, Average speed, Mode choice.

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Chapter 1: Introduction

1.1 General Introduction

In recent years, most of the cities in UAE, especially Sharjah, have been experiencing a significant increase in private vehicle use and slow development of infrastructure. As a result, the problem of urban traffic congestion has become a serious phenomenon. One of the main reasons that led to this problem is the limited growth of the transportation system supply which does not match the increase in travel demand. Simply, enhancing the road capacity by adding extra lanes or adding some infrastructures (bridges or tunnels) cannot satisfy the rapid growth of travel demand. Changes in land use and travel behavior encourage the use of private vehicles. Enhancing the infrastructure of a transportation system as intensive augmentation is usually expensive. Therefore, alternative solutions to mitigate traffic congestion are needed. One of the common approaches to reduce traffic congestion is to increase the mode share for public transportation, which can be achieved through some system modifications, such as transit signal priority and XBLs. Such system modifications may help in reducing the number of vehicles on the road and reducing the total travel time in the urban road network [1, 2].

This research focuses on the use of XBLs as one of the most widely-used applications to improve the bus system performance. An XBL is a designated lane from the road to be used exclusively by public buses. Figure 1 illustrates an example of XBLs.

Figure 1: Exclusive Bus Lane, XBLs, [3]

Exclusive bus lanes became part of the advanced sustainable multimodal transportation systems, in many cities around the world, and are considered an efficient and effective way to address urban congestion problems. In addition to that, XBLs are regarded as an effective approach to mitigate urban traffic congestion and reduce air pollution, as they result in less road space per capita and higher average occupancy per vehicle leading to a higher efficiency of the road network. Bus service quality in terms of travel time, delay, and average speed are well secured by XBLs in most cases.

In practice, XBLs have been implemented in a number of cities to reduce bus travel time and improve the bus system reliability and accessibility. However, a lane taken away from the road and designated as an XBL would create more congestion on adjacent lanes for the other vehicles, particularly during peak periods.

1.2 Problem Statement

The city of Sharjah, United Arab Emirates, launched a new public transportation system which is still under development. However, public buses operate in the context of existing traffic jams and mixed traffic conditions, which results in very high travel time and delay for the bus service. Accordingly, the bus system is not attracting a reasonable percentage of the travel demand within the city. One of the factors that can improve the bus performance is the use of XBLs.

On the other hand, there has been a very high increase in the private vehicle ownership in Sharjah over the past few decades. As the right of way is limited, the significantly high number of vehicles results in excessive traffic congestions and delays. The bus system in Shrajah is expected to grow significantly to match the growth in travel demand. As a consequence, there is a need to evaluate the effectiveness of using XBLs on urban road networks. This research attempts to further address this issue by conducting a parametric study to evaluate the impact of XBLs on the performance of urban traffic networks and measure the effectiveness of XBLs while considering their possible effects on the surrounding traffic (private vehicle) conditions. Also, it provides some guidelines to improve the performance of the bus system.

1.3 Research Objectives

The goal of this study is to analyze and evaluate the effectiveness of XBLs on the traffic network. The main objectives of this research are to:

1. Evaluate the impact of introducing the XBLs on urban arterial roads, for different roadways and traffic conditions.
2. Quantify the impact of different parameters on the performance of the XBLs.
3. Determine the market share for buses, at which the XBLs will be effective.

1.4 Significance of the Research

The rapid growth of private vehicle ownership in the United Arab Emirates especially, in Sharjah, has caused a proportional growth in the transportation system. As the available infrastructure (roads, bridges, and tunnels) space is limited, the increase in the number of vehicles resulted in severe traffic congestions. Also, the lack of well-structured public transportation systems in terms of coverage area, schedule adherence (reliability), and priority, which result in a large number of private vehicles entering the transport market to meet the travel demand [4]. Thus, there is a need for deploying efficient bus priority schemes such as XBLs to relieve traffic congestion and improve traffic quality. However, enhancing the performance of XBLs will usually cause unfavorable traffic conditions for private vehicles' users [5]. Therefore, there is a need to have some guidelines for the successful implementation of XBLs while maintaining a sustainable traffic system. To reach an optimized stage, it is necessary to build a balanced system through establishing XBLs based on full investigation of their impact and performance on the traffic network [1]. However, the impact of providing an XBL on adjacent traffic is not always reported at the same level of detail as in this study. The scope of the current understanding of XBLs in the UAE is still limited in terms of its impact on traffic performance. As a consequence, this research has the potential to investigate and analyze the advantages as well as the disadvantages to achieve better an XBL design. This work investigates the various effects of deploying XBLs on a traffic network in terms of travel time, intersection delay, and average speed for buses and other vehicles on adjacent lanes.

1.5 Organization of Thesis

The manuscript is organized into the following chapters:

- ***Chapter 1: Introduction.*** Gives an overview of the topics that form the background of the research, and sets out the context and aim of the thesis.
- ***Chapter 2: Background.*** Presents a literature review on the types, evaluations and considerations of exclusive bus Lane (XBL) applications.
- ***Chapter 3: Experimental Design.*** Describes the experimental design of this research, which provides a description of the background of the parametric study model and defines the traffic parameters and simulation scenarios studied in this research.
- ***Chapter 4: Modeling Environment.*** Explains the micro-simulation software, VISSIM, measures of effectiveness, the code of the scenarios, and the mode choice made for the evaluations.
- ***Chapter 5: Results and Discussion.*** Presents the results and analyses from these evaluations on the XBLs' impact and effectiveness.

  Chapter 6: Conclusions and Recommendations. Provides the main key findings and general suggestions for future studies.

Chapter 2: Literature Review

The effects of implementing XBLs on urban traffic performance are frequently researched by scholars. Several studies and papers have been published to investigate before and after studies, compare different XBL applications, and identify the performance measures of XBLs on urban street networks in different parts of the world. The results tend to be mixed between successful and unsuccessful implementations of XBLs. Due to unsophisticated technology and unavailability of robust software in the early 1970`s, before and after studies were conducted. However, some of the before and after studies were carried out recently as well. After that, some software programs were developed to model the impact of XBLs among different traffic operational conditions. The development of these advanced tools made it more feasible for researchers to evaluate the impact of XBLs through computer simulation. In addition, to achieve environmental sustainability, the economic effects of installing XBLs on energy savings in terms of fuel consumption efficiency are also researched in only few published papers. The following subsections discuss four main groups of research, namely, research developed based on before and after studies, on utilizing computer simulation, on parametric studies, and on economic evaluations.

2.1 Before and After Studies for the Implementation of XBLs

Erdman and Panuska [6] conducted a study to investigate the impact of XBLs on a two-directional roadway with two lanes in each direction in the Baltimore metropolitan region. Although the commuters' total trip time using the automobile increased and the commuters' bus total trip time decreased after the implementation of the XBL, it was found that the average travel time for the majority of commuters during the morning peak using the XBL instead of automobile was 50 percent longer. The average time did not include the waiting time at the bus stop or the travel time from home to the bus station. The authors concluded that the XBL had a negative impact for both automobile and bus movement. Similarly, Sarin et al. [7] studied the effect of XBLs when the system was first introduced in Delhi, India, in 1976. The study discovered that the system failed to save travel time due to the lack of enforcement of the system and the non-compliance to the XBL's rules and regulations by commuters. As a result, the system was discontinued in 1981.

In contrast to the studies that showed a negative impact of XBLs, Cox [8] performed a study to evaluate XBL designs that were implemented in the city of Dallas. The results revealed that the bus reserved lanes had no effect on the level of service of other vehicles, the travel time for buses was reduced, and the speed of buses was increased. Moreover, the enhancement in level of service after adding XBLs had encouraged more commuters to use the buses. Similarly, Rouphail [9] performed a study to investigate the effect of bus priority strategies on the operation of traffic networks in two cases in simulated traffic environment: one with XBLs and the other with no XBLs. Two types of strategies were studied (1) contra-flow bus lanes which are located on a downtown street and (2) signal settings that depend on the minimization of passenger delays instead of vehicle delays. The study was conducted on a Chicago downtown street where a contra-flow bus lane was installed and the operational setting reflected actual observations in the summer of 1980. The outcomes showed that the bus performance operation enhanced dramatically because of the use of XBLs as well as the improvement in the observed overall speed on the bus lane.

Tanaboriboon and Toonim [10] conducted a study to identify the effect of bus movement and vehicle traffic due to the condition of with-flow bus lanes on selected streets in the central part of Bangkok, Thailand. The results indicated that bus travel time savings had a wide range, from 0.11 to 1.66 minutes on all selected streets, equivalent to an improvement percentage of 0.7% to 23%, respectively. Similarly, Wasten et al. [11] conducted a study to evaluate the contra-flow bus lane proposal and to highlight the reasons for considering it with the flow alternative solution. The study objectives were reducing passenger travel time, reducing operating cost, enhancing public bus reliability, and the removal of 80 buses from the congested traffic lanes. The introduction of XBLs and their specific design schemes led to achievement of the main objectives of the study. The successful results of a two month trial of contra-flow bus lanes led to the construction XBLs early in 1987. The study took place in Kwinana city where the XBLs has were constructed on Kwinana Freeway, Perth, Australia.

Shalaby and Soberman [12] tested the impact of the provision of reserved bus lanes on bus travel times on individual segments of the road. The results proposed the possibilities of using XBLs on a selective segment along a specified road, and the necessity to reconsider whether to allow taxis to use XBLs. Similarly, Katsuragi [13] presented the use of XBLs in Kanazawa City, Japan. The city implemented different schemes to solve the chronic traffic congestion; one of them was XBLs which were implemented in 1972. Unlike other cities, the city of Kanazawa allowed the use of XBLs by high-occupancy vehicles (HOVs) as part of its solution to reduce traffic congestion. After two years of implementation, the city approved the HOVs to use the XBLs with an occupancy of 4 passengers or more. This occupancy increased the number of vehicles that used XBLs by 17.9% and did not hinder bus operation. However, an occupancy of 3 increased the number of vehicles that use XBLs by 59.3%, which jeopardized bus operations.

Choi et al. [14] conducted a study in South Korea and showed the bus travel time was considerably reduced. The shift in mode from car to bus was expected to be more than 12% and the commuters' accident rates were reduced as well. Similar positive effects were reported by Kim [15] who performed a study to evaluate the impact of XBLs in South Korea. His work showed that XBLs were successful in enhancing the performance of average buses in terms of relative speed compared to other adjacent traffic. Similar results were reported by Wei et al. [16] who conducted a study to evaluate the performance before and after 2 years of operation of XBLs when it was first implemented in Kunming, China, in 1999. The study revealed that the average speed of buses increased significantly, from 9.6km/h to 15.2 km/h (about 58%). A different approach was presented by Karim [17], who evaluated the effect of XBLs on the travel time of other modes using the floating car technique. The outcomes indicated that the average travel time for other vehicles significantly increased after the implementation of an XBL during the morning and evening peak hours.

Ismail et al. [18] conducted a study to compare the performance of two bus routes that pass through two sections: mixed traffic lane and XBL. A real-life case study using intercity bus operation data was conducted. The outcomes concluded that the delays that the bus experiences in the mixed traffic lane can be significantly reduced by using XBLs. Also, the decline in bus speed during mixed traffic can be avoided through the application of XBLs.

Yamada [19] presented the effect of bus service schemes such as XBLs, bus priority signals, bus bays (designated spot on the side of a road), and a bus location system which combined into a key route bus system. The system launched for the first time in 1982 on the Toko Line, then in 1985 on the Shin-Dekicho Line, in Nagoya. Because of the features of XBLs and bus priority signals, the system operates at a faster speed than ever and it was noticed to have reliable schedule adherence. Therefore, the system became very attractive to passengers. The effects of the key route bus system on the passenger demand are summarized briefly. Then the data collected from the Toko Line was used to analyze the effect of bus service level on the passenger demand. The mode choice is predicted by the use of a disaggregate model and time and cost are calculated. The results showed that the service level in terms of line-haul (in-vehicle time and line-haul cost) has greater impact on bus passenger demand than the effect caused by access time or cost.

To sum up, bus priority schemes such XBLs are implemented as traffic congestion solutions to enhance bus performance. Some of the reviewed papers showed that XBLs are not effective such as [6, 7], while others clearly state that XBLs enhance bus performance in terms of travel time, travel speed and delay [8, 9, 15, 17]. Other researchers discussed the possibility of allowing taxis and HOVs to use XBLs [12, 13]. However, there is no consistent trend in the literature that confirms the improvement of bus performance. Also, most of the papers generalize the enhancement in bus performance after the implementation of XBLs without reporting values except for [16]. In this research, the improvement percentage of the bus performance in terms of travel time, intersection delay, and average speed have been reported under different D/C ratios.

2.2 Evaluating XBLs Through Simulation

Levinson and Sanders [20] developed a person delay model that examines the feasibility and practicability of implementing an XBL on freeway bus lanes in urban areas. The model considered the peak hour trips on a six-lane, two-direction highway. The model help to determine the number of buses needed to justify adding an XBL and represents a tool to allow urban transportation planners to determine the feasibility of XBL operations on urban freeways. Similarly, Pogun and Satir [21] conducted a study to show the development and investigation of the alternative dispatching and route policies for XBLs. The system was categorized by the number of passengers generated and shows the geometric features of the lane. In order to evaluate the new dispatching and routing polices, a micro-simulation model, representing the operational conditions, was developed. Also, the model introduced alternative dispatching and routing policies. Dispatching policies were introduced in terms of dispatching headway for each route by the use of XBLs. Route policies are expressed with respect to bus stops served, while focusing on the ring and express services. Four types of performance measured were introduced to evaluate and compare between the developed alternative policies.

Alpern and Gersten [22] conducted a study to evaluate the use of XBLs in New Jersey. Freeway simulation software (FREQ8PL) was utilized to investigate the feasibility of the proposed exclusive bus lanes. Optimizing the use of bottleneck capacity has been emphasized as one of the results. It also showed that the priority lane must start before the end of the queue of other vehicles. The FREQ8PL model has some limitations such as not accounting for reduced processing capability at blocked on-ramps. To overcome this problem, an external spreadsheet procedure was developed to adjust the ramp volume. Similarly, Shalaby [23] utilized the TRANSYT-7F simulator to identify changes and to investigate performance measures of implementing an XBL on an urban arterial in downtown Toronto, Canada. The outcomes showed that the implementation of XBLs was successful in enhancing bus performance as well as increasing the number of bus ridership and reduce the volumes of commuters in adjacent traffic.

Currie et al. [24] suggested a reasonable scope of work for roadway space reallocation related to transit priority. A simulation model was applied to identify the performance measures of transit priority. The main goal of the study was to identify a wide range of travel time, environmental, and social impacts of the implementation of transit priority while making sure its implementation had a positive net impact. The results revealed the important benefit the buses gained in terms of less travel time, especially at high traffic volumes after the implementation of the bus lane. In their latest study [25], they introduced a methodology to evaluate trade-offs in the use of the limited road space in Melbourne, Australia for new bus and tram priority projects. The approach implemented a micro-simulation traffic model to evaluate road space re-allocation effects, a travel pattern model to evaluate changes in travel behavior, and a social cost-benefit scope to assess effects. The outcomes indicate that the priority rule is viable as low proportion of the results showed positive net economic gains after introducing bus schemes. Also, the public bus priority is more viable and has higher net positive economic returns when the bus has a high level of frequency and the traffic volume is low.

Gan et al. [26] established a decision model that could be used to evaluate the operational performance to justify the use of XBLs on an arterial street. The model takes into account overall average person travel time under two different scenarios: with and without a bus lane. A micro-simulation model was developed by CORISM to estimate the bus and non-bus travel speeds under different scenarios of prevailing traffic conditions like bus volume, non-bus volume, right-turn volume, bus stop location, bus stop density, presence of bus bay, number of bus berths, mean dwell time, green ratio, cycle length, signal offset, and number of lanes. The output was considered instead of field data in an empirical modeling of relationships between travel speeds and the prevailing traffic conditions. The speed model was used to calculate person travel time under different XBL scenarios and prevailing conditions. The model proved its reliability by producing speeds that were closely matching to those reported in the previous literature under the given input situations. Similarly, Mori et al. [27] used a simulation model called NETSTREAM to assess the use of XBLs on the Nagoya-Seto Expressway, which is the main expressway link from the Tomei Expressway in Japan. The implementation of exclusive bus lanes was proposed during the Expo of 2005. After the implementation of XBLs, the travel time decreased from 30 to 26 minutes which resulted in almost a 13% improvement.

Chen et al. [28] carried out a study to examine the effect of XBLs and transit signal priority (TSP) on bus rapid transit (BRT) in China. A micro-simulation analysis was created based on extensive field data collection. The study considered the first segment road of the North-South Central Axis BRT system in Beijing as the case study where Vissim was used to model different scenarios such as median bus lane versus curb bus lane, with versus without TSP. The analysis showed that XBLs and TSP have a significant impact on the operational performance of BRT if both are implemented simultaneously. Also, they studied the effect of XBLs when they are separated from the other lanes by physical infrastructure such as median bus lane or curbside, in which each type has different impacts on the traffic flow on the roadway and traffic flow on the intersection. After the implementation of TSP, the traffic flow conditions improved considerably along the BRT route.

Arasan and Vedagiri [29] tested the effect of introducing XBLs on a highly heterogeneous traffic flow on urban roads using a computer micro-simulation model called HETEROSIM, in Indian cities. The effect of XBLs was measured in terms of reducing the speed of other categories of vehicles. The results indicated that if the XBL is implemented under highly heterogeneous traffic conditions, then the maximum allowable volume-to-capacity ratio that will guarantee a level of service (LOS) C for the traffic flow including all vehicles users, except the buses, is about 0.53. In a later study [30], they proposed a method to modify and adjust a micro-simulation model of heterogeneous traffic flow and to study the effect of implementing XBLs on urban roads. During this study, the procedure for modification to provide XBLs was defined clearly. The outcomes of the study revealed the possibility to implement XBLs on specified urban roads, and to improve the level of service of the bus without having a great impact on the level of service of other modes of transportation under the prevailing traffic conditions. The study also concluded that the implementation of XBLs will enhance the level of service of the buses and this result may also lead to a mode shift from passenger vehicle to bus, for some users. The study also considered the estimation of the probability of the mode shift from vehicle commuters to bus commuters because of the enhancement in level of service after the installation of XBLs. A mode choice probability curve was developed to account for the probable modal shift from vehicle to bus. This mode choice curve uses the difference in travel time between the two modes to work as a user-friendly tool to forecast the possible modal shift for the variety of variables involved. Recently, a group of researchers conducted a study to validate and modify a micro-simulation model of heterogeneous traffic flow to investigate the impact of the XBL on urban roads. The study was carried out in India under specified road geometric features and traffic conditions such as typical eight lanes divided urban road with a width of 14.5 m per direction. The effect of introducing the XBLs was measured in terms of reduction in speed of motor vehicles. The results showed that the maximum allowable volume-to-capacity ratio that will guarantee a level of service of C for the traffic flow including other vehicles is about 0.62. The average speed of the bus is about 65 km/h. At capacity, the reduction in travel time for the XBL is almost 70% and for other vehicles, the increase in travel time varies from 3 to 8% [4].

Yu and Kun [31] studied the effect of implementing XBLs by establishing an evaluation model to assess the traffic efficiency adaptability of bus lanes in Guangzhou, China. The study considered intersection delay, capacity, saturation flow, and link travel time as indices for adaptability evaluation. It evaluated the impact of XBLs on both intersections and road sections using the methods of the Criterion of Urban Road Design in China and the Highway Capacity Manual from America. The results showed that the arrangement of XBLs will help to increase travel speed of public buses on the road section as well as improve passenger capacity, which is obviously much higher than vehicle capacity, and bring indirect benefits such as relieving traffic jams which will improve the traffic environment and reduce pollution. Similarly, Biao and Qing-fang [32] proposed an evaluation method to compare traffic efficiency before and after the implementation of XBL on an intersection. The micro-simulation software VISSIM4.30 was used to model an intersection, in Changchun city, to verify the proposed method. In order to eliminate the effect of right turning vehicles, it was assumed that no vehicles were turning right. The simulated results indicated significant improvements as the average bus delay was reduced by 31.6% and the travel speed increased by 45.2% from 8.4 km/h to 12.2 km/h. The number of buses did not change before and after the installation of bus lane, so if the travelers' mode choice shift is considered, the traffic enhancement is expected to be more.

Li and Ju [33] evaluated the implementation of XBLs by applying a multimode dynamic traffic assignment (DTA) model. The multimode point–queue model was used to present the relationship between cars and buses under two scenarios: network with and without XBLs. A variational inequality (VI) formulation was proposed to capture the travel behaviors of mode choices, departure travel time choices, and path choices. The measures of effectiveness (MOEs) such as travel cost, bus passengers and queue length are proposed to compare the performance of the network with the two scenarios: with and without bus lanes. The outcomes showed that the XBLs have direct benefits to the network such as reducing total system time, total system cost, and total bus queues.

In this section, different methods were used to assess the impact of XBLs on the traffic network performance such as [22, 23, 26, 27]. A number of case studies around the world are considered and different traffic parameters are introduced [28, 29, 31]. Most of the researchers generalized the positive impact of XBLs on the bus performance except [27, 30, 32]. However, most of the results from the reviewed papers did not clearly state at what D/C ratio XBLs are effective and did not include the effect of traffic turning percentages on the performance of XBLs which is one of the focuses of this research.

2.3 Parametric Studies to Evaluate XBLs

Ardila and Rodríguez [34] proposed different parameters to enhance the performance of XBLs of in Bogota´, Columbia. The system was estimated to handle up to 28,000 passengers per hour per direction (pphpd). However, a passenger count reported that more than 35,000 pphpd were using XBLs. Even though the system suffered from poor operational conditions, little police control, no system management, and scarce information for users, high passenger flow was achieved. These conditions should reflect negatively on passenger flow of XBLs. Bogota´ XBLs carry more passengers than all bus ways. The study suggested that Bogota´ XBLs have the ability to move more passengers because of three factors. First, the bus operation agencies provide more incentive for bus drivers to work effectively. Second, they use a new geometric design which provides two lanes to allow other vehicles to overtake as well as a station that allows six buses to alight/deport passengers. Third, the buses move in platoons along the XBLs. The platoon has a number of buses (from 12 to 16) with an average headway of 96 seconds. In addition to that, time-distance diagrams showed that the platoons are not stable because drivers keep moving from one platoon to another. The study emphasized the trade-off between passengers flow, level of service, and system operation.

Yang and Yin [35] performed a research to study the effect of locating XBLs on its performance; the two common locations are curb lane and median lane. The study used average delay for buses under different traffic conditions as a measure of effectiveness to compare between these two locations. In addition to that, the paper evaluates the two types of locating bus stops: nearside and far-side bus stops for the median bus lane. After the establishment of the model of the bus average delay and simulation analysis, the optimal location of bus stops is determined through the use of a micro-simulation model.

Dong et al. [36] proposed a model to study the impact of setting up XBLs in urban areas by examining the essential principles of service level improvement with the constraint of travel time reliability. The objective function was to minimize the setup cost of bus lanes. The model used a bus line in Singapore as a case study to validate the model. Similarly, Yao et al. [2] used a bi-level model approach to analyze the combinational optimization problem of XBLs with variable bus frequencies in multi-modal transportation networks. The upper level objective function was an optimal decision-making program for setting up exclusive bus lanes and bus frequencies. The lower level was a multi-modal transportation network equilibrium model. The objective function was to minimize the transit operating costs and the sum of the road users' travel costs. The results indicated that the performance of the combinatorial optimization scheme becomes better with more traffic demand, while the operating efficiency of the transportation system can be reduced by oversetting the XBLs. A similar study was presented by Meng et al. [37], who considered a study to solve an integrated problem of selection and scheduling of XBLs. The selection problem was to decide which roads should have XBLs while the scheduling problem is to decide the best time phase of the day. A bilevel optimization model was formulated to minimize the traffic total travel time with and without an XBL. The outcomes confirmed that a trade-off between other traffic and buses is necessary to improve the system when an XBL is installed. This provides the opportunity to traffic engineers to select the best alternatives that can improve the performance of the system with a multimode transportation system environment and achieve a sustainable operation.

Zhu [38] conducted a numerical study based on a cellular automata traffic flow model and the concept of public transportation priority. He proposed a two-lane traffic model and studied the properties of urban traffic flow. The fundamental diagram of velocity-density profiles was developed. The results showed that XBLs have the advantage of releasing buses from the traffic and the disadvantage of disturbing other traffic. Also, it pointed out that XBLs are more suitable for low traffic flow in a two-lane traffic system. This limitation can be solved by opening the bus lane for the road users when the bus lanes are not in use by buses. Similarly, Zhou and Peng [39] investigated the impact of using XBLs on urban traffic flow. A two-lane cellular automata simulation model was established under the periodic boundary condition. The characteristics of traffic flow were tested by performing the analysis of the velocity-density and flow-density diagrams. The conclusions of their study indicated the importance of bus lanes to significantly improve traffic flow.

Xia et al. [40] performed a study to analyze the influence of XBLs on traffic operation at an intersection. A simulation model was used to analyze vehicle total delay, vehicle average delay, passenger total delay, and passenger average delay by assigning the bus lanes at different settings. VISSIM software was utilized to simulate the traffic operation at an intersection in Changsha, China. The results indicated that bus performance was enhanced in terms of time, and the vehicle delay and passenger delay decreased after the implementation of XBLs at the intersection. The experiment proposed a reasonable way of setting bus lanes on the intersection to improve traffic operation.

Chen et al. [41] performed a capacity analysis of an urban signalized intersection in China. The considered intersection has median bus lanes with midblock stop. Four factors were considered: green-to-cycle time ratio (g/C), ratio between through and right turn volume, distance between the end of the bus lane and stop line of the intersection, and number of right turn buses. A micro-simulation model powered by VISSIM was developed to simulate general traffic. Varieties of field data are collected such as geometric configurations, traffic characteristics, traffic signal control, and transit information used as input to the model. The configuration of the studied intersection is shown in Figure 2. The results from the simulation model were compared with results obtained from another analytical model, and validated against field data. The validation process showed a reasonable match between the simulation results and field data, with a relatively small error.

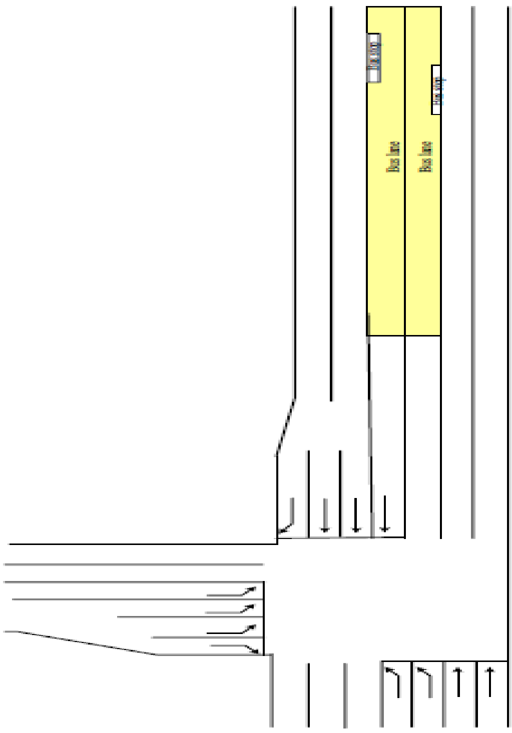

Figure 2: The studied intersection with median bus lane [42]

In a later study [42], a methodology was proposed to analytically estimate the capacity of an urban expressway section with median XBL in different locations like near off-ramps and on-ramps. Three factors were considered which have an effect on the capacity: bus exiting and entering flow rate, bus ratio in traffic flow, and bus exiting, and entering length, as indicated in Figure 3. All three factors are examined and their sensitivities with the capacities are found to be high. A microscopic simulation model was developed with an arbitrary section along the third ring road in Beijing with off-ramp and on-ramp. This section is used to make sure that the proposed model is valid because no XBL has been installed on the ring road expressway. Figure 3 illustrates the interactions of different flows for the provision of a median XBL. The right-hand lane is the outside lane where acceleration and deceleration occur near off-ramps or on-ramps. The left-hand lane is the XBL.

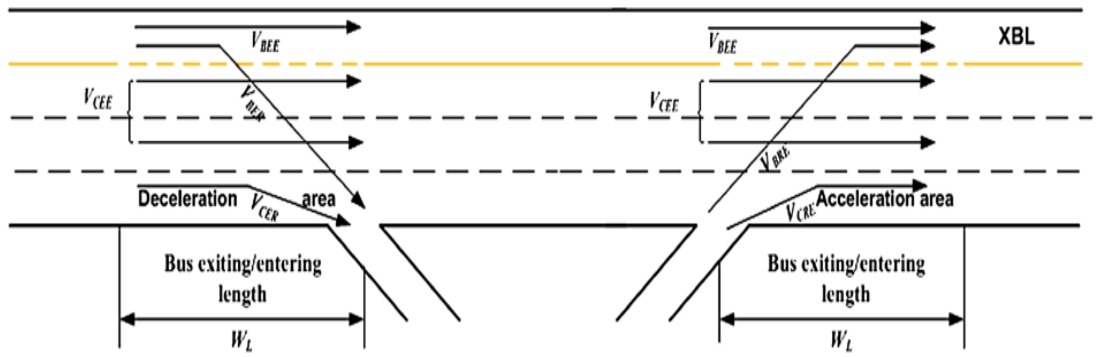

Figure 3: Traffic operations on the urban expressway section near the off-on-ramp under the median XBL [42]

The median XBL was implemented and the capacity was calculated by the proposed model. The capacity values obtained from the proposed analytical model were compared against the results of the simulation and showed close matching with relatively small errors. Another location was used to validate the proposed method and compared with collected field data, in which the results also showed small errors. So, the methodology provides a reliable estimation of the capacity of an urban expressway section with a median XBL with near off/on-ramps.

Similarly, Chen et al. [43] developed a micro-simulation model to study the capacity issues at multiple weaving areas on an urban expressway in Beijing with the implementation of XBLs. Three types of XBL configurations were considered as shown in Figure 4. They include median bus lane with off- and on-ramps [Configuration (a)], curbside bus lane with on- and off-ramps [Configuration (b)], and curbside bus lane with off- and on-ramp configuration [Configuration (c)]. Different parameters are considered to design simulation scenarios such as headway, weaving section length, main traffic volume, as well as off-ramp and on-ramp volumes for general traffic. After running the simulation model, the capacity of general traffic on the weaving section is evaluated and the effect of both weaving section length and headway on the capacity is evaluated.

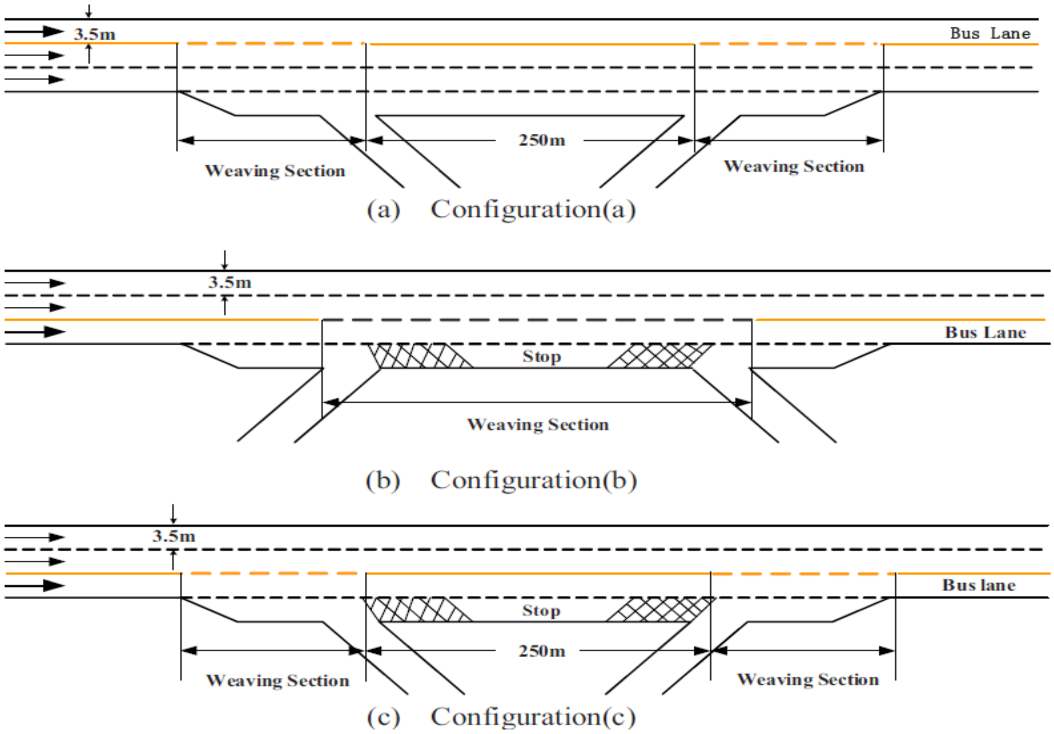

Figure 4: Three XBL configurations [43]

The results revealed that weaving section length and headway have different impacts on the capacity of general traffic for the different XBL configurations. Additionally, the results indicated that both weaving section length and headway have more of an effect in the on- and off-ramps scenario than in the off- and on-ramps scenario with the curb bus lane configuration.

