DYNAMIC BUS LANE

by

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ABSTRACT

DYNAMIC BUS LANE

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This dissertation documents the research conducted to investigate the feasibility of implementing a “Dynamic Bus Lane” (DBL) system on Westheimer Road in Houston, Texas, and to determine the particular conditions when the system could be applied to other arterial streets. The DBL system is a bus preferential system which would turn a normal traffic lane into a bus lane when a bus is approaching a bus stop at a major intersection. The bus would activate a dynamic message sign that would change the lane use from a normal traffic lane to a bus lane for the time when the bus is present, and then it would change the lane use back to general traffic use when the bus leaves. The main idea behind this system is to use a large dynamic message sign before the intersection, which will convey a clear and compelling message of the system operation to the general public.

Two simple linear regression models were constructed using the bus queue travel time before it reached the bus stop as the response variable, and the vehicle queue in front of the bus as the predictor variable. One model was developed for the morning peak hour, and another model was developed for the afternoon peak hour. These models predicted that the bus travel time would be reduced by 2.7% and 5.6% during the morning and afternoon peak hours, respectively. These results are much lower than those reported elsewhere for similar systems.

The Highway Capacity Manual (HCM) methodology was used to assess the impact of the DBL system on other vehicles. Generally, the impact was that the DBL would cause the intersection level of service to drop one level. However, the total system impact on other vehicles was much greater than the DBL benefits in terms of person-hour delay. The total system impacts are larger than the benefits by factors of 50 and 90 in the morning and afternoon peak hours, respectively. The HCM model showed that the impact on the delay of the other vehicles on other streets with less number of lanes was that the intersection level of service also dropped by one level.

A sensitivity analysis of the intersection saturation levels versus the DBL benefits and impacts showed that the DBL system would perform ideally at or below the 90% saturation level. Also, it was found that because of the high level of traffic saturation on Westheimer, it would be very difficult for vehicles to change lanes when the DBL system is activated. The spacing between major intersections should be at least 9/10th of a mile to allow for lane-change maneuvers. The DBL system improved the transit levels of service for the test section by one level for both peak hours.

The marginal adverse impacts of the DBL system on other vehicles outweighed the benefits for this test section of Westheimer. The person-hour delay impacts were greater than the benefits by an order of magnitude. The most significant factor attributable to the high level of impacts on vehicle and person delay impact was the high level of traffic saturation on this section of Westheimer. Even though the transit level of service would be improved, it was found that it would not be advisable to implement the DBL system on Westheimer. It was found that it would be advisable to implement it on other arterial streets with lower saturation levels, such as Bellaire Blvd and Gessner Road in Houston, Texas. A step-by-step procedure is recommended to determine whether the DBL system is feasible to implement on other arterial streets.

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CHAPTER 1

INTRODUCTION

This dissertation documents the research conducted to investigate the feasibility of implementing a “Dynamic Bus Lane” (DBL) system on Westheimer Road in Houston, Texas, and to determine the particular conditions when the system could be applied to other arterial streets. The DBL system is a bus preferential system which would turn a normal traffic lane into a bus lane when a bus is approaching a bus stop at a major intersection. The bus would activate a dynamic message sign that would change the lane use from a normal traffic lane to a bus lane for the time when the bus is present, and then change the lane use back to general traffic use when the bus leaves. This system seeks to reduce the travel time that the bus experiences in reaching a bus stop located at a major intersection during the peak hours.

1.1 Background

There are currently several preferential treatments for buses in the United States (US), including exclusive bus lanes, bus signal priority, queue bypass, queue jump, curb extensions, boarding islands, and other similar measures. Figure 1.1 shows an existing bus preferential treatment sign located in downtown Houston, Texas. This proposal consists of implementing a new bus preferential treatment: an exclusive bus lane on a temporary basis with the aid of a dynamic message sign.

The idea for the DBL system was developed for a Metropolitan Transit Authority of Harris County (METRO) project in 2008. The purpose of the project was to implement bus signal priority on four corridors in Houston: Westheimer, Richmond, Bissonnet, and Post Oak. Figure 1.2 shows these four corridors. The bus travel time studies revealed that the buses were experiencing a significant amount of delay at the major signalized intersections. Figure 1.3

shows a sample of the bus travel time measurements obtained on Westheimer Road at all the signalized intersections from Smith Street in downtown to State Highway 6, which is 16 miles to the West from downtown. Several data points shown on this graph are over 150 seconds in "stopped delay." The "stopped delay" measurements shown in this figure were the travel times that the buses experienced measured from when the bus joined the back of the vehicle queue at the intersection until the bus crossed the middle of the intersection. This travel time includes the time to unload and load passengers at the corner bus stop, or "dwell" time. This corridor is highly saturated, so it was determined that signal priority alone would not be sufficient to improve the bus operations significantly, and the DBL concept was developed to improve the bus operations further.

Figure 1.1 Bus Preferential Sign

1.2 Problem Statement

The current bus operation on Westheimer experiences significant time losses at the major intersections along its service corridor. However, there is not currently a measure that would significantly improve the bus operation on a street without making one of the traffic lanes an exclusive bus lane or implementing other strategies, which require roadway construction. An exclusive bus lane would be significantly detrimental to the intersection level-of-service, and it would only serve a significantly smaller number of people on the bus lane than in passenger cars due to the relatively low frequency of buses, which is 15 minutes. The concept of the dynamic bus lane was developed as a potential solution to improve the average bus speeds along the Westheimer corridor and other similar corridors, while minimizing the impact on the other vehicles, passenger cars and trucks.

1.3 Research Objectives

The dynamic bus lane seeks to achieve a balanced operation of a traffic lane for buses and other vehicles. The dynamic bus lane also seeks to give preferential treatment to the buses without severely affecting the intersection level of service. The dynamic bus lane would turn a traffic lane into a bus lane when a bus is approaching the intersection.

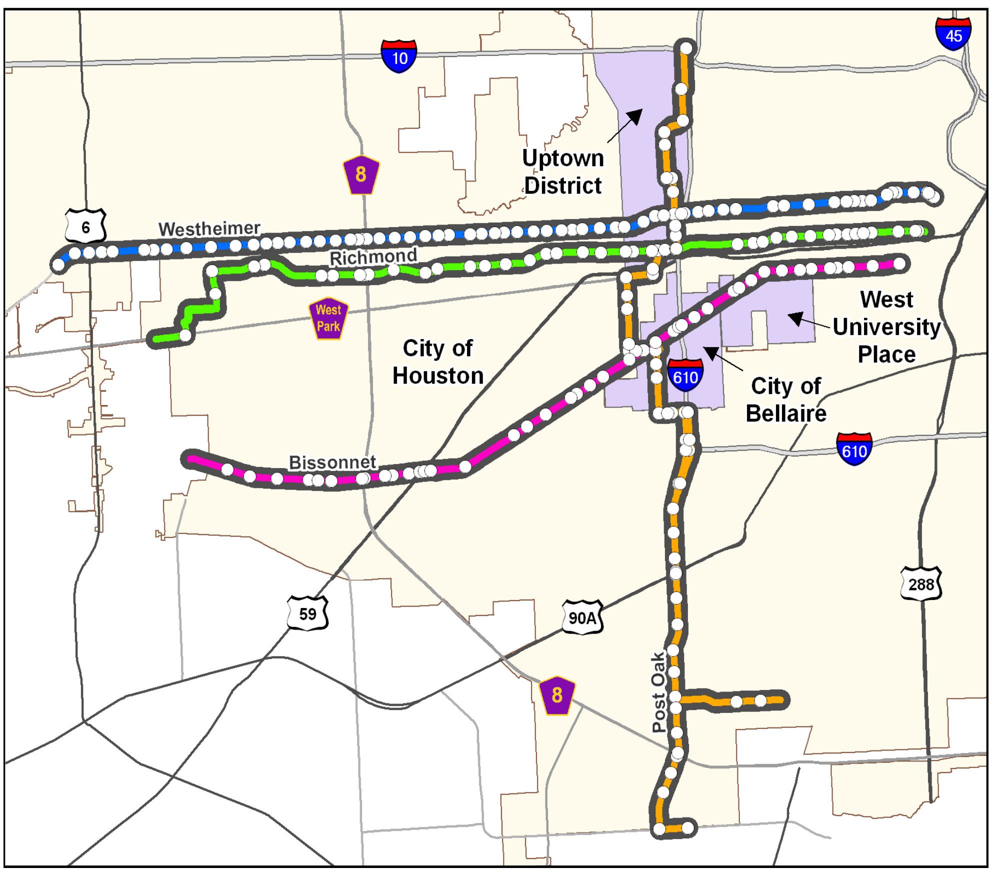


Figure 1.2 METRO Project Corridors

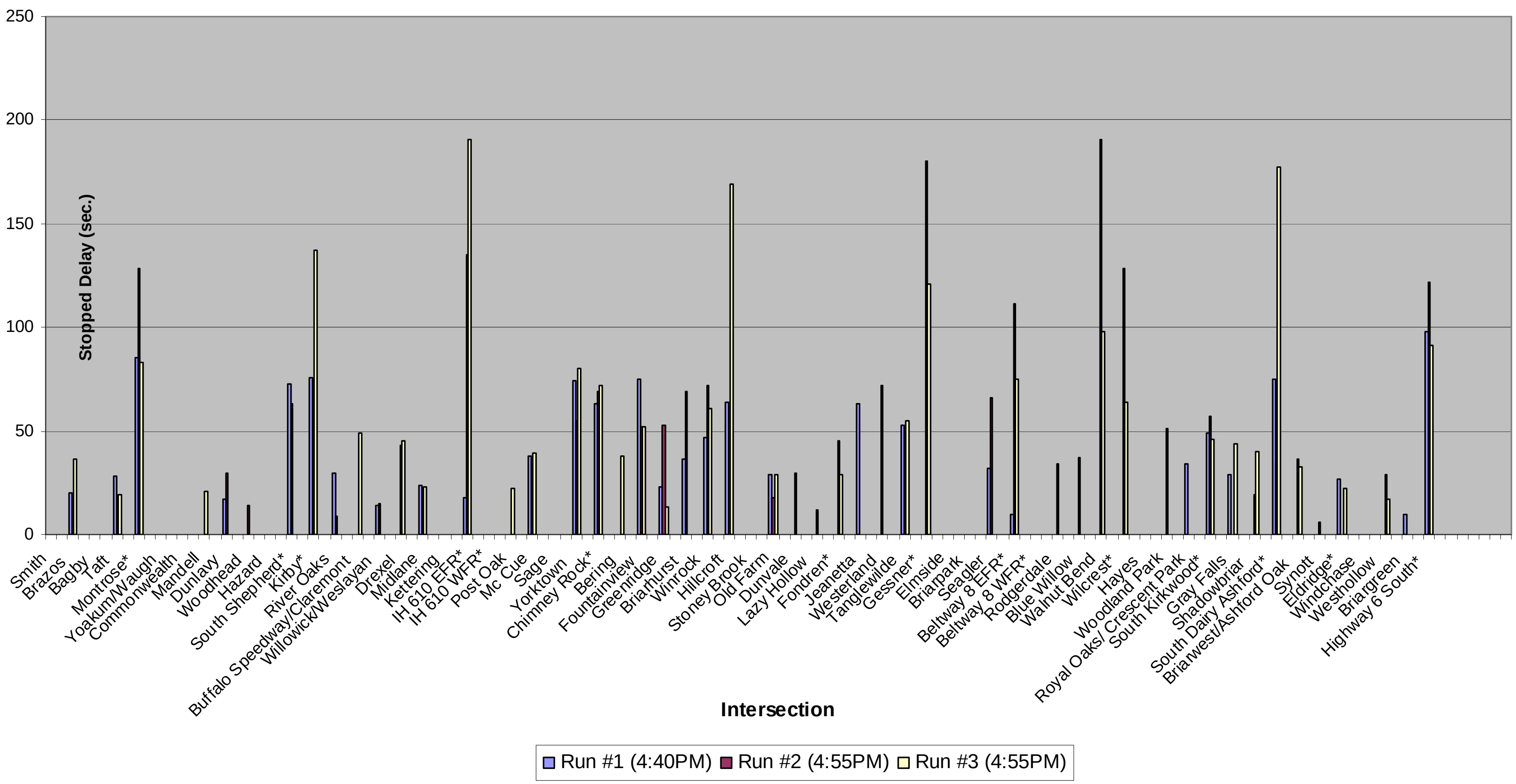


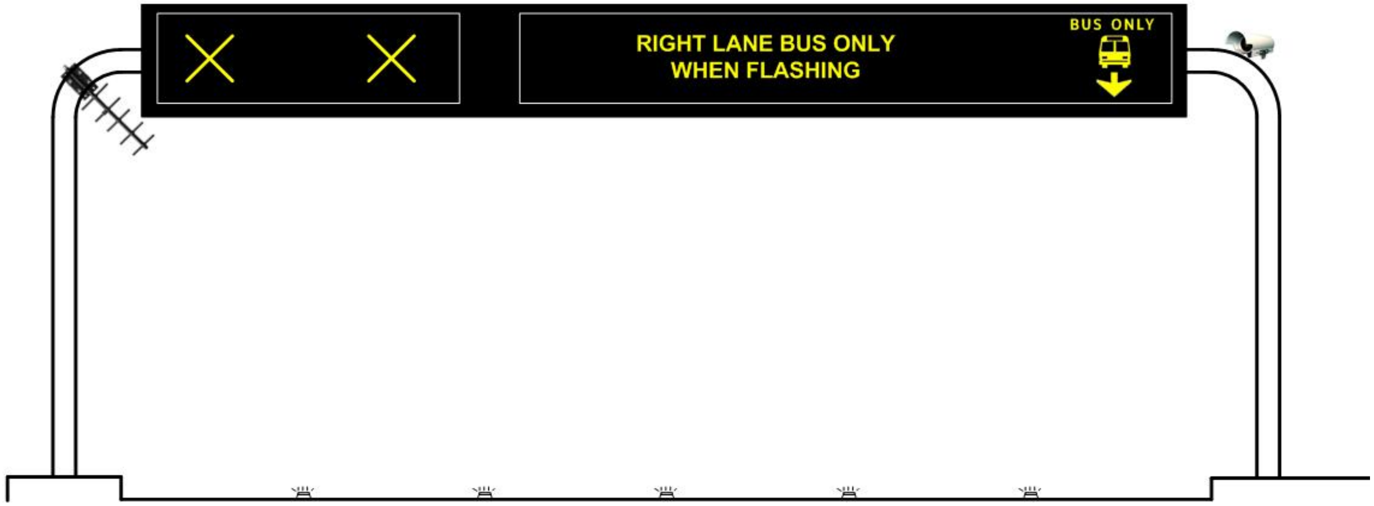
Figure 1.3 Bus Intersection Travel Times