Wang and Li [44] mainly concentrated on the use of additional capacity of XBLs by other vehicles during peak hours as well as on reducing traffic congestions to control and balance road recourses between bus lanes and adjacent lanes by the use of the principle of public transportation priority. The system is monitored by a traffic control center, which takes the responsibility of transferring dynamic information and modifying dynamic bus lanes. In order for the allowed vehicles to use the facility of XBLs, the vehicles must meet the requirement which is not being part of illegal incidents happened during the last year. During operation, only HOVs with more than three passengers are allowed to use the facility of XBLs. The results showed that almost

20% of vehicles are allowed to use the additional capacity of XBLs with an expectation of more than 5% increase in total traffic volume during peak hours. It is also found that this strategy is accepted by 87.5% of car drivers.

In summary, transit priority strategies such as XBLs are widely-used applications to solve traffic congestion and release buses from the traffic jams. Some of the researchers used optimization techniques to prove the validity of XBLs such as [36, 37], others created micro-simulation models using computer software and validated the outputs against field data [41, 42]. The application of XBLs on two lanes was evaluated with limited justification [38, 39]. However, most of the time, no clear pattern in the results of bus performance were reported to show that XBLs are valid everywhere. Also, other parameters were not considered like buses taking left turns, vehicles' performance on adjacent lanes, and road congestion release by the increase of mode share, and at what percentage. All of these parameters are the focus of this thesis.

2.4 Economic Evaluation of XBLs

The previous sections evaluate and investigate the impact of implementing XBLs on the performance of a traffic network under different traffic conditions. However, only a few published studies assess the impact of setting up XBLs on energy saving, enhancement of fuel consumption efficiency, and achievement of environmental goals. Yang et al. [45] evaluated the characteristics of fuel consumption of a bus operating in XBLs and in mixed traffic conditions (regular city streets). Also, they investigate probable causes of inefficiency and identify area for improvements. An on-board emission measurement system (OEM) is used to collect fuel consumption data on a bus, while the bus is in service. The outcomes reveal that the bus in XBLs (1) is more energy efficient when operating in mid-blocks because of the reduction in the level of interaction between the bus and other road traffic and (2) it has a high percentage of idling time because of station and intersection delay. The improvement areas are to enhance energy and operational efficiency; these may include redesign of traffic signals, renovation of bus station design and operations, and eco-driving training for bus drivers. Promoting some policies such as the use of energy-efficient bus fleets at idling time and acceleration/deceleration would be helpful in saving fuel in city operations. Similarly, Fwa and Ang [46] performed a study to evaluate one of the transportation policies that was implemented by Singapore in the early 1970s to reduce traffic congestion and enhance the efficiency of traffic performance. One of these policies was the implementation of XBLs to reduce travel times and improve service reliability of public buses. By the end of 1992, the total road segments used by XBLs reached about 70 km. Two models were used as the basis to evaluate fuel consumption. After the implementation of XBLs, the results showed that the reduction in fuel consumption of buses was in the range of 18.7% to 18.8% in the morning peak hours and 23% to 18.7% in the evening peak hours. On the other hand, there was an increase in fuel consumption for cars, which was in the range of 10% to 12.1% in the morning peak hours and 5.80% to 0% in the evening peak hours.

2.5 Chapter Summary

The evaluation of bus priority schemes in general and XBL strategies in particular has been researched widely in the literature. In this chapter, the evaluation is categorized into four main streams: before and after studies for the implementation of XBLs, evaluating XBLs through simulation, parametric studies to evaluate XBLs, and economic evaluation of XBLs. The first three categories considered the assessment of the buses’ traffic performance evaluations such as travel time, average delay, speed performance, and overall traffic performance. From all the reviewed papers, it is noticed that XBLs reported an improvement in bus performance (travel time, delay, and average speed). This outcome is reasonable because this is the main purpose of any XBL system. However, most of the time, the improvement gained in bus performance is accompanied by deterioration in the performance of the private vehicles in adjacent lanes. Analysis of the overall traffic performance is usually performed to do an overall evaluation of the traffic network by combining the bus improvement and general traffic deterioration. However, no consistent pattern of the change in overall traffic performance is observed in the literature reviewed. Economic evaluation of XBLs can assess projects based on fuel consumption and energy savings by using certain generic models which make XBL projects economically feasible. As the forgoing literature review shows, there is no conclusive evidence that XBLs are effective everywhere in reducing traffic congestion and travel time or increasing travel speed. However, insights are drawn from these studies to investigate how XBLs would impact the traffic flow performance on a typical intersection in Sharjah.

Chapter 3: Methodology

In this chapter, an experimental traffic micro-simulation model (Typical Intersection Model) was created to study the impact of an XBL on traffic network performance. The following sections provide the tasks followed in the methodology of this research.

3.1 Parametric Study

To study the impact of an XBL on the traffic network performance, the Typical Intersection Model was created to represent a typical 4-leg intersection. The following sub-sections introduce the geometric details, signal information, parameters, and simulation scenarios applied in this model.

3.1.1 Geometric details of the parametric study.

A micro-simulation model using VISSIM was created to study the implementation of an XBL on a typical 4-leg intersection. The Typical Intersection Model represents the main road traffic network and local traffic conditions based on the data acquired from Sharjah Road and Transportation Authority (SRTA) with a number of major assumptions such as no U-turn movement on the main road based on the traffic count from SRTA, there is a small percentage of the vehicles making a U-turn movement, no actuation from pedestrian signals because there are no actuation from pedestrian signals in Shajah, fixed signal timing because this is the typical type of signal in Sharjah, and fixed ratio of right turn. The purpose of using the Typical Intersection Model was to isolate the impact of individual traffic parameters by reducing the fluctuation in results due to unrelated factors such as U-turning movement blockages or pedestrian actuations, which may affect the studied parameter's impact from one simulation run to another. The intersection details such as geometric layout and number of lanes of the parametric study are coded in the Typical Intersection Model using VISSIM. The geometric characteristics of the Typical Intersection Model are shown in Table 1.

Table 1: Geometric characteristics of the Typical Intersection Model

	North	South	East	West
Lane width (m)	3.65	3.65	3.65	3.65
Lane Length (m)	350	350	350	1000
Median width (m)	1.5	1.5	1.5	1.5
Through lanes (per approach)	2	2	2	2
Left lanes (per approach)	1	1	1	1
Share lanes (left + through)	1	1	1	1
Storage length of left-turn (m)	125	125	125	125
Right-turn lanes (per approach)	1	1	1	1
Right-turn control type	Free	Free	Free	Free

Figure 5 illustrates the general layout of the Typical Intersection Model in VISSIM while the geometric characteristics of the parametric study before and after the implementing of an XBL are shown in Figures 6 and 7, respectively. In the Typical Intersection Model, one of the traffic lanes is dedicated as the XBL. In other words, the number of lanes available to other vehicles is reduced.

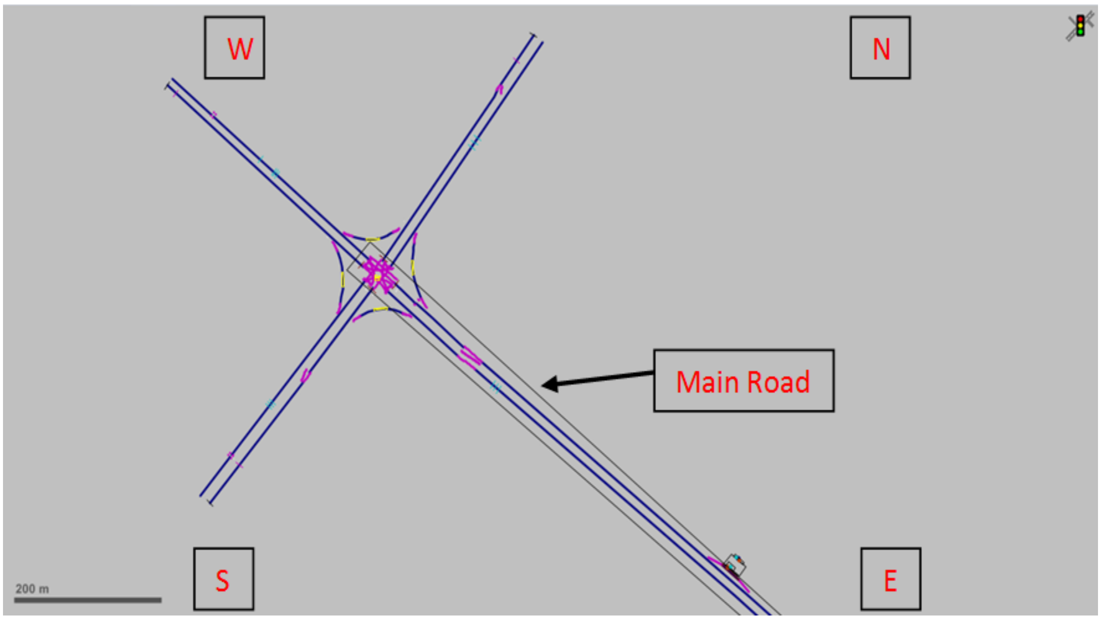

Figure 5: Wireframe layout of the Typical Intersection Model

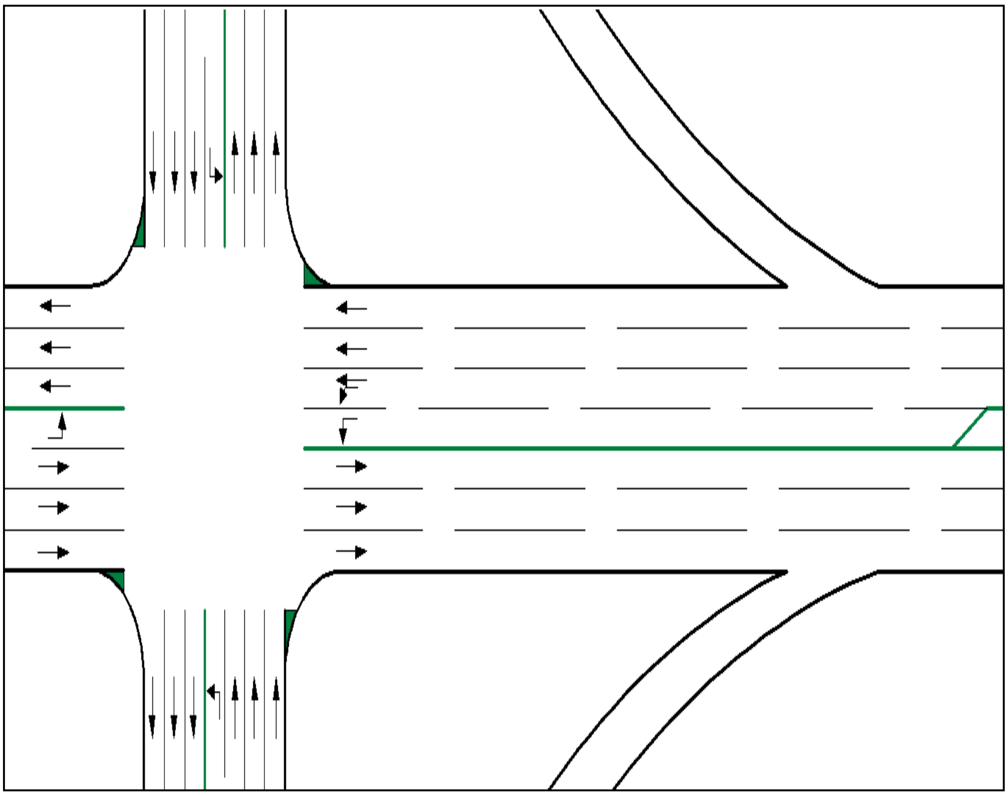

Figure 6: Geometric details of the Typical Intersection Model before implementing the XBL

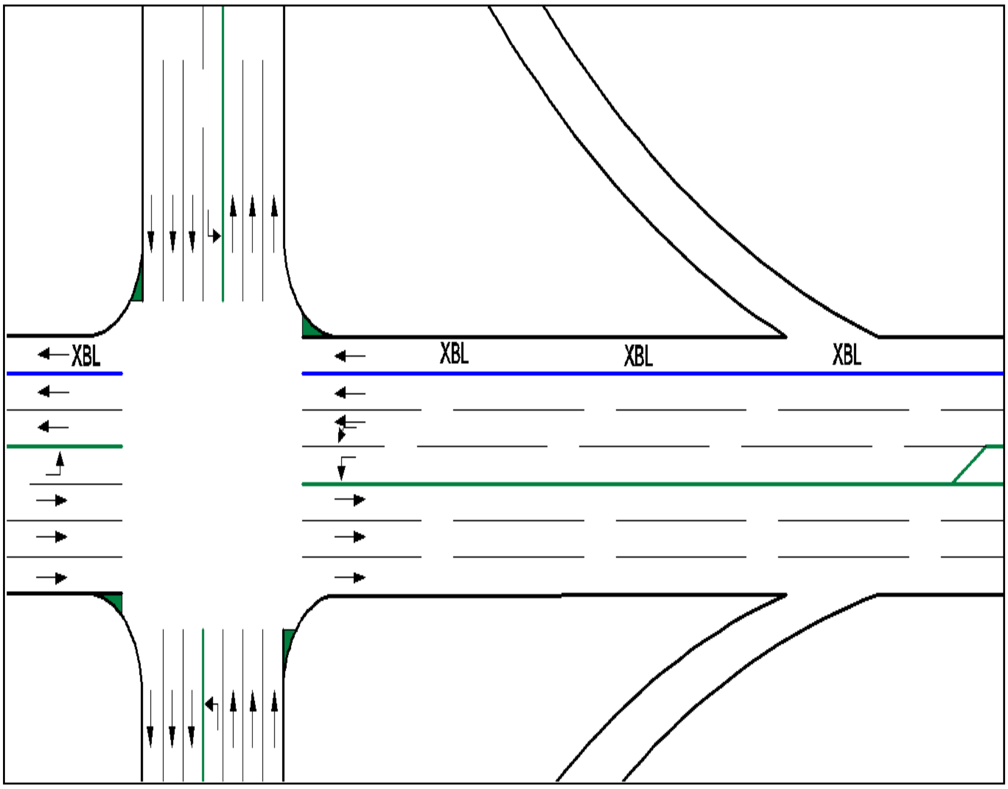

Figure 7: Geometric details of the Typical Intersection Model after implementing the XBL

3.1.2 Signal control.

The parametric study includes one signal timing, which is coded in the Typical Intersection Model. The signal timing and phasing were obtained from Sharjah Road and Transportation Authority (SRTA), as shown in Figure 8. Field measurements were conducted to check their accuracy and were found to be very accurate. This signal has different timing depending on the time of the day in terms of peak hours. The morning peak hours' timing was coded in the Typical Intersection Model.

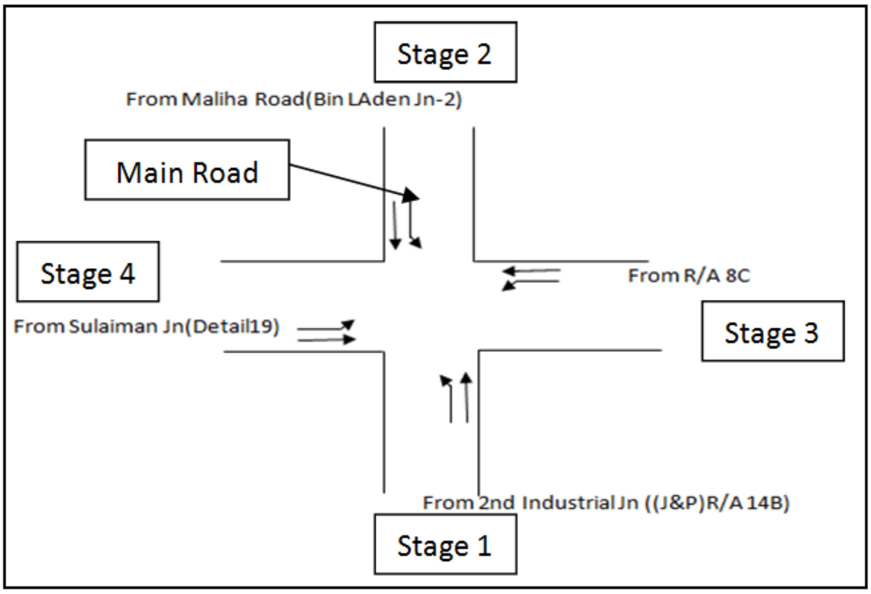

Figure 8: Typical intersection phasing

The signal timing includes the default values of amber and all-red of 3 seconds each per stage and the cycle length is 189 seconds. The signal timing for each stage is shown in Table 2.

Table 2: Signal timing

Stage	Time (seconds)
Stage 1	36
Stage 2	56
Stage 3	21
Stage 4	76

It should be noted that the signal was assumed to have fixed timings in all the simulation scenarios and no optimizations are performed for different volumes to capture the effect of an XBL on traffic performance of the network.

3.1.3 Parameters considered for XBL implementation.

XBLs are designed to provide a dedicated lane for buses on a road segment. A priority strategy, if designed properly, could provide a continuous lane for the buses on the road segment, thereby reducing travel time and delay along bus lanes. However, XBLs may also have negative effect on the general traffic in the road network, adjacent traffic in particular. As a result, consideration of the surrounding traffic environment and the evaluation of all possible XBLs effects should be considered when designing XBLs while maintaining a successful overall traffic performance level.

The application of an XBL was implemented on a typical 4-leg intersection in the parametric study, but it has some association with real-life conditions. In other words, XBL could be successful along one corridor in terms of delay reduction while failing on others, or could be suitable to be applied during specific periods of time. Of note, the success of XBL can be measured by the improvement in traffic network performance. These considerations can be categorized into five main areas:

- Vehicular volumes,
- Traffic movements (left and through flows),
- Bus headways,
- Bus direction; and
- Bus stop location.

Table 3 provides a brief explanation of these traffic parameters.

Table 3: Traffic parameters and definitions

Traffic Parameters	**Definition**
Main Road Volume	Total volume on the main Road (i.e., the E-W arterial corridor where the buses run).
Traffic Movements (Left & Through Flows)	Different percentages will be applied to divide the assumed volume between the left & through flows.
Bus Headway	The average time difference between two successive buses.
Bus Direction	The bus may continue through on the Main Road or go left after the intersection.
Bus Stop Location	The bus stop location with respect to the intersection.

Each of these traffic parameters varies individually to capture its effect on the implementation of an XBL on the typical intersection, described earlier.

3.1.4 Simulation scenarios of the parametric study.

XBLs were evaluated individually by varying the five traffic parameters described in Section 3.1.3. The Typical Intersection Model was created as the base case and the default parameters of the model are described in Section 4.3 and summarized in Table 4.

Table 4: Default parameters for Typical Intersection Model

Main Road Volume	(1011 vph) for westbound and variation for eastbound
Traffic Turning %	10% for right turn, (40%-70%) for through and (50%-20%) for left
Bus Headway	5 – 20 minutes (Base Case), no XBL
Bus Stop Location	Mid-block
Bus Movement	Through & Left Turn

To capture the effect of each individual parameter, the model was adjusted to isolate the effect of each traffic parameter while keeping all other parameters fixed as shown in Table 4. Default values of traffic parameters are used for the analyses unless otherwise specified. As shown in Figure 9, different parameters were considered in the analysis of the parametric study using the Typical Intersection Model, including four different D/C ratios on the main road, four traffic turning percentages, two bus movements, four bus headways, and one bus stop location (mid-block). The ratios of demand-to-capacity of the main road were chosen to represent low, moderate, high, and very high traffic congestion levels. It should be noted that Figure 9 below illustrates the parameters for one path only, but the same parameters apply for the others paths as well. The following sections describe the scenarios for the experiments.

3.1.4.1 Main road volume scenarios.

The XBL performance is examined for four different main road D/C ratios. These ratios represent different volume scenarios. The considered main road volume ratios are shown in Table 5.

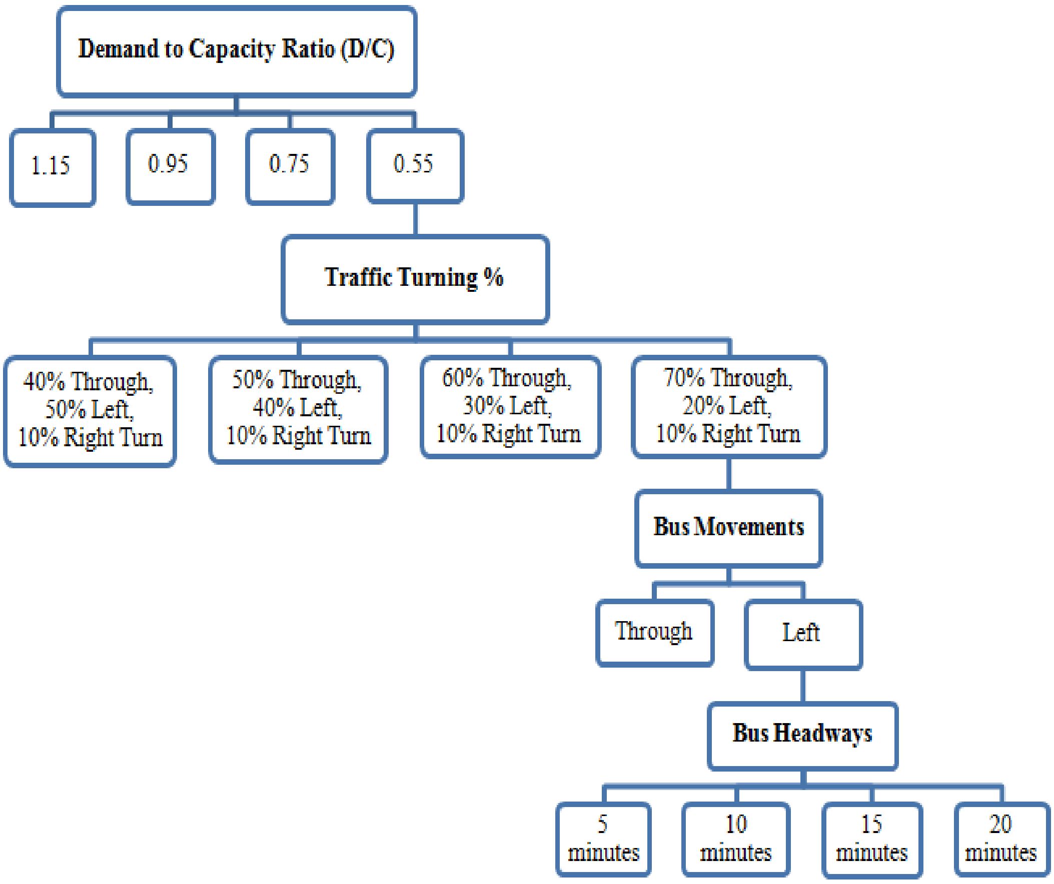

Figure 9: Parameters used in the parametric study

Table 5: The main road ratios and volumes

No.	D/C Ratio	Volume (vph)
1	0.55	786
2	0.75	1071
3	0.95	1357
4	1.15	1642

These values of the main road demand represent a range of major traffic D/C ratios from 0.55 to 1.15 (i.e. higher than capacity). Based on the lane capacity, which is approximately equal to 476 v/h/l. The lane capacity of the main road in the Typical Intersection Model was calculated using the following formula:

$$c = (g/C).s$$

where:

c = capacity (pcu/hour)

g = effective green time for the phase (sec)

C = cycle length (sec)

s = saturation flow rate (pcu/hour)

By substituting the value of each parameter in the formula: g = 50 second, C =189 second, and s = 1800 v/h/l, the lane capacity was calculated.

3.1.4.2 Through and left turn movement scenarios.

Different scenarios of through and left turn movements were used to examine their impact on the performance of an XBL. Different percentages were assumed for the through and left turn movements. The volumes and the percentages of through and left movements are shown in Table 6. These values are coded into the Typical Intersection Model.

Table 6: Through and left movement distributions

D/C	**Main Road Volume**	**Through Movement**		**Left Turn Movement**	
	Vehicles / Hour	**Percentage**	**Flow**	**Percentage**	**Flow**
		%	**vph**	**%**	**vph**
0.55	**786**	40%	314	50%	393
		50%	393	40%	314
		60%	471	30%	236
		70%	550	20%	157
0.75	**1071**	40%	432	50%	540
		50%	540	40%	432
		60%	648	30%	324
		70%	756	20%	216
0.95	**1357**	40%	543	50%	679
		50%	679	40%	543
		60%	814	30%	407
		70%	950	20%	271
1.15	**1642**	40%	648	50%	810
		50%	810	40%	648
		60%	972	30%	486
		70%	1134	20%	324

3.1.4.3 Right turn movement scenarios.

Based on the traffic counts obtained from Sharjah Road and Transportation Authority (SRTA), it is observed that the right turn movement had approximately a constant percentage, so it was assumed that the right turn movement has a constant value of 10% for all scenarios and it is coded into the Typical Intersection Model.

3.1.4.4 Bus headway scenarios.

The bus line headway scenarios were used to assess the performance of bus lines that run in the morning peak (i.e., east-to-west direction) as well as to assess the delay on the main road itself. These values were coded into the Typical Intersection Model. The bus headways considered are shown in Table 7.

Table 7: Bus headways

No.	Bus Headway (minutes)
1	5.0
2	10.0
3	15.0
4	20.0

Four bus line headways were studied to examine the travel time of the bus. The marginal headways were selected to be 5-minutes in the lower end and 20-minutes in the upper end. The 5-minute headway represents the smallest value implemented and the 20minute headway represents the off-peak headway of the current bus operation in the parametric study.

3.1.4.5 Bus turning movement scenarios.

To examine the effect of an XBL on the traffic network performance and to link them to actual bus line operations, it was assumed that the bus may have two movements; the first one is through, in which the bus will continue through after the intersection. The second one is left, in which the bus will make a left turn at the intersection.

3.1.4.6 Bus stop location scenario.

In this scenario, the effects of the bus stop were studied through one set of experiments that considers a mid-block bus stop, which is the standard location for bus stops in Sharjah. Figure 10 shows the location of mid-block bus stop locations in the

Typical Intersection Model. The geometric features of the bus stop location are based on the Dubai Geometric Design manual [47].

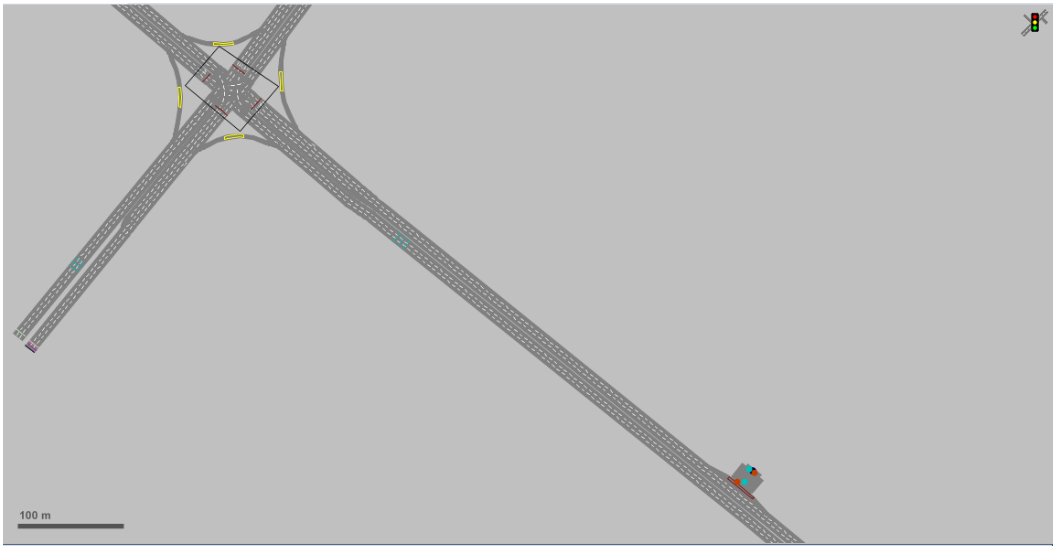

Figure 10: Mid-block bus stop location

Chapter 4: Modeling Environment

In this chapter, VISSIM micro-simulation software was utilized to model the implementation of an XBL and evaluate its impact under different traffic conditions. The following sub-sections describe the setup of the experiment used in VISSIM simulation software, the measures of effectiveness (MOEs) of the evaluations, and the traffic input data.

4.1 VISSIM

VISSIM is a microscopic transportation simulation software developed in Germany [48]. It's a time step and behavior based simulation model of urban traffic and public transit operations. Such simulation models play a very important role in decision making since they visualizes the problem in a very realistic and relatively accurate approach. The program can be used to analyze urban traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc. Also, it can visualize the network in 3D to look more realistic. All these features play an essential role in evaluating different alternatives that are based on a traffic and transportation engineering background and building an effective road network. In addition to that, VISSIM calculates important data such as volume, queue length, delay time, network performance, etc., thereby making it a useful tool for the evaluation of various transportation problems.

VISSIM has a number of features that make it a useful tool for modeling urban public transportation and other traffic conditions [48]:

- **To Model Public Transportation:** Public transportation can run either in mixed traffic conditions with other vehicles or on an exclusive bus lane. It can be defined separately from other traffic geometry by taking one lane from the existing geometry or adding lanes.
- **To Model Dwelling at Bus Stops:** VISSIM can track the load on each bus, generate passenger arrivals at stops following a Poisson distribution, and determine passenger alighting based on a fixed or user-supplied proportion of the load for each stop.
- **To Model Travel Time:** During a simulation run, VISSIM can evaluate average travel times (smoothed) if travel time measurement sections have been defined in the network. The average travel time (including waiting

time or dwell time) is calculated based on the time required for a vehicle to cross a section.

- **To Model Delay Time:** The definition of delay time measurement is based on one or more travel time measurements, regardless of vehicle class. The delay time is measured for all vehicle classes as part of the travel time measurements. No additional definitions are needed because delay measurements depend on travel time segments only.
- **To Model Bus Volume and Headway:** Bus volumes and bus headways are the factors that govern the effectiveness of XBLs, which can be modeled and customized within VISSIM.
- **To Model Desired Vehicle Speed Distribution:** For any vehicle type, the speed distribution is an important parameter that has a significant influence on roadway capacity and achievable travel speeds. If not hindered by other vehicles, a driver will travel at his desired speed (with a small stochastic variation called oscillation). The more vehicles differ in their desired speed, the more platoons are created.
- **To Model Signal Operation:** VISSIM has a user-programmable traffic signal controller that operates separate from the traffic simulation, with a limited interface. The signal operation can be fixed-time, vehicle-actuated or user-defined.

For output presentations, VISSIM allows user-customized output files of measures of effectiveness such as vehicle number, mean speed, travel time, delay, queue lengths, number of stops, and time-space diagram. In addition, VISSIM provides a variety of animation capabilities, (e.g., displaying traffic situations for different scenarios as printouts and visualizing vehicle movements in 2- and 3-dimensional animations) [48].

4.2 Traffic Performance Evaluation

The effectiveness of XBLs can be determined by one or more of the following traffic performance criteria:

- Bus performance, including bus travel time, delay and average speed;
- General vehicle performance, such as vehicle travel time, delay and average speed. These performance criteria will be determined through the use of simulation.

4.2.1 Bus performance evaluation.

One of the important objectives of implementing XBLs was to enhance the travel time performance and efficiency of bus lines and to increase the mode share of commuters riding the bus over the commuters driving private vehicles. A successful XBL would result in improvements in bus performance such as reductions in bus travel time and delay, and increases in bus speed.