The bus would activate an overhead sign that would change the lane use. This would theoretically reduce the amount of passenger cars stopping in front of the bus, which delay the bus in reaching the bus stop at a major intersection. This way, the bus would be able to pass through the intersection faster than it would otherwise, and minimize the disruption to the intersection operation. Since the dynamic bus lane is proposed to be on the right lane of the street, the right-turn movements would need to be allowed from this lane. This would be accomplished by alternating messages on the dynamic message signs. The proposed dynamic message sign would be mounted on an overhead sign structure, and it would be a full matrix sign that could display symbols as well as text. This sign could also be used for dynamic lane assignment, travel information, and explanatory messages. A conceptual drawing of the proposed dynamic message sign for the dynamic bus lane system with two sample displays is shown in Figure 1.4.

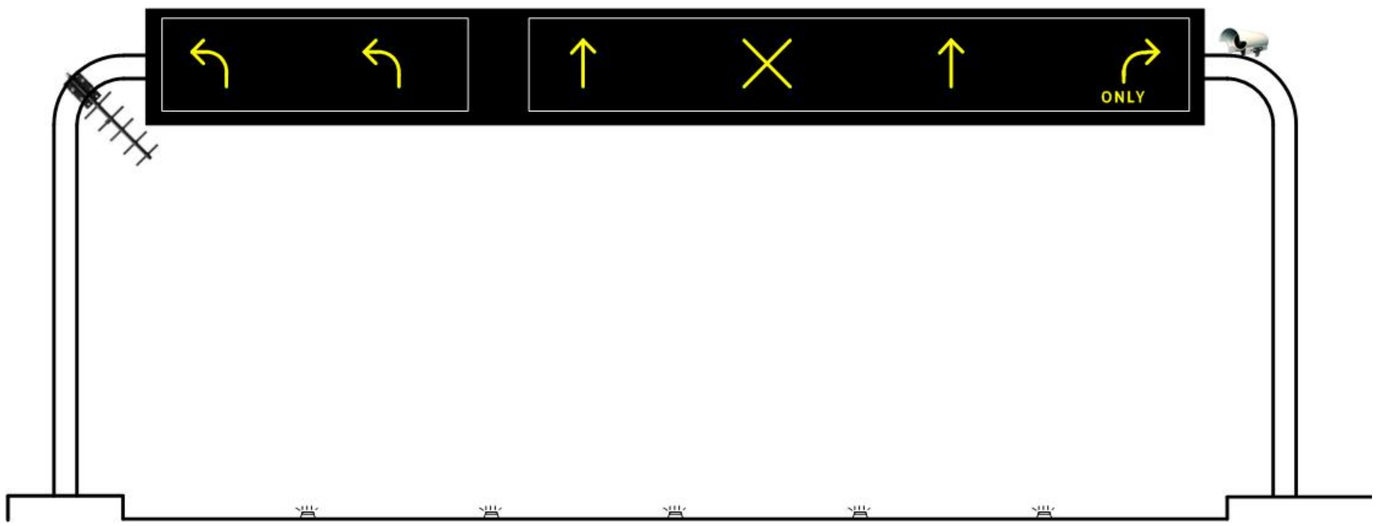
1.4 Scope of Project

This research project consisted of evaluating the effectiveness of implementing a dynamic bus lane system along Westheimer Road, from South Dairy Ashford to Wilcrest Drive, and other similar arterial streets. The dynamic bus lane would convert the right lane on Westheimer Road from a general-purpose traffic lane to a bus-only lane as the bus approaches, and revert it back to a general-purpose traffic lane when the bus leaves. The implementation of the system is proposed to be accomplished using an overhead dynamic message sign in advance of the bus stops at the two major intersections along this corridor section: one at South Dairy Ashford, and one at Wilcrest.

The objective of the three-year research project was to determine whether the dynamic bus lane system would significantly improve the bus operation along major arterial streets such as Westheimer Road.



(a)



(b)

Figure 1.4 Dynamic Bus Lane Sign with (a) Display #1 and (b) Display #2

This would be the case where it is not practical to add bus-only lanes due to right-of-way or budget restrictions, or to convert the general-purpose traffic lanes to bus lanes for entire peak-hour periods or permanently. The relation to longer-term goals of the project is that this idea could applied to the other arterial streets in Houston where METRO is considering implementing bus signature lines with improved service reliability.

The present state of knowledge in the field is that J. M. Viegas developed the original concept of operation for the Intermittent Bus Lane (IBL), a similar system to the proposed dynamic bus lane, in 1996. Viegas also conducted a demonstration project of the IBL system in Lisbon, Portugal, in 2005. In addition, there have been several publications related to the assessment, design, screening formulae, and evaluation of the IBL system by C. Daganzo in Berkeley, California since 2005.

1.5 Structure of Dissertation

The dissertation consists of five chapters in addition to this introduction, including literature review, data collection and study design, bus queue travel time estimation and prediction interval, DBL system impact on other vehicles, and conclusions. The descriptions of the major sections are described below.

1.5.1 Chapter 2 Literature Review

This chapter documents the literature review conducted for the Dynamic Bus Lane (DBL) system concept and related topics. It begins with a review of the Highway Capacity Manual 2010 (HCM). It follows with a review of the work conducted on the Intermittent Bus Lanes (IBL) by Jose Manuel Viegas and his associates in Lisbon, Portugal. Then, the related work to the IBL conducted by Carlos F. Daganzo and his associates in Berkeley, California. Finally, a review of other related work conducted in France, Australia, and the US is included in this chapter.

1.5.2 Chapter 3 Data Collection and Study Design

This chapter documents the field data collection and the study design for the DBL experimental testing on the analysis section of the Westheimer corridor, from South Dairy Ashford Road to Wilcrest Drive. The data collection strategy formulation is presented. The candidate dependent variables which may affect the response variable were identified, so that they could be measured in the field. Statistical confidence intervals for all of the variables collected in the field were computed according to a specified confidence interval.

1.5.3 Chapter 4 Bus Queue Travel Time Estimation and Prediction Interval

This chapter documents the task of identifying the determinants of a probabilistic model for the bus queue travel time. The number of stopped vehicles in front of the bus was chosen as the independent variable because these vehicles block the bus from getting to a bus stop. This variable has a probabilistic distribution, which resulted in a probabilistic estimate of the bus queue travel time at a bus stop. This resulted in a probabilistic model for the estimation of the bus queue travel time at the bus stops at the signalized intersections, which has a prediction interval based on a defined confidence level and the sampling error.

The analysis of the relation between the number of vehicles stopped in front of the bus and the bus queue travel time were determined by developing two simple linear regression models, one for the morning peak hour and one for the afternoon peak hour. These probabilistic models were tested for the linearity of the slope coefficients, and that the residuals had constant variance and were normally distributed. The models then yielded inferences on the mean response and the prediction interval for the bus queue travel time with the DBL system in place for the morning and the afternoon peak hours.

1.5.4 Chapter 5 DBL Impact on Other Vehicles

This chapter contains the development of a vehicle control delay model to assess the impact of the dynamic bus lane system on other vehicles. The process consisted of determining the control delay for the two test intersections using the procedures for signalized intersections in the Highway Capacity Manual. The analysis included the DBL performance with different driver compliance levels, different lane geometry, and different intersection saturation levels.

1.5.5 Chapter 6 Conclusions

The conclusions of the dissertation present the findings of the dynamic bus lane operation in terms how much it would improve bus operations and impact other vehicles along a suburban arterial street. The potential impact of the implementation of the system on other vehicles is also presented, including the results of a sensitivity analysis using different saturation levels. The results of a platoon dispersion analysis and the recommended spacing for the spacing of the DBL system are also included. Finally, a step-by-step procedure to determine the feasibility to implement the system on other arterial streets is included, as well as potential topics for further research.

CHAPTER 2

LITERATURE REVIEW

This section documents the literature review conducted for the Dynamic Bus Lane (DBL) system concept and related topics. It begins with a review of the Highway Capacity Manual 2010 (HCM). It follows with a review of the work conducted on the Intermittent Bus Lanes (IBL) by Jose Manuel Viegas and his associates in Lisbon, Portugal. Then, the work related to the IBL conducted by Carlos F. Daganzo and his associates in Berkeley, California. Finally, a review of other related works conducted in France, Australia, and the US is included at the end of this section.

The HCM[1] does not have any material directly related to the DBL. It only has a methodology to compute the capacity of an exclusive bus lane and the capacity of a bus operating in a mixed-traffic lane. The methodology to compute the capacity of an exclusive bus lane is based on the average operating speed of the bus in its own lane. The computation of the average operating speed contains a term to account for the bus running time losses, which has a typical value of 0.5 to 1.0 minutes/mile for exclusive bus lanes and 0.7 to 1.5 minutes/mile for mixed traffic outside the central business district (CBD). For comparison purposes, the existing running time losses for the test section are 1.36 and 1.08 minutes/mile for the morning and afternoon peak hours, respectively. The existing test section is a mixed traffic situation and its bus running time losses are within the HCM typical range. The capacity analysis methodology for a bus operating in a mixed-traffic lane is the same as for any other vehicle.

The original idea for the operation of the DBL system was introduced by Jose Manuel Viegas and Baichuan Lu in 1996, which they called the Intermittent Bus Lane (IBL).[2] The methodology used to analyze the performance of the IBL system operating with bus priority presented in this article consists of an objective function with two terms, one representing the advantages of the bus and the other representing the impacts on the other vehicles. Simulation results for the IBL with transit priority showed that when the bus was as important as five vehicles, the bus travel time would be decreased by 30%, while the impact on the other vehicles would result in only a 3% increase in additional travel time. The bus was given a weight of five, while the other vehicles were given a weight of one in the objective function to produce these results.

A real-world demonstration project was conducted by Viegas in Lisbon from September 2005 to June 2006[3]. The test section consisted of an 800-meter road section just outside the CBD, which has a mixture of university traffic and commuter traffic. This congested road has two lanes in each direction. The right lane in one of the directions was converted to an IBL. The project tested the following principles: (1) the bus speed and reliability are improved when the bus operates independently from the general traffic, (2) permanent bus lanes are inefficient when the bus frequency is low, and (3) the road is congested, so that one lane is reserved for just enough time for the bus to move separately from the other vehicles. The IBL operating mechanism consisted of a controller to monitor traffic in real time, which had the ability to monitor the bus position in the IBL by a global positioning system. The controller would activate the IBL when the road was congested by activating a variable message sign (VMS) and flash LED in-pavement lights (IPLs) installed longitudinally along the lane lines separating the IBL from the adjacent lane. When the IBL was activated, vehicles that were already in the IBL drove forward, clearing the road section before the bus arrived. When the bus priority was no longer needed, then all signalization (VMS and IPLs) was turned off, and the IBL operated as a regular lane. No other changes to the road section were made, so that the IBL benefit would be measured against the same base condition. However, improvements to the IBL operation were made during the test. These improvements consisted of activating the IBL only when the road was congested, and installing loop detectors for this purpose.

The project was used to measure the impact of the IBL on bus travel time, and the impact of the IBL on the general traffic. This was accomplished by collecting "before" travel time data for one month and "after" travel time data during six months. During the last two weeks of the test, "before" data was collected during one week, and "after" data was collected during the last week. The results showed that the bus speed was improved by an average of 20% (15% to 25%), with "no visible impact on general traffic." The impact on other vehicles was measured using the variability of queue, flow, and speed patterns.

The test required police enforcement during the first few weeks of implementation. Negative results were obtained during evening operations due to uncongested conditions, which led to the activation of the IBL only when the road was congested. A public campaign was conducted before the experiment, which resulted in good compliance in general. Drivers understood that "a lane was taken away" only when necessary. However, disobedience went unpunished. In conclusion, the authors stated that this system gave good results when the bus frequencies were low. Figure 2.1 shows pictures of the IBL demonstration project in Lisbon.

(a) (b)

Figure 2.1 IBL Demonstration project in Lisbon[3] (a) Dynamic message sign and (b) In-pavement lights

Additional research by Viegas has been conducted on the enforcement side of the IBL system[4]. The concept for a wireless law enforcement system has been developed which uses license plate recognition technology from a device embedded in one of the in-pavement light enclosures along the IBL. This system was yet in its preliminary stages of development at the time of the publication of this article in 2006. No further research on the topic was found.

Michael D. Eichler's master's thesis entitled "Bus Lanes with Intermittent Priority: Assessment and Design," University of California at Berkeley[5], explores the signing, pavement marking, and operational compatibility issues to implement this system in the United States versus the guidelines in the US Manual on Uniform Traffic Control Devices (MUTCD); as well as inter-jurisdictional, enforcement, equity, and liability issues. According to Eichler, the difference between the Bus Lane with Intermittent Priority (BLIP) and the IBL concept developed by Viegas is that the BLIP does not rely on transit signal priority (TSP) to flush the vehicle queues in front of the bus, as the IBL does. Eichler discusses how the BLIP system relates to advanced public transit systems, mode shift, exclusive bus lanes, temporal vehicle regulations, dynamic lane assignment such as reversible lanes, and in-pavement lighting systems. Eichler explains how the MUTCD includes guidelines for the use of dynamic symbols for reversible lane systems, changeable message signs, preferential lane signs, flashing beacons, and warning signs for lane reductions, which would be applicable to the BLIP system. Eichler recommends using standard devices as much as possible to avoid driver confusion due to unfamiliarity with the system, and to obtain permission from the US Department of Transportation for the experimental use of new devices as specified in the MUTCD. Eichler also discusses the use of bus-mounted enforcement cameras for the BLIP system, and how this may require some changes to the vehicle enforcement code.

Michael D. Eichler and Carlos F. Daganzo also published "Bus Lanes with Intermittent Priority: Screening Formulae and an Evaluation" in 2005[6]. In this article, the authors developed a methodology to compute the BLIP capacity, which was basically the capacity of the lane system with a reduced number of lanes during the time when the BLIP is activated. The BLIP was modeled as a “moving bottleneck,” which creates long-lasting queues that propagate upstream when traffic demand is at capacity. The flow-density diagram in a steady state was used to model the effect of the BLIP on long roads and short roads. For their analysis, the BLIP used the VMS to flush the vehicle queue in front of the bus, not the signal timings. The authors of this article modeled travel time savings to autos and buses of under-saturated BLIP systems, and determined the proper domain of application for BLIPs. They found that the BLIP would work well in under-saturated conditions, provided that the bus headways are much larger than the cycle length, and the demand is close to the capacity of the reduced street system. They also determined that bus signal priority can enhance the BLIP operation, but be potentially disruptive to autos. Based on their theoretical work, they recommended a qualitative ranking of rough domains of application as follows:

1. Use dedicated bus lanes with or without transit signal priority when the traffic demand is less than 80% or 90% of the capacity of the reduced lane system
2. Use the bus lane with intermittent priority (BLIP) system with or without transit signal priority when the traffic demand is close to the capacity of the reduced lane system
3. Use transit signal priority alone, with queue-jump lanes if possible, when the traffic demand is over 120% of the capacity of the reduced lane system

Another article by Eichler, Daganzo, Todd, Barth, and Shaheen, “Enhanced Transit Strategies: Bus Lanes with Intermittent Priority and ITS Technology Architectures for TOD Enhancement[7],” presented a detailed analysis of the BLIP operation using traffic signal offset, queue clearance time, and relaxation time. The relaxation time is the duration of the disturbance created by the activation of the BLIP. They also presented equations to compute the average BLIP benefit, which was an objective function to minimize the signal queue delay. They recommend the BLIP system for bus routes with large headways (around 15 minutes) on major urban and suburban multi-lane arterials with medium traffic congestion during the peak periods. They reported that the BLIP system yields benefits in reduced travel time and reduced travel time variation for the buses. They modeled two approaches to the signal operation: a conservative approach and a liberal approach. In the conservative approach, the BLIP would operate for an entire cycle length; while in the liberal approach, the BLIP would operate only during a portion of the cycle length. They determined that the liberal approach was better than the conservative approach; because the conservative approach had no significant start-up effect on the signal operation as opposed to the conservative approach, which it did. The start-up effect causes traffic disturbances at the beginning of the BLIP. They also concluded that the BLIP system would reduce bus travel time variation, which improves reliability and decreases transit agency costs.

There is also literature supporting transit's need to have a competitive advantage over the car to maintain the increased levels of ridership due to the increase in gasoline prices[8]. The authors of this article stated that this could be accomplished with more dense and reliable transit service, and responding to the dynamic nature of urban traffic through intelligent transportation systems and more comprehensive traffic management strategies. Their research consisted of conducting over 300 travel time runs to compare bus operations versus car operations along two routes in Minneapolis. Their results showed that the car had a 3.5-minute advantage over the bus on a 24-minute bus trip length. Their results tend to support bus-only shoulder operations, stop consolidation, serving major streets with fewer stops, and signal priority. An example of bus-only lanes along arterial streets in the US was the access management project for International Blvd in the Seattle metropolitan area[9]. This arterial street was reconstructed from a five-lane cross-section with a continuous left-turn lane to a four-lane cross-section with a raised median and an additional HOV lane in the southbound direction, which operated as an high occupancy lane (HOV) only during the PM peak-hour period. The HOV lane was opened to the general traffic during the other times of the day.

These types of bus-priority considerations are not happening only in the US, but also throughout the world. In Paris, France, officials converted the shoulders of a highway using variable message signs and an automatic movable barrier for bus use and relief for incidents during the peak periods[10]. The shoulder on the A48 highway was converted to a bus lane in two phases. The first phase of the project was 1,100 meters long, while the second phase was 4,200 meters long. The project consisted of the pavement construction of the shoulder, restriping of narrower traffic lanes, seven emergency areas with telephones, a computer system, three lane assignment signs, three variable message signs, 20 incident detection cameras, four traffic counting cameras, 19 bus signals, and one access control system. The first phase of the projected reported improvements of bus travel times of 16%. No performance data was reported for the second phase. Concerns regarding legal issues about using the shoulders for this use were raised, as well as concerns for the relatively high cost of implementation and maintenance of the system.

In Melbourne, Australia, the Intermittent Bus Lane – Dynamic Fairway (IBL-DF) project for trams has been in operation since 2001[11]. They have reported good driver compliance and positive performance benefits, but not as good as the Lisbon IBL demonstration project. The tram project operates on Toorak Road, which is an undivided suburban arterial street with two lanes in each direction. The tram uses the inside two lanes in mixed-traffic conditions during the peak hours only, and in the peak direction only. Toorak Road is highly saturated and has a lot of commercial sign clutter. Parking is prohibited during the peak hours. The system uses two approach overhead variable message signs (VMS), flashing in-pavement lights, and upstream induction loops at each intersection. Since traffic drives on the left in Australia, the right-turn movements become the critical movements at the intersections. The system uses a traffic signal clearance interval to remove the right-turning traffic ahead of the tram at each intersection, with the exception of a few intersections where the right turns are prohibited. The project had a limited evaluation due to the “before” data collected during the holiday season in

December. They reported tram travel time savings of 10% during the morning peak period, and only 1% during the afternoon peak period. The cost of the project was $500,000. Figure 2.1 shows a picture of the IBL-DF tram system in operation.

Figure 2.2 Dynamic Fairway Tram System, Melbourne, Australia[11]

It was reported that the drivers displayed "good lane discipline," better than with conventional bus and tram operations. The VMSs display arrows and messages such as "NO ENTRY" and "TRAMS EXCEPTED" with flashing borders. The system also uses advance static signs with "FAIRWAY – DO NOT DELAY TRAMS" messages. In general, they have had good safety results with no evidence of high-risk maneuvers. They have developed the following guidelines for future implementation:

- "The tram route has slow-running trams with poor reliability and high patronage
- There is an existing part-time or full time fairway (or tram lane)
- There is a history of (right-turning) traffic delaying the trams

- The tram operates in mixed traffic
- Tram priority is not or cannot be utilized effectively
- One traffic lane and one fairway lane are usual; and
- Intersections experience lengthy delays at the site, but the road is not at capacity (if the road is saturated midblock, it is difficult for two lanes to merge)"

They also recommend an education campaign and good publicity for the system; since there has been mixed results from the political leadership opinion regarding the effectiveness of the system. They have also developed some minimum design parameters for future "Moving Bus-Tram Lanes" (MBTL) systems for implementation, as follows:

- "It must be clear to the motorist what he or she has to do
- It must be possible for the motorist to do what is required
- The MBTL must provide a benefit for the bus or tram in terms of travel time or reliability, or both, and
- It must be possible for the use of the lane to be enforced"

They concluded that the IBL-DF system has yielded travel time improvements for the tram while limiting impacts on traffic, that auto drivers will modify their behavior in response to dynamic signs, and that the system is a good tool to provide for transit priority in urban systems.

The literature review has also found that Thomas Bauer and Saeed Sahami with PTV America have published a report documenting the simulation of the IBL (which they called Bus Lane with Intermittent Priority or BLIMP) system using VISSIM[12]. In this report, they simulated the lane closure with link attributes and detectors, and the dynamic vehicle class control where right-turning cars were allowed to enter the BLIMP. They used a perception-reaction time of 1.5 seconds when the BLIMP was activated and the cars needed to leave the BLIMP. They reported a simulated decrease of 16% in bus travel time for a five-lane road with nine signalized intersections.

Finally, the author of this dissertation and David Worley have published an article on a dynamic sign that uses graphics for a triple-left turn operation at US 59 at SH 6 in Sugar Land, Texas.[13] This is the first sign of this kind ever built. The triple-left sign was developed by the author as a modification of the DBL sign design. Figure 2.2 shows the dynamic sign with the graphics for the triple left turn system in operation in 2010. The main idea behind the triple left sign system is similar to the DBL sign application, where the effectiveness of the system depends largely on the fact that the dynamic message sign has to display a clear and commanding message in order to be effective. The triple-left turn system has allowed the city of Sugar Land reduce the signal cycle length from 180 seconds to 120 seconds, which has reduced the vehicle delays at this intersection significantly. The relevance of the triple-left project to the DBL system is that the use of dynamic message signs at signalized intersections to optimize the use of existing traffic lanes has already had positive results.

Figure 2.3 Triple Left Dynamic Message Sign, Sugar Land, Texas[13]

In conclusion, the literature review conducted for the Dynamic Bus Lane system found the following:

- The basic idea for the operation of the DBL system has been around for 15 years
- The demonstration project in Lisbon showed potential benefits of 20% in reduced bus travel times
- The tram project in Melbourne also showed benefits but to a lesser extent than those obtained in Lisbon, from 1% to 10% in tram travel time savings
- The theoretical research in the US has explored compliance issues with the Manual on Uniform Traffic Control Devices, and developed formulae to compute the capacity and the benefits of the system
- There is the need to implement such a system in the US and outside the US as evidenced by projects using bus-only intermittent use of highway shoulders in Minneapolis and Paris
- The use of intermittent HOV lanes on arterial streets has been implemented in Seattle
- A similar application of a dynamic message sign has been successfully used by the author of this dissertation in Sugar Land, Texas
- There has not been a dynamic bus lane sign as presented in this dissertation proposed or implemented anywhere yet

The concept for the DBL system has been in a developmental stage for several years, but there is no literature evidence that it has been implemented for permanent operation anywhere in the world yet. The demonstration project in Lisbon had a limited duration, and it did not become a permanent system anywhere. The tram project in Melbourne is as close as it gets to a real DBL system in operation, but it is for a different transit vehicle. The BLIMP project in Eugene, Oregon may be the first similar system to the DBL that gets implemented in the US.

CHAPTER 3

DATA COLLECTION AND STUDY DESIGN

The dynamic bus lane system was analyzed for a portion of the Westheimer corridor, from South Dairy Ashford Road to Wilcrest Drive, in Houston, Texas. This corridor section has a total of eight lanes of traffic, a high density of signalized intersections, and uniform geometric conditions. Figure 3.1 shows a schematic drawing of the analysis section. Bus and passenger car travel time studies for the study section, as well as intersection bus travel time studies were conducted.