4.2.2 General vehicle and adjacent traffic performance.

In addition to investigating the effect of an XBL on bus performance, traffic performance of other vehicles will be evaluated as well. In most scenarios, performance of general traffic, adjacent traffic in particular, may be sacrificed as the XBL is implemented. However, blind building of an XBL without any consideration for private vehicles would result in excessive delays and queues and may create a more complicated situation.

4.3 Traffic Input Data

Five traffic groups were coded in the Typical Intersection Model. Table 8 summarizes the five groups and their assumed average traveling speeds. Details of the traffic groups are described in the following sub-sections.

Table 8: Defined average speed of traffic groups

Traffic Groups	Average Speed (km/h)
Private Vehicles (Cars & Taxi)	60
Heavy Vehicles	60
Work Bus	60
School Bus	60
Bus lines	60

4.3.1 General traffic data.

Table 9: Traffic counts for morning peak (7:00 – 8:00 am)

The traffic counts and actual morning peak hour traffic (7:00 – 8:00 am) obtained from SRTA for the year 2013, are shown in Table 9.

Direction	Volumes (vph)
Northbound	1327
Southbound	506
Eastbound	Variations
Westbound	1011

The actual traffic counts were coded in the Typical Intersection Model except along the main road corridor. During the morning peak (7:00 – 8:00 am), the actual data for northbound and southbound traffic volumes are 1327 vph and 506 vph, respectively. These volumes will remain constant throughout the simulations. The movement percentages for left, through, and right movements for each direction are shown in Table 10. The actual number of vehicles for each direction is shown in Table 11. All these values are coded into the Typical Intersection Model.

Table 10: Percentage distributions for each direction

From	Right Turn %	Through Flow %	Left Turn %
NB	13 %	67 %	20 %
SB	15 %	46 %	39 %
EB	10%	Variable	Variable
WB	43 %	31 %	26 %

For the direction of the main road corridor (EB-WB), it is assumed that 10% is used to indicate that the right turning flow is a fixed percentage from the assumed volume. However, variable indicates that through and left volumes have variation percentages from (40% - 70%) and (50% - 20%) respectively.

Table 11: Traffic Volume

From	Right Turn Flow (vph)	Through Flow (vph)	Left Flow (vph)
NB	166	895	266
SB	80	231	195
EB	10% (variable)	Variable	Variable
WB	429	316	266

Table 12 shows the vehicle composition for each direction. These compositions are coded into the Typical Intersection Model. It should be noted that the percentage of each type of vehicle has been calculated based on the actual data for the morning peak hour, obtained from SRTA.

Table 12: Vehicle compositions for each direction

Direction	Vehicle Composition %		
	Passenger Cars	**OGV**	**Other Buses**
Northbound	72 %	19 %	8 %
Southbound	45 %	42 %	12 %
Eastbound	71 %	21 %	7 %
Westbound	62 %	28 %	10%

It should be noted that OGV represents other goods vehicles and other buses include school and work buses. These percentages are coded into the Typical Intersection Model. Furthermore, motorcycles were not considered with traffic input volumes. Table 13 summarizes the vehicle equivalency rate (persons/veh) used in the simulations and calculations in this research. These values are the standard values used in traffic simulation models in SRTA.

Table 13: Occupancy rate of the vehicles

Vehicle	Occupancy Rate (Persons)
Private Vehicles	1.77
Public Buses	25

4.3.2 School and wok buses.

To reflect reality, school buses and work buses, in the Typical Intersection Model can use any lane on the network as it operates in the same way in real life. The route for the school and work buses were coded in the Typical Intersection Model based on the turning percentages on the approaches.

4.3.3 Bus line.

In the Typical Intersection Model, the bus line was allowed to operate in the rightmost lane as well as to run in the center lane which reflects reality. This aims to allow the bus line to stop at the bus stops.

4.4 Coding the Scenarios

Each single scenario is given a unique code to follow the assumed parameters for each case. The coding style used is as follows:

- Bus headway in Roman numerals i.e. (I, II, III, IV, etc).
- Traffic turning percentages in Arabic numerals i.e. (1, 2, 3, 4, etc).
- Demand-to-capacity D/C ratio in English letters i.e. (A, B, C, D, etc).

The bus headway has four cases (20, 15, 10, and 5) minutes, and the Roman numerals represent these cases, in which Roman numeral I represents 20 minutes headway and Roman numeral II represents 15 minutes headway and so on. All the Roman numerals from I to IV are for through movement of the bus. Then the Roman numeral of V used for 20 minutes headway for left movement of the bus. The traffic turning percentages have four cases (40% Through – 50% Left, 50% Through – 40%

Left, 60% Through – 30% Left, and 70% Through – 20% Left), and an Arabic numeral is used to represent each case such as 1 for (40% Through – 50% Left) and 2 for (50% Through – 40% Left) and so on. In addition, The demand-to-capacity D/C ratio has four cases (0.55, 0.75, 0.95, and 1.15), and the English letter represents these cases, in which English letter A represents a D/C ratio of 0.55 and English letter B is for a D/C ratio of 0.75 and so on. For all the cases, the right turn movement represents 10%.

For example, V-4 represents the bus headway of 5 minutes with traffic turning percentages of (70% through – 20% left) for all D/C ratios of the main road with buses moving left, and II-2 represents the bus headway of 15 minutes with traffic turning percentages of (50% through – 40% left) for all D/C ratios of the main road with buses moving through. Likewise, A-3 represents the mode share with D/C ratio of 0.55 with traffic turning percentages of (60% through – 30% left) with buses moving through. The symbols used to code each parameter and their values are summarized in Table 14.

Table 14: Parameters coding style

Parameters	**Symbol**		**Values**
Bus headways	Roman number	I, II, III, and IV	20, 15, 10, and 5 minutes
Traffic turning %	Arabic number	1, 2, 3, and 4	(40% straight – 50% left), (50% straight – 60% left), (60% straight – 30% left), and (70% straight – 20% left)
Demand over capacity ratio D/C	English letter	A, B, C, and D	0.55, 0.75, 0.95, and 1.15

The coding style is grouped as follows:

1- The parametric study:
   - Roman numerals from I to IV are used to represent the scenarios for the bus headway of (20, 15, 10, and 5) minutes with through movement of the buses.
   - V is only used to represent the scenarios for the bus headway of (20) minutes with left movement of the buses. This is the only scenario considered to check the validity of implementing an XBL with buses moving left.

2- The mode share:

- From A to D are used to represent the mode share analysis for demand-to-capacity D/C ratios of (0.55, 0.75, 0.95, and 1.15) with through movement of the buses.

4.5 Mode Choice

In this research, the mode choice determination was based on the equilibrium point between the travel time of the buses in XBLs and the travel time of the private vehicles with XBLs. The modal shift happens if one mode of transportation achieves better performance in terms of travel time, capacity, and cost than others. Many factors contribute to the modal shift such as socio-economic factors, purpose of the trips, etc. The main factor of the modal shift here was the difference between the travel time experience by the users of private vehicles and the travel time faced by the commuters of the buses. As the provision of XBLs will enhance the performance of the buses in terms of travel time, this may lead to a modal shift from private vehicles to buses. This research intends to estimate the number of modal shifts from private vehicles to buses by the use of an equilibrium point to quantify the modal shift from providing XBLs. After the simulation results, the steps include the following:

1- Draw the travel time of the buses in XBLs and the travel time of the private vehicles with XBLs to locate the intersection point between both of them under different D/C ratios on the main road. The x-axis represents the number of buses and the y-axis represents the travel time.

2- In each case, increase one line at a time (the line will have a number of buses based on the bus headway, i.e. 20 minutes headway will generate three buses for each line).

3- By adding a line, the number of passengers using these buses will be, for the same example, 3 buses * 25 = 75 passengers.

4- Reduce the number of private vehicles on the main road by the number of vehicles equivalent to the number of passengers on the buses. Following the same example, the number of reductions will be 75 / 1.77 = 42.37, say 42 private vehicles.

5- Re-do the simulation with new volumes and get the travel time of the buses in XBLs and the private vehicles with XBLs.

6- If the travel time of the buses in XBLs does not intersect with the travel time of the private vehicles with XBLs, then increase the number of buses; otherwise, the recommended number of buses is fine.
7- Get the exact number of buses from the graph.
8- Perform back calculation by converting the number of buses to equivalent private vehicles and divide the result by the assumed traffic volume times 100.

4.5.1 Coding of the mode choice analysis.

In the coding style of the mode choice analysis, there are different traffic volumes associate with each D/C ratio. These volumes represent different public transportation mode shares, assuming that some passenger car users will shift to public buses. Accordingly, as the number of buses increases, the number of vehicles on the road will decrease.

For example, scenario B-4, represents the mode choice analysis with three volumes (1038, 953, and 911 vph), and these volumes represent the total volume for a D/C ratio of 0.75, considering different mode shares, for traffic turning percentages of (70% through – 20% left) and buses moving through. Also, scenario D-1 represents the mode choice analysis with five volumes (1578, 1493, 1451, 1366 and 1196 vph) for a D/C ratio of 1.15, traffic turning percentages of (70% through – 20% left) and buses moving through.

In addition to that, each D/C ratio was evaluated individually to capture the equilibrium point of the travel time between the buses and private vehicles in the case of an XBL. The equilibrium point is the mode share value at which the buses and other vehicles will have the same travel time through the considered corridor.

4.6 Model Simulation

In this research, a simulation period length of 1 hour was used to analyze the scenarios. To be more realistic, the network used 15 minutes of warm-up time to load vehicles into the network. A simulation period of 1 hour would allow the buses to complete a full trip in the direction of east-to-west, the direction of the bus line, in the Typical Intersection Model under moderate to high traffic volumes. During the 15-minute warm-up period, no statistics are gathered. Each micro-simulation run presents a random seed; thus each scenario runs five times, for five different seeds, to account for the randomness of traffic volumes in VISSIM, which is required for ensuring the validity and stability of the results.

A trimmed mean was calculated by excluding the largest and the smallest values from the results and taking the arithmetic mean of the remaining three values. The trimmed mean approach was used to reduce the effects of extreme values on the calculated mean.

Chapter 5: Results and Discussions

The VISSIM simulation model, discussed in Chapters 3 and 4, has been utilized to evaluate different scenarios in order to determine the effect of different traffic parameters on the performance of an XBL in the traffic network. The traffic parameters considered are:

- Main road volume;
- The percentage of left and through flows;
- Bus direction; and
- Bus headway.

The following sections provide the discussion of the results and analyses conducted for these scenarios.

5.1 Parametric Study Analysis

In this section, each scenario will be analyzed individually to study the impact of an XBL in the Typical Intersection Model on the traffic network performance in terms of travel time, intersection delay, and average speed for the buses and other vehicles operating with and without an XBL.

5.1.1 Scenario I-1.

This scenario represents the following conditions: bus direction (through), four D/C ratios (0.55, 0.75, 0.95 and 1.15), traffic turning percentages (40% through – 50% left), and bus headway (20 minutes).

Figure 11 compares the travel time of buses along the main road corridor with and without the XBL under different D/C ratios on major traffic volume. The buses' travel time along the main road increases as the D/C ratio for mixed traffic conditions on the main road increases, which represents a typical link performance function. Additionally, when considering the XBL, the buses' travel time improves significantly as the buses will have a constant travel time regardless of the level of congestion on the main road. Therefore, it indicates the importance of the XBL to improve the performance of the buses travel time along the main road corridor.

Figure 12 shows the effect of using the XBL on the travel time of the other vehicles on the main road. For D/C ratios of 0.75 or less, the XBL has almost no effect on the other vehicles on the main road since the network is operating below its capacity, thus allowing other vehicles to maneuver freely without hindering the traffic. However for D/C ratios of 0.95 or more, the network is fully congested and the other vehicles are trapped in traffic congestion. The more the demand, the greater the impact the XBL will have on the other vehicles in terms of increasing the travel time. Simply, the implementation of the XBL has a negative impact on the other vehicles' travel time in adjacent lanes, especially at high volume when the network reaches its capacity (i.e. D/C ≥ 1.0). This is because the capacity of the road was reduced after taking one lane from the existing geometry and assigning it for the XBL.

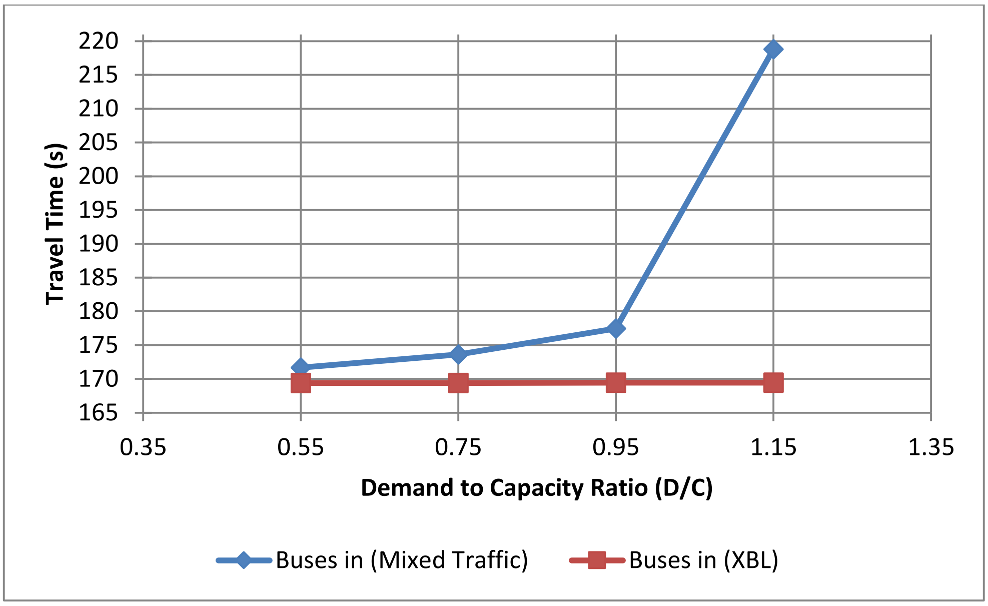

Figure 11: Travel time for the buses along the main road corridor with and without XBL (I-1)

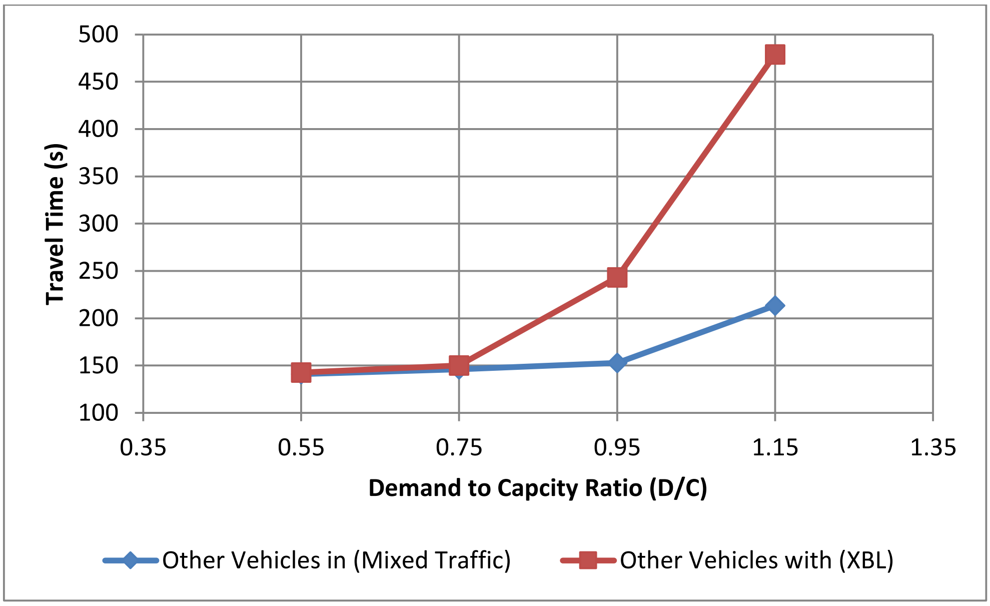

Figure 12: The effect of using XBL on the travel times of the other vehicles (I-1)

The improvement percentage in bus travel time under different D/C ratios, as a result of implementing the XBL is illustrated in Figure 13.

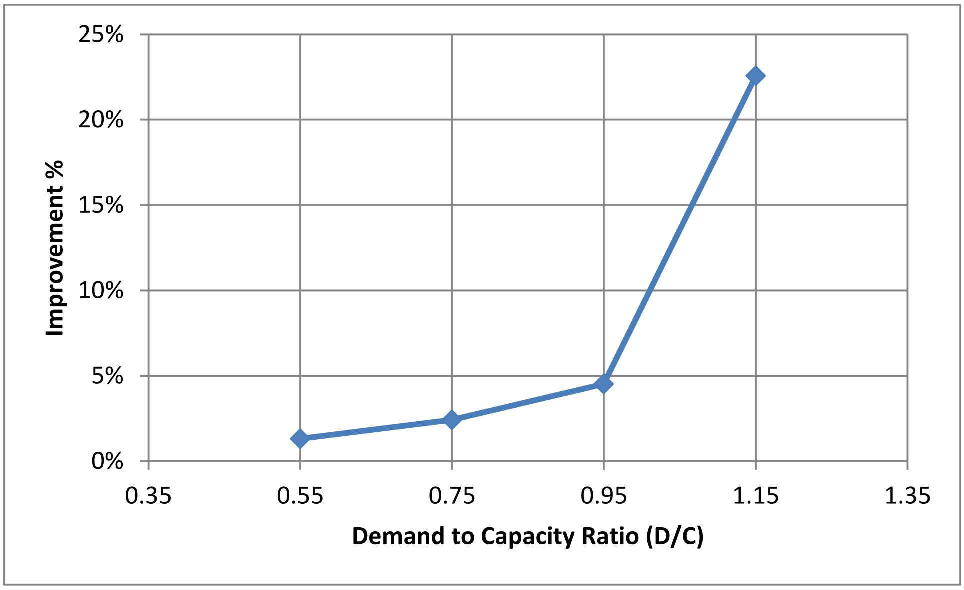

Figure 13: Improvement percentages of the buses' travel time (I-1)

For D/C ratios of 0.75 or less, the percentage of the buses' travel time reduction due to the use of the XBL is around 2%. In this range of D/C ratios, which is medium volume, there is a small improvement since all vehicles do not experience high delays. For D/C ratios higher than 0.95, the improvement with the XBL shows a higher rate of increase. Since the demand is very high and the other vehicles experience excessive traffic delay, this shows the effectiveness of the XBL in improving the performance of buses' travel time as the network reaches its capacity (i.e. D/C ≥ 1.0). At capacity, the XBL saves almost 8% of bus travel time and it improves significantly.

Figure 14 compares intersection delay for the buses along the main road corridor with and without the XBL under different D/C ratios on major road volumes. Similar to the travel time, the bus delay increases with the increase in the traffic volume (or D/C ratio) in the mixed traffic conditions. After adding the XBL, the delay is almost constant.

The effect of setting up the XBL on the delay of the other vehicles in adjacent lanes along the main road is shown in Figure 15. The graph shows that for D/C ratios of 0.75 or less, there is no effect of the XBL on the other vehicles because the network operates at a low traffic volume. However, for high volume when the network reaches its maximum capacity (i.e. D/C ≥1.0), the effect of the XBL is very clear as the intersection delay has increased almost to 3 times the intersection delay in the case of the other vehicles that operate in mixed traffic conditions. At capacity, the other vehicles experience difficulties in changing lanes as the road space allocated, to the other vehicles, after taking lane for bus, is fully congested.

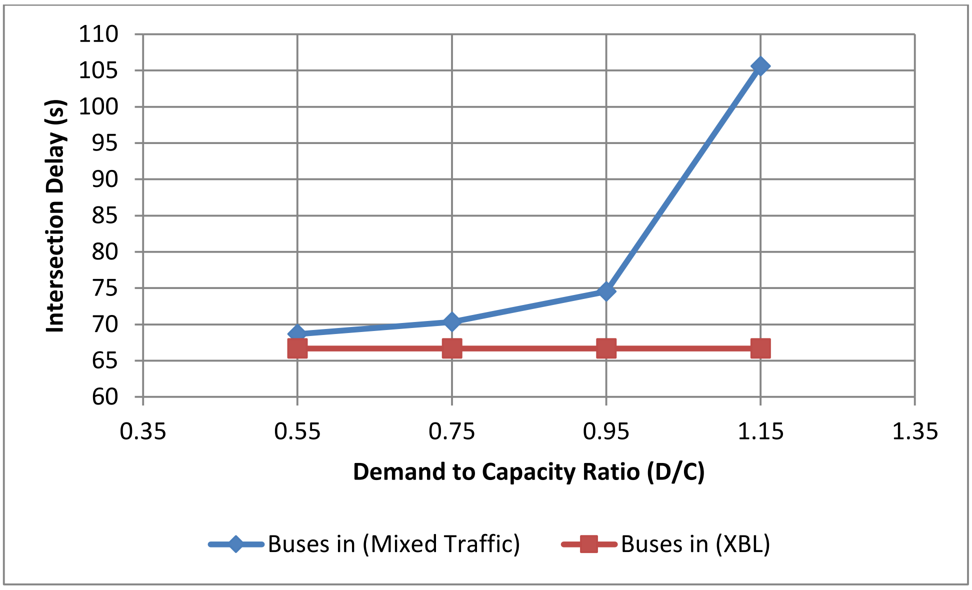

Figure 14: Intersection delay for the buses along the main road with and without XBL (I-1)

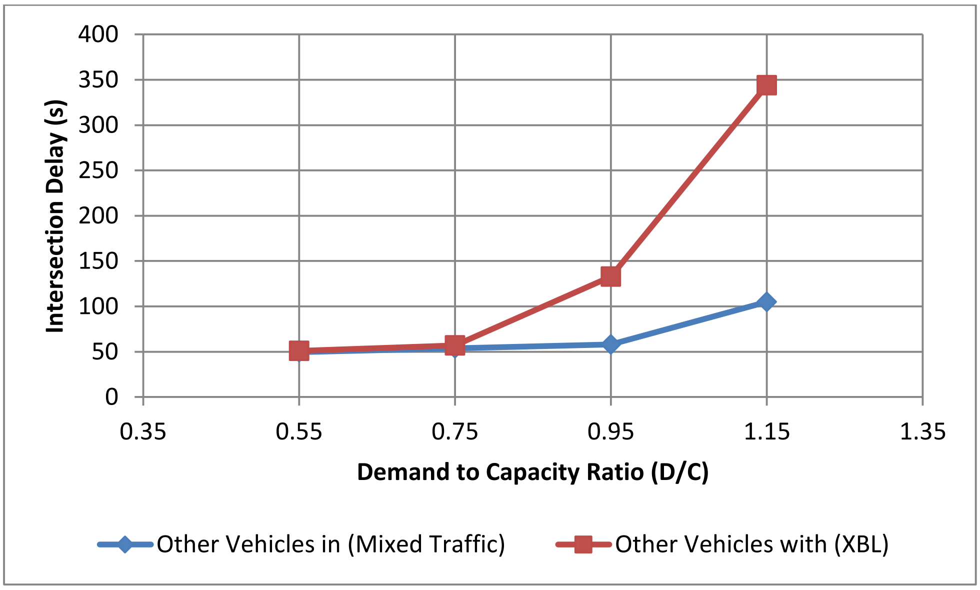

Figure 15: The effect of XBL on other vehicles in adjacent lanes along the main road (I-1)

Figure 16 illustrates the improvement percentages of intersection delay for buses with the XBL for different D/C ratios along the main road. At low congestion levels (D/C ratios of 0.75 or less), the percentage of reduction in the bus intersection delay, after using the XBL, gets close to 5%. Under this medium traffic volume, the improvement is small since the other vehicles face small delays. As the D/C ratio reaches to 0.95, the improvement percentage reaches to 10%, thus showing the effectiveness of using the XBL to improve intersection delays for buses along the main road. However, the intersection delay for adjacent commuters increases after including the XBL. The improvement percentage with the XBL shows that as the D/C of major volumes along the main road increases, the improvement percentage increases as well. At capacity, the improvement in the buses' delay is very significant as it reaches to 20%.

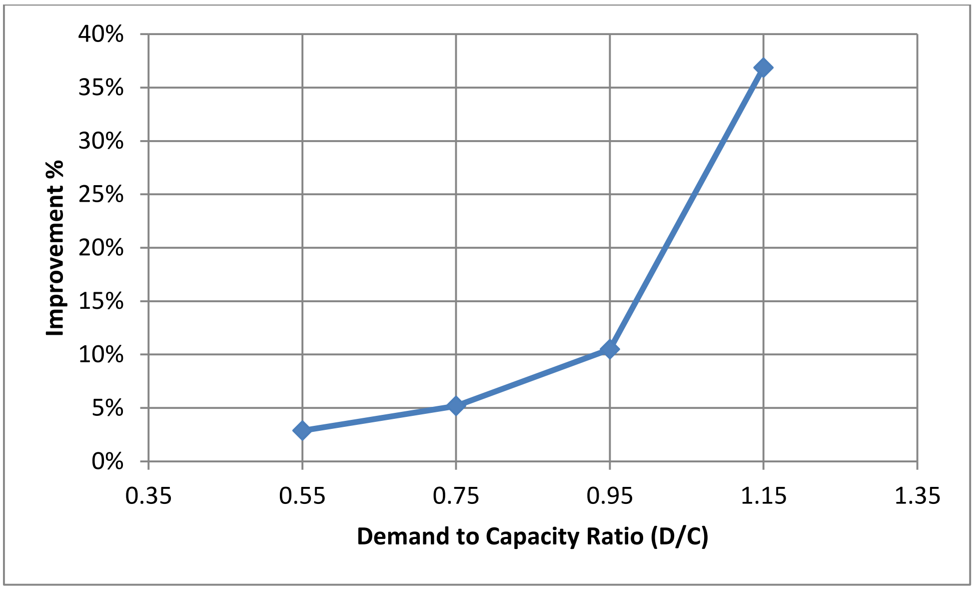

Figure 16: Improvement percentages of the buses' intersection delay (I-1)

Figure 17 presents the average speed of the buses along the main road with and without the XBL under different D/C ratios. In mixed traffic conditions, the average speed of the buses along the main road decreases as the demand increases. The deterioration in average speed of the buses reaches its maximum value when the network operates at or above its capacity (i.e. D/C ≥1.0). However, the effect of the XBL on the average speed of the buses is very obvious as the buses maintain a constant speed along the whole segment of the road, where the XBL is implemented, because there is no interaction between the buses and other vehicles. Thus, indicate the importance of XBL to improve the performance of the buses' average speed at level of congestions.

On the other hand, the effect of installing the XBL on the average speed of the other vehicles in adjacent traffic lanes along the main road is introduced in Figure 18. The average speed of the other vehicles, in mixed traffic condition, experiences a significant drop when the D/C ratio is equal to 0.95 or more, because the other vehicles try to maneuver from one lane to another and overtake other vehicles to reach their destination. While with the XBL, vehicles on the main road start to have a decrease in average speed for D/C ratios of 0.75 or more, which shows the negative effect of implementing the XBL on the non-bus commuters in adjacent lanes. This drop occurs at a much higher rate because the available road space for the other vehicles, after reserving one lane for the XBL, is less than before. As a result, the other vehicles experience very low speed because of adding the XBL.

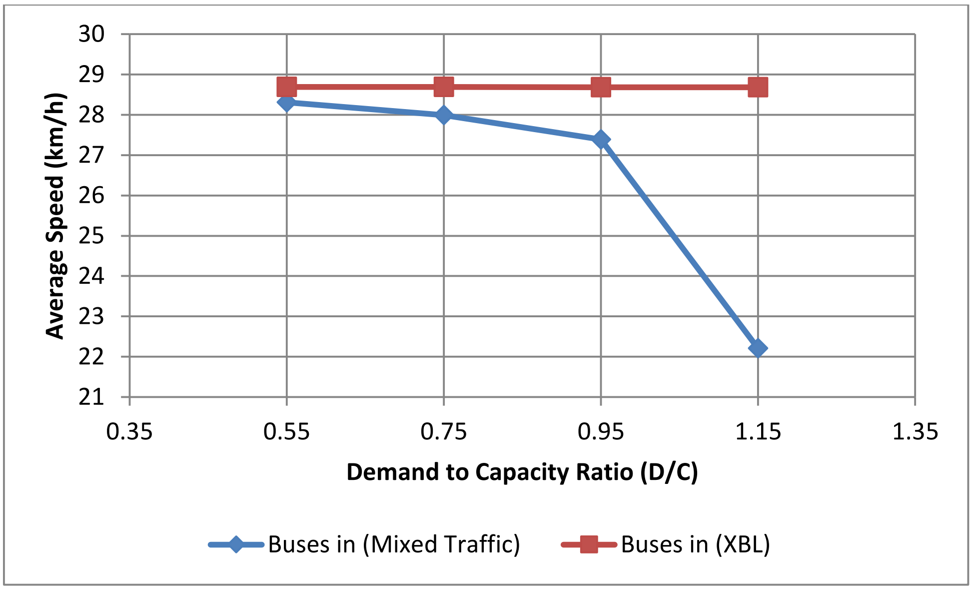

Figure 17: Average speed for the buses along the main road with and without XBL (I-1)

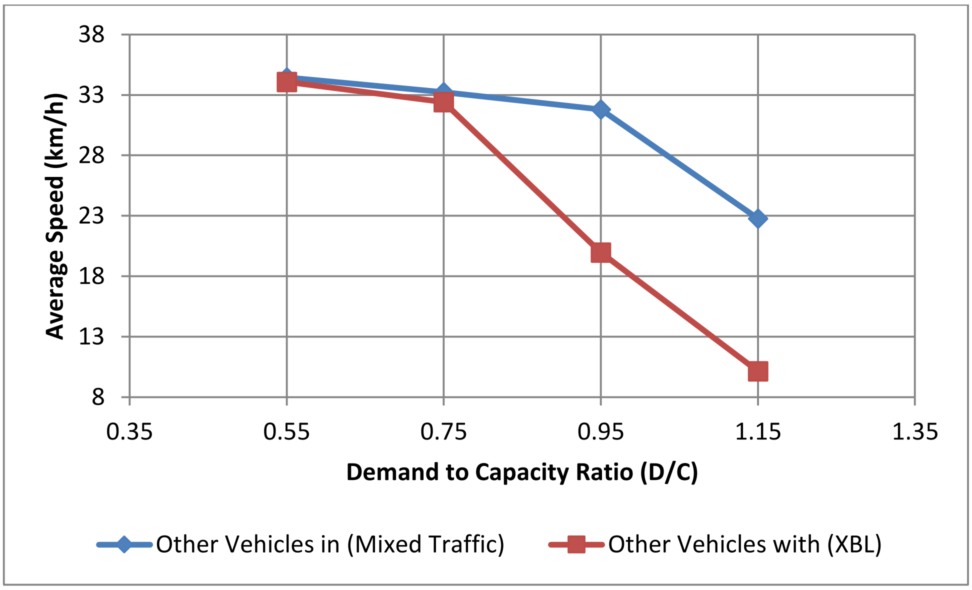

Figure 18: Average speed of the other vehicles with and without XBL (I-1)

After the implementation of the XBL, the improvement percentages of the buses' average speed under different D/C ratios on the main road is shown in Figure

19. The improvement percentage of the buses' average speed by the use of the XBL gets close to 2% when the D/C ratio is equal to 0.75 or less. In this range of D/C ratios, which is medium volume, the improvement is low because there is less interaction between the buses and other vehicles. For D/C ratio of 0.95, which is high volume, the improvement percentage reaches about 4.5%, thus showing the effectiveness of using the XBL to improve the average speed of the buses along the main road, while at the same time decreasing the average speed for commuters in adjacent lanes. The improvement percentage with the XBL shows that as the D/C ratios on major volumes along the main road increase, the improvement percentage increases too with great impact as it reaches about 19% at a D/C ratio of 1.15.