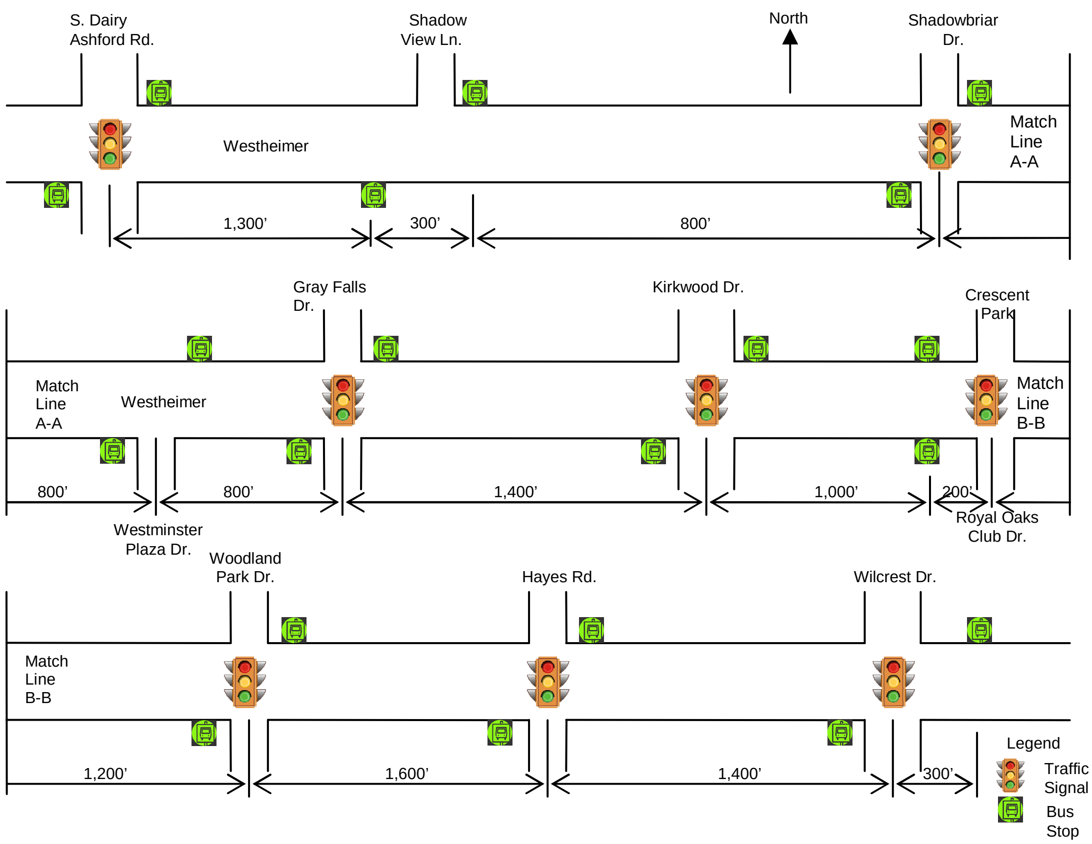


Figure 3.1 Analysis Section

The intersection bus travel time studies were conducted at the two major intersections in the analysis section, which are Westheimer at Wilcrest and Westheimer at Dairy Ashford, and are located at both ends of the analysis section. The data collection strategy formulation consisted of identifying the candidate independent variables which may affect the response variable, so that these variables could be measured in the field. The sample size requirements were determined based on a 90%-probability confidence level. Finally, the data collection plan and schedule were developed for implementation.

The study design task consisted of developing an "operations plan" for the dynamic bus lane system. This plan outlined where the advance dynamic signs would need to be placed to inform vehicles that the bus lane is being activated, what messages these signs would display, and for how long. A conceptual diagram for the dynamic bus lane operation is shown in Figure 3.2. This diagram shows the variables that were considered in the study.

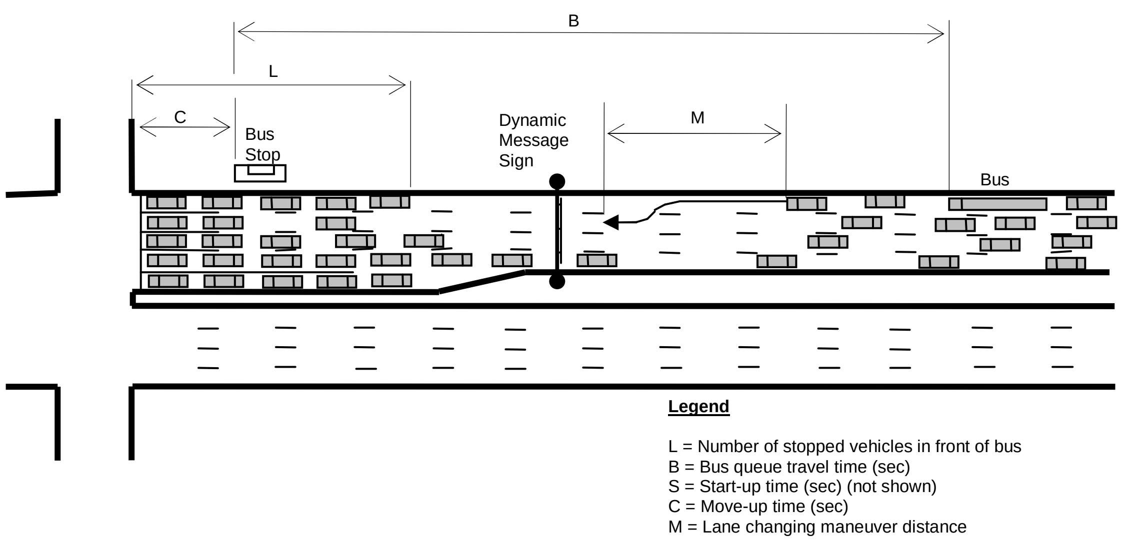


Figure 3.2 Study Design

The bus delay data collection effort was conducted by undergraduate engineering students with the following instructions:

Group Project - Groups will be composed of two to four students. Each group will perform data collection and analysis tasks for the "Dynamic Bus Lane" system. This system will consist of converting the right lane of an arterial street to a bus lane when the bus is approaching a major intersection. After the bus crosses the intersection, the right lane reverts back to general traffic use. In general, each group will be responsible of gathering a set of bus delay measurements (data points) to estimate the bus delay savings that this system could achieve. The proposed test section is Westheimer from Wilcrest to South Dairy Ashford.

Measure the existing bus delay at the intersections of Westheimer at Wilcrest (eastbound 6:30-8:30AM) and Westheimer at Dairy Ashford (westbound 4:30-6:30PM). Obtain a total sample of at least 30 data points (approximately two days for each direction). Collect the data during a typical weekday, Tuesday, Wednesday, or Thursday (away from holidays). Use the attached form. The "BUS STOPPED DELAY" field form used by the students is shown in Table 3.1. The data collection form consisted of the following items:

1) Intersection name, date, direction of travel, day of the week, name of data collector, and peak period
2) Activity
    a) Bus arrives to vicinity (back of the queue) of the intersection
    b) Bus arrives to bus stop and opens door
    c) Bus closes the door
    d) Bus leaves bus stop
    e) Bus leaves intersection (crosses stop line)
3) Time (HH:MM:SS): shows the recorded time for each event listed in item 2
4) Number of stopped vehicles on the right lane in front of the bus
5) Number of vehicles turning right at the intersection in front of the bus
6) State of the traffic signal (Red, Yellow or Green). Also, record when the signal turns green

The results of this field data collection effort are presented after the results of the bus and car travel time studies performed for the entire analysis section, which are presented next.

Table 3.1 Field Data Collection Form

BUS STOPPED DELAY

DATA COLLECTION FORM

Intersection Name________________________________ Date________________

Direction of Travel________________________________ Day of the Week______

Name of Data Collector____________________________ Peak Period_________

Activity	Time (HH:MM:SS)	Number of Stopped Vehicles on the Right Lane in Front of the Bus	Number of Vehicles Turning Right at the Intersection in Front of the Bus	State of the Traffic Signal (Red, Yellow or Green) Also Record When the Signal Turns Green
Bus arrives to vicinity of the intersection				
Bus arrives to bus stop and opens door				
Bus closes door				
Bus leaves bus stop				
Bus leaves intersection (crosses stop line)				

Bus and car travel time studies were conducted for the entire analysis section in 2008 and 2010. The results of the travel time studies for the analysis section, Westheimer from South Dairy Ashford to/from Wilcrest, are shown in Table 3.2. This table shows that the eastbound bus travel time during the AM peak hour averaged 10.45 minutes in February 2008. After the implementation of bus signal priority, the average travel time was reduced to 9.88 minutes in

October 2008, or 5.4%. However, the westbound bus travel time during the PM peak hour was reduced from 11.62 to 11.58, only 0.3%, after bus signal priority for METRO was implemented. A new set of bus travel time studies, as well as car travel time studies were conducted in April 2010 for this research effort. All of these data sets are part of the "before" data. The "after" data for the DBL project was modeled, and is presented in the latter sections of this dissertation.

Table 3.2 "Before" DBL Travel Time Studies for Analysis Section

Date	Mode of Travel	Direction of Travel and Peak Period	Number of Travel Time Runs	Travel Time (minutes)
February 2008 (Before signal priority)	Bus	Eastbound (AM peak)	3	10.45
		Westbound (PM peak)	3	11.62
October 2008 (After signal priority)	Bus	Eastbound (AM peak)	3	9.88
		Westbound (PM Peak)	3	11.58
April 2010 (After signal priority)	Bus	Eastbound (AM Peak)	5	9.34
		Westbound (PM Peak)	5	10.09
April 2010 (After signal priority)	Car	Eastbound (AM peak)	9	6.52
		Westbound (PM peak)	7	6.57

The 2010 bus travel time studies resulted in an average travel time of 9.34 minutes in the eastbound direction during the AM peak hour, and 10.09 minutes in the westbound direction during the PM peak hour. These represent a further reduction in travel time when compared to the initial studies collected in February 2008, 10.6 % in the eastbound direction and 13% in the westbound direction. No signal timing adjustments were done between October 2008 and April 2010, so the reduction in travel time is attributed to a reduction in traffic volume. The Texas Department of Transportation planning map[14] shows an average daily traffic volume of 61,000 vehicles per day for 2008, and 58,000 vehicles per day for 2010, a reduction of 4.9%, for this section of Westheimer (FM 1093 on the map). The car travel time studies resulted in 6.52 minutes in the eastbound direction during the AM peak hour, and 6.57 in the westbound direction during the PM peak hour. The bus and car travel times are used to compute the transit levels of service for the "before" the DBL system and model the "after" the DBL system conditions for the transit analysis section in Chapter 5. The travel time data details are included in Tables A.1, A.2, A.3, and A.4 in Appendix A.

The results of the field measurements taken with the "BUS STOPPED DELAY" form are shown in Tables 3.3 and Table 3.4. Table 3.3 shows the results of the morning peak period intersection bus travel time study. Table 3.3 shows that 17 data points were collected at the intersection of Westheimer at Wilcrest in the eastbound direction during the morning peak hour period. The data point numbers are shown in column #1, while the dates are shown in column #2, and the times are shown in column #3. Column #4 is labeled "Bus Queue Travel Time (sec)," and it is the difference between the recorded time for "Bus arrives to bus stop and opens door" and "Bus arrives to vicinity of the intersection" in the field data form shown in Table 3.1. This is the time that the DBL system seeks to reduce; therefore, it is the response variable for this research effort. There were three data points with zero in this column. This means that there was not a vehicle queue and the bus arrived to the bus stop without any queue travel time during these three events. Column #5 is labeled "Dwell Time (sec)," and it is the difference between "Bus closes door" and "Bus arrives to bus stop and opens door." Column #6, labeled "Start-up Time (sec)," is the difference between "Bus leaves intersection (crosses stop line)" and "Bus leaves stop." Column #7, labeled "Move-up Time (sec)," is the difference between "Bus leaves the intersection (crosses stop line)" and "Bus leaves bus stop." The values shown in column #8, labeled "Number of Stopped Vehicles in Front of the Bus," are the values recorded in the field form under the same label. The values under this column represent the independent variable for this research effort. This means that if the value of this variable can be reduced with the DBL system, then the value of the response variable in column #4 can also be reduced.

The values shown in column #9, labeled "Number of Vehicles Turning Right in Front of the Bus" are the same values recorded in the field form under the same label.

Table 3.3 AM Peak Period Intersection Bus Travel Time Study

Westheimer at Wilcrest Eastbound Approach									
Col. #1	Col. #2	Col. #3	Col. #4	Col. #5	Col. #6	Column #7	Col. #8	Col. #9	Col. #10
Data Point	Date	Time	Bus Queue Travel Time (sec)	Dwell Time (sec)	Start-up Time (sec)	Move-up Time (sec)	Number of Stopped Vehicles in Front of the Bus	Number of Vehicles Turning Right in Front of the Bus	State of the Traffic Signal (Red, Yellow or Green)
1	9/16/ 2009	7:13 AM	0	23	4	30	0	0	R/G
2		7:22 AM	0	25	22	3	3	1	R/G
3		7:41 AM	15	6	1	4	3	1	G
4		8:36 AM	12	7	1	8	4	0	G
5	9/9/ 2009	7:41 AM	22	0	0	25	10	1	R/G
6		8:08 AM	24	33	36	41	10	0	G
7		8:18 AM	31	37	37	43	14	7	G
8	9/3/ 2009	7:42 AM	0	0	8	1	0	0	G
9		8:02 AM	5	7	2	1	0	2	G
10		8:06 AM	11	2	1	1	4	0	R/G
11		8:14 AM	5	8	1	3	5	0	G
12		8:34 AM	23	5	1	5	9	0	R/G
13	3/23/ 2011	7:23 AM	24	0	1	1	5	1	G
14		7:24 AM	30	0	1	1	8	3	G
15		7:49 AM	26	10	59	1	5	0	G/R/G
16		8:11 AM	32	8	1	5	13	4	G
17		8:25 AM	30	9	44	5	6	2	G/R/G
Mean			17.1	10.6	12.9	10.5	5.8	1.3	
Standard deviation			11.8	11.7	19.1	14.5	4.3	1.9	
Student distribution at 90% probability			1.746	1.746	1.746	1.746	1.746	1.746	
Sample error at 90% probability			2.9	2.9	4.7	3.5	1.0	0.5	

Finally, the values shown in column #10 labeled "State of the Traffic Signal (Red, Yellow or Green)," are the same values recorded in the field form with the label "State of the Traffic Signal (Red, Yellow or Green) Also Record When the Signal Turns Green." However, only a few recordings were taken when the signal turned green, so they were omitted from this report. The fact that the data shown in column #10 shows the number of times the signal state changed proved more meaningful than the time when the signal turned green. The results shown at the bottom of Table 3.3 show the mean value, standard deviation, the student probability distribution at 90% probability, and the sample error at 90% probability for each column. The student probability distribution was used because the true standard deviations of the test samples are unknown. The 90% confidence interval for the mean of the response variable, the bus queue travel time, is 17.1 ± 2.9 seconds. The 90% confidence interval for the mean of the independent variable, the number of stopped vehicles in front of the bus, is 5.8 ±1.0 vehicles. This means that the true value of the bus queue travel time lies between 14 and 20 seconds, and the true value of the number of vehicles stopped in front of the bus lies between 5 and 7 vehicles. This research effort will show how much the bus queue travel time can be reduced if the number of vehicles stopped in front of the bus is reduced. Likewise, 90% confidence intervals can be constructed for the other variables collected in the field and shown in Table 3.3. If all the bus travel time variables are added, the sum represents the total time that the bus spent at the intersection. This sum is 51.1 seconds for the morning peak period data.