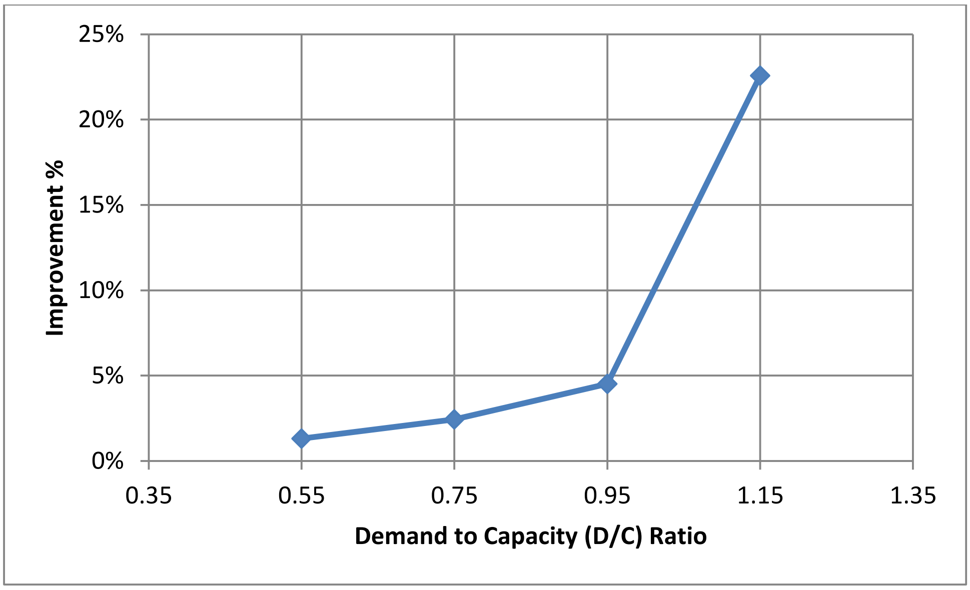

Figure 19: Improvement percentages of the buses' average speed (I-1)

5.1.2 Scenario I-2.

This scenario considers the following variables: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (50% through – 40% left), and bus headway (20 minutes). Table 15 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on major traffic volume.

Table 15 shows that the travel time and intersection delay of the other vehicles in mixed traffic conditions increases as the D/C ratio of major volume along the main road increases. Nevertheless, the effect of implementing the XBL on the other vehicles' travel times and intersection delay is clear as they both have greater values than the other vehicles without XBL. By dedicating one lane for buses, the XBL, the available road space for the other vehicles becomes smaller than before. However, the same levels of demands from the other vehicles are using less area of the main road than before. As a result, the other vehicles experience very high delays because of the implementation of the XBL. The average speed of the other vehicles decreases as the D/C of major volume on the main road increases, while the average speed of the other vehicles decreases significantly after the installation of the XBL, thus showing the negative impact of the XBL on non-bus commuters in adjacent lanes.

Table 15: Measures of effectiveness for other vehicles and buses for scenario I-2

<table>
<tr><th></th><th></th><th></th><th colspan="4">D/C Ratios</th></tr>
<tr><th></th><th></th><th></th><th>0.55</th><th>0.75</th><th>0.95</th><th>1.15</th></tr>
<tr><td rowspan="6">Other Vehicles</td><td rowspan="2">Travel Time (s)</td><td>with XBL</td><td>141.97</td><td>148.44</td><td>241.94</td><td>471.37</td></tr>
<tr><td>*w/o XBL</td><td>140.39</td><td>145.23</td><td>147.46</td><td>167.15</td></tr>
<tr><td rowspan="2">Intersection Delay (s)</td><td>with XBL</td><td>52.65</td><td>57.95</td><td>139.25</td><td>351.35</td></tr>
<tr><td>*w/o XBL</td><td>51.19</td><td>55.45</td><td>57.14</td><td>74.10</td></tr>
<tr><td rowspan="2">Average Speed (km/h)</td><td>with XBL</td><td>34.23</td><td>32.74</td><td>20.09</td><td>10.31</td></tr>
<tr><td>*w/o XBL</td><td>34.62</td><td>33.46</td><td>32.96</td><td>29.08</td></tr>
<tr><td rowspan="9">Buses</td><td rowspan="2">Travel Time (s)</td><td>with XBL</td><td>169.43</td><td>169.43</td><td>169.36</td><td>169.36</td></tr>
<tr><td>*w/o XBL</td><td>172.26</td><td>174.68</td><td>177.92</td><td>184.39</td></tr>
<tr><td rowspan="2">Intersection Delay (s)</td><td>with XBL</td><td>66.68</td><td>66.69</td><td>66.69</td><td>66.67</td></tr>
<tr><td>*w/o XBL</td><td>69.08</td><td>71.19</td><td>74.82</td><td>81.67</td></tr>
<tr><td rowspan="2">Average Speed (km/h)</td><td>with XBL</td><td>28.68</td><td>28.68</td><td>28.70</td><td>28.70</td></tr>
<tr><td>*w/o XBL</td><td>28.21</td><td>27.82</td><td>27.31</td><td>26.36</td></tr>
<tr><td rowspan="3">Improvement %</td><td>Travel Time</td><td>1.64%</td><td>3.00%</td><td>4.82%</td><td>8.15%</td></tr>
<tr><td>Intersection Delay</td><td>3.47%</td><td>6.32%</td><td>10.87%</td><td>18.37%</td></tr>
<tr><td>Average Speed</td><td>1.67%</td><td>3.09%</td><td>5.06%</td><td>8.87%</td></tr>
</table>

* w/o XBL: without exclusive bus lane.

When the buses operate in mixed traffic conditions with the other vehicles, the average speed of the buses decreases as the D/C ratio of major volume on the main road increases. However, the buses maintain a constant average speed along all D/C ratios of the main road after the implementation of the XBL. Furthermore, the impact of using the XBL on the buses performance in terms of intersection delay and travel time is impressive as the buses experience almost a constant intersection delay and travel time, thus indicating the importance of the XBL. The improvement percentages for the buses' travel time, intersection delay, and average speed present significant enhancements at high levels of volumes (i.e. D/C ratios of 0.95 or more). The improvement percentages for buses' travel time, intersection delay, and average speed are 4.52%, 10.50%, and 4.52% respectively. At capacity (D/C = 1.0), the improvement percentage reaches its maximum value of enhancement for the buses' performance. Similar trends are noticed in scenario I-2 as in scenario I-1, which indicates that the results are consistent but the improvement percentages for the buses run in the XBL such as travel time, intersection delay, and average speed are better than scenario I-1. This happened because the percentage of left turning of the other vehicles in this scenario is 40%, which results in less maneuvering between the vehicles and less travel time and intersection delay and more average speed.

5.1.3 Scenario I-3.

This scenario includes the following parameters: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (60% through – 30% left), and bus headway (20 minutes). The measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on major traffic volume are summarized in Table 16.

Table 16: Measures of effectiveness for other vehicles and buses for scenario I-3

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.28	148.72	298.00	495.23
		***w/o XBL**	140.53	145.05	146.76	162.48
	Intersection Delay (s)	**with XBL**	54.80	60.33	194.71	386.31
		***w/o XBL**	53.21	57.36	58.78	73.38
	Average Speed (km/h)	**with XBL**	34.16	32.68	16.31	9.81
		***w/o XBL**	34.58	33.51	33.12	29.91
Buses	**Travel Time (s)**	**with XBL**	169.44	169.43	169.37	169.43
		***w/o XBL**	173.46	176.10	178.46	185.07
	Intersection Delay (s)	**with XBL**	66.68	66.77	66.69	66.68
		***w/o XBL**	70.26	72.80	75.71	82.13
	Average Speed (km/h)	**with XBL**	28.68	28.68	28.69	28.68
		***w/o XBL**	28.02	27.60	27.23	26.26
	Improvement %	**Travel Time**	2.32%	3.78%	5.09%	8.45%
		Intersection Delay	5.09%	8.28%	11.92%	18.82%
		Average Speed	2.37%	3.92%	5.37%	9.23%

* w/o XBL: without exclusive bus lane.

This scenario, I-3, shows similar trends to the previous scenarios, which indicates that the results are consistent. The improvement percentages for the measures of effectiveness such as travel time, intersection delay, and average speed for the buses in the XBL are better than scenarios I-1 and I-2 for low and high volume (i.e. D/C ratios of 0.55 and 0.95) and the improvement percentages are 2.32%, 5.09%, and 2.37%, respectively, for the low volume while the improvement percentages for the high volume are 5.09%, 11.92%, and 5.37%, respectively. This can be attributed to fact that in this scenario the percentage of vehicles turning left is 30%, so the interaction between the vehicles is less than the previous two scenarios, I-1 and I-2, which results in better performance for the buses in terms of travel time, intersection delay, and average speed.

5.1.4 Scenario I-4.

This scenario defines the following: bus direction (through), four D/C ratios (0.55, 075, 0.95, and 1.15), traffic turning percentages (70% through – 20% left), and bus headway (20 minutes). Table 17 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on major traffic volume.

Table 17: Measures of effectiveness for other vehicles and buses for scenario I-4

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.73	152.54	427.29	539.35
		***w/o XBL**	140.46	145.10	147.51	176.05
	Intersection Delay (s)	**with XBL**	56.86	65.85	326.56	439.44
		***w/o XBL**	54.76	59.02	61.46	89.22
	Average Speed (km/h)	**with XBL**	34.05	31.86	11.37	9.01
		***w/o XBL**	34.60	33.49	32.95	27.61
Buses	**Travel Time (s)**	**with XBL**	169.44	169.36	169.43	169.46
		***w/o XBL**	173.65	176.57	180.42	205.52
	Intersection Delay (s)	**with XBL**	66.68	66.68	66.68	66.68
		***w/o XBL**	70.37	73.32	77.79	102.88
	Average Speed (km/h)	**with XBL**	28.68	28.70	28.69	28.68
		***w/o XBL**	27.99	27.52	26.94	23.65
	Improvement %	**Travel Time**	2.43%	4.09%	6.10%	17.54%
		Intersection Delay	5.24%	9.05%	14.29%	35.19%
		Average Speed	2.49%	4.26%	6.49%	21.28%

* w/o XBL: without exclusive bus lane.

The travel time, intersection delay, and average speed values in scenario I-4 show similar trends to those of previous scenarios, as expected. In this scenario, for D/C ratios of 0.95 or less the improvement percentages for the buses in the XBL have the best performance among all other scenarios in terms of travel time, intersection delay, and average speed. At D/C ratio equal to 0.95, the improvement percentages of the buses' travel time, intersection delay, and average speed are 6.10%, 14.29%, and 6.49%, respectively. For low volumes, such as D/C ratios of 0.55 or less, the improvement percentages of the buses' travel time, intersection delay, and average speed are 2.43%, 5.24%, and 2.49%, respectively. The main reason for these results is the fact that the percentage of vehicles performing a left turn is 20%, which is the least value among all other scenarios. At this percentage of left turn, the effect of the other vehicles on each other is less in terms of overtaking and changing lanes, which result in less travel time and intersection delay, and more average speed.

Figure 20 compares the improvement percentages for the buses' travel time for all the scenarios in case I (headway of 20 min) under different D/C ratios on major volume on the main road.

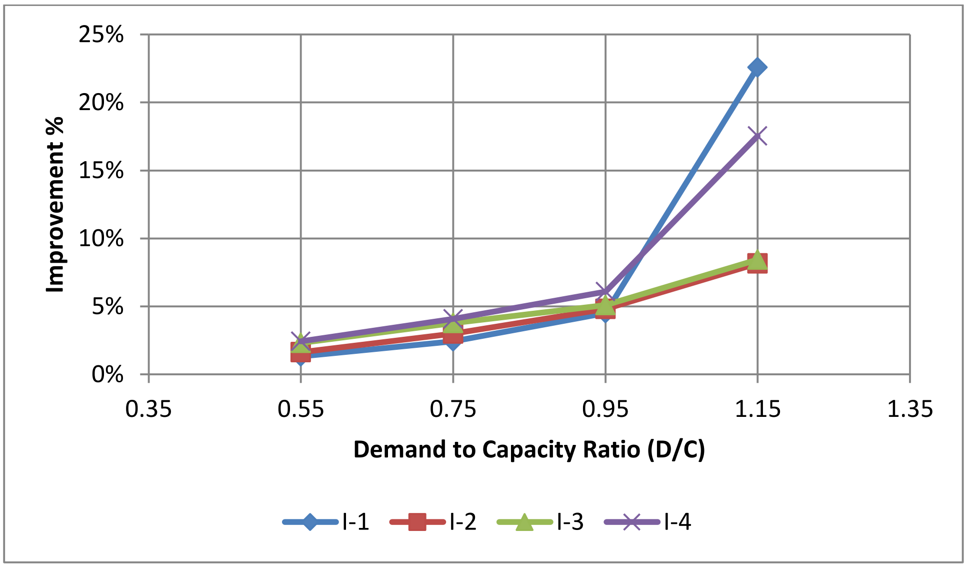

Figure 20: Improvement percentages for the buses' travel time for all scenarios in case I

The improvement percentages for buses' travel time show the best performance for scenario I-4 along all D/C ratios for the main road corridor than other scenarios except at D/C ratio of 1.15, because of the high percentages of the vehicles turning left which is 50% in scenario I-1. Consequently, the buses consume more travel time. This scenario represents (70% through – 20% left – 10% right) for the turning movement approaching the main road. The XBL are most effective in scenario I-4 than other scenarios for D/C ratios of 0.95 or less. The best performance at D/C > 1.0 is achieved in Scenario I-1.

After the implementation of the XBL, the improvement percentages for the buses' intersection delay for all the scenarios in case I (20 minutes headway) under different D/C ratios on the main road are shown in Figure 21.

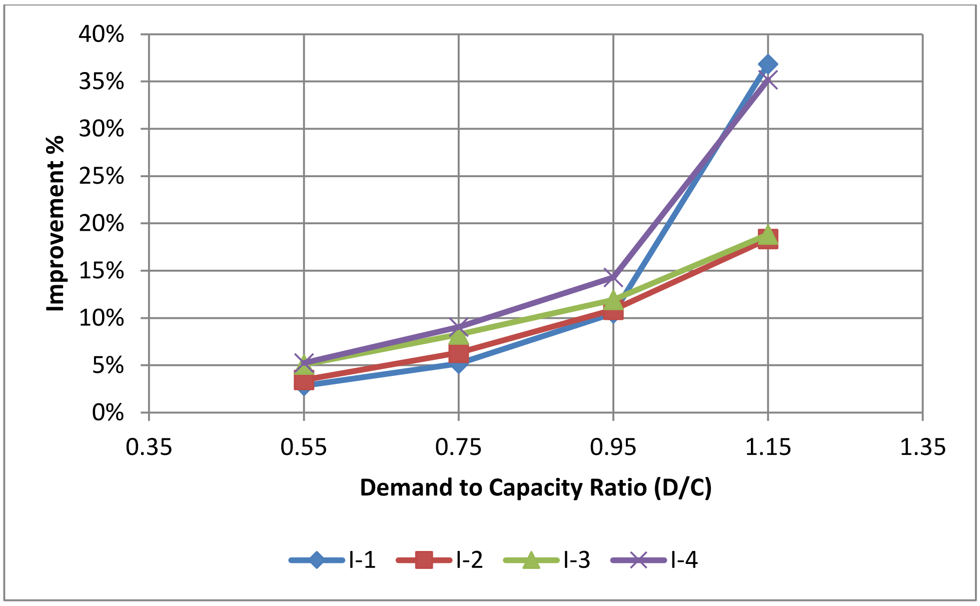

Figure 21: Improvement percentages for the buses' intersection delay for all scenarios in case I

Scenario I-4 has the best buses' intersection delay performance among all D/C on the main road. The XBL have the great impact when the traffic of the main road has the following traffic turning percentages (70% through – 20% left – 10% right), which represents scenario I-4.

A comparison between all the improvement percentages for the buses' average speed for all the scenarios in case I (20 minutes headway) under different D/C ratios on the main road are presented in Figure 22.

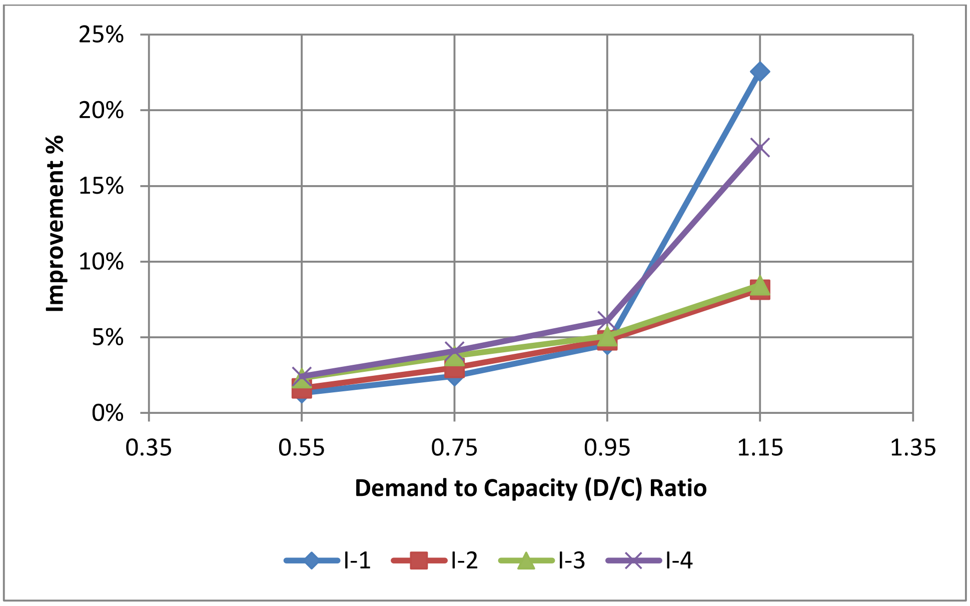

Figure 22: Improvement percentages for the buses' average speed for all scenarios in case I

The best performance of improvement percentages for the buses' average speed is scenario I-4 for all D/C ratios on the main road except at D/C ratios of 1.15. This happened because in scenario I-1, the percentage of vehicles going left is 50%, which results in more maneuvering and overtaking other vehicles. As a result, the buses' average speed is significantly reduced in mixed traffic conditions. Therefore, the percentage of improvement in bus speed is much higher than in other scenarios. The effect of the XBL on the traffic network causes increases in travel time and intersection delay, and decreases in average speed for the other vehicles. It also causes decreases in travel time and intersection delay, and increases in average speed for the buses.

5.1.5 Scenario II-1.

This scenario represents the following criteria: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (40% through – 50% left), and bus headway (15 minutes). The measures of effectiveness considered such as travel time, intersection delay and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 18.

Table 18: Measures of effectiveness for other vehicles and buses for scenario II-1

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.66	150.01	245.00	478.68
		***w/o XBL**	141.22	146.48	152.25	210.52
	Intersection Delay (s)	**with XBL**	51.09	56.88	132.62	343.79
		***w/o XBL**	49.60	54.10	57.91	103.49
	Average Speed (km/h)	**with XBL**	34.07	32.40	19.84	10.15
		***w/o XBL**	34.41	33.18	31.92	23.09
Buses	**Travel Time (s)**	**with XBL**	175.53	175.53	175.53	175.53
		***w/o XBL**	179.06	181.10	183.44	217.70
	Intersection Delay (s)	**with XBL**	72.88	72.89	72.89	72.89
		***w/o XBL**	76.82	78.83	80.59	109.54
	Average Speed (km/h)	**with XBL**	27.69	27.69	27.69	27.69
		***w/o XBL**	27.14	26.84	26.49	22.32
	Improvement %	**Travel Time**	1.97%	3.07%	4.31%	19.37%
		Intersection Delay	5.12%	7.53%	9.56%	33.46%
		Average Speed	2.01%	3.17%	4.51%	24.02%

* w/o XBL: without exclusive bus lane.

The results show similar trends to scenario I-1, but the improvement percentages for the buses' travel time, intersection delay, and average speed are better.

As the D/C ratio increases, the improvement percentages of the buses increase too. For example, when D/C is equal to 0.75, the improvement percentages of the buses are 3.07%, 7.53%, and 3.17% for the travel time, intersection delay, and average speed, respectively. Also, for D/C ratios of 0.95 or more, the improvement percentages of the buses' travel time, intersection delay, and average speed are 4.31%, 9.56%, and 4.51%, respectively. So as the buses' frequency increases from 3 buses/hr (20 minutes headway) to 4 buses/hr (15 minutes headway), the buses' performance in terms of travel time, intersection delay, and average speed improve significantly.

5.1.6 Scenario II-2.

This scenario considers the following variables: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (50% through – 40% left), and bus headway (15 minutes). Table 19 summarizes the measures of effectiveness considered which are travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road.

Table 19: Measures of effectiveness for other vehicles and buses for scenario II-2

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	141.97	148.43	241.83	471.84
		***w/o XBL**	140.51	145.34	147.52	168.08
	Intersection Delay (s)	**with XBL**	52.72	57.97	139.06	351.35
		***w/o XBL**	51.24	55.57	57.23	75.49
	Average Speed (km/h)	**with XBL**	34.23	32.74	20.10	10.30
		***w/o XBL**	34.59	33.44	32.94	28.91
Buses	**Travel Time (s)**	**with XBL**	175.53	175.53	175.53	175.53
		***w/o XBL**	180.26	182.47	184.97	191.59
	Intersection Delay (s)	**with XBL**	72.88	72.89	72.88	72.89
		***w/o XBL**	78.08	79.67	82.00	89.29
	Average Speed (km/h)	**with XBL**	27.69	27.69	27.69	27.69
		***w/o XBL**	26.96	26.64	26.27	25.37
	Improvement %	**Travel Time**	2.62%	3.80%	5.10%	8.38%
		Intersection Delay	6.66%	8.52%	11.11%	18.38%
		Average Speed	2.69%	3.95%	5.38%	9.15%

* w/o XBL: without exclusive bus lane.

In this scenario, similar trends are noticed to scenario I-2. For D/C ratios equal to 0.95 or more, the improvement percentages of the buses' travel time, intersection delay, and average speed are 5.10%, 11.11%, and 5.38%, respectively, which are better than scenario II-1. On the other hand, for low levels of demand (i.e. D/C of 0.55 or less), the improvement percentages of the buses' travel time, intersection delay, and average speed are 2.62%, 6.66%, and 2.69%, respectively. These values indicate the importance of the XBL in improving the buses performance at high and low levels of congestion.

5.1.7 Scenario II-3.

This scenario includes the following parameters: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (60% through – 30% left), and bus headway (15 minutes). The measures of effectiveness considered such as travel time, intersection delay and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 20.

Table 20: Measures of effectiveness for other vehicles and buses for scenario II-3

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.28	148.74	297.99	495.70
		***w/o XBL**	140.65	145.14	147.08	161.85
	Intersection Delay (s)	**with XBL**	54.85	60.36	194.59	386.03
		***w/o XBL**	53.29	57.43	59.01	72.75
	Average Speed (km/h)	**with XBL**	34.16	32.68	16.31	9.80
		***w/o XBL**	34.55	33.48	33.04	30.03
Buses	**Travel Time (s)**	**with XBL**	175.53	175.53	175.53	175.53
		***w/o XBL**	180.44	182.85	185.96	192.34
	Intersection Delay (s)	**with XBL**	72.88	72.89	72.88	72.89
		***w/o XBL**	78.23	80.02	83.25	90.08
	Average Speed (km/h)	**with XBL**	27.69	27.69	27.69	27.69
		***w/o XBL**	26.93	26.58	26.13	25.27
	Improvement %	**Travel Time**	2.72%	4.00%	5.61%	8.74%
		Intersection Delay	6.85%	8.92%	12.46%	19.08%
		Average Speed	2.80%	4.17%	5.94%	9.58%

* w/o XBL: without exclusive bus lane.

In this scenario, the buses' improvement percentages show better performance for the travel time, intersection delay, and average speed compared to scenarios II-2 and II-1. Because the traffic turning percentages of the other vehicles taking left turns are 30% compared to 40% in scenario II-2 and 50% in scenario II-1, so there is less maneuvering between the buses and the other vehicles. For example, at low traffic volumes such as D/C ratios of 0.55 or less, the improvement percentages of the buses' travel time, intersection delay, and average speed are 2.72%, 6.85%, and 2.80%. On the other hand, for high volumes such as D/C ratio equal to 0.95, the improvement percentages of the buses' travel time, intersection delay, and average speed are 5.61%, 12.46%, and 5.94%. Also, the results present similar trends to scenario I-3.

5.1.8 Scenario II-4.

The following parameters are set for this scenario: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (70% through – 20% left), and bus headway (15 minutes). Table 21 summarizes the measures of effectiveness considered which are travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road.

Table 21: Measures of effectiveness for other vehicles and buses for scenario II-4

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.74	152.62	427.29	540.21
		***w/o XBL**	140.63	145.10	147.69	185.95
	Intersection Delay (s)	**with XBL**	56.90	65.94	326.32	439.90
		***w/o XBL**	54.87	58.98	61.67	98.53
	Average Speed (km/h)	**with XBL**	34.05	31.84	11.37	9.00
		***w/o XBL**	34.56	33.49	32.91	26.14
Buses	**Travel Time (s)**	**with XBL**	175.53	175.53	175.53	175.53
		***w/o XBL**	181.08	183.92	187.86	211.48
	Intersection Delay (s)	**with XBL**	72.88	72.87	72.89	72.89
		***w/o XBL**	78.40	81.03	84.82	108.82
	Average Speed (km/h)	**with XBL**	27.69	27.69	27.69	27.69
		***w/o XBL**	26.84	26.42	25.87	22.98
	Improvement %	**Travel Time**	3.06%	4.56%	6.56%	17.00%
		Intersection Delay	7.04%	10.07%	14.06%	33.01%
		Average Speed	3.16%	4.78%	7.02%	20.48%

* w/o XBL: without exclusive bus lane.

As the D/C ratio increases on the main road, the improvement percentages of the buses' travel time, intersection delay, and average speed increase with great impact. When the D/C is equal to 0.75 (medium volume) or 0.95 or more (high volume), the improvement percentages of the buses' travel time, intersection delay, and average speed are 4.56%, 10.07%, and 4.78%, respectively for the medium volume, and 6.56%, 14.06%, and 7.02%, respectively for the high volume. However, the buses' improvement percentages improve significantly which shows better performance in terms of travel time, intersection delay, and average speed than previous scenarios. This can be attributed to the fact that the traffic percentage of the vehicles turning left is less than that of the previous scenarios. Also, the results indicate similar trends to scenario I-4.

Figure 23 shows a comparison between the improvement percentages of the buses' travel time for all scenarios in case II (15 minutes headway) under different D/C ratios on the main road corridor.

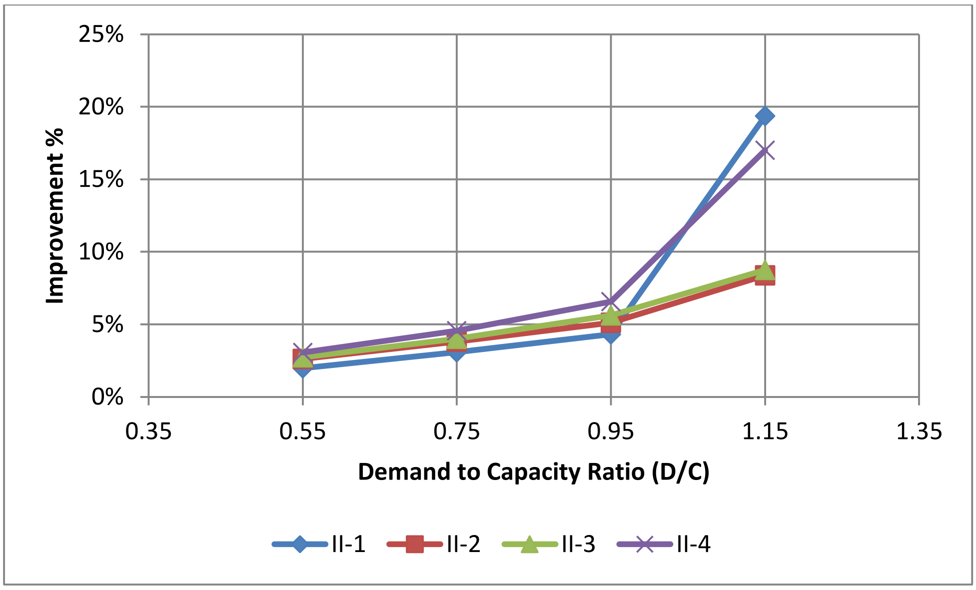

Figure 23: Improvement percentages for the buses' travel time for all scenarios in case II

Scenario I-4 has the best improvement percentage performance of the buses' travel time among all other scenarios for all D/C ratios on the main road corridor except at D/C ratio of 1.15. This is because in scenario II-1, the percentage of the other vehicles making left turn is 50%, (the extreme case), which results in more maneuvering and overtaking between the buses and the other vehicles. As a result, the buses consume more travel time to reach their destination in mixed traffic conditions. Having very high travel times in scenario II-1 and low travel times after using the XBL causes the improvement percentage to be higher than in other cases.

Figure 24 compares the improvement percentages of the buses' intersection delay for all scenarios in case II (15 minutes headway) under different D/C ratios of the main road corridor. The intersection delay follows a very similar trend to the travel time because of the same justifications provided earlier.

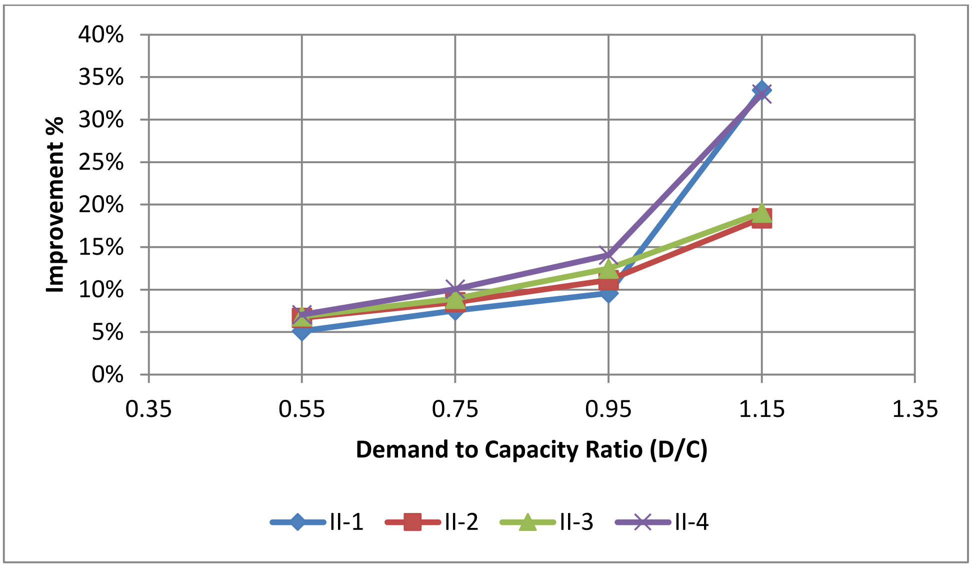

Figure 24: Improvement percentages for the buses' intersection delay for all scenarios in case II

A comparison between the improvement percentages of the buses' average speed in all scenarios in case II (15 minutes) under different D/C ratios of the main road is shown in Figure 25. For all D/C ratios of the main road corridor, scenario I-4 has the best improvement percentage performance of the buses' average speed among all other scenarios except for D/C of 1.15. In scenario II-1, the buses' average speed was reduced because of the interaction between the buses and vehicles turning left, which was a large portion of the traffic turning percentage (50%) in scenario II-1.

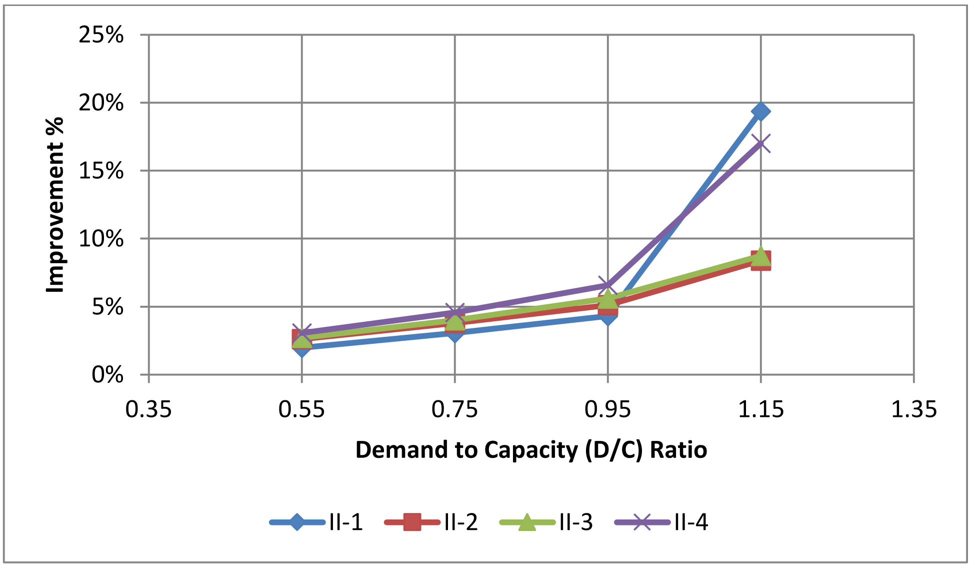

Figure 25: Improvement percentages for the buses' average speed for all scenarios in case II

5.1.9 Scenario III-1.

This scenario represents the following criteria: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (40% through – 50% left), and bus headway (10 minutes). The measures of effectiveness considered such as travel time, intersection delay and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 22.