The mean of the number of vehicles turning right in front of the bus is 1.3 vehicles. This variable represents the minimum number of vehicles that could be stopped in front of the bus after the DBL system is implemented, since right turns would still be allowed. The vehicles turning right would also be able to improve their operation with the DBL system, since they will be able to turn right on a red signal without being blocked by a vehicle going straight. In reality, this variable does not affect the response variable because the bus stop is at 40 feet from the intersection stop line, which would allow at least one car to be in front of the bus to make a right turn without impacting the bus operation. Therefore, any bus queue travel time resulting from a vehicle queue larger than one vehicle would theoretically be zero. The other variables shown in the other columns were used to test different linear regression models in Chapter 4.

Table 3.4 shows the bus travel time data collected at Westheimer at South Dairy Ashford during the afternoon peak period. Table 3.4 shows that 55 data points were collected at the intersection of Westheimer at South Dairy Ashford in the westbound direction during the afternoon peak period. The columns in this table represent the same variables shown in Table 3.3. There were seven data points with zero in column #4, the bus queue travel time. This means that there was not a vehicle queue and the bus arrived to the bus stop without any queue travel time during these seven events.

The 90% confidence interval for the mean of the response variable, the bus queue travel time, is 44.1 ±7.1 seconds. The 90% confidence interval for the mean of the independent variable, the number of stopped vehicles in front of the bus, is 9.1 ±1.3 vehicles. This means that the true value of the bus queue travel time lies between 37 and 51 seconds, and the true value of the number of vehicles stopped in front of the bus lies between 8 and 10 vehicles. This research effort will show how much of the bus queue travel time can reduced if the number of vehicles stopped in front of the bus is reduced. Likewise, 90% confidence intervals can be constructed for the other variables collected in the field and shown in Table 3.4. If all the bus travel time variables are added, the sum represents the total time that the bus spent at the intersection. This sum is 102.7 seconds for the afternoon peak period data.

The mean of the number of vehicles turning right in front of the bus is 2.6 vehicles. This variable represents the mean number of vehicles that could be in front of the bus, the independent variable, since right turns would still be allowed with the DBL system. Contrary to the morning peak period data, this variable would affect the response variable because the bus stop is at only 10 feet from the intersection stop line, which would not allow any cars to be in front of the bus to make a right turn without impacting the bus operation. Therefore, the bus travel time resulting from a vehicle queue larger than zero would theoretically be non zero. The other variables shown in the other columns were used to test different linear regression models in Chapter 4, similar to the morning peak period data.

Table 3.4 PM Peak Period Intersection Bus Travel Time Study

Westheimer at South Dairy Ashford Westbound Approach									
Col. #1	Col. #2	Column #3	Col. #4	Col. #5	Col. #6	Column #7	Column #8	Column #9	Column #10
Data Point	Date	Time	Bus Queue Travel Time (sec)	Dwell Time (sec)	Start-up Time (sec)	Move-up Time (sec)	Number of Stopped Vehicles in Front of the Bus	Number of Vehicles Turning Right in Front of the Bus	State of the Traffic Signal (Red, Yellow or Green)
1	9/15/ 2009	4:37 PM	0	4	1	3	1	1	G
2		4:57 PM	26	2	1	3	11	3	G
3		5:08 PM	0	15	187	4	0	0	R/G
4		5:28 PM	20	2	69	3	3	2	R/G
5		6:09 PM	30	10	1	4	6	1	G
6		6:24 PM	22	0	0	1	8	4	R/G
7	9/24/ 2009	4:40 PM	1	13	60	8	2	0	R/G
8		5:12 PM	0	25	78	2	0	3	G/R/G
9		5:29 PM	29	8	2	2	11	6	G
10		5:55 PM	0	8	90	4	0	0	R/G
11		6:04 PM	33	12	79	7	10	5	G/R
12	9/10/ 2009	4:40 PM	0	10	30	3	0	0	G/R/G
13		4:49 PM	1	16	1	1	0	0	G
14		5:34 PM	32	20	9	0	8	3	R/G
15		6:10 PM	0	1	3	3	0	0	G
16	9/10/ 2009	4:39 PM	0	10	30	3	0	0	R/G
17		4:48 PM	2	14	2	1	0	0	G
18		5:33 PM	33	20	9	1	8	3	G/R/G
19		6:02 PM	10	4	57	5	1	0	G
20	9/29/ 2009	4:33 PM	2	33	17	2	0	0	R/G
21		4:52 PM	4	1	1	50	6	1	R/G/R/G
22		5:59 PM	45	3	15	2	8	0	R/G
23		6:13 PM	37	5	52	0	7	0	G/R/G
24	3/23/ 2011	4:39 PM	50	8	4	4	9	3	R/G
25		4:51 PM	64	11	1	7	11	5	R/G
26		5:09 PM	61	4	6	3	5	2	R/G
27		5:14 PM	57	10	125	4	15	3	R/G/R/G
28		5:36 PM	99	22	81	10	17	6	R/G/R/G
29		5:55 PM	9	20	78	8	5	2	G/R/G

Table 3.4 – *Continued*

30	3/23/ 2011	4:39 PM	55	8	7	4	9	3	R/G
31		4:51 PM	59	16	5	4	11	5	R/G
32		5:09 PM	51	7	3	6	5	2	R/G
33		5:14 PM	52	13	96	6	16	3	R/G
34		5:36 PM	107	19	82	9	17	6	R/G/R/G
35	3/23/ 2011	4:39 PM	49	8	4	4	9	3	R/G
36		4:51 PM	64	11	1	7	11	5	R/G
37		5:08 PM	53	7	2	4	5	2	R/G
38		5:14 PM	55	10	102	5	16	3	G/R/G
39		5:37 PM	104	21	83	5	16	6	R/G/R/G
40		5:55 PM	88	2	98	2	14	7	R/G/R/G
41	3/23/ 2011	5:14 PM	55	44	150	4	16	3	R/G/R/G
42		5:36 PM	85	17	85	4	16	6	R/G/R/G
43		5:55 PM	101	17	78	5	15	7	R/G/R/G
44	3/24/ 2011	4:39 PM	47	8	4	6	9	3	R/G
45		4:51 PM	64	11	1	7	11	5	R/G
46		5:09 PM	40	7	2	4	5	2	R/G
47		5:14 PM	55	10	102	5	16	3	R/G/R/G
48		5:37 PM	104	21	83	5	16	6	R/G/R/G
49		5:55 PM	88	2	98	2	14	7	R/G/R/G
50	3/24/ 2011	4:39 PM	47	8	4	6	9	3	R/G
51		4:51 PM	64	11	1	7	11	5	R/G
52		5:09 PM	40	7	2	4	5	2	R/G
53		5:14 PM	55	10	102	5	16	3	R/G/R/G
54		5:37 PM	104	21	83	5	16	6	R/G/R/G
55		5:55 PM	88	2	98	2	14	7	R/G/R/G
Mean			44.1	11.8	46.8	6.2	9.1	3.3	
Standard deviation			32.1	9.1	47.4	10.2	6.1	2.6	
Normal distribution at 90% prob.			1.282	1.282	1.282	1.282	1.282	1.282	
Sample error at 90% probability			7.1	2.0	10.4	2.2	1.3	0.6	

CHAPTER 4

BUS QUEUE TRAVEL TIME ESTIMATION AND PREDICTION INTERVAL

This section documents the development of a probabilistic model for estimating the bus queue travel time due to a queue of vehicles stopped in front of the bus. The queue of vehicles impedes the bus from reaching the bus stop. The proposed Dynamic Bus Lane (DBL) system seeks to reduce the number of vehicles stopped in front of the bus by converting the right lane to a bus lane when the bus is approaching a bus stop at a major intersection.

The experimental design task consisted of determining how the experiment was conducted to find out how effective the proposed system was. In general, the experiment consisted of evaluating the "before" and the "after" conditions. The "before" conditions were sampled from existing field conditions, while the "after" conditions were modeled using a probabilistic model. The probabilistic model emulated realistically the independent variable, the vehicle queue length variation, and obtained a confidence interval for the response variable, the expected bus queue travel time using the DBL system.

The probabilistic model is a simple linear regression model where the predictor variable is the number of vehicles stopped in front of the bus, or "vehicle queue" for shorter notation, and the response variable is the bus queue travel time. The vehicle queue may include trucks, which would increase the bus travel time. There are other variables related to the traffic signal operation; such as roadway geometry characteristics, and the number of vehicles turning right on red that were considered constant and excluded from the regression model analysis. This section presents the interval estimation for the bus queue travel time when the DBL system is activated.

4.1 Delay Model Variables

In addition to the bus queue travel time (response variable) and vehicle queue (predictor variable), there are other variables that could affect the response variable. The variables related to the traffic signal operation, such as the cycle length, the approach green interval, and the saturation level of the intersection, would make a difference in the response variable, but are kept constant during this analysis. Likewise, the geometry features of the roadway, such as the number of lanes and the driveway density, are considered constant during the analysis. The theoretical effect of different number of approach traffic lanes (two, three, and four) with the DBL system was considered as part of this research effort, and is presented later.

Another important variable for this analysis is the number of vehicles turning right in front of the bus, as discussed in the previous chapter. This variable is part of the predictor variable, the number of vehicles stopped in front of the bus. Therefore, this variable is directly correlated to the predictor variable, so it is not an independent variable for the regression model. The mean number of vehicles turning right is accounted for as a constraint in the predictor variable. The constraint will be the lower bound of the predictor variable. This project seeks to minimize the number of vehicles stopped in front of the bus; however, the right turns will still be allowed to happen in front of the bus. Therefore, the queue in front of the bus will be at least the number of vehicles turning right. As previously stated in Chapter 3, the distance of the bus stop to the intersection stop line affects the number of vehicles turning right. In the case of the morning data, one vehicle can fit between the bus stop and the intersection. So, in this case, the lower bound for this variable is one vehicle. In the case of the afternoon peak hour, there was no room for any vehicles to fit between the bus stop and the intersection. So, in this case, the lower bound for this variable is zero. However, the bus stop locations were not considered when computing the response variable. Therefore, the DBL benefit results of the response variable based on the morning peak-hour data were slightly underestimated, while the DBL benefit results based on the afternoon peak-hour data were not affected.

Another variable is the other vehicles drivers' compliance with the regulation imposed by the DBL system to not use the right lane, unless they are turning right. The driver compliance variable is considered to cause a shorter or longer vehicle queue when estimating the prediction interval of the bus queue travel time. The bus drivers represent another variable, which was assumed constant.

4.2 General Linear Regression Model

A general linear regression model was developed to evaluate all of the variables and their possible relationships as follows: The general form of the linear regression model is as follows:

$$Y_{1i} + Y_{2i} + Y_{3i} + Y_{4i} = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \varepsilon_i$$

Where:

Y_{1i} = Mean response variable representing the bus queue travel time (seconds)

Y_{2i} = Mean response variable representing the dwell time (seconds)

Y_{3i} = Mean response variable representing the start-up time (seconds)

Y_{4i} = Mean response variable representing the move-up time (seconds)

β_0 = Parameter representing the constant of the linear regression model (seconds)

β_1 = Parameter representing the coefficient of the vehicle queue stopped in front of the bus (seconds/vehicle)

β_2 = Parameter representing the coefficient of the vehicles turning right in front of the bus (seconds/vehicle)

β_3 = Parameter representing the coefficient of the state of the traffic signal (red or green)

X_{1i} = Mean predictor variable representing the vehicle queue stopped in front of the bus or vehicle queue (vehicles)

X_{2i} = Mean predictor variable representing the vehicles turning right in front of the bus (vehicles)

X_{3i} = Mean predictor variable representing the state of the traffic signal (red or green)

ε_i = Random error term

The bus "control" delay was considered as the sum of the vehicle queue travel time, the star-up time, and the move-up time, in similar nomenclature to the HCM manual. So the bus "control delay" was the total time the bus spends at an intersection, except for the dwell time. The following regression models were considered for preliminary analysis:

Model #1: Bus queue travel time as a function of vehicle queue:

$$Y_{1i} = \beta_0 + \beta_1 X_{1i} + \varepsilon_i$$

Model #2: Bus "control" delay as a function of vehicle queue:

$$Y_{1i} + Y_{3i} + Y_{4i} = \beta_0 + \beta_1 X_{1i} + \varepsilon_i$$

Model #3: Bus "control" delay as a function of the difference between vehicle queue and right-turning vehicles:

$$Y_{1i} + Y_{3i} + Y_{4i} = \beta_0 + \beta_1 (X_{1i} - X_{2i}) + \varepsilon_i$$

The main criteria used to select the model were the correlation coefficient and the simplicity of the model. Other factors such as residual distributions and obtaining negative predictor variables were also considered. Table 4.1 shows the candidate models, their corresponding regression coefficient, and comments. An examination of the residual plots for the three models revealed that model one have its residuals more balanced over the zero line than models two and three. The residual versus predictor plots for model number one are shown in Figures 4.4 (b) and 4.5 (b) for the morning and afternoon peak hour data, respectively. The residual versus predictor plots for model number two are shown in Figures 4.6 (a) and (b) for the morning and afternoon peak hour data, respectively. The residual versus predictor plots for model number three are shown in Figures 4.7 (a) and (b) for the morning and afternoon peak hour data, respectively.

From the comments in Table 4.1 and the residual plots, it can be concluded that the best regression model form is model number one. Model numbers two and three were discarded. The negative predictor values in model number three resulted from the difference between the vehicle queue and the number of vehicles turning right. In two instances, one in the morning data set and one in the afternoon data set, this resulted in negative values because some of the vehicles turning right did not stop at the intersection. The regression analysis and scatter plots for model number one is shown in Figure 4.1, while the scatter plots for models number two and three are shown in Figures B.1 and B.2 in Appendix B.

Table 4.1 Candidate Regression Models

Model Number	Peak Hour	Model	Corr. Coeff.	Comments
1	AM	$Y_{1i} = 4.00 + 2.24X_{1i}$	0.667	Highest correlation coefficients, simple model form
	PM	$Y_{1i} = 2.05 + 4.95X_{1i}$	0.7514	
2	AM	$Y_{1i} + Y_{3i} + Y_{4i} = 13.0 + 4.71X_{1i}$	0.3735	Lower correlation coefficients, complex model form
	PM	$Y_{1i} + Y_{3i} + Y_{4i} = 14.0 + 9.01X_{1i}$	0.6473	
3	AM	$Y_{1i} + Y_{3i} + Y_{4i} = 18.0 + 4.95(X_{1i} - X_{2i})$	0.2717	Lowest correlation coefficients, complex model form, negative predictor values
	PM	$Y_{1i} + Y_{3i} + Y_{4i} = 26.7 + 11.7(X_{1i} - X_{2i})$	0.5692	

4.3 Simple Linear Regression Model

A simple linear regression model was selected to predict the expected bus queue travel time due to a vehicle queue at the intersection, as follows:

AM Peak Hour Model: $Y_{1i} = 4.00 + 2.24X_{1i}$

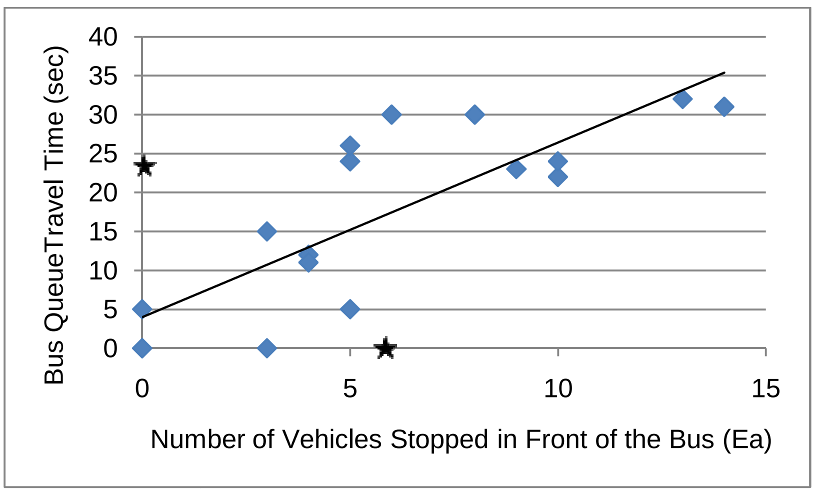
PM Peak Hour Model: $Y_{1i} = 2.05 + 4.95X_{1i}$

Where:

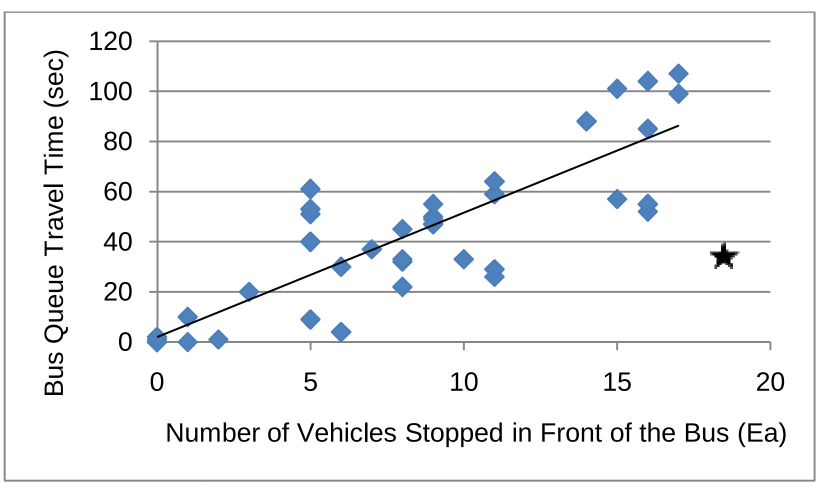
Y_{1i} = Mean response variable representing the bus queue travel time (seconds)

Mean predictor variable representing the number of vehicles stopped in front of the bus or "vehicle queue" (vehicles)

The scatter plots for these linear regression models are illustrated in Figure 4.1. The star symbols on these graphs are outliers, while the other symbols are the data points. The y-intercepts on these two graphs represent the bus queue travel time when the vehicle queue is zero. In the AM peak hour model, the y-intercept is 4.00 seconds, while in the PM peak hour model the y-intercept is 2.05 seconds. The simple linear regression calculations are included in Tables 4.2 and 4.3.



(a)



(b)

Figure 4.1 Simple Linear Regression Model #1 (a) AM Peak (b) PM Peak

Table 4.2 AM Peak Simple Linear Regression Data for Model #1

Data Point #	Stopped Vehicle Queue (Each)	Bus Queue Delay (secs)	Square Predictor Deviation	Estimated Mean Response (secs)	Residuals	Square Residuals
i	*Xi*	*Yi*	$(Xi-X)^2$	*Ŷi*	*Yi-Ŷi*	$(Yi-\hat{Y}i)^2$
1	0	0	24.69	4.00	-4.00	16.0
2	3	0	3.88	10.73	-10.73	115.1
3	3	15	3.88	10.73	4.27	18.2
4	4	12	0.94	12.97	-0.97	0.9
5	10	22	25.31	26.42	-4.42	19.6
6	10	24	25.31	26.42	-2.42	5.9
7	14	31	81.56	35.39	-4.39	19.3
8	0	0	24.69	4.00	-4.00	16.0
9	0	5	24.69	4.00	1.00	1.0
10	4	11	0.94	12.97	-1.97	3.9
11	5	5	0.00	15.21	-10.21	104.3
12	9	23	16.25	24.18	-1.18	1.4
13	5	24	0.00	15.21	8.79	77.2
14	8	30	9.19	21.94	8.06	65.0
15	5	26	0.00	15.21	10.79	116.4
16	13	32	64.50	33.15	-1.15	1.3
17	6	30	1.06	17.45	12.55	157.4
Totals			307	290	0	739

Table 4.3 PM Peak Simple Linear Regression Data for Model #1

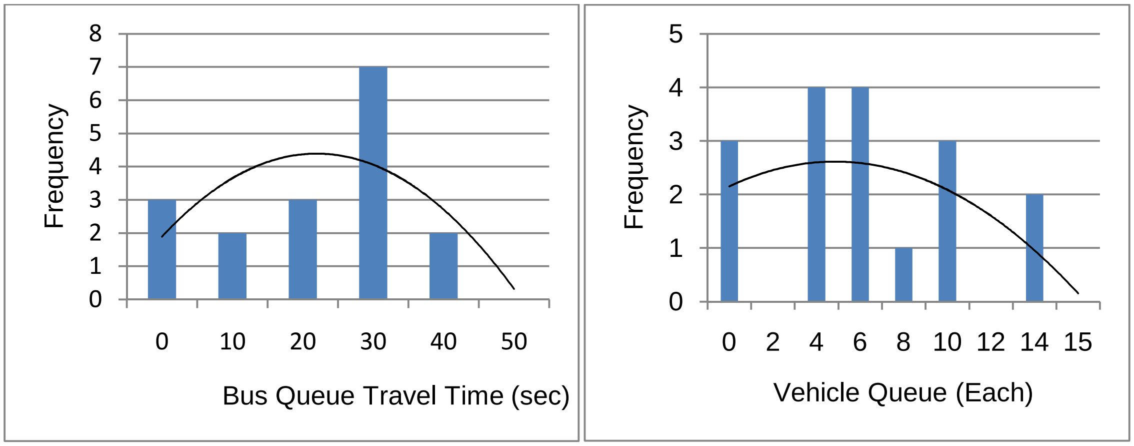
Data Point #	Stopped Vehicle Queue (Each)	Bus Queue Delay (secs)	Square Predictor Deviation	Estimated Mean Response (secs)	Residuals	Square Residuals
i	*Xi*	*Yi*	$(Xi\text{-}X)^2$	*Ŷi*	*Yi-Ŷi*	$(Yi\text{-}\hat{Y}i)^2$
1	1	0	23.27	7.00	-7.00	49.0
2	11	26	26.80	56.54	-30.54	932.8
3	0	0	33.91	2.05	-2.05	4.2
4	3	20	7.97	16.91	3.09	9.6
5	6	30	0.03	31.77	-1.77	3.1
6	8	22	4.74	41.68	-19.68	387.3
7	2	1	14.62	11.96	-10.96	120.0
8	0	0	33.91	2.05	-2.05	4.2
9	11	29	26.80	56.54	-27.54	758.5
10	0	0	33.91	2.05	-2.05	4.2
11	10	33	17.44	51.59	-18.59	345.5
12	0	0	33.91	2.05	-2.05	4.2
13	0	1	33.91	2.05	-1.05	1.1
14	8	32	4.74	41.68	-9.68	93.7
15	0	0	33.91	2.05	-2.05	4.2
16	0	0	0.00	2.05	-2.05	4.2
17	0	2	0.00	2.05	-0.05	0.0
18	8	33	64.00	41.68	-8.68	75.3
19	1	10	1.00	7.00	3.00	9.0
20	0	2	0.00	2.05	-0.05	0.0
21	6	4	36.00	31.77	-27.77	771.3
22	8	45	64.00	41.68	3.32	11.0
23	7	37	49.00	36.73	0.27	0.1
24	9	50	81.00	46.63	3.37	11.3
25	11	64	121.00	56.54	7.46	55.6
26	5	61	25.00	26.82	34.18	1168.5
27	15	57	225.00	76.36	-19.36	374.7
28	17	99	289.00	86.27	12.73	162.2
29	5	9	25.00	26.82	-17.82	317.5
30	9	55	81.00	46.63	8.37	70.0
31	11	59	121.00	56.54	2.46	6.0
32	5	51	25.00	26.82	24.18	584.8

Table 4.4 – *Continued*

33	16	52	256.00	81.31	-29.31	859.2
34	17	107	289.00	86.27	20.73	429.9
35	9	49	81.00	46.63	2.37	5.6
36	11	64	121.00	56.54	7.46	55.6
37	5	53	25.00	26.82	26.18	685.5
38	16	55	256.00	81.31	-26.31	692.3
39	16	104	256.00	81.31	22.69	514.8
40	14	88	196.00	71.40	16.60	275.4
41	16	55	256.00	81.31	-26.31	692.3
42	16	85	256.00	81.31	3.69	13.6
43	15	101	225.00	76.36	24.64	607.3
44	9	47	81.00	46.63	0.37	0.1
45	11	64	121.00	56.54	7.46	55.6
46	5	40	25.00	26.82	13.18	173.8
47	16	55	256.00	81.31	-26.31	692.3
48	16	104	256.00	81.31	22.69	514.8
49	14	88	196.00	71.40	16.60	275.4
50	9	47	81.00	46.63	0.37	0.1
51	11	64	121.00	56.54	7.46	55.6
52	5	40	25.00	26.82	13.18	173.8
53	16	55	256.00	81.31	-26.31	692.3
54	16	104	256.00	81.31	22.69	514.8
55	14	88	196.00	71.40	16.60	275.4
Totals			5,624	2,441	0	14,599

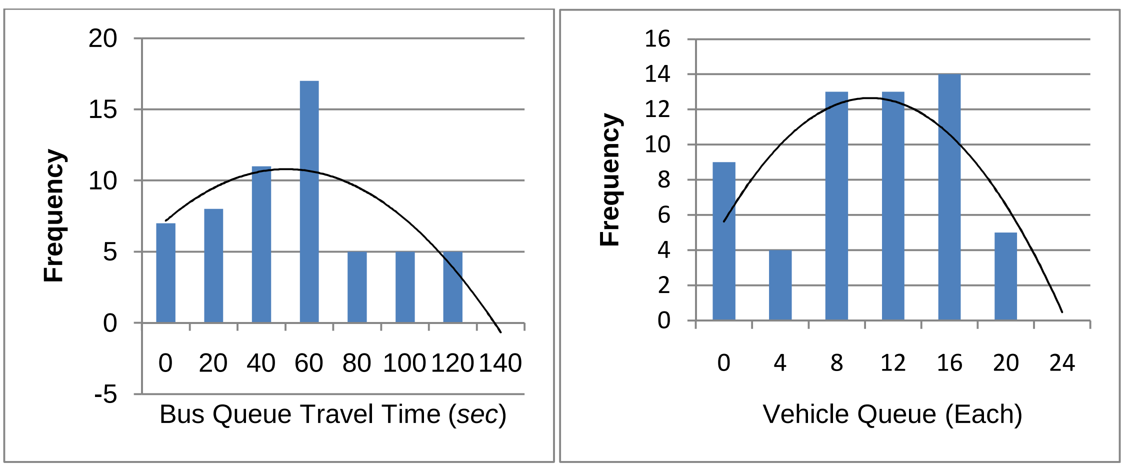
4.4 Variable Frequency Distributions

Both, the vehicle queue (predictor) and bus queue travel time (response) variables have normal frequency distributions. The chi square goodness of fit test was satisfied with 90% probability. The histograms with a linear trend line illustrating the normality of the data are shown in Figures B.3 and B.4. The frequency data is included in Table B.3 in Appendix B.