Table 22: Measures of effectiveness for other vehicles and buses for scenario III-1

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.66	150.02	244.22	477.36
		***w/o XBL**	141.42	146.48	153.01	209.63
	Intersection Delay (s)	**with XBL**	51.31	57.04	132.11	341.71
		***w/o XBL**	49.86	54.16	58.22	102.93
	Average Speed (km/h)	**with XBL**	34.07	32.40	19.90	10.18
		***w/o XBL**	34.37	33.18	31.76	23.18
Buses	**Travel Time (s)**	**with XBL**	188.02	187.99	188.01	187.96
		***w/o XBL**	195.94	196.62	197.85	220.12
	Intersection Delay (s)	**with XBL**	90.67	90.67	90.67	90.66
		***w/o XBL**	93.83	94.18	95.97	117.67
	Average Speed (km/h)	**with XBL**	25.85	25.85	25.85	25.86
		***w/o XBL**	24.80	24.72	24.56	22.08
	Improvement %	**Travel Time**	4.05%	4.39%	4.98%	14.61%
		Intersection Delay	3.37%	3.72%	5.53%	22.96%
		Average Speed	4.22%	4.59%	5.24%	17.11%

* w/o XBL: without exclusive bus lane.

The results provide similar trends to scenario II-1 except for the D/C ratio of 1.15. However, the buses' improvement percentages for travel time and average speed are better than scenario II-1 for D/C ratio of 0.55 or less (low level of demand), and D/C ratio of 0.95 or more (high level of demand). The improvement percentages of the buses' travel time and average speed are 4.05% and 4.22%, respectively for low level of demand, and 4.98% and 5.24%, respectively for high level of demand. However, the buses' improvement percentages for intersection delay are less than scenario II-1. For example, for D/C ratios of 0.55 or less (low level of demand) and D/C ratios of 0.95 or more (high level of demand), the improvement percentages of the buses' intersection delay are 3.37% and 5.53%, respectively. This can be attributed to fact that the bus headway of 15 minutes generates 3 buses/hr while the bus headway of 10 minutes generates 4 buses/hr. The higher number of buses causes more delay as the buses delay each other.

5.1.10 Scenario III-2.

This scenario considers the following variables: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (50% through – 40% left), and bus headway (10 minutes). Table 23 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios of the main road.

Table 23: Measures of effectiveness for other vehicles and buses for scenario III-2

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	141.97	148.44	245.07	472.83
		***w/o XBL**	140.77	145.58	147.89	172.78
	Intersection Delay (s)	**with XBL**	52.89	58.13	141.20	351.54
		***w/o XBL**	51.55	55.81	57.52	79.26
	Average Speed (km/h)	**with XBL**	34.23	32.74	19.83	10.28
		***w/o XBL**	34.52	33.38	32.86	28.13
Buses	**Travel Time (s)**	**with XBL**	188.00	188.03	187.96	187.97
		***w/o XBL**	196.29	197.00	199.82	207.30
	Intersection Delay (s)	**with XBL**	90.67	90.67	90.68	90.66
		***w/o XBL**	93.90	94.57	97.46	105.06
	Average Speed (km/h)	**with XBL**	25.85	25.85	25.86	25.86
		***w/o XBL**	24.76	24.67	24.32	23.44
	Improvement %	**Travel Time**	4.23%	4.55%	5.94%	9.33%
		Intersection Delay	3.44%	4.12%	6.96%	13.71%
		Average Speed	4.41%	4.77%	6.31%	10.29%

* w/o XBL: without exclusive bus lane.

The improvement percentages of the buses' travel time, intersection delay, and average speed in this scenario, III-2, are improved significantly compared to scenario III-1. At high levels of congestion (i.e. D/C ratios of 0.95 or more), the improvement percentages of the buses' travel time, intersection delay, and average speed are 5.94%, 6.96%, and 6.31%, respectively. For low levels of congestion (D/C ratios of 0.55 or less), the improvement percentages of the buses' travel time, intersection delay, and average speed are 4.23%, 3.44%, and 4.41%. Moreover, the results show similar trends to scenario II-2 which verifies the consistency of the outputs.

5.1.11 Scenario III-3.

This scenario includes the following parameters: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (60% through – 30% left), and bus headway (10 minutes). The measures of effectiveness considered such as travel time, intersection delay and average speed for both the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 24.

Table 24: Measures of effectiveness for other vehicles and buses for scenario III-3

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.28	148.74	299.86	497.09
		***w/o XBL**	140.91	145.38	147.23	161.97
	Intersection Delay (s)	**with XBL**	55.04	60.50	196.22	387.44
		***w/o XBL**	53.53	57.65	59.17	73.04
	Average Speed (km/h)	**with XBL**	34.16	32.68	16.21	9.78
		***w/o XBL**	34.49	33.43	33.01	30.01
Buses	**Travel Time (s)**	**with XBL**	188.00	188.01	187.97	188.01
		***w/o XBL**	196.50	197.50	200.09	205.23
	Intersection Delay (s)	**with XBL**	90.67	90.67	90.67	90.66
		***w/o XBL**	94.14	95.18	97.62	103.25
	Average Speed (km/h)	**with XBL**	25.85	25.85	25.86	25.85
		***w/o XBL**	24.73	24.61	24.29	23.68
	Improvement %	**Travel Time**	4.33%	4.81%	6.06%	8.39%
		Intersection Delay	3.68%	4.73%	7.12%	12.19%
		Average Speed	4.52%	5.05%	6.45%	9.16%

* w/o XBL: without exclusive bus lane.

This scenario showed better improvement percentages of the buses' travel time, intersection delay, and average speed than scenarios III-1 and III-2. The improvement percentages of the buses' travel time, intersection delay, and average speed are 4.81%, 4.73%, and 5.05% for the D/C ratio equal to 0.75. The improvement percentages of the buses' travel time, intersection delay, and average speed are 6.06%, 7.12%, and 6.45% for D/C ratio of 0.95. This scenario has a smaller left turning percentage. As a result, the interaction between the buses and the other in terms of maneuvering and overtaking is less than in scenarios III-1 and III-2. The results illustrate similar trends to scenario II-3.

5.1.12 Scenario III-4.

The parameters in this scenario are defined as follows: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (70% through – 20% left), and bus headway (10 minutes). Table 25 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios of the main road.

Table 25: Measures of effectiveness for other vehicles and buses for scenario III-4

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.74	152.55	426.35	538.88
		***w/o XBL**	140.79	145.27	147.78	187.34
	Intersection Delay (s)	**with XBL**	57.08	65.99	324.66	438.41
		***w/o XBL**	55.05	59.24	61.62	99.36
	Average Speed (km/h)	**with XBL**	34.05	31.86	11.40	9.02
		***w/o XBL**	34.52	33.46	32.89	25.94
Buses	**Travel Time (s)**	**with XBL**	188.00	187.96	188.02	188.00
		***w/o XBL**	197.01	197.95	201.58	223.06
	Intersection Delay (s)	**with XBL**	90.67	90.68	90.65	90.64
		***w/o XBL**	94.35	95.40	99.40	120.73
	Average Speed (km/h)	**with XBL**	25.85	25.86	25.85	25.85
		***w/o XBL**	24.67	24.55	24.11	21.79
	Improvement %	**Travel Time**	4.58%	5.05%	6.73%	15.72%
		Intersection Delay	3.89%	4.95%	8.80%	24.92%
		Average Speed	4.80%	5.31%	7.21%	18.65%

* w/o XBL: without exclusive bus lane.

This scenario has the least left turning percentage among other scenarios. The improvement percentages of the buses' travel time, intersection delay, and average speed are 6.73%, 8.80%, and 7.21%, respectively, for high levels of demand such as D/C ratios of 0.95 or more. While low levels of demand like D/C ratios of 0.55 or less, the improvement percentages of the buses' travel time, intersection delay, and average speed are 4.58%, 3.89%, and 4.80%, respectively. Furthermore, the results provide similar trends to scenario II-4 except for the D/C ratio of 1.15.

Figure 26 illustrates a comparison between the improvement percentages of the buses' travel time of all scenarios in case III (10 minutes headway) under different D/C ratios on the main road corridor.

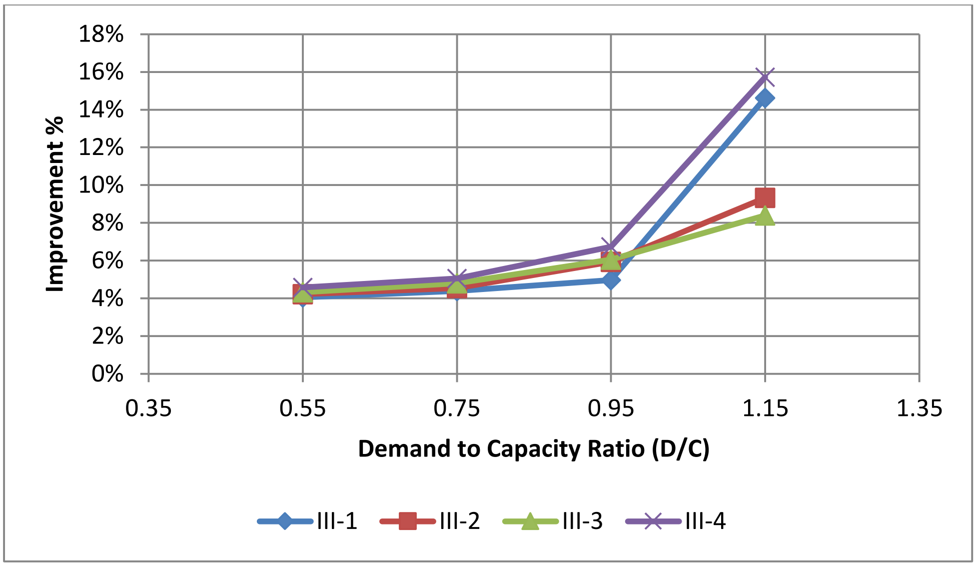

Figure 26: Improvement percentages for the buses' travel time for all scenarios in case III

Scenario III-4 has the best improvement percentage performance of the buses' travel time across all D/C ratios of the main road corridor because this scenario has the lowest left turning percentage. As a consequence, the interaction in terms of maneuvering and overtaking between the buses and the other vehicles is less.

A comparison between the improvement percentages of the buses' intersection delay of all scenarios in case III (10 minutes headway) under different D/C ratios of the main road corridor is shown in Figure 27. The best improvement percentage performance of the buses' intersection delay is scenario III-4 for the same reason mentioned earlier.

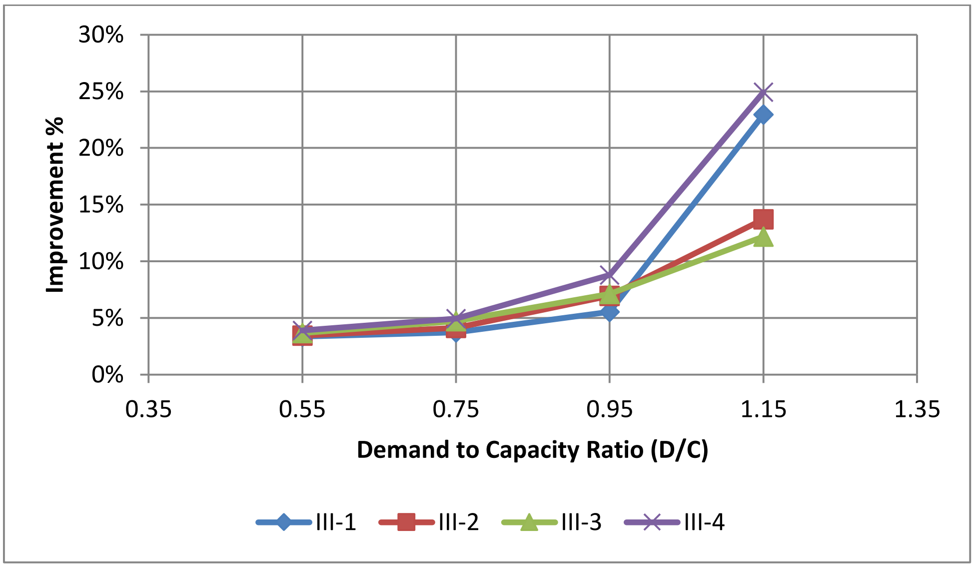

Figure 27: Improvement percentages for the buses' intersection delay for all scenarios in case III

Figure 28 compares between the improvement percentages of the buses' average speed for all scenarios in case III (10 minutes headway) under different D/C ratios on the main road corridor.

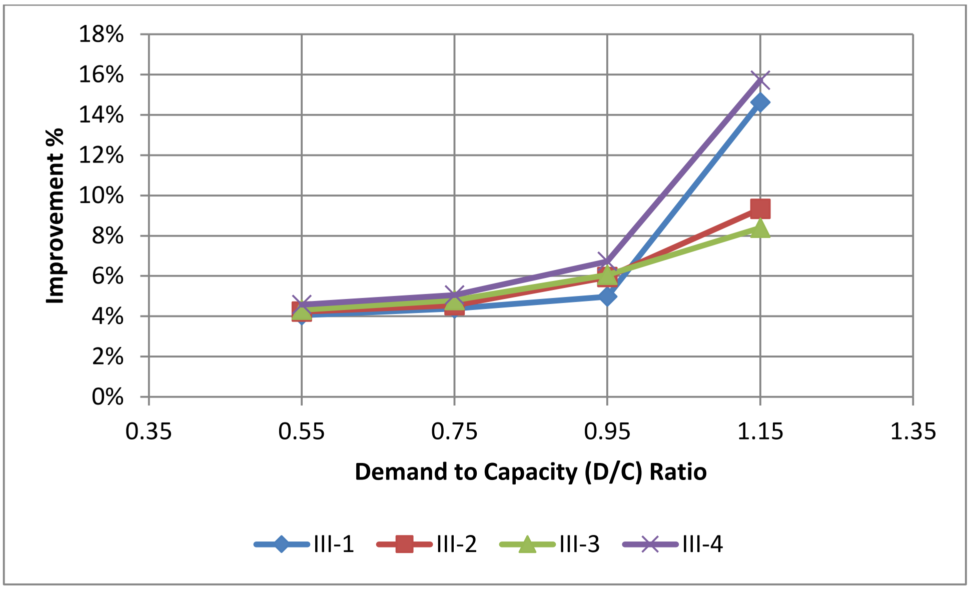

Figure 28: Improvement percentages for the buses' average speed for all scenarios in case III

For all D/C ratios of the main road corridor, scenario III-4 has the best improvement percentage performance of the buses' average speed among other scenarios (i.e. III-1, III-2, and III-3) for the same reason explained earlier.

5.1.13 Scenario IV-1.

This scenario represents the following criteria: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (40% through – 50% left), and bus headway (5 minutes). The measures of effectiveness considered such as travel time, intersection delay and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 26.

In this scenario, the improvement percentages of the buses' travel time and average speed are smaller than in scenario III-1 for D/C ratio of 0.55 (low volume), and D/C ratio of 0.95 (high volume). The improvement percentages of the buses' travel time and average speed are 2.79% and 2.87%, respectively for low volume and 4.77% and 5.01%, respectively for high volume. While the improvement percentages of the buses' intersection delay are greater than scenario III-1 for low and high volume (i.e. D/C ratios of 0.55 and 0.95), the improvement percentages of the buses' intersection delay are 4.88% and 9.31%, respectively. As the buses headway changes from 10 minutes to 5 minutes, the number of buses generated from these headways changes from 5 buses/hr to 11 buses/hr, respectively. This causes an increase in the travel time and average speed improvement percentages and a decrease in the intersection delay improvement percentages. This happened because the 5 minutes headway generated 11 buses/hr which causes the buses to delay each other. Furthermore, the results show similar trends to scenario III-1.

Table 26: Measures of effectiveness for other vehicles and buses for scenario IV-1

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.66	149.91	247.32	477.97
		***w/o XBL**	141.86	147.08	153.51	216.25
	Intersection Delay (s)	**with XBL**	51.37	56.94	133.85	340.55
		***w/o XBL**	50.16	54.62	58.88	107.57
	Average Speed (km/h)	**with XBL**	34.07	32.42	19.65	10.17
		***w/o XBL**	34.26	33.04	31.66	22.47
Buses	**Travel Time (s)**	**with XBL**	179.33	179.32	179.35	179.34
		***w/o XBL**	184.47	186.17	188.34	227.45
	Intersection Delay (s)	**with XBL**	78.11	78.09	78.10	78.09
		***w/o XBL**	82.12	83.57	86.12	120.43
	Average Speed (km/h)	**with XBL**	27.10	27.10	27.10	27.10
		***w/o XBL**	26.35	26.10	25.80	21.37
	Improvement %	**Travel Time**	2.79%	3.68%	4.77%	21.15%
		Intersection Delay	4.88%	6.55%	9.31%	35.16%
		Average Speed	2.87%	3.82%	5.01%	26.82%

* w/o XBL: without exclusive bus lane.

5.1.14 Scenario IV-2.

This scenario shows the results for the following variables: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (50% through – 40% left), and bus headway (5 minutes). Table 27 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road.

In all D/C ratios across the main road, the improvement percentages of the buses' travel time, intersection delay, and average speed have better performance than scenario IV-1. For example, for D/C ratio equal to 0.95, improvement percentages of the buses' travel time, intersection delay, and average speed are 5.38%, 10.52%, and 5.68%, respectively. For D/C ratio of 0.55 or less, improvement percentages of the buses travel time, intersection delay, and average speed are 3.0%, 5.31%, and 3.09%, respectively. The better results for this scenario occur because it has 40% of the vehicles taking left turns compared to 50% in scenario IV-1. In addition to that, the results provide similar trends to scenario III-2.

Table 27: Measures of effectiveness for other vehicles and buses for scenario IV-2

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	141.97	148.44	242.32	474.73
		***w/o XBL**	141.10	145.98	148.20	167.01
	Intersection Delay (s)	**with XBL**	52.96	58.12	138.80	351.95
		***w/o XBL**	51.76	56.13	57.90	74.16
	Average Speed (km/h)	**with XBL**	34.23	32.74	20.06	10.24
		***w/o XBL**	34.44	33.29	32.79	29.10
Buses	**Travel Time (s)**	**with XBL**	179.33	179.33	179.32	179.36
		***w/o XBL**	184.88	187.28	189.51	204.64
	Intersection Delay (s)	**with XBL**	78.11	78.10	78.11	78.12
		***w/o XBL**	82.49	84.35	87.29	102.25
	Average Speed (km/h)	**with XBL**	27.10	27.10	27.10	27.10
		***w/o XBL**	26.29	25.95	25.65	23.75
	Improvement %	**Travel Time**	3.00%	4.24%	5.38%	12.35%
		Intersection Delay	5.31%	7.41%	10.52%	23.60%
		Average Speed	3.09%	4.43%	5.68%	14.10%

* w/o XBL: without exclusive bus lane.

5.1.15 Scenario IV-3.

This scenario includes the following parameters: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (60% through – 30% left), and bus headway (5 minutes). The measures of effectiveness considered for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road are summarized in Table 28.

The improvement percentages of the buses' travel time, intersection delay, and average speed show better performance than the previous scenarios, IV-2 and IV-1. This happened due to the traffic turning left being 30% as compared to 40% and 50% in scenarios IV-2 and IV-1. This results in less maneuvering and greater ease in overtaking other vehicles without hindering the traffic network. For medium volumes (i.e. D/C ratios equal to 0.75), improvement percentages of the buses' travel time, intersection delay, and average speed are 4.60%, 8.05%, and 4.82%, respectively, while for high volumes like D/C ratios of 0.95 or more, the improvement percentages of the buses' travel time, intersection delay, and average speed are 6.03%, 11.68%, and 6.42%, respectively. Also, the results present similar trends to scenario III-3.

Table 28: Measures of effectiveness for other vehicles and buses for scenario IV-3

<table>
<tr><th colspan="3"></th><th colspan="4">D/C Ratios</th></tr>
<tr><th colspan="3"></th><th>0.55</th><th>0.75</th><th>0.95</th><th>1.15</th></tr>
<tr><td rowspan="6">Other Vehicles</td><td rowspan="2">Travel Time (s)</td><td>with XBL</td><td>142.28</td><td>148.74</td><td>295.12</td><td>494.87</td></tr>
<tr><td>*w/o XBL</td><td>141.29</td><td>145.74</td><td>147.77</td><td>167.26</td></tr>
<tr><td rowspan="2">Intersection Delay (s)</td><td>with XBL</td><td>55.06</td><td>60.48</td><td>190.98</td><td>383.42</td></tr>
<tr><td>*w/o XBL</td><td>53.79</td><td>57.89</td><td>59.58</td><td>77.53</td></tr>
<tr><td rowspan="2">Average Speed (km/h)</td><td>with XBL</td><td>34.16</td><td>32.67</td><td>16.47</td><td>9.82</td></tr>
<tr><td>*w/o XBL</td><td>34.40</td><td>33.35</td><td>32.89</td><td>29.06</td></tr>
<tr><td rowspan="9">Buses</td><td rowspan="2">Travel Time (s)</td><td>with XBL</td><td>179.33</td><td>179.32</td><td>179.33</td><td>179.35</td></tr>
<tr><td>*w/o XBL</td><td>185.14</td><td>187.96</td><td>190.83</td><td>206.23</td></tr>
<tr><td rowspan="2">Intersection Delay (s)</td><td>with XBL</td><td>78.11</td><td>78.10</td><td>78.11</td><td>78.10</td></tr>
<tr><td>*w/o XBL</td><td>82.79</td><td>84.93</td><td>88.44</td><td>104.10</td></tr>
<tr><td rowspan="2">Average Speed (km/h)</td><td>with XBL</td><td>27.10</td><td>27.10</td><td>27.10</td><td>27.10</td></tr>
<tr><td>*w/o XBL</td><td>26.25</td><td>25.86</td><td>25.47</td><td>23.57</td></tr>
<tr><td rowspan="3">Improvement %</td><td>Travel Time</td><td>3.14%</td><td>4.60%</td><td>6.03%</td><td>13.03%</td></tr>
<tr><td>Intersection Delay</td><td>5.66%</td><td>8.05%</td><td>11.68%</td><td>24.97%</td></tr>
<tr><td>Average Speed</td><td>3.24%</td><td>4.82%</td><td>6.42%</td><td>14.99%</td></tr>
</table>

* w/o XBL: without exclusive bus lane.

5.1.16 Scenario IV-4.

This scenario defines the following: bus direction (through), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (70% through – 20% left), and bus headway (5 minutes). Table 29 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road.

The results indicate similar trends to scenario III-4. This scenario has the best bus performance in terms of travel time, intersection delay, and average speed among other scenarios such as IV-1, IV2, and IV-3, because this scenario has the least number of vehicles going left relative to other scenarios. For high volumes (i.e. D/C ratios of 0.95 or more), improvement percentages of the buses' travel time, intersection delay, and average speed are 6.53%, 12.65%, and 6.98%, respectively. For low volumes, like

D/C ratios of 0.55 or less, improvement percentages of the buses' travel time, intersection delay, and average speed are 3.47%, 6.38%, and 3.60%, respectively.

Table 29: Measures of effectiveness for other vehicles and buses for scenario IV-4

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.74	152.62	427.00	540.60
		***w/o XBL**	141.21	145.75	148.17	190.36
	Intersection Delay (s)	**with XBL**	57.08	66.05	323.75	437.73
		***w/o XBL**	55.31	59.47	61.96	102.88
	Average Speed (km/h)	**with XBL**	34.05	31.84	11.38	8.99
		***w/o XBL**	34.42	33.34	32.80	25.53
Buses	**Travel Time (s)**	**with XBL**	179.33	179.32	179.33	179.33
		***w/o XBL**	185.78	188.04	191.85	234.25
	Intersection Delay (s)	**with XBL**	78.11	78.11	78.23	78.09
		***w/o XBL**	83.43	85.11	89.56	131.92
	Average Speed (km/h)	**with XBL**	27.10	27.10	27.10	27.10
		***w/o XBL**	26.16	25.85	25.33	20.75
	Improvement %	**Travel Time**	3.47%	4.64%	6.53%	23.44%
		Intersection Delay	6.38%	8.23%	12.65%	40.80%
		Average Speed	3.60%	4.86%	6.98%	30.62%

* w/o XBL: without exclusive bus lane.

A comparison between the buses' travel time improvement percentages for all scenarios in case IV (5 minutes) under different D/C ratios of the main road corridor is shown in Figure 29.

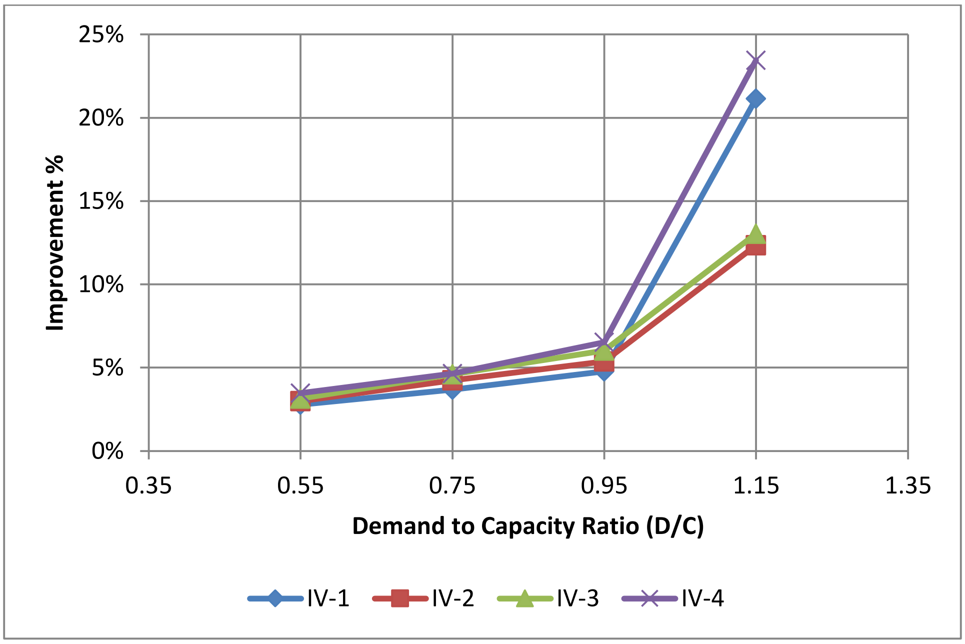

Figure 29: Improvement percentages for the buses' travel time for all scenarios in case IV

For high levels of demand (i.e. D/C ratio of 1.15), scenario IV-4 has the best performance improvement percentage of the buses' travel time among the others. Still, the values of the travel time improvement percentages of other scenarios are very close to each other for the D/C ratios of 0.95 or less. Scenario IV-4 has the least left turning percentage of vehicles, which is 20% among other scenarios. The same trends of behavior are noticed for the buses' improvement percentages in terms of intersection delay and average speed in scenario IV-4 among other scenarios and are shown in Figures 30 and 31, respectively.

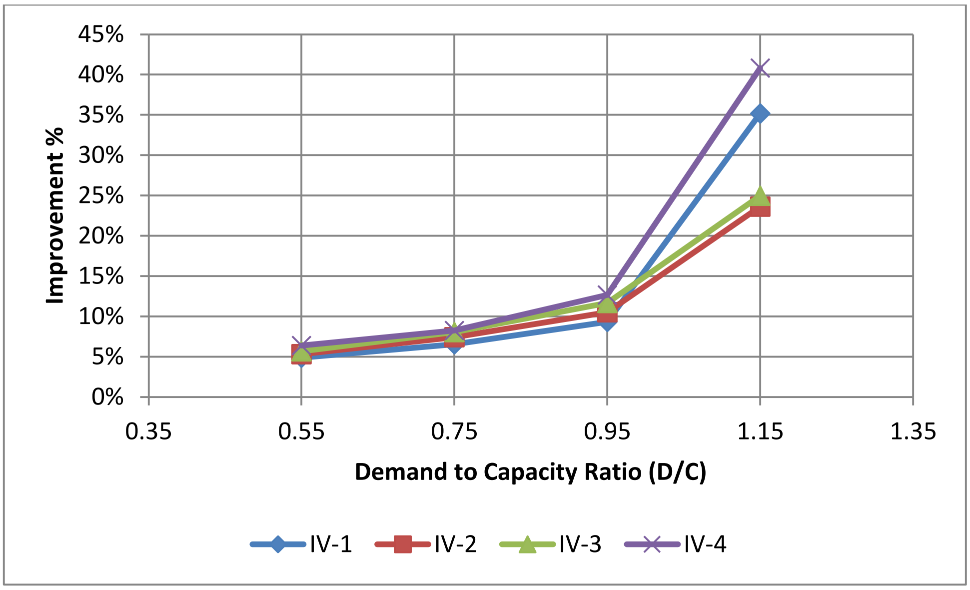

Figure 30: Improvement percentages for the buses' intersection delay for all scenarios in case IV

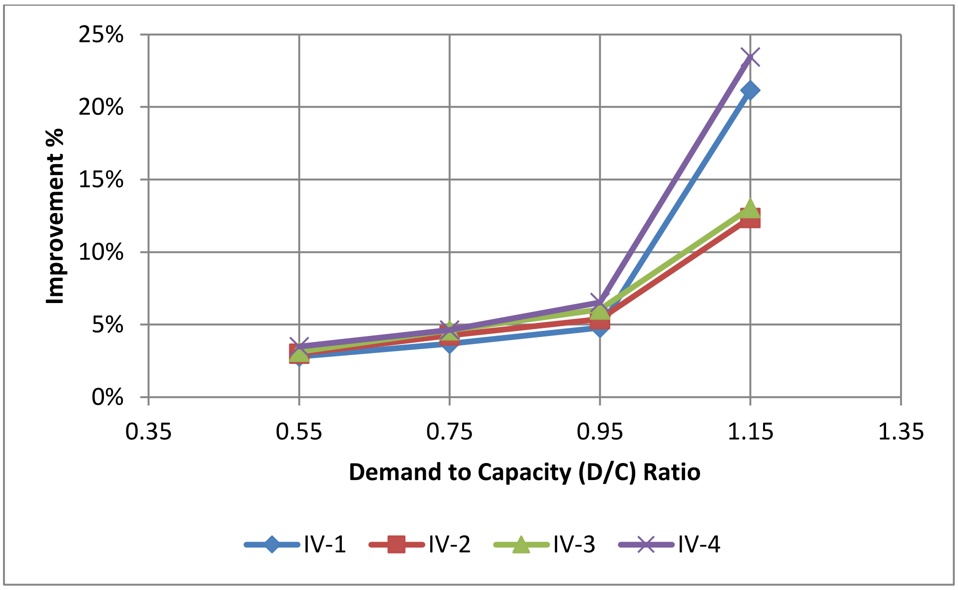

Figure 31: Improvement percentages for the buses' average speed for all scenarios in case IV

Figure 32 compares the effect of bus headways (20, 15, 10, and 5) minutes on the buses' performance travel time for the traffic turning percentages (40% through – 50% left) for different D/C ratios on the main road.

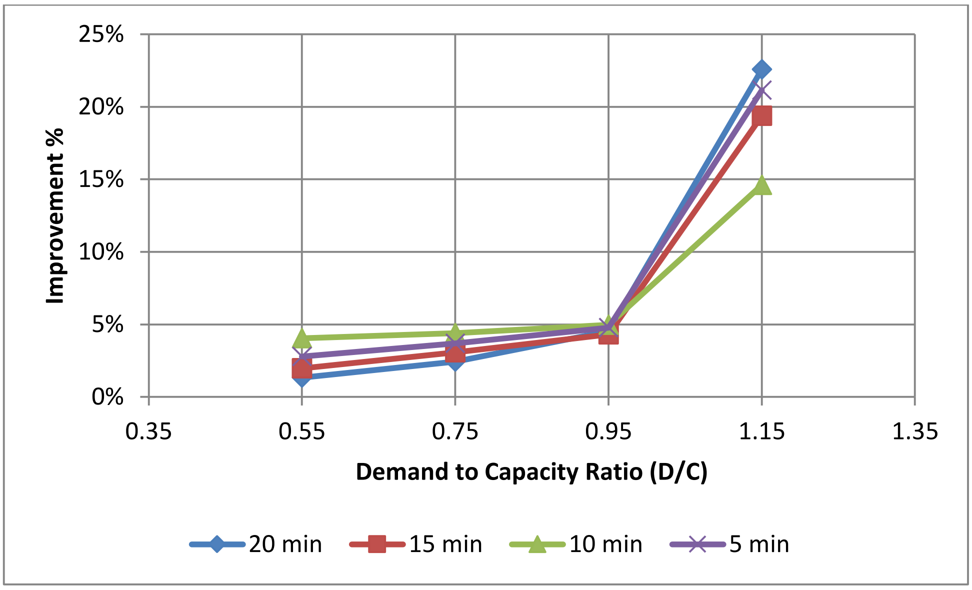

Figure 32: Travel time improvement percentages for different bus headways for traffic turning percentages (40% through - 50% left)

The graph indicates that the bus headway of 10 minutes has the best bus performance in terms of travel time for all D/C ratios on the main road corridor except for D/C ratio of 1.15. On the other hand, the bus headway of 10 minutes has the worst bus performance in terms of intersection delay improvement, for all D/C values, as shown in Figure 33.

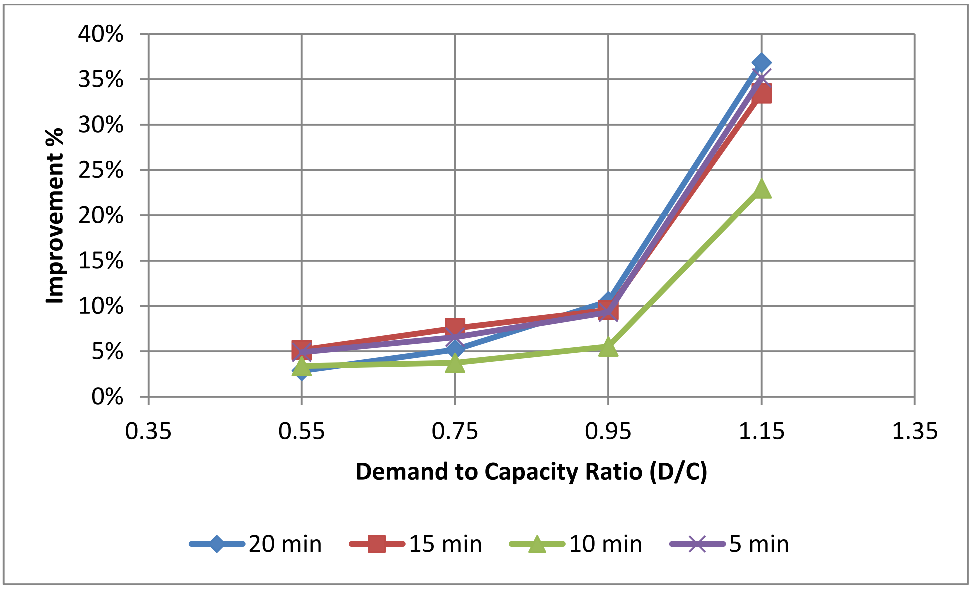

Figure 33: Intersection delay improvement percentages for different bus headways for traffic turning percentages (40% through - 50% left)

As the D/C ratio on the main road increases, the bus headway of 10 minutes shows the best bus performance in terms of travel time among all other bus headways for traffic turning percentages (50% through – 40% left) except for D/C ratio of 1.15, as shown in Figure 34. However, this bus headway of 10 minutes has the least intersection delay improvement among other headways for all D/C ratios of the main road, while the bus headway of 15 minutes has the best performance of the buses' intersection delay for all D/C ratios of the main road except when the D/C ratio equals 1.15 as shown in Figure 35.

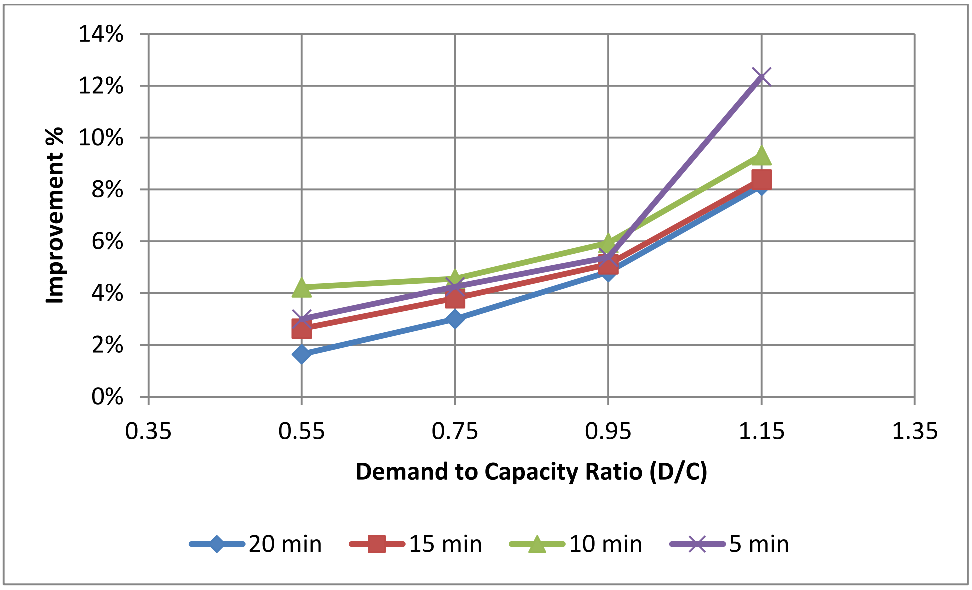

Figure 34: Travel time improvement percentages for different bus headways for traffic turning percentages (50% through - 40% left)

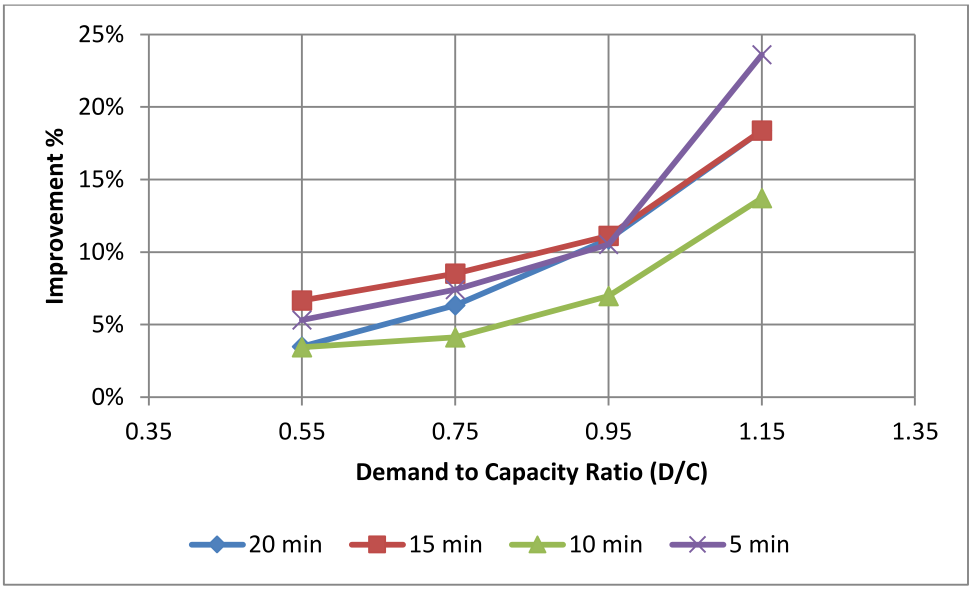

Figure 35: Intersection delay improvement percentages for different bus headways for traffic turning percentages (50% through - 40% left)

Similar trends of behavior are noticed in terms of travel time and intersection delay for the traffic turning percentages (60% through – 30% left) and (70% through – 20% left) as shown in Figures 36 to 39.

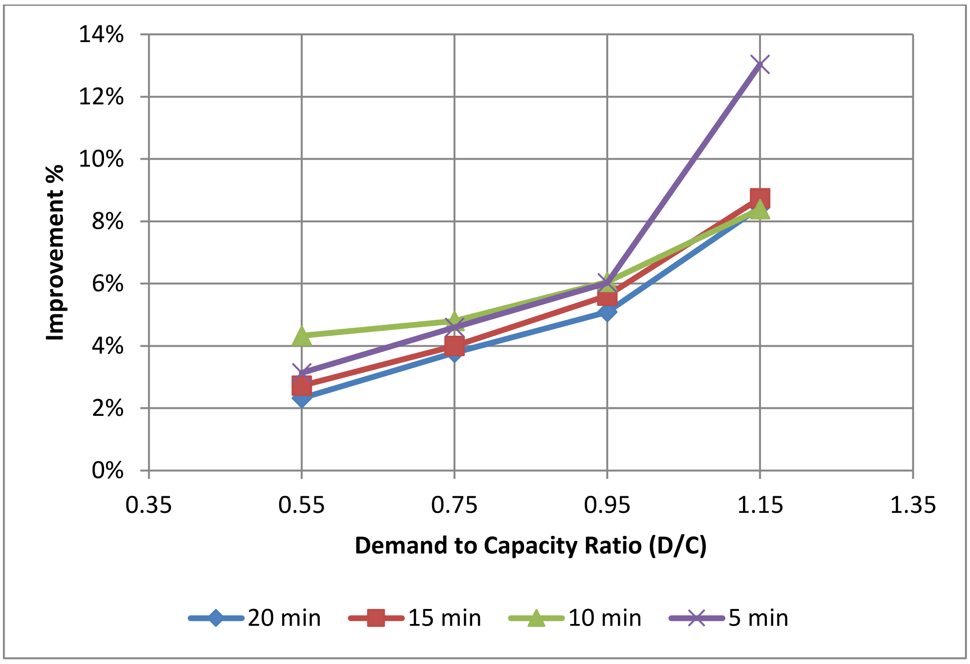

Figure 36: Travel time improvement percentages for different bus headways for traffic turning percentages (60% through - 30% left)

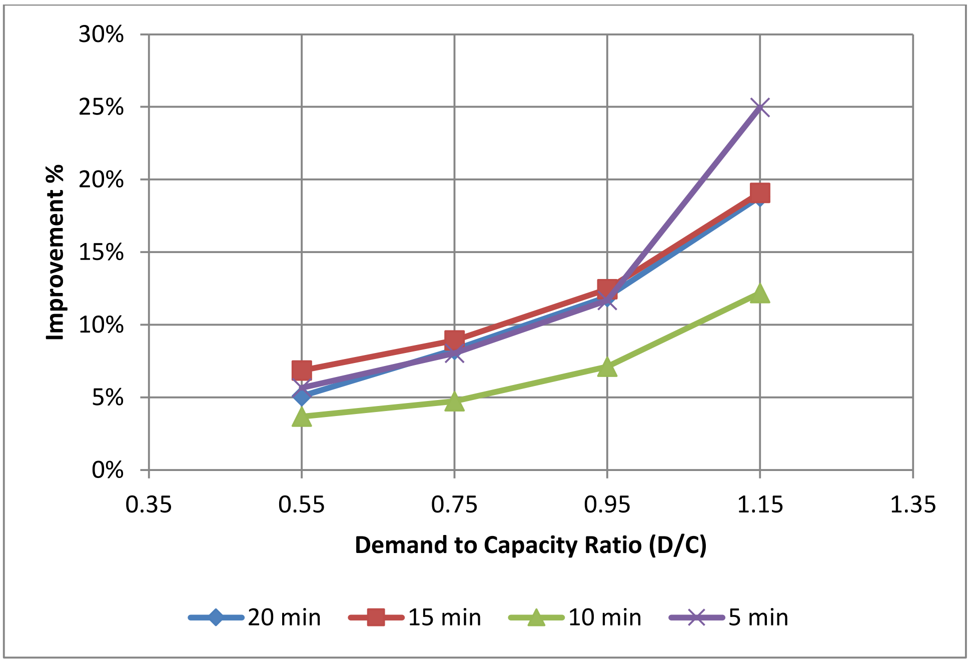

Figure 37: Intersection delay improvement percentages for different bus headways for traffic turning percentages (60% through - 30% left)

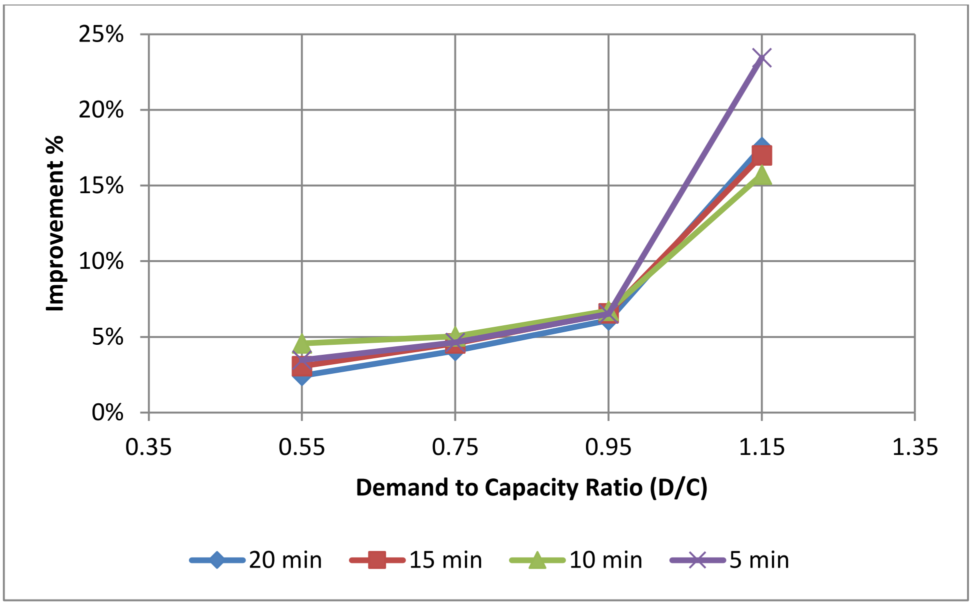

Figure 38: Travel time improvement percentages for different bus headways for traffic turning percentages (70% through - 20% left)

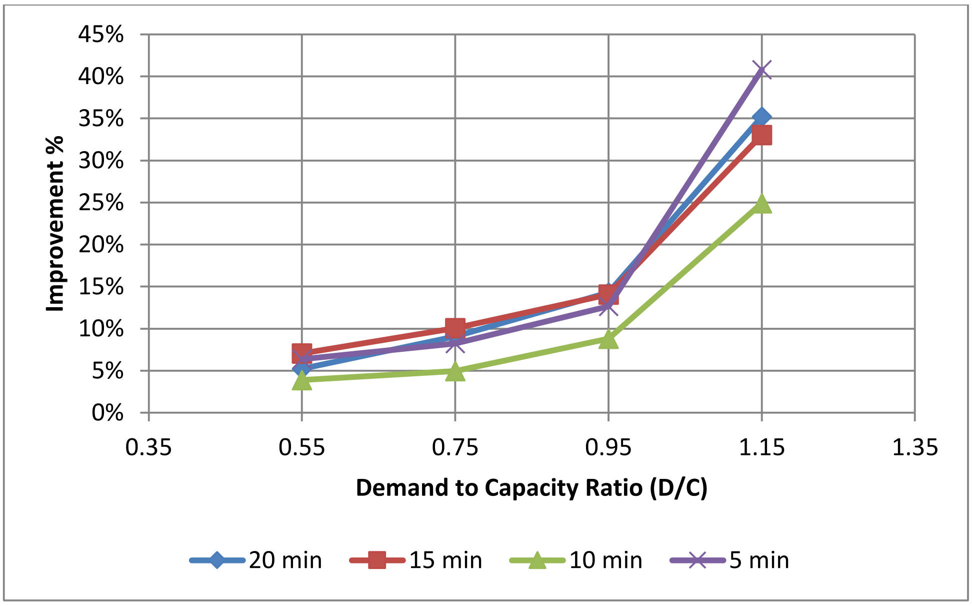

Figure 39: Intersection delay improvement percentages for different bus headways for traffic turning percentages (70% through - 20% left)

5.1.17 Scenario V-1.

This scenario represents the same conditions as scenario I-1, except for the bus movement, which is through in scenario I-1 and left in this scenario V-1. The other parameters remain the same (four D/C ratios of 0.55, 0.75, 0.95, and 1.15), traffic turning percentages (40% through – 50% left), and bus headway of 20 minutes.

The travel time of buses along the main road corridor with and without the XBL under different D/C ratios on major traffic volume is shown in Figure 40.

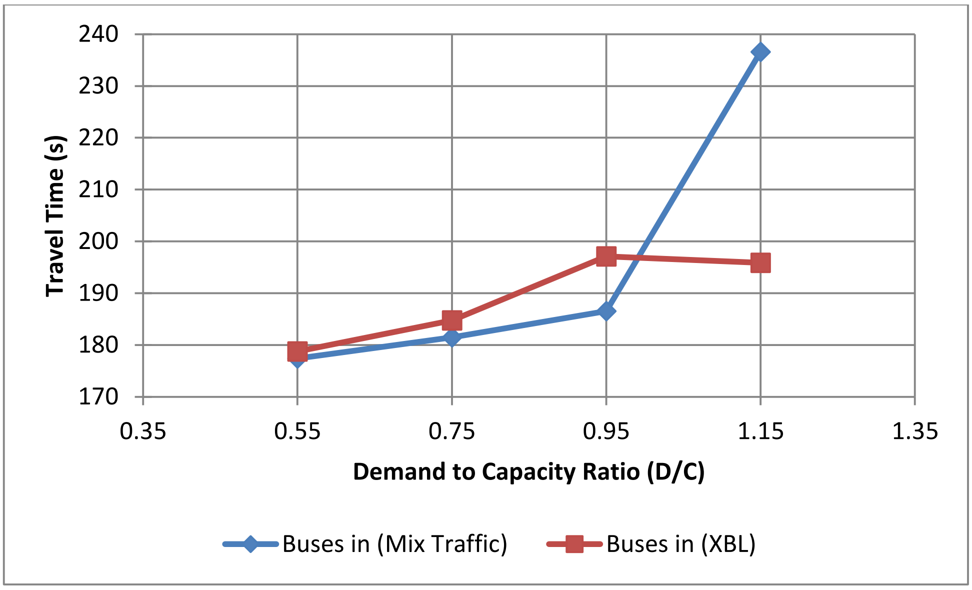

Figure 40: Travel time for the buses along the main road corridor with and without the XBL (V-1)

As the D/C ratio of the main road increases for the buses in mixed traffic conditions, the buses' travel time increases too. The XBL has a negative effect on the buses' travel time run in the XBL for D/C ratios of 0.95 or less on the main road corridor. This happened because the buses are forced to change lanes from the far right to the far left lane to make a left turn. On other hand, for D/C ratio of 1.15, the XBL has positive effect on the buses' travel time because the buses experience significant improvement inside the XBL, while the other vehicles are experiencing much higher travel times in the other lanes. The effect of using the XBL on the travel time of the other vehicles on the main road is shown in Figure 41.

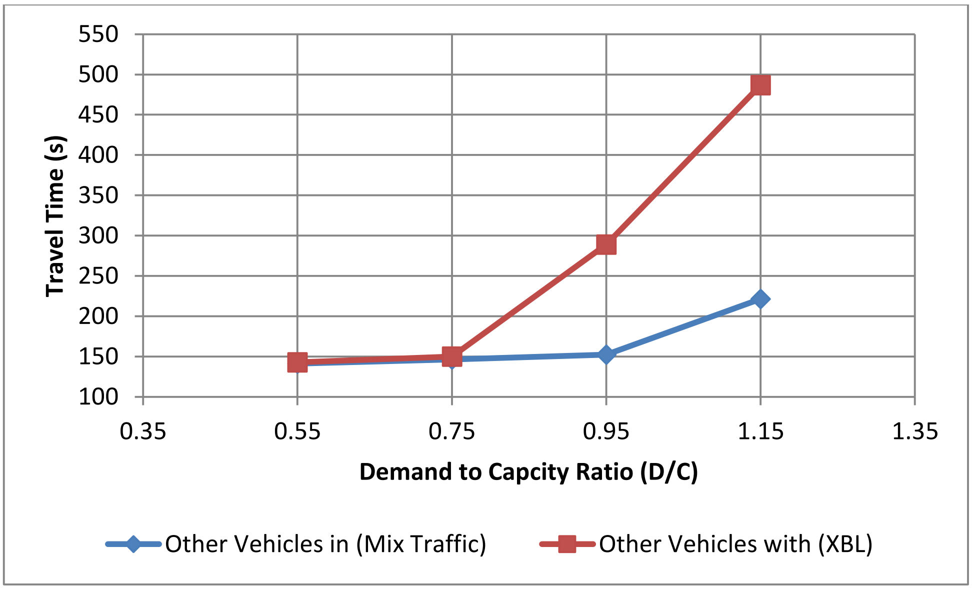

Figure 41: The effect of using the XBL on the travel times of the other vehicles (V-1)

The graph clearly shows small effect of the XBL on the other vehicles' travel time with the XBL for D/C ratios of 0.75 or more. It can be noticed that the other vehicles' travel time in mixed traffic conditions has less magnitude relative to the other vehicles with the XBL as the travel time is reduced to about half of the travel time of the other vehicles with the XBL when D/C ratio is equal to 0.95 or more.

The improvement percentages of buses' travel time with the XBL under different D/C ratios of main road is presented in Figure 42.

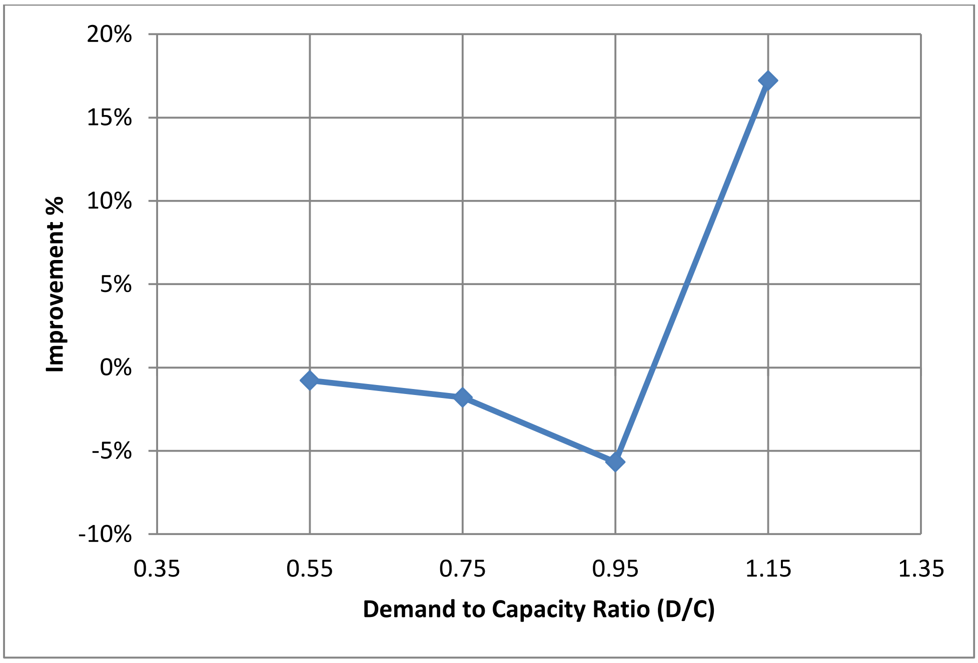

Figure 42: Improvement percentages of the buses' travel time (V-1)

The improvement percentages of the buses' travel time indicates negative values in all D/C ratios on the main road except when the D/C ratio is equal to 1 or more. At this level of congestion, the network is full and the travel time of the buses with the XBL take less time than the buses run in mixed traffic conditions. The XBL can only save time at capacity (i.e. D/C is equal to 1.0 or more) because the performance of the buses' travel time improves significantly in the XBL compared to the buses' travel time, in mixed traffic conditions, that increases as D/C ratios of the main road increase because the buses are trapped in the congestion. Otherwise, the time saving inside the XBL will be lost if the buses decide to maneuver from one lane to another for D/C ratios of 0.95 or less.

Figure 43 compares the intersection delay for the buses along the main road corridor with and without the XBL under different D/C ratios on major volumes.

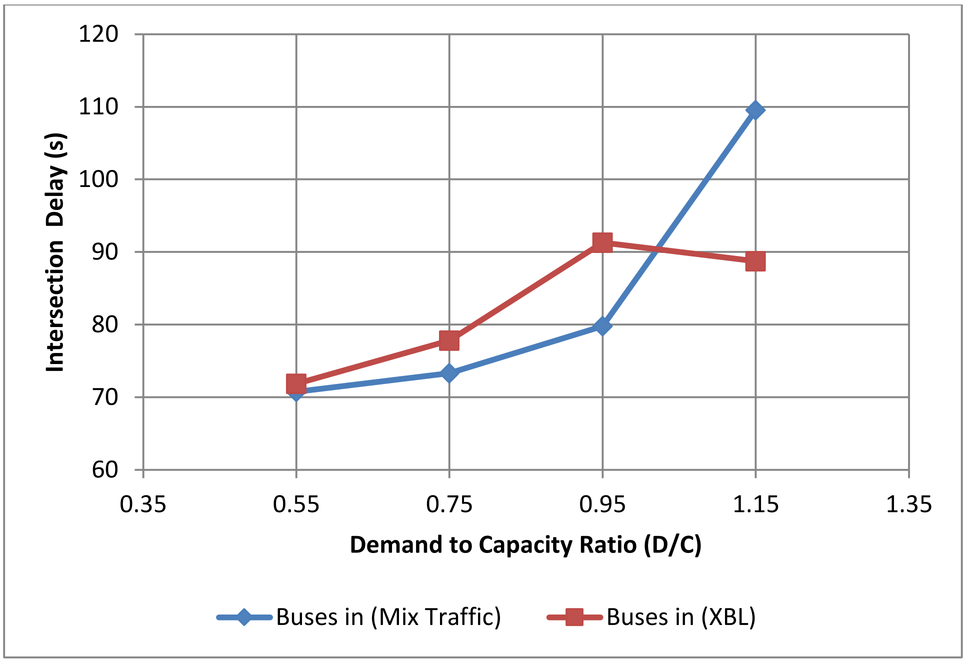

Figure 43: Intersection delay for the buses along the main road with and without the XBL (V-1)

For the buses operating in mixed traffic conditions, the intersection delay increases as the D/C ratio on the main road corridor increases due to the buses trapped in the congestion with other vehicles, especially at high levels of demand. However, the XBL does not improve the buses' intersection delay because the buses face more delays as they maneuver from one lane to another to make a left turn for the D/C ratios of 0.95 or less. As a result, the buses' intersection delays increase significantly. The XBL shows a positive impact when the network operates at its full capacity (i.e. D/C equal to 1.0 or more) because at this levels of congestion, the delay of the buses is reduced significantly with help of the XBL. In addition to that, the XBL help the buses to reach the intersection at the end of the XBL and avoid waiting for multiple signal cycles, as other vehicles.

Figure 44 shows the effect of setting up the XBL on the intersection delay of the other vehicles in adjacent lanes along the main road. The other vehicles' intersection delay increases, in mixed traffic conditions, as the D/C ratio on the main road corridor increases. On the other hand, the XBL increases the other vehicles' intersections delays to almost 3 times the intersection delay of the other vehicles in mixed traffic conditions at D/C ratios equal to 0.95 or more. This happens because the number of the other vehicles is allocated to less area after the implementation of the XBL.

The improvement percentages of the buses' intersection delays with the XBL under different D/C ratios along the main road are illustrated in Figure 45.

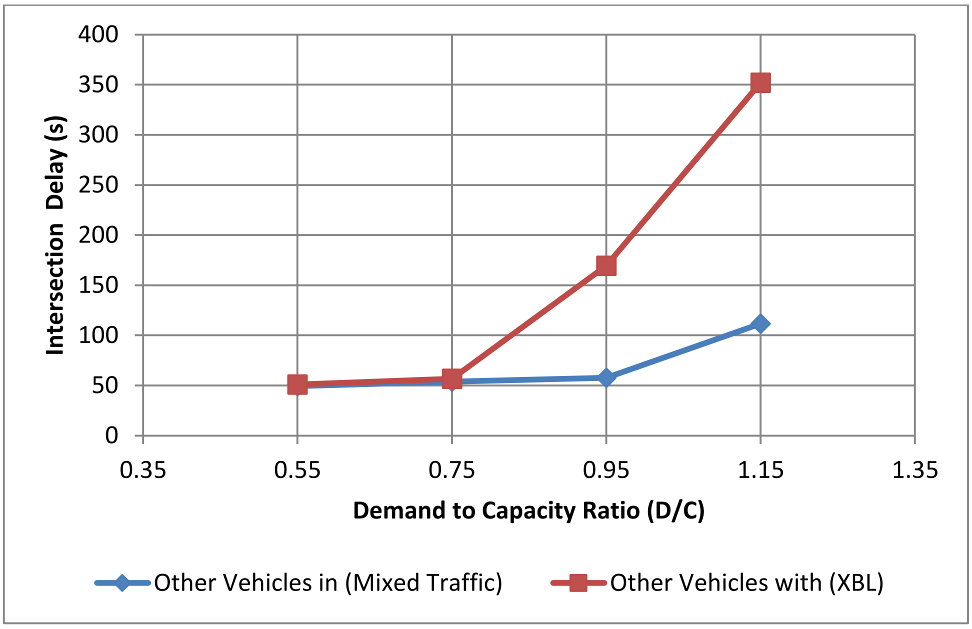

Figure 44: The effect of XBL on the other vehicles' intersection delay in adjacent lanes along the main road (V-1)

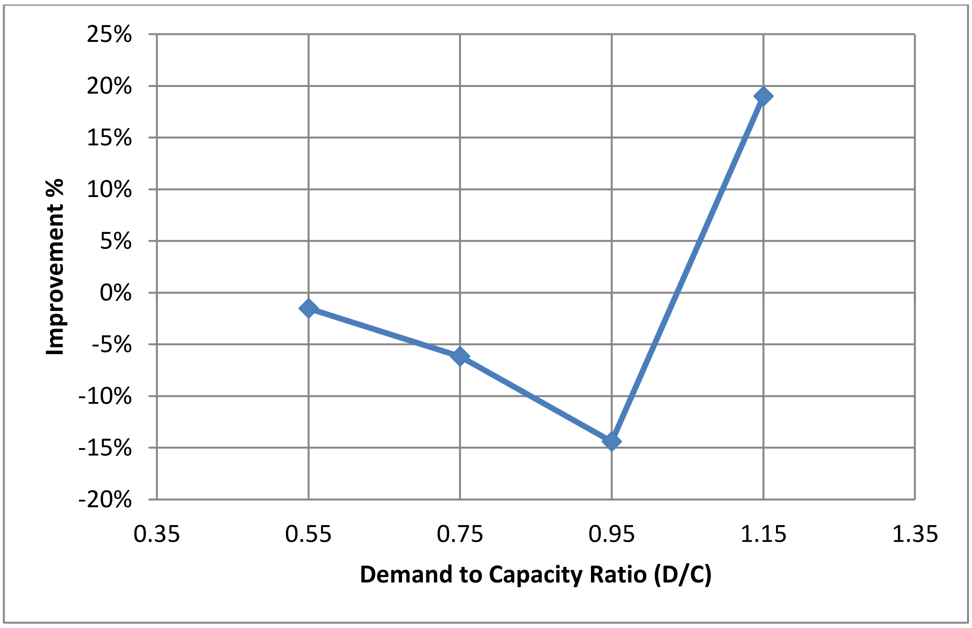

Figure 45: Improvement percentages of the buses' intersection delay (V-1)

The improvement percentages illustrate a positive value when the network operates at its full capacity (i.e. D/C ratio equal to 1.0 or more). At high levels of congestion, the XBL shows positive impacts on the performance of the buses' intersection delay because the buses' delay is reduced effectively by the help of the XBL. In contrast, the XBL shows negative effect on the performance of the buses' intersection delay for D/C ratios of 0.95 or less. This is happened because the time needed for the buses to shift lane from the far right to far left to make a left turn is greater than the improvement the buses gain inside XBL. The buses in mixed traffic conditions can maneuver after departing/alighting the passengers at the bus stop. However, the buses with XBL cannot change lane until the end of the XBL segment and sometime completely stop for couple of seconds waiting for the other vehicles in adjacent lanes to stops to allow the buses to maneuver and make a left turn.