(a) (b)

Figure 4.2 AM Peak Variable Frequency Distribution for Model #1 (a) Bus Queue Travel Time (b) Vehicle Queue



(a) (b)

Figure 4.3 PM Peak Variable Frequency Distribution for Model #1 (a) Bus Queue Travel Time (b) Vehicle Queue

4.5 Regression Outliers and Analysis of Variance Table

There were two outliers in the AM peak-hour model and three outliers in the PM peak-hour model. Cook's statistic[15] was used to confirm the outliers with a value of 2.0 or greater. Table 4.4 contains the five outliers that were removed from the field data set, after confirmation of data collection issues. Three of the outliers are shown with the star symbols on Figure 4.1. Two of the outliers were not shown, since they fell outside the charts. Table 4.5 contains the analysis of variance results. These results are used in the next section to determine whether there was a strong relationship between the two variables.

Table 4.4 Regression Model Outliers

Date	Time	Bus Travel Time (sec)	Vehicle Queue (Ea)	Cook's Statistic
9/9/2009	8:36 AM	0	6	2.0
3/23/2011	7:14 AM	23	0	2.2
9/24/2009	4:40 PM	36	18	2.2
9/10/2009	5:18 AM	41	20	2.4
9/10/2009	5:19 AM	41	20	2.4

Table 4.5 Analysis of Variance Table

Source of Variability	Degrees of Freedom	Sum of Squares	Mean Sum of Squares
AM Peak Hour Model			
Model	1	1,480	1480
Residual	15	739	49.3
Total	16	2,219	139
PM Peak Hour Model			
Model	1	44,118	44,118
Residual	53	14,599	275
Total	54	58,716	1,087

4.6 Variable Relationship Tests

In order to determine whether there is a strong statistical relationship between the response variable and the predictor variable, the slope of the linear regression has to be nonzero with a high level of confidence. To this end, the following hypothesis is tested with 90% confidence:

$$H_0: \ \beta_1 = 0$$

$$H_1: \ \beta_1 \neq 0$$

The null hypothesis is that the slope is zero, while the alternate hypothesis is that the slope is not zero. The test for the slope to be zero is that the t-ratio of the slope has to be greater than the t-statistic for the level of confidence (α) and degrees of freedom (*n-2*) as follows:

$$\frac{slope}{\sqrt{MSE/\sum(X_i - X)^2}} > t(1-\frac{\alpha}{2}, n-2)$$

Where:

$slope =$ regression model slope

$MSE =$ mean sum of squares

The t-ratio of the slopes for both, the AM and PM peak hour models are equal or greater that the t-statistic for 90% confidence, so we can conclude that the slopes of linear regression models are not zero. This means that there is a strong statistical relationship between the vehicle queue and the bus queue travel time. Table B.3 in Appendix C contains the result summary of this analysis.

4.7 Regression Diagnostic Tests

A series of diagnostics tests were conducted on the linear regression models to determine the appropriateness of the data for this type of models, as follows:

1. Nonlinearity of Regression Function
2. Non Constancy of Error Variance
3. Presence of Outliers
4. Non Independence of Error Terms
5. Non Normality of Error Terms
6. Omission of Important Predictor Variables

For both models, the residual versus predictor plots show that there are as many residuals on top of the zero line as below it, which is desirable as shown in Figures 4.4 (a) and 4.5 (a). The square residual plots show that the scatter plots are pretty uniform as shown in Figures 4.4 (b) and 4.5 (b). The residual normality plots show that the frequency distributions resemble a normal distribution as shown in Figures 4.4 (c) and 4.5 (c). The predictor time plots show that the vehicle queues increase with time during the peak hours, as it should be expected for this type of data, as shown in Figures 4.4 (d) and 4.5 (d). Likewise, the predictor sequential plots indicate that the data vehicle queues increase because the data is arranged time wise, as shown in Figures 4.4 (e) and 4.5 (e). In conclusion, the regression models have passed these tests.

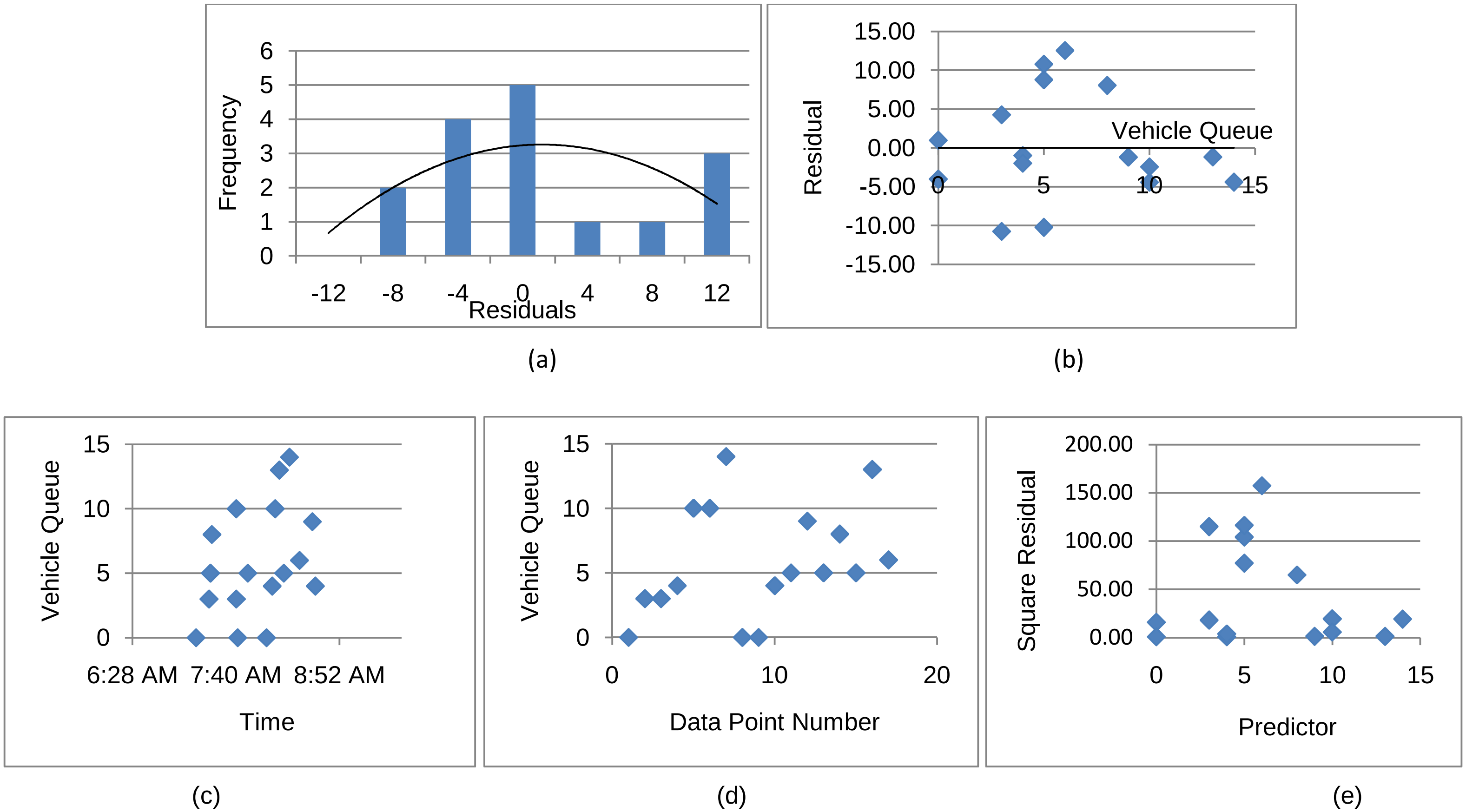


Figure 4.4 AM Peak Regression Diagnostic Test Plots for Model #1 (a) Residual Normality (b) Residual versus Predictor (c) Predictor Time Plot (d) Predictor Sequential Plot (e) Square Residual versus Predictor

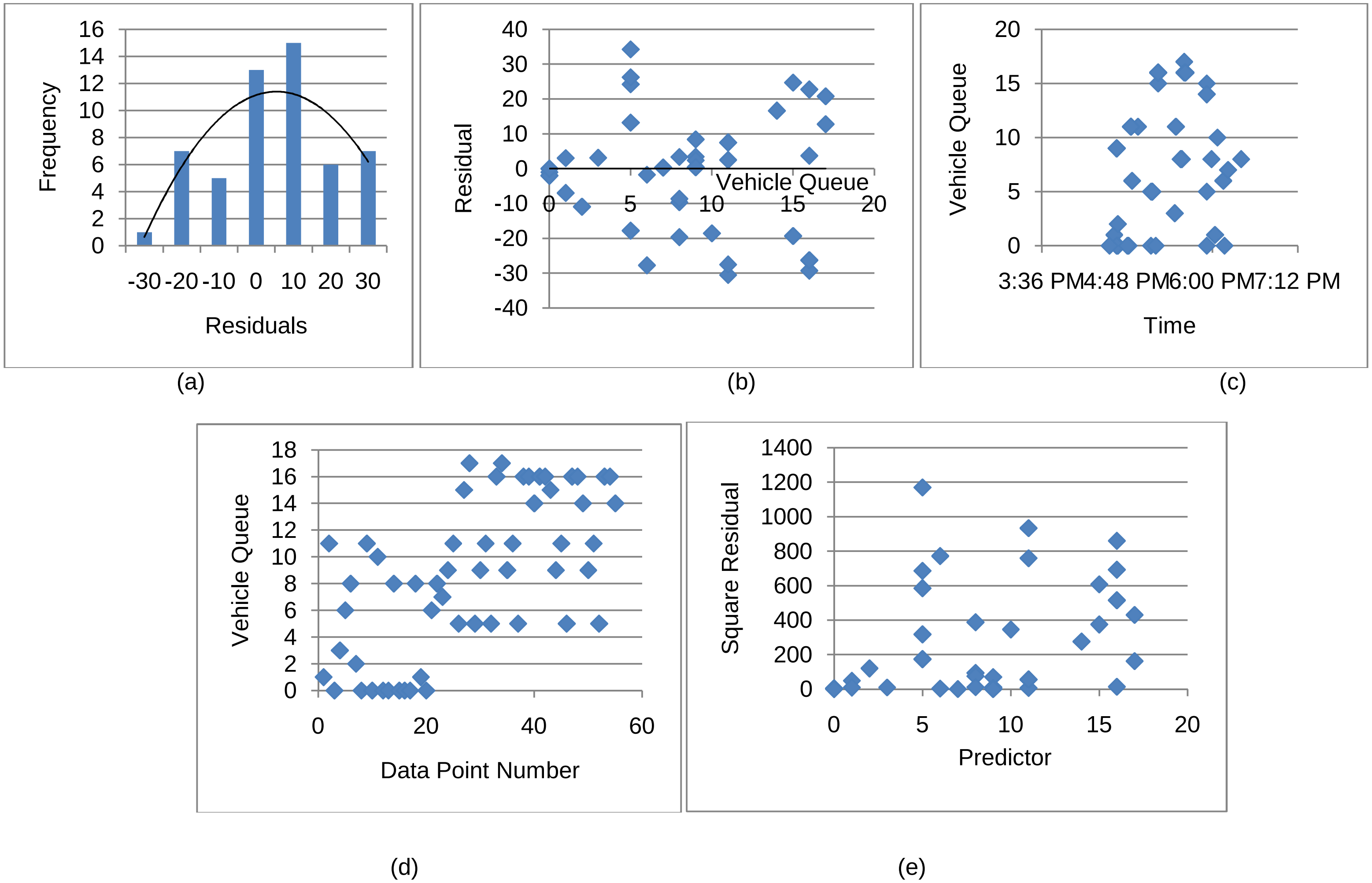
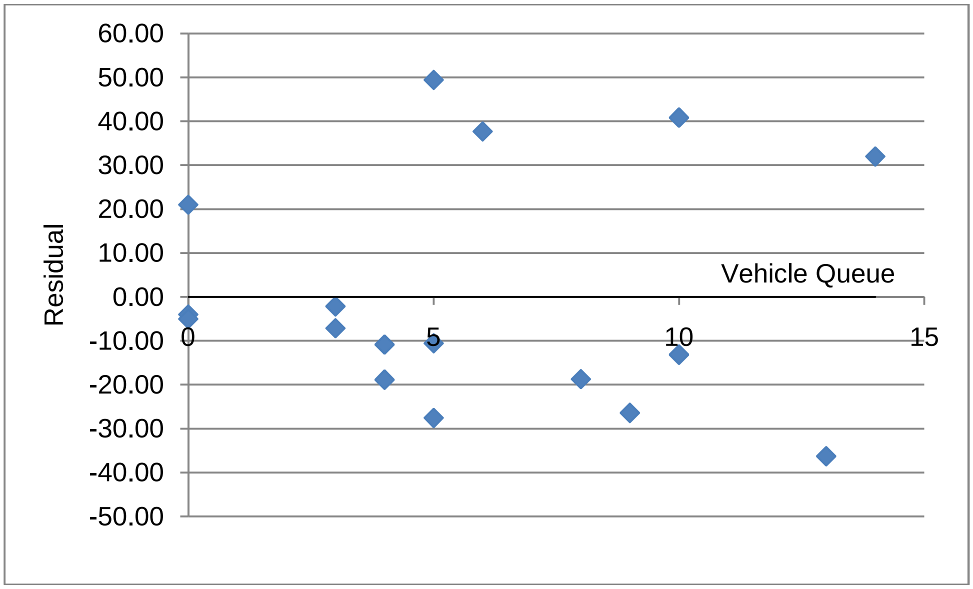
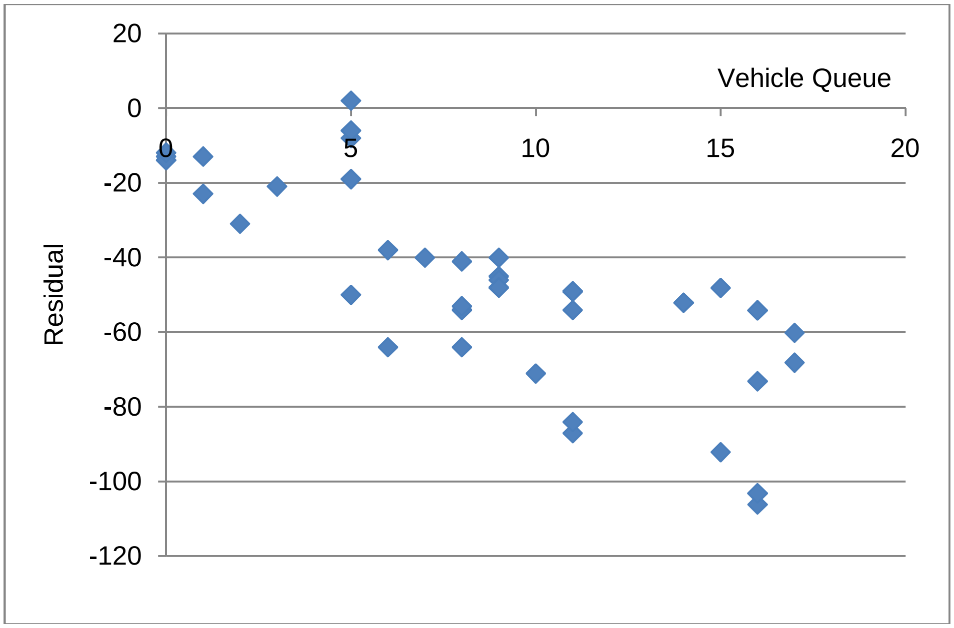


Figure 4.5 PM Peak Regression Diagnostic Test Plots for Model #1 (a) Residual Normality (b) Residual versus Predictor (c) Predictor Time Plot (d) Predictor Sequential Plot (e) Square Residual versus Predictor

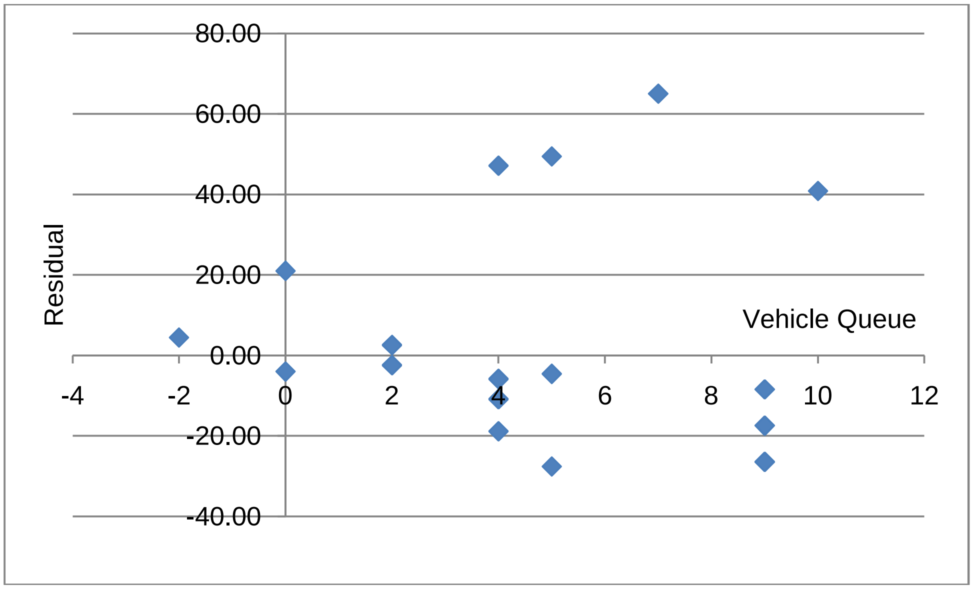


(a)

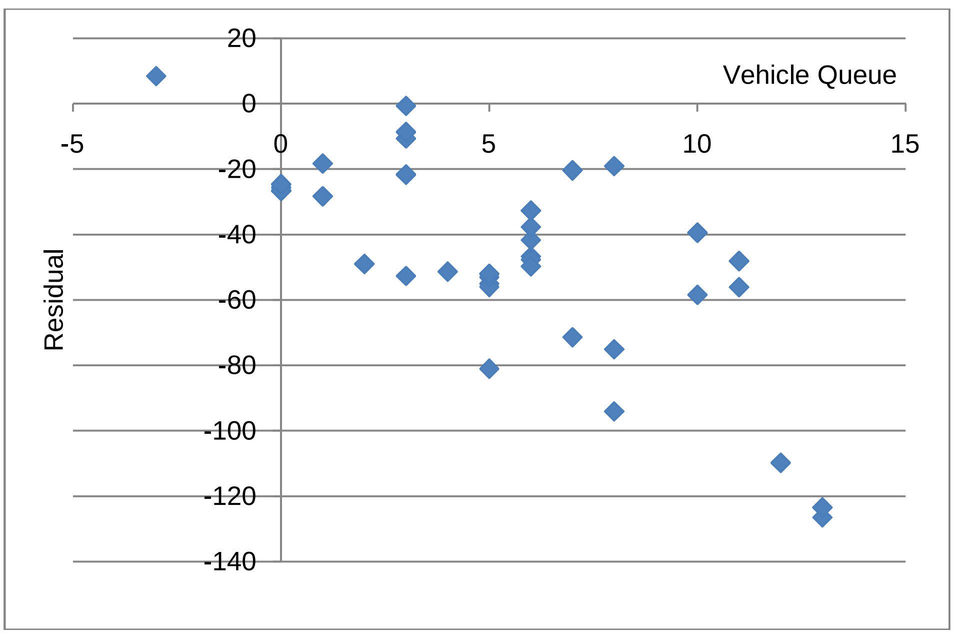


(b)

Figure 4.6 Model #2 Residual versus Predictor Plot (a) AM Peak (b) PM Peak



(a)



(b)

Figure 4.7 Model #3 Residual versus Predictor Plot (a) AM Peak (b) PM Peak

4.8 Interval Estimation for the Response Variable

An interval estimate for the bus queue travel time (response variable) for a value of the vehicle queue (predictor variable) can be stated in terms the corresponding t-statistic and the estimated standard deviation of the predictor variable. The value of the bus queue travel time at the sample mean of the vehicle queue can be stated as follows:

$$\hat{Y}_h \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{\hat{Y}\}$$

Where:

$\hat{Y}_h$ = Value of the response variable corresponding to the sample mean of the predictor variable using the simple linear regression model

$t\left(1-\frac{\alpha}{2}; n-2\right)$ = t-statistic

$s\{\hat{Y}\}$ = Estimated standard deviation of the response variable, which is

$$s\{\hat{Y}\} = \sqrt{MSE\left[\frac{1}{n}+\frac{(X_h-X)^2}{\sum(X_i-X)^2}\right]}$$

Likewise, an interval estimate for the bus queue travel time corresponding to the reduced vehicle queue when the DBL system is activated can be stated in a similar manner. The DBL system is expected to reduce the vehicle queue and the bus queue travel time, assuming different compliance levels from the drivers. The value of the bus queue travel time at a reduced vehicle queue was calculated as follows:

$$Predmean \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{predmean\}$$

Where:

$Predmean$ = Value of the response variable corresponding to the reduced predictor variable

$t\left(1-\frac{\alpha}{2}; n-2\right)$ = t-statistic

$s\{predmean\}$ = Estimated standard deviation of the response variable,

$$s\{predmean\} = \sqrt{MSE\left[\frac{1}{m} + \frac{1}{n} + \frac{(X_h - X)^2}{\sum(X_i - X)^2}\right]}$$

The results of the interval estimate for the bus queue travel time for different driver compliance levels are shown in Table 4.6. The interval estimates worksheet is included in Table B.4 in Appendix B.

Table 4.6 Bus Queue Travel Time Estimation

Driver Compliance	AM Peak Bus Queue Travel Time (seconds)	PM Peak Bus Queue Travel Time (seconds)	Statistical Confidence Level (1-α)
0%	17.0 ± 1.0	32.2 ± 1.9	26%
20%	15.0 ± 1.0	28.8 ± 1.9	26%
40%	13.0 ± 1.8	25.3 ± 3.4	45%
60%	10.9 ± 2.8	21.9 ± 5.2	63%
80%	8.9 ± 4.0	18.4 ± 6.9	77%
100%	6.9 ± 5.3	14.9 ± 8.7	86%

The first row of Table 4.6 shows the existing or “no build” situation, where the bus queue travel times are 17.0 and 32.2 seconds for the morning and afternoon peak hours, respectively. The second row shows that the expected bus queue travel times with the DBL system activated, but with only 20% driver compliance would be 15.0 and 28.8 for the morning and afternoon peak hours, respectively. In order to avoid that the results for the 0% driver compliance interval overlap with the 20% driver compliance interval overlap, the statistical confidence level was lowered to 26%, so that the t-statistic value was smaller. This way, the errors for the morning and afternoon results are only ± 1.0 second and ± 1.9 seconds, respectively. Likewise, the bus queue travel time intervals have been estimated for driver compliance levels of 40%, 60%, 80%, and 100%. The 100% driver compliance level is the highest benefit expected by the DBL system, but it is highly unlikely that this can be achieved even with police enforcement. This maximum benefit would be a bus queue travel time reduction of 10.1 and 17.3 seconds for the morning and afternoon peak hours, respectively. A 60% driver compliance level is considered more practically achievable, which would result in bus queue travel times of 10.9 and 21.9 seconds for the morning and afternoon peak hours, respectively. This would represent a benefit of 6.1 and 10.3 seconds per bus for the morning and afternoon peak hours, respectively. The benefits of the DBL system will be compared to the impact of the DBL system on the passenger cars and trucks in the next chapter.

In conclusion, the analysis shown in this section indicates that a simple linear regression model is appropriate for this data set. However, the driver compliance level required to obtain a higher level of confidence in the reduction of the bus queue travel time due to the DBL system is also relatively high.

CHAPTER 5

DBL IMPACT ON OTHER VEHICLES

This section contains the development of a delay model to assess the impact of the dynamic bus lane (DBL) system on other vehicles at a major signalized intersection. The DBL system would block the right lane to all vehicles, except for the bus and the right-turning vehicles. This task consisted of determining the control delay for the two street approaches of the test section using the procedures for signalized intersections in the Highway Capacity Manual (HCM). The test section was Westheimer, between South Dairy Ashford and Wilcrest, in Houston. The test approaches were the eastbound approach on Westheimer at Wilcrest in the morning peak-hour period, 7-8 am, and the westbound approach on Westheimer at South Dairy Ashford in the afternoon peak hour, 5-6 pm. The peak-hour turning movement counts were collected in 2008. No adjustments were made to the counts, since there has been negligible traffic change in the area in the last three years, as noted in chapter three. The current signal timings were used.

5.1 HCM Delay Model

In order to accurately estimate the impact of the DBL system to other vehicles, the control delay for the two test intersections was calculated for the existing conditions and the proposed conditions with the DBL system activated. Control delay for a lane group at a signalized intersection approach is defined as the sum of the initial deceleration delay, the queue move-up time, the stopped delay, and the final acceleration delay for the vehicles using that intersection approach during the analysis period. The control delay is computed using two equations; one for the uniform delay, and one for the incremental delay. The initial queue delay was taken as zero, since there were no initial queues observed in the field. According to the HCM 2010[1] methodology, the control delay can be computed with the following equations:

$$d = d_1(PF) + d_2 + d_3$$

$$d_1 = \frac{0.5C\left(1 - \frac{g}{C}\right)}{1 - \left[min(1, X)\frac{g}{C}\right]}$$

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}}\right]$$

$$d_3 = 0$$

Where:

d = control delay (secs/veh)

d_1 = uniform delay (secs/veh)

d_2 = incremental delay (secs/veh)

d_3 = initial queue delay (secs/veh)

PF = progression adjustment factor

X = volume to capacity ratio (degree of saturation) for the lane group

C = cycle length (sec)

c = capacity of the lane group (veh/hr)

g = effective green time of lane group (sec)

T = duration of analysis period (hr)

k = incremental delay adjustment for the actuated control

I = incremental delay adjustment for the filtering or metering by upstream signals

The “default” HCM delay model was constructed with the following default parameters. A progression adjustment factor (PF) of 0.767 was used for a favorable progression quality on Westheimer at Wilcrest in the morning peak hour. A progression adjustment factor of 1.000 was used for a random arrival progression on Westheimer at South Dairy Ashford in the afternoon peak hour. The cycle length (C) was 150 seconds, while