The average speed of the buses along the main road with and without the XBL under different D/C ratios is presented in Figure 46.

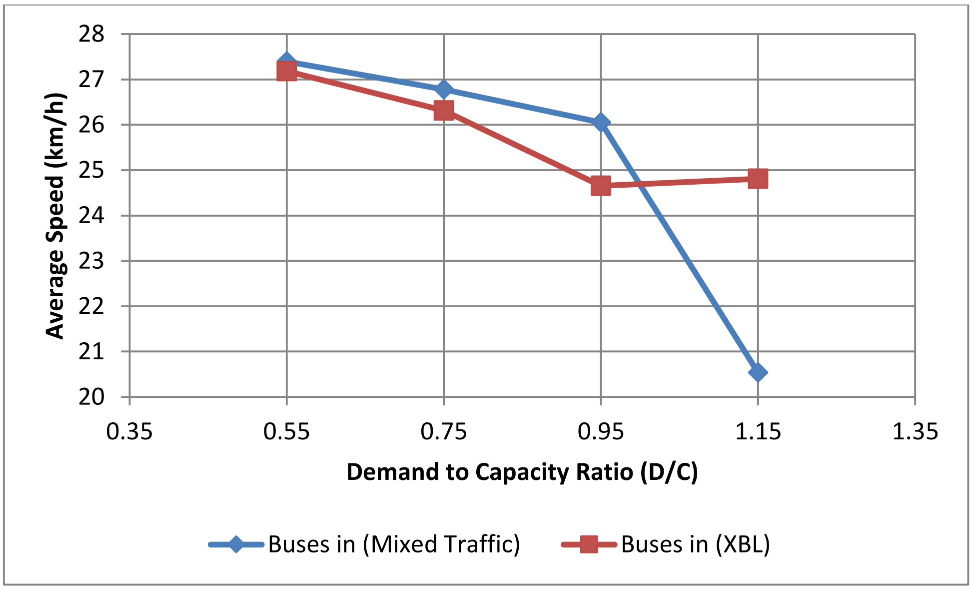

Figure 46: Average speed for buses along the main road with and without XBL (V-1)

As the number of the other vehicles on the main road corridor increases, the buses' average speed, in mixed traffic conditions, decreases gradually. Also, the buses' average speed in the XBL has a worse performance than the buses' average speed in mixed traffic conditions for all D/C ratios on the main road except for D/C ratio of 1.15 because the buses' average speed improves significantly by the use of XBL, while the buses' average speed, in mixed traffic conditions, deteriorates because the buses experience high levels of congestion. The XBL shows improvement only at high levels of congestion such as capacity (i.e. D/C >= 1.0) as the buses inside the XBL experience significant improvement compared to others trapped in the traffic congestions.

The effect of installing the XBL on the average speed of the other vehicles in adjacent traffic lanes along the main road is depicted in Figure 47. The graph shows that the other vehicles' average speed, in mixed traffic conditions, decreases as the D/C ratio on the main road increases. After the implementation of the XBL, the other vehicles' average speed decreases dramatically, especially when the D/C ratio is equal to 0.95 or more. At this level of congestion, the same demand is distributed on fewer lanes after the implementation of the XBL. This shows the negative impact of the XBL on the performance of the other vehicles' average speed at levels of congestions.

Figure 48 shows the improvement percentages of the buses' average speeds with the XBL under different D/C ratios on the main road.

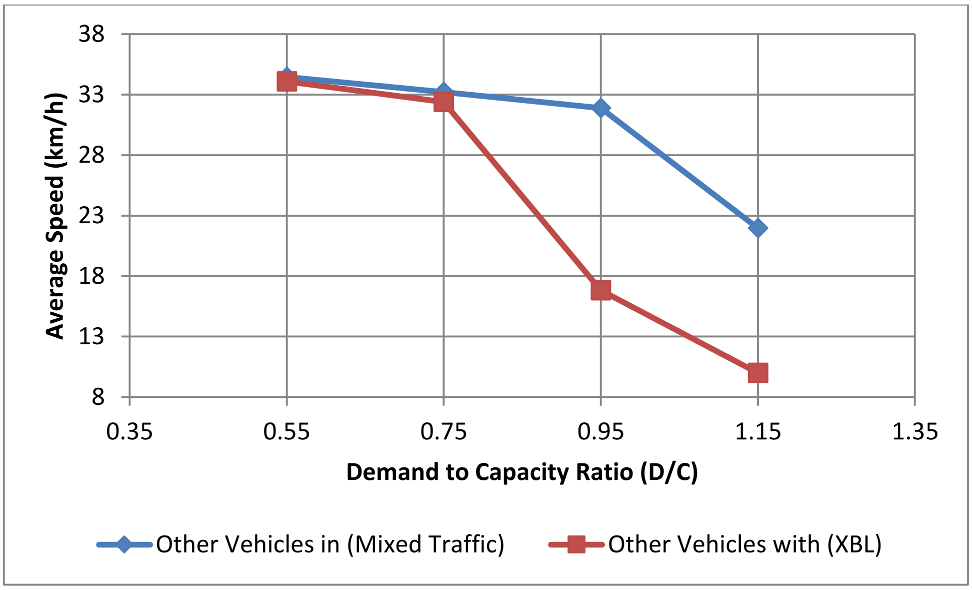

Figure 47: Average speed of the other vehicles with and without XBL (V-1)

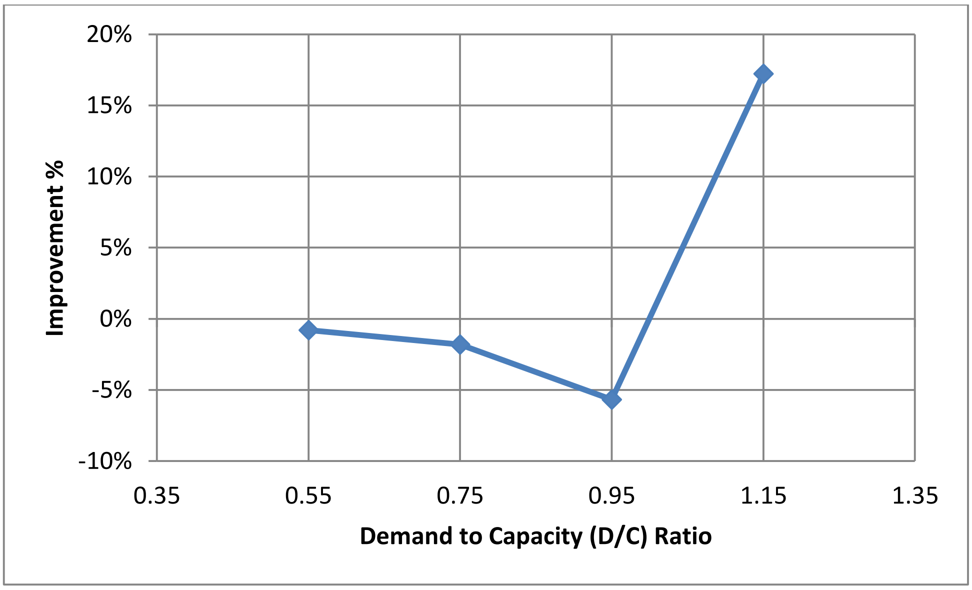

Figure 48: Improvement percentages of the buses' average speed (V-1)

The improvement percentages of the buses' average speed after the implementation of XBL illustrate negative values for D/C ratios of 0.95 or less. The only positive value of the improvement percentages is at high levels of volume when the network reaches capacity (i.e. D/C ratio equal to 1.0 or more). The XBL greatly improve the performance of the buses' average speed at high level, because the buses' average speed after the setting of the XBL gain significant improvement compared to the buses' average speed in the case of mixed traffic conditions that face high traffic jams.

5.1.18 Scenario V-2.

This scenario represents the following criteria: bus direction (left), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (50% through – 40% left), and bus headway (20 minutes). Table 30 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on the major road.

Table 30: Measure of effectiveness for other vehicles and buses for scenario V-2

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.10	148.73	273.85	487.36
		***w/o XBL**	140.41	145.24	147.47	166.72
	Intersection Delay (s)	**with XBL**	52.78	58.35	166.48	366.72
		***w/o XBL**	51.09	55.38	57.10	74.22
	Average Speed (km/h)	**with XBL**	34.20	32.68	17.75	9.97
		***w/o XBL**	34.61	33.46	32.96	29.15
Buses	**Travel Time (s)**	**with XBL**	178.12	183.30	196.41	196.59
		***w/o XBL**	176.53	179.86	182.45	209.54
	Intersection Delay (s)	**with XBL**	70.88	77.03	90.11	90.18
		***w/o XBL**	69.76	72.04	75.77	102.91
	Average Speed (km/h)	**with XBL**	27.29	26.51	24.74	24.72
		***w/o XBL**	27.53	27.02	26.64	23.19
	Improvement %	**Travel Time**	-0.90%	-1.91%	-7.66%	6.18%
		Intersection Delay	-1.61%	-6.93%	-18.92%	12.36%
		Average Speed	-0.89%	-1.88%	-7.11%	6.59%

* w/o XBL: without exclusive bus lane.

As the D/C ratios on the main road increase, the improvement percentages of the buses' travel time, intersection delay, and average speed decrease for all D/C ratios of the main road corridor except for D/C ratio of 1.15. This happened because after the implementation of the XBL, the buses' performances in terms of travel time, intersection delay, and average speed improved significantly. On the other hand, the buses in mixed traffic conditions got trapped in the congestion, and the travel time, intersection delay, and average speed deteriorate especially at a D/C ratio of 1.15. Also, this scenario shows less improvement performance than scenario V-1 in terms of travel time, intersection delay, and average speed. This can be attributed to the fact that the traffic turning percentage in this scenario, V-2, shows that 50% of the drivers going through, which is higher than that of scenario V-1 which has 40%. This increased the interaction between the buses and the other vehicles and increased the difficulties for the buses to maneuver since the buses are trying to cross the adjacent lanes to make a left turn. Furthermore, the results present similar trends to scenario V-1 which indicates the consistency of the results.

5.1.19 Scenario V-3.

This scenario considered the following variables: bus direction (left), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (60% through – 30% left), and bus headway (20 minutes). The measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without an XBL under different D/C ratios on the major road are summarized in Table 31.

The improvement percentages of the buses' travel time, intersection delay, and average speed decrease gradually as the D/C ratios of the main road increase for D/C ratios of 0.95 or less. This scenario, V-3, has smaller improvement percentages of the buses' travel time, intersection delay, and average speed than the previous scenario, V-2 and V-1. This because the percentage of traffic moving through in this scenario is 60% compared to 50% and 40% in the previous scenarios. This leads to more difficulties for the buses to cross the adjacent lanes since a great number of drivers are heading through which forces the buses to wait for drivers in adjacent lanes to stop in order for the bus to change lanes. At high levels of congestion (i.e. D/C ratios of 1.15), the improvement percentages of the buses' travel time, intersection delay, and average speed show positive values. This is because the XBL improve the performance of the buses significantly in terms of travel time, intersection delay, and average speed. The results illustrate similar trends to scenario V-1.

Table 31: Measures of effectiveness for other vehicles and buses for scenario V-3

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.74	150.53	332.60	505.63
		***w/o XBL**	140.55	145.05	146.72	163.20
	Intersection Delay (s)	**with XBL**	55.10	62.29	226.83	396.44
		***w/o XBL**	53.14	57.28	58.66	74.12
	Average Speed (km/h)	**with XBL**	34.05	32.29	14.61	9.61
		***w/o XBL**	34.58	33.51	33.12	29.78
Buses	**Travel Time (s)**	**with XBL**	178.00	183.72	197.73	199.06
		***w/o XBL**	175.86	179.17	180.93	202.00
	Intersection Delay (s)	**with XBL**	70.22	77.01	90.70	92.96
		***w/o XBL**	69.06	71.69	74.17	99.71
	Average Speed (km/h)	**with XBL**	27.30	26.45	24.58	24.41
		***w/o XBL**	27.64	27.13	26.86	24.06
	Improvement %	**Travel Time**	-1.22%	-2.54%	-9.28%	1.46%
		Intersection Delay	-1.68%	-7.42%	-22.29%	6.77%
		Average Speed	-1.20%	-2.48%	-8.49%	1.48%

* w/o XBL: without exclusive bus lane.

5.1.20 Scenario V-4.

This scenario defined the following: bus direction (left), four D/C ratios (0.55, 075, 0.95 and 1.15), traffic turning percentages (70% through – 20% left), and bus headway (20 minutes). Table 32 summarizes the measures of effectiveness considered such as travel time, intersection delay, and average speed for the other vehicles and the buses operating with and without the XBL under different D/C ratios on major traffic volume.

The results clearly indicate that the improvement percentages of the buses' travel time, intersection delay, and average speed decrease as the D/C ratios on the main road corridor increase for D/C ratios of 0.95 or less. In this scenario, the improvement percentages of the buses have the worst performance in terms of travel time, intersection delay, and average speed among other scenarios (V-1, V-2, and V-3) because this scenario has the highest traffic turning percentages of the drivers going through which is 70%. This increases the interaction between the buses turning left and the vehicles moving through. As a result, the buses gain extra travel time and delay to maneuver. The XBL significantly enhance the performance of the buses in terms of travel time, intersection delay, and average speed, especially at very high levels of congestion (i.e. D/C ratios of 1.0 or more) by saving time and reducing delay. In contrast, the buses' performance, in mixed traffic conditions, deteriorates significantly at D/C ratios of 1.0 or more. Moreover, the results show similar trends to scenario V-1 which indicates the consistency of the results.

Table 32: Measures of effectiveness for other vehicles and buses for scenario V-4

			D/C Ratios			
			0.55	**0.75**	**0.95**	**1.15**
Other Vehicles	**Travel Time (s)**	**with XBL**	142.84	155.15	440.76	545.87
		***w/o XBL**	140.50	145.04	147.45	183.01
	Intersection Delay (s)	**with XBL**	56.98	68.41	340.42	446.47
		***w/o XBL**	54.71	58.92	61.29	95.95
	Average Speed (km/h)	**with XBL**	34.02	31.32	11.03	8.90
		***w/o XBL**	34.59	33.51	32.96	26.56
Buses	**Travel Time (s)**	**with XBL**	177.38	183.22	202.93	201.00
		***w/o XBL**	175.01	178.21	178.98	210.91
	Intersection Delay (s)	**with XBL**	69.22	76.40	96.43	102.30
		***w/o XBL**	68.05	70.84	72.70	103.77
	Average Speed (km/h)	**with XBL**	27.40	26.52	23.95	24.18
		***w/o XBL**	27.77	27.27	27.15	23.04
	Improvement %	**Travel Time**	-1.35%	-2.81%	-13.38%	4.70%
		Intersection Delay	-1.71%	-7.84%	-32.64%	1.42%
		Average Speed	-1.33%	-2.74%	-11.80%	4.93%

* w/o XBL: without exclusive bus lane.

As the left movement percentages increase and the through movement percentages decrease of the other vehicles on the main road, the buses turning left experience high difficulties to change lanes and vice versa. For levels of demand (D/C ratio of 0.55), the XBL shows negative effect on the performance of the buses' travel time, intersection, and average speed. This is because the buses are not allowed to maneuver until the end of the XBL segment and wait the other vehicles in adjacent lanes to stop to allow the buses to maneuver. This makes the buses gain extra travel time and delay. On the other hand, at high levels of demand such as a (D/C ratio of 1.15), the buses, in mixed traffic conditions, experience excessive delays as the buses maneuver from one lane to another because the buses have a very long queue which causes excessive travel times and intersection delays. In contrast, the saving time for the buses running in XBL is significant and the effect of shifting lanes becomes minimal compared to the total travel time.

Figure 49 shows the deterioration percentages of the other vehicles' travel time in adjacent lanes for all traffic turning percentages under different D/C ratios of the main road corridor.

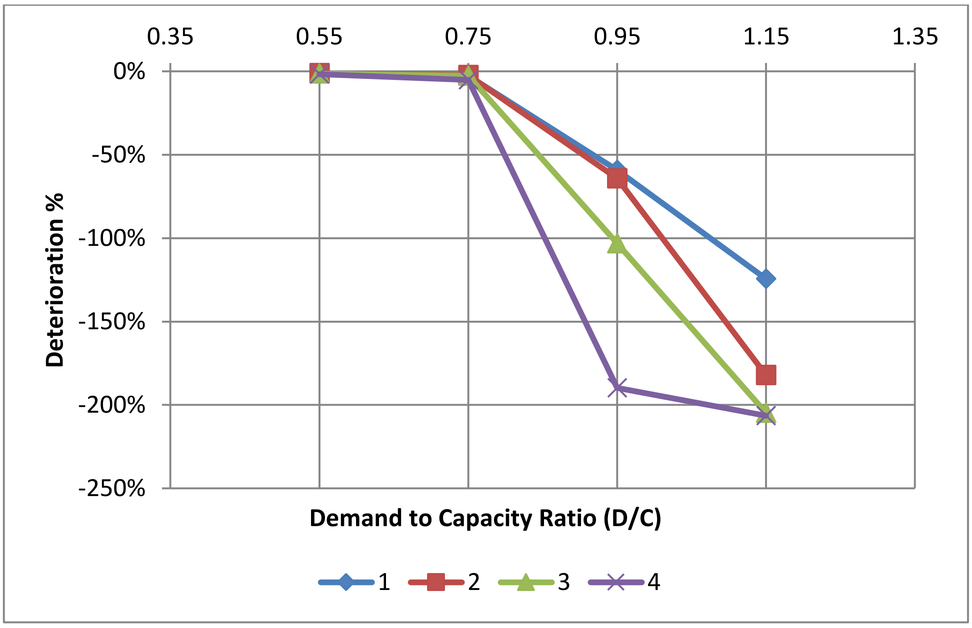

Figure 49: The deterioration percentage of the other vehicles' travel time for all traffic turning percentages

As the D/C ratios on the main road corridor increase, the deterioration percentages for all traffic turning percentages of the other vehicles' travel time, with the XBL, decrease. For medium levels of volume (i.e. D/C of 0.75 or less), the deterioration percentage of the other vehicles' travel time in all traffic turning percentages (1, 2, 3, and 4) is almost -5%. This indicates the small effect of the XBL on the other vehicles' travel time performance, because the network has a moderate level of demand and the vehicles can freely change lanes and overtake others. However, for high levels of demand like D/C ratio equal to 0.95, the deterioration percentage of the vehicles' travel time increases significantly (nearly -55%) for traffic turning percentages 1 and 2, and to almost -105% and -190% for traffic turning percentages 3 and 4, respectively. Therefore, this shows the huge negative impact of the XBL on the other vehicles' travel time in adjacent lanes, especially at high levels of volume, because the same number of vehicles, before the implementation of XBL, was distributed across lanes after the implementation of the XBL.

After the implementation of the XBL, the deterioration percentages of the other vehicles' intersection delay in adjacent lanes for all traffic turning percentages under different D/C ratios of the main road corridor is illustrated in Figure 50. The deterioration percentages of the other vehicles' average speed, with the XBL, decrease as the D/C ratios of the main road corridor increase except for traffic turning percentage 4 at a D/C ratio of 1.15, because at this traffic turning percentage there was a demand latent. In other words, the number of other vehicles that were not allowed to enter the traffic network until the end of the simulation.

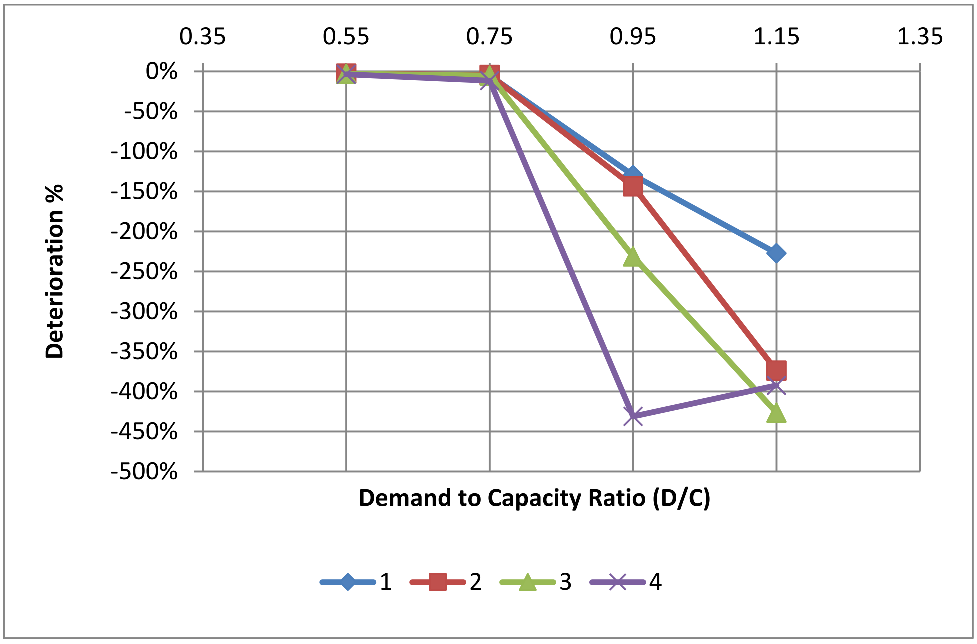

Figure 50: The deterioration percentage of the other vehicles' intersection delay for all traffic turning percentages

The XBL has a small effect on the performance of the other vehicles' intersection delay in adjacent lanes. At medium levels of demand (i.e. D/C ratios of 0.75 or less), the deterioration percentage of the vehicles' intersection for all traffic turning percentages (1, 2, 3, and 4) gets close to -11%. In contrast, the deterioration percentages of the vehicles' intersection delay at high levels of volume like D/C ratio equal to 0.95 are almost -130% for traffic turning percentages of 1 and 2, and -230%, and -430% for traffic turning percentages of 3 and 4, respectively. This shows the huge effect of the XBL on the performance of vehicles' intersection delay at high levels of congestion, because the same number of the other vehicles, before taking a lane for the XBL, was served by fewer lanes after taking a lane for the XBL, which results in huge congestions. Also, as the traffic turning percentage of the other vehicles turning left decreases and the traffic percentages of the other vehicles moving through increases, the deterioration percentages of the vehicles' intersection delay, with the XBL, increases and vice versa.

The deterioration percentages of the other vehicles' average speed in adjacent lanes for all traffic turning percentages under different D/C ratios of the main road corridor, as a result of implementing the XBL, are shown in Figure 51.

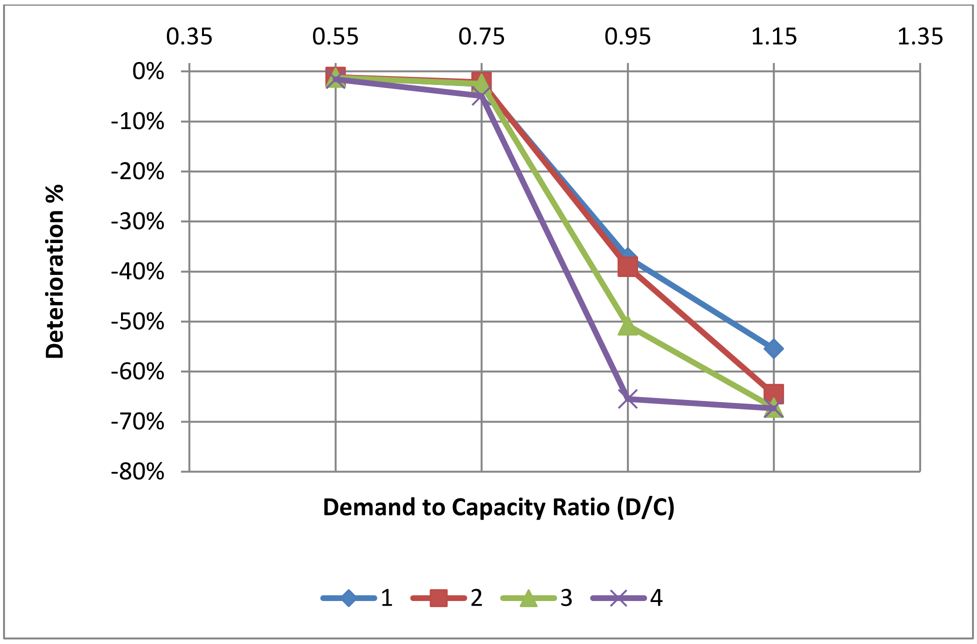

Figure 51: The deterioration percentage of the other vehicles' average speed for all traffic turning percentages

The deterioration percentages of the other vehicles' average speed, with the XBL, for all traffic turning percentages increase as the D/C ratio of the main road corridor increases. At medium congestion levels (i.e. D/C ratios of 0.75 or less), the deterioration percentages of the vehicles' average speed in adjacent lanes is less than -5% for all traffic turning percentages (1, 2, 3, and 4). This illustrates the low impact of the XBL on the performance of the other vehicles' average speed, because the network has a low level of volume which allows free movement for the other vehicles. On the other hand, the deterioration percentages of the vehicles' average speed are near -37% for traffic turning percentages of 1 and 2, and almost -50% and -65% for traffic turning percentages of 3 and 4, respectively at D/C ratio equal to 0.95. This shows the negative impact the XBL has on the performance of the vehicles' average speed in adjacent lanes at high levels of demand, because the network is fully occupied especially after taking a lane for the XBL. This congests the traffic network as the vehicles move bumper to bumper. In addition to that, the deterioration of the vehicles' average speed, with the XBL, in adjacent lanes increases with the increase in the traffic turning percentages of the vehicles moving through and with the decrease in the traffic turning percentages of the vehicles turning left and vice versa.

Table 33 shows the deterioration percentages of the other vehicles' travel time, intersection delay, and average speed in adjacent lanes for all traffic turning percentages under different D/C ratios of the main road corridor.

Table 33: The deterioration percentages of the other vehicles with XBL

				D/C Ratio			
	Measure of Effectiveness (MOEs)	**NO.**	**Traffic Turning %**	**0.55**	**0.75**	**0.95**	**1.15**
Deterioration %	**Travel Time**	**1**	**40 Through – 50 Left**	-1.13%	-2.60%	-59.22%	-124.28%
		2	**50 Through – 40 Left**	-1.13%	-2.21%	-64.07%	-182.01%
		3	**60 Through – 30 Left**	-1.25%	-2.54%	-103.06%	-204.80%
		4	**70 Through – 20 Left**	-1.62%	-5.13%	-189.67%	-206.35%
	Intersection Delay	**1**	**40 Through – 50 Left**	-3.06%	-5.49%	-129.51%	-227.44%
		2	**50 Through – 40 Left**	-2.85%	-4.52%	-143.70%	-374.17%
		3	**60 Through – 30 Left**	-2.98%	-5.18%	-231.24%	-426.44%
		4	**70 Through – 20 Left**	-3.83%	- 11.57%	-431.36%	-392.53%
	Average Speed	**1**	**40 Through – 50 Left**	-1.12%	-2.53%	-37.19%	-55.41%
		2	**50 Through – 40 Left**	-1.11%	-2.16%	-39.05%	-64.54%
		3	**60 Through – 30 Left**	-1.23%	-2.47%	-50.75%	-67.19%
		4	**70 Through – 20 Left**	-1.59%	-4.88%	-65.48%	-67.36%

Table 33 shows that the turning percentage 4 has the highest deterioration percentages compared to the other turn percentages (1, 2, and 3) for the other vehicles' travel time, intersection, and average speed. This is can be attributed to the fact that there is unbalance distribution of the demand reaching the intersection and inefficient use of the signal timing and left turn lane. For turning movement 4, there are 70% of the vehicles moving through and 20% of the vehicles make a left turn which result in high levels of vehicles moving through and fewer number of vehicles are making a left turn. As a result, the through movement gains more time and delay and inefficient use of the signal time and left lane as fewer numbers of vehicles are making a left turn movement.

5.2 Mode Choice Analysis

In this section, a comparison based on the travel time of the buses in the XBL and the travel time of the other vehicles with XBL were analyzed to capture the equilibrium point in which the buses' travel time operating in the XBL will be equal to the other vehicles' travel time operating with the XBL on the main road corridor.

5.2.1 Scenario I-1.

This scenario has the same parameters defined in Section 5.1.1. Figure 52 presents a comparison between the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL under different D/C ratios on the main road corridor.

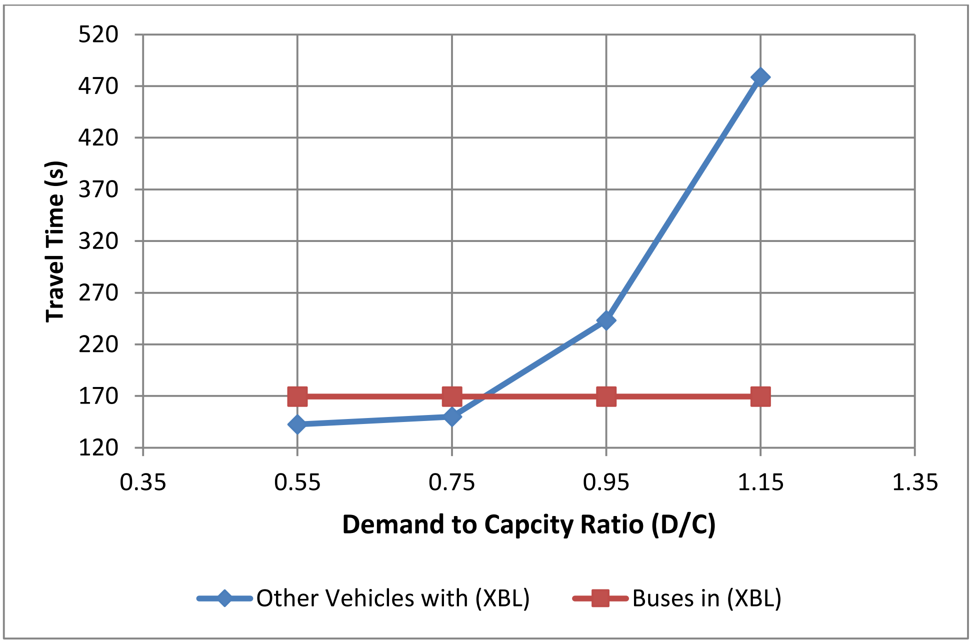

Figure 52: The travel time of the buses in XBL and the other vehicles with XBL (I-1)

The results show that the XBL is effective at D/C ratios of 0.80 or more because at this level of demand, which is considered to be high, the other vehicles experience huge delays because the traffic network is full and the other vehicles face difficulties maneuvering and overtaking others. However, the buses maintain a constant travel time along the main road corridor. This indicates the importance of the XBL in improving the buses' travel time.

5.2.2 Scenario I-2.

The parameters of this scenario are explained in section 5.1.2. A comparison between the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL under different D/C ratios on the main road is illustrated in Figure 53.

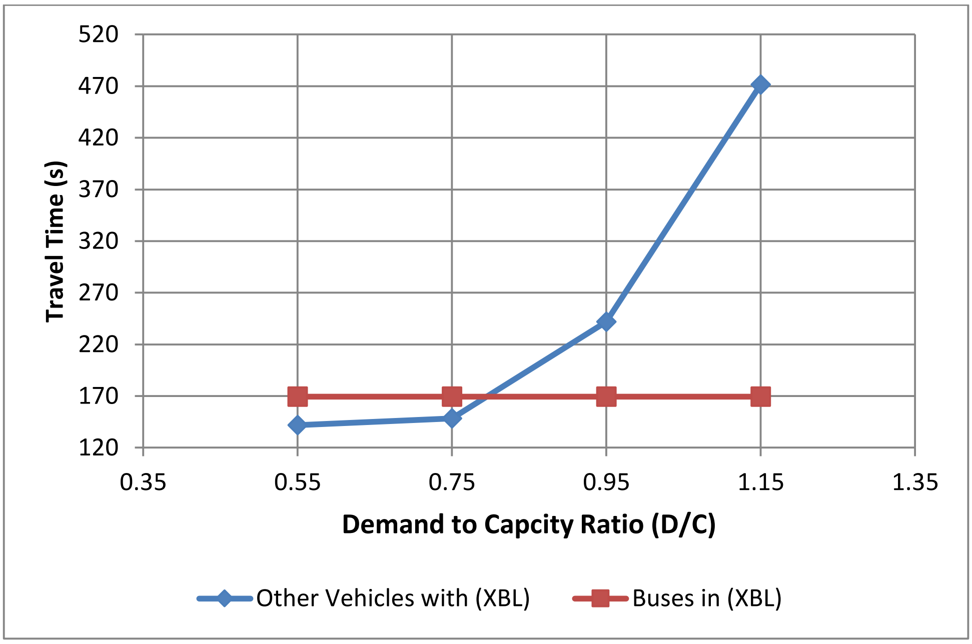

Figure 53: The travel time of the buses in XBL and the other vehicles with XBL (I-2)

The graph clearly shows that the XBL is effective at D/C ratios of 0.80 or more, in which the buses' performance in terms of travel time is better than the other vehicles' travel time performance, because at D/C ratios of 0.80 or more, the other vehicles have difficulty changing lanes and overtaking other vehicles.

5.2.3 Scenario I-3.

The conditions for each parameter in this scenario are presented in section 5.1.3. Figure 54 illustrates a comparison between the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL under different D/C ratios in the main road corridor. After the implementation of the XBL, the buses' travel time performance is better than the other vehicles' travel time performance at D/C ratios of 0.80 or more which indicates the importance of XBL at high level of volumes.

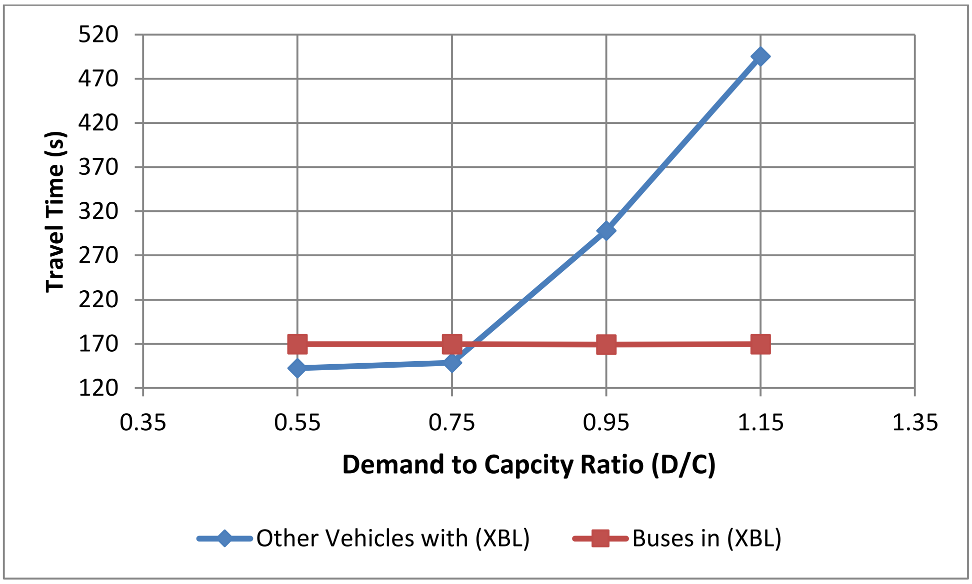

Figure 54: The travel time of the buses in XBL and the other vehicles with XBL (I-3)

5.2.4 Scenario I-4.

The categories of this scenario are defined in section 5.1.4. A comparison between the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL under different D/C ratios on the main road is shown in Figure 55.

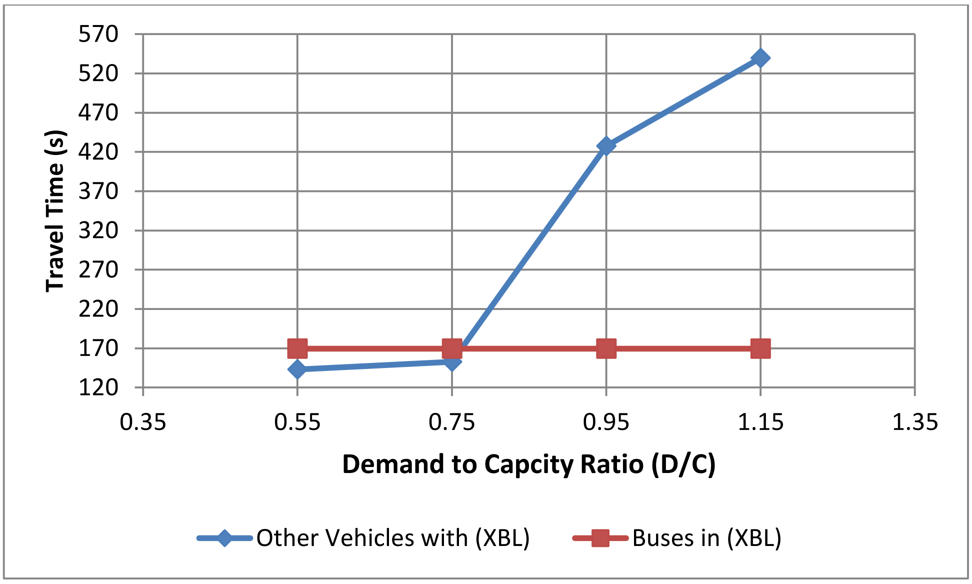

Figure 55: The travel time of the buses in XBL and the other vehicles with XBL (I-4)

At D/C ratios of 0.80 or more, an XBL is effective in improving the buses' travel time performance. In contrast, the other vehicles' travel time increase as the D/C ratios on the main road increase due to traffic congestion.

5.2.5 Scenarios II, III, and IV.

The considered variables in scenarios II-1 to II-4, III-1 to III-4, and IV-1 to IV-4 are defined in the previous sections (5.1.5, 5.1.6, 5.1.7, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.13, 5.1.4, 5.1.15, and 5.1.16, respectively). Table 34 summarizes the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL under different D/C ratios along the main road corridor.

Table 34: A comparison between the travel time of the buses in XBL and the travel time of the other vehicles with XBL for scenarios II, III, and IV.

						D/C Ratios			
						0.55	**0.75**	**0.95**	**1.15**
Bus Headways	**15 M**	**Travel Time (s)**	**II-1**	**Other Vehicles**	**w XBL**	142.66	150.01	245.00	478.68
				Buses	**w XBL**	175.53	175.53	175.53	175.53
			II-2	**Other Vehicles**	**w XBL**	141.97	148.43	241.83	471.84
				Buses	**w XBL**	175.53	175.53	175.53	175.53
			II-3	**Other Vehicles**	**w XBL**	142.28	148.74	297.99	495.70
				Buses	**w XBL**	175.53	175.53	175.53	175.53
			II-4	**Other Vehicles**	**w XBL**	142.74	152.62	427.29	540.21
				Buses	**w XBL**	175.53	175.53	175.53	175.53
	10 M	**Travel Time (s)**	**III-1**	**Other Vehicles**	**w XBL**	142.66	150.02	244.22	477.36
				Buses	**w XBL**	188.02	187.99	188.01	187.96
			III-2	**Other Vehicles**	**w XBL**	141.97	148.44	245.07	472.83
				Buses	**w XBL**	188.00	188.03	187.96	187.97
			III-3	**Other Vehicles**	**w XBL**	142.28	148.74	299.86	497.09
				Buses	**w XBL**	188.00	188.01	187.97	188.01
			III-4	**Other Vehicles**	**w XBL**	142.74	152.55	426.35	538.88
				Buses	**w XBL**	188.00	187.96	188.02	188.00

	5 M	Travel Time (s)	IV-1	**Other Vehicles**	**w XBL**	142.66	149.91	247.32	477.97
				Buses	**w XBL**	179.33	179.32	179.35	179.34
			IV-2	**Other Vehicles**	**w XBL**	141.97	148.44	242.32	474.73
				Buses	**w XBL**	179.33	179.33	179.32	179.36
			IV-3	**Other Vehicles**	**w XBL**	142.28	148.74	295.12	494.87
				Buses	**w XBL**	179.33	179.32	179.33	179.35
			IV-4	**Other Vehicles**	**w XBL**	142.74	152.62	427.00	540.60
				Buses	**w XBL**	179.33	179.32	179.33	179.33

* w XBL: with exclusive bus lane.

* M: minutes.

Even though the buses' headway changes from 15 minutes, to 10 minutes, and to 5 minutes in scenarios II, III, and IV, respectively, which results in a different number of buses starting from 4 buses/hr for scenario II to 12 buses/hr for scenario IV, the equilibrium point when D/C is around 0.80, in which the travel time of the buses, in the XBL, intersects with the travel time of the other vehicles, with XBL. At high levels of congestion such as D/C equal to 0.75 or more, the buses' travel time improves impressively after the implementation of an XBL, which represents an attractive point for the users of the other vehicles to switch to buses as alternative sources of transportation. All of these scenarios (II, III, and IV) have similar trends to scenario I-1, which indicates the consistency of the results.

5.2.6 Scenario A-1.

This scenario defined by the following: bus direction (through), three volumes (743, 659, and 616 vph, where these volumes represent a D/C ratio of 0.55 minus the number of vehicles removed by the adding of extra bus lines), traffic turning percentages (40% through – 50% left), and three numbers of buses (6, 12, and 15 buses). The travel time of the buses in the XBL and the other vehicles with the XBL on the main road corridor is shown in Figure 56.

In this scenario at a D/C ratio of 0.55 (low volume), the travel time of the buses in the XBL shows higher values than the travel time of the other vehicles with the XBL because the buses use more time to depart/alight the passengers at the bus stop. Also, the buses accelerate and decelerate before and after the bus stop. As a result, the travel time of the buses in the XBL is greater than the travel time of the other vehicles with XBL. Other scenarios such as A-2, A-3, and A-4 show a similar trend to scenario A-1 which indicates the consistency of the results.

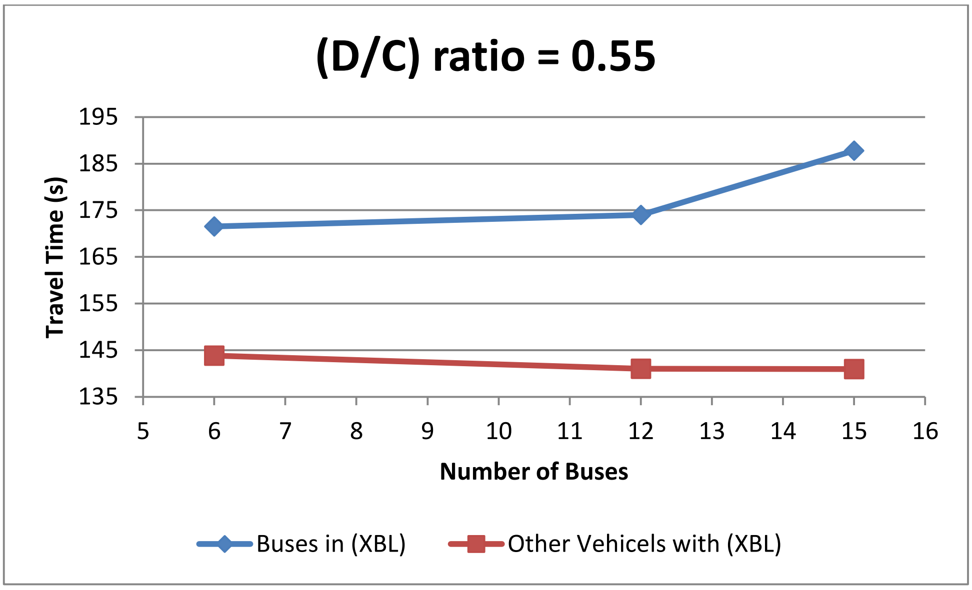

Figure 56: The travel time of the buses in XBL and the other vehicles with XBL (A-1)

5.2.7 Scenario B-1.

This scenario included the following parameters: bus direction (through), three volumes (1038, 953, and 911 vph, where these volumes represent a D/C ratio of 0.75 minus the number of vehicles removed by the adding of extra bus lines), traffic turning percentages (40% through – 50% left), and three numbers of buses (6, 12, and 15 buses).

Figure 57 shows the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL on the main road corridor. As the D/C ratio increases from 0.55 to 0.75 in scenario A-1 to B-1, the travel time of the buses in the XBL is still higher than the travel time of the other vehicles with XBL. This is because the buses consumed more travel time to depart/alight the passengers at the bus stop as well as decelerate/accelerate before and after the bus stop. At this level of demand, which is considered to be medium volume, the other vehicles have the ability to maneuver freely in the traffic network without hindering the traffic. As a result, the other vehicles with the XBL have less travel time than the buses in the XBL. Furthermore, the travel time of the buses in the XBL increases as the number of the buses increases while the travel time of the other vehicle decreases. This scenario, B-1, and others such as B-2, B-3, and B-4 present similar trends to scenario A-1. This shows the consistency of the results.

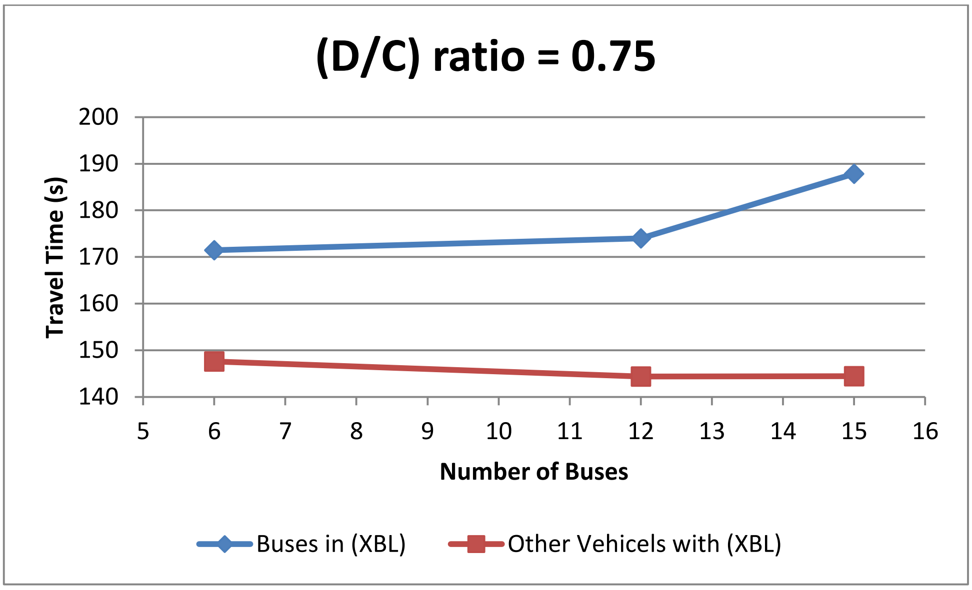

Figure 57: The travel time of the buses in XBL and the other vehicles with XBL (B-1)

Table 35 summarize the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL on the main road corridor for different D/C ratios, traffic distributions, and numbers of buses.

Table 35: The travel time of buses and other vehicles for scenarios A and B.

	D/C Ratios	Scenarios	Traffic Turning %	With XBL	Number of Buses: 6	12	15
Travel Time (s)	0.55	A-2	50 St - 40 L	Buses	171.54	174.11	187.82
				Other Vehicles	143.51	141.00	140.42
		A-3	60 St - 30 L	Buses	171.54	174.15	187.86
				Other Vehicles	143.37	140.90	140.35
		A-4	70 St - 20 L	Buses	171.54	174.14	187.84
				Other Vehicles	144.21	141.18	140.32
	0.75	B-2	50 St - 40 L	Buses	171.48	174.01	187.92
				Other Vehicles	146.72	143.68	144.24
		B-3	60 St - 30 L	Buses	171.47	174.00	187.85
				Other Vehicles	146.82	144.06	144.14
		B-4	70 St - 20 L	Buses	171.47	174.06	187.85
				Other Vehicles	149.69	145.67	144.65

All of these scenarios show similar trends to scenario A-1 and indicate that at this level of demand (D/C ratios of 0.55 and 0.75), the traffic turning percentages have no effect on the other vehicles' ability to maneuver, as the other vehicles have the freedom to move and change lanes freely from one lane to another. Also, the travel time of the buses in the XBL increases as the number of buses increase. This is because the buses have to stop completely at the bus stop to depart/alight the passengers which cause the buses in the XBL to consume more time. As a result, the travel time of the buses in the XBL is more than the travel time of the other vehicles with XBL.

5.2.8 Scenario C-1.

This scenario considered the following variables: bus direction (through), three volumes (1315, 1230, and 1188 vph, where these volumes represent a D/C ratio of 0.95 minus the number of vehicles removed because of the assumed mode shift from vehicles to additional buses), traffic turning percentages (40% through – 50% left), and three numbers of buses (6, 12, and 15 buses).

A comparison between the buses' travel time in the XBL and the other vehicles' travel time on the main road corridor is shown in Figure 58. At high levels of congestion such as D/C ratio of 0.95, the travel time of the other vehicles with XBL, is higher than the travel time of the buses in the XBL, when the number of buses is small. At this level, the traffic network is fully congested and the other vehicles have difficulty maneuvering from one lane to another. On the other hand, the buses in the XBL save more time because of installing the XBL on the main road corridor. As the number of buses increases on the main road from six to fifteen, and the volume of the other vehicles decreases because of adding theses buses, the travel time of the buses in the XBL starts to increase while the travel time of the other vehicles with XBL, begins to decrease. This is because the traffic network, after adding these buses, is less congested than before. To reach the equilibrium, in which the travel time of the buses in the XBL is equal to the travel time of the other vehicles with XBL, the number of buses needed is about ten.

The buses' travel time in the XBL and the other vehicles' travel time with the XBL are summarized in Table 36.

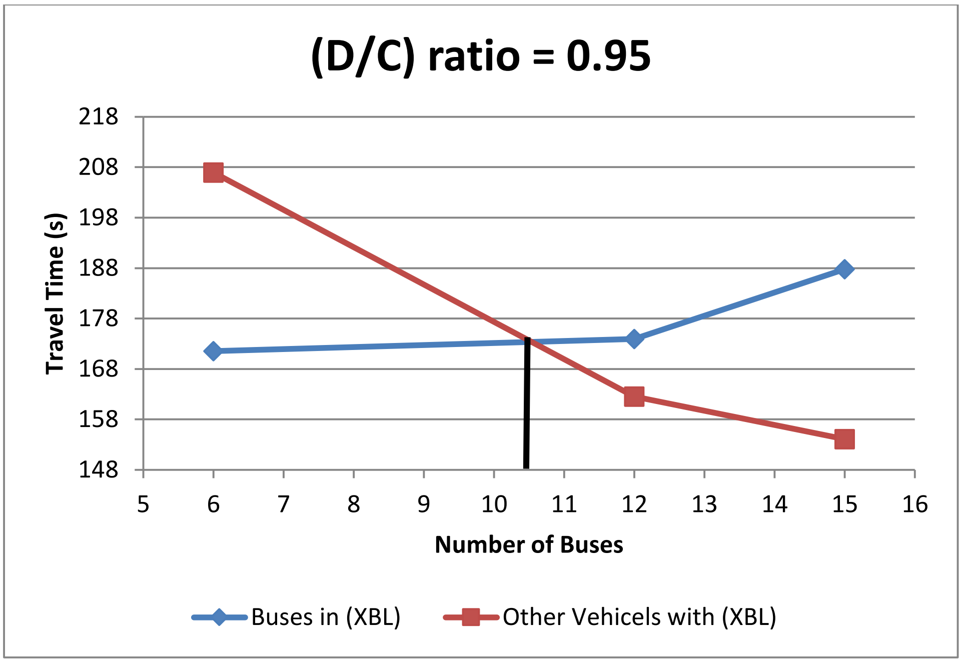

Figure 58: The travel time of the buses in XBL and the other vehicles with XBL (C-1)

Table 36: The travel time of the buses and the other vehicles for scenario C

					Number of Buses		
	D/C Ratios	**Scenarios**	**Traffic Turning %**	**With XBL**	**6**	**12**	**15**
Travel Time (s)	**0.95**	**C-2**	**50 St - 40 L**	**Buses**	171.47	173.95	187.83
				Other Vehicles	211.40	158.74	154.84
		C-3	**60 St - 30 L**	**Buses**	171.45	173.93	187.85
				Other Vehicles	243.22	171.25	157.87
		C-4	**70 St - 20 L**	**Buses**	171.49	173.96	187.85
				Other Vehicles	357.11	222.43	171.66

As the traffic turning percentage changes, the equilibrium point between the travel time of the buses in the XBL and the travel time of the other vehicles, with XBL, in all scenarios (C-2, C-3, and C-4), changes too. Furthermore, these scenarios show similar trends to scenario C-1 which indicates the consistency of the results. Table 37 illustrates the number of buses needed to achieve equilibrium between the travel time of the buses and the travel of the other vehicles, and the mode choice percentage on the main road.

Table 37: The numbers of buses and the mode choice percentage for scenario C

D/C ratio	Scenarios	Number of Buses	Mode Share
	-	**#**	**%**
0.95	C-1	10	10%
	C-2	10	10%
	C-3	12	12%
	C-4	14	15%

The mode share percentage increases with the increase in the number of the other vehicles heading through and the reduction in the number of other vehicles heading left. Because of the unbalance distribution of the volume reaching the intersection and inefficient use of signal timing and left, this causes a huge delay to the other vehicles going through. As a result, there is an increase in the travel time of both other vehicles (through and left), so the number of buses needed is more to reach equilibrium between the travel time of the buses in the XBL and the travel time of the other vehicles, with XBL. In addition, the high level of demand shows a turning point for the users of other vehicles to start using the buses as a valid option of transportation since the buses have faster travel time, especially at high levels of demand.

5.2.9 Scenario D-1.

This scenario represents the following conditions considered for each parameter: bus direction (through), five volumes (1578, 1493, 1451, 1366 and 1196 vph, where these volumes represent a D/C ratio of 1.15 minus the number of vehicles removed by the adding of extra bus lines), traffic turning percentages (40% through – 50% left), and five numbers of buses (6, 12, 15, 21 and 33 buses).

Figure 59 illustrates the travel time of the buses in the XBL and the travel time of the other vehicles with the XBL on the main road corridor. In this scenario, the traffic network is fully congested when the D/C ratio is equal 1.15, and the other vehicles are moving bumper to bumper. As the number of buses in the XBL increases and the number of other vehicles on the main road decreases after the adding these buses, the travel time of the other vehicles with the XBL starts to decrease because the network is releasing some of the congestion in terms of fewer vehicles and converting them to buses, while the buses almost maintain the same travel time along the main road corridor.

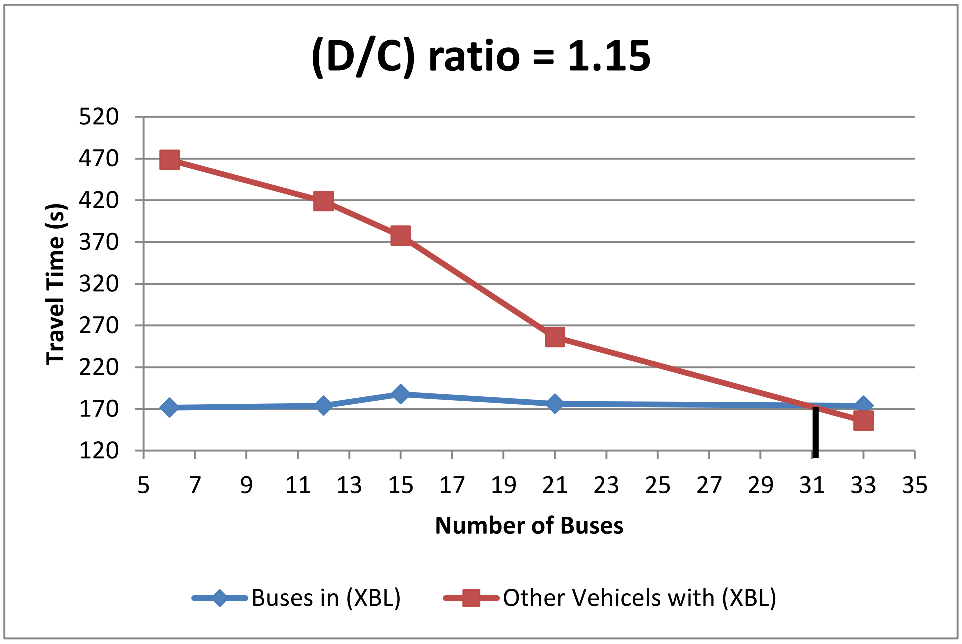

Figure 59: The travel time of the buses in XBL and the other vehicles with XBL (D-1)

In addition to that, the number of buses needed to achieve equilibrium, in which the travel time of the other vehicles and the buses in the XBL is equal to each other, is about thirty one buses. Other scenarios such as D-2, D-3, and D-4 show similar trends to scenario D-1 which indicates the consistency of the results. These scenarios are with different traffic turning percentages and different travel times for the buses and the other vehicles with XBL, and the number of buses and the mode choice percentage are summarized in Tables 38 and 39, respectively.

Table 38: The travel time of the buses and the other vehicles for scenario D

	D/C Ratios	Scenarios	Traffic Turning %	With XBL	Number of Buses 6	12	15	21	33
Travel Time (s)	**1.15**	**D-2**	**50 St - 40 L**	**Buses**	171.46	174.00	187.81	176.24	173.69
				Other Vehicles	468.21	418.91	377.57	255.76	155.90
		D-3	**60 St - 30 L**	**Buses**	171.46	173.99	187.83	176.26	173.66
				Other Vehicles	460.63	411.72	375.33	251.11	155.17
		D-4	**70 St - 20 L**	**Buses**	171.46	173.96	187.86	176.25	173.71
				Other Vehicles	487.95	455.77	422.23	313.69	159.29

Table 39: The numbers of buses and the mode choice percentage for scenario D

D/C ratio	Scenarios	Number of Buses	Mode Share
	-	#	%
1.15	D-1	31	27%
	D-2	31	27%
	D-3	32	28%
	D-4	33	29%

At a D/C ratio of 1.15, the mode choice percentage presents great value which indicates that a huge number of other vehicles needed to be removed from the main road corridor and converted to buses to achieve equilibrium. These buses in the XBL provide a major attraction point for non-bus commuters to start switching from the vehicles to the bus as an alternative source of transportation.

Chapter 6: Conclusions and Recommendations

6.1 Conclusion

Exclusive bus lanes (XBLs) are commonly used as bus priority strategies to improve bus system performance. Sharjah has launched its public bus system recently and the system is still under development to build a better public transportation system. With the dramatic increase in vehicle ownership and the lack of sufficient development of infrastructure (bridge and tunnel) within urban areas of Sharjah, the necessity of an efficient public transportation system is clear. One of the possible strategies to improve the performance of the bus transit system in Sharjah is the use of an XBL. In this thesis, a parametric study was performed to investigate the impact of XBLs on traffic network performance. VISSIM, a micro-simulation model, was utilized to model the impact of adding an XBL, under different traffic conditions, on the buses and other vehicles' performance.

The parameters included in the investigation were demand-to-capacity ratios D/C, traffic turning percentages (through and left), bus movement, and bus headway. With the same sets of traffic conditions, two scenarios were developed for each case: buses operating in mixed traffic conditions and buses running in XBLs.

To capture the impact of XBLs on the traffic network performance, different measures of effectiveness (MOEs) were tested such as travel time, intersection delay, and average speed. In addition, the improvement percentages of the buses' travel time, intersection delay, and average speed were calculated. In addition, the deterioration rates of other vehicles' travel time, delay, and average speed, were also analyzed. Finally, the mode choice percentages based on the travel time equilibrium point between the buses and the other vehicles were obtained.

The findings of this study can be summarized as follows:

1. XBL was found to be effective at D/C ratios of 0.80 or more, because the travel time per bus in the XBL is lower than the travel time per vehicle with the XBL which indicates the effectiveness of the XBL to save travel time for the passengers at high levels of congestion. However, for D/C ratios of 0.75 or less, the travel time per bus in the XBL is higher than the travel time of the other vehicles moving in the adjacent lanes, which indicates that there is no need to operate the XBL at low levels of congestion.

2. For the traffic turning percentages reaching the intersection (through and left), as the left turn movement percentage decreases and the through movement increase, the improvement percentages of the buses' travel time, intersection delay, and average speed increase and vice versa. This is because of the unbalance distribution of the vehicles reaching the intersection and inefficient use of the signal timing and left lane. This causes high levels of volumes moving through and fewer numbers of vehicles moving left. As a result, the interaction between the buses and the other vehicles increase. This negatively affects the performance of the buses moving through in mixed traffic conditions.
3. For the buses turning left, the results showed that the XBL was not effective for D/C ratios of 0.95 or less on the main road corridor, because all the time savings the buses gain from the XBL is lost due to the extra time the buses experience when they are trying to change lanes after getting out of the XBL and waiting for other drivers to stop completely to complete the weaving maneuver. In contrast, for a D/C ratio of 1.15, the results showed that the XBL is very effective, because its improves the performance of the buses' travel time, intersection delay, and average speed significantly while the performance of the buses in mixed traffic conditions keeps deteriorating because of the traffic jams.
4. When considering the different bus headways, the results indicated that the improvement percentages of the buses' travel time and average speed presented the highest improvement percentage for the bus headway of 10 minutes among others for D/C ratios of 0.95 or less for traffic turning percentages (40% through – 50% left) and (50% through – 40% left). However, the bus headway of 10 minutes has the least improvement percentage of the intersection delay among other headways for all D/C ratios for all traffic turning percentages in all D/C ratios on the main road corridor.
5. The minimum mode choice percentage, at which the XBL is effective, for a D/C ratio of 0.95 has a range of (10% - 15%) depending on the traffic turning percentages. In contrast, for a D/C ratio of 1.15, the mode choice percentage has a range of (27% - 29%) depending also on the traffic turning percentages. For low and medium levels of traffic congestion (i.e. D/C ratios of 0.75 or less), the travel time of the buses is greater than the travel time of the other vehicles because the

buses use more travel times for departing/alighting the passengers at the bus stop, while other vehicles moving on the adjacent lanes do not experience any delays.

6. After the implementation of XBL, the results illustrated that the performance of the vehicles in adjacent lanes in terms of travel time, intersection delay, and average speed are sacrificed because the same demand, which existed before the installation of the XBL, was distributed over a fewer number of lanes, after setting up the XBL. The deterioration percentages for D/C ratios of 0.75 or less for the travel time, intersection delay, and average speed are -5%, -11%, and -5%, respectively, for all traffic turning percentages. The deterioration percentages for D/C ratio equal to 0.95 for the travel time, intersection delay, and average speed are about -55%, -130%, and -37%, respectively, for traffic turning percentages 1 and 2, and almost -105%, -230%, and -50%, respectively, for traffic turning percentage 3, and close to -190%, -430%, and -65%, respectively, for traffic turning percentage 4.

6.2 Recommendations

Based on the outcomes of the present work, the following recommendations can be made:

- The application of the XBL can be based on time. In other words, the XBL can be used by other vehicles during off-peak hours. This will help in reducing the negative impacts of XBLs at low volumes (D/C= 0.55 or 0.75).
- The implementation for the XBL should avoid links in which the buses will turn left. This can be applied by allowing the buses that are turning left to use the common lanes instead of using the XBL.
- There should be some improvements to the bus service in the city to help in attracting passengers. These improvements may include more comfort inside the buses, higher levels of punctuality, a reasonable pricing system, etc.

In addition to these general recommendations, the following are some suggested topics for future research:

- Combination of transit signal priority and exclusive bus lanes to study the impact of XBLs on traffic network performance.

- Implementing a dynamic traffic assignment instead of a static traffic assignment for vehicle routing.
- Investigating the use of median lane bus stops instead of curbside bus stops, especially when the bus takes a left turn at the intersection.
- Optimizing the signal for different D/C ratios while considering the volume of the cross street.
- Developing a mode choice model for local conditions in Sharjah to estimate a more robust mode share for the buses before and after implementing the XBL.
- Considering the impact of XBLs on a road network as a whole (i.e. not on one corridor only).

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Vita

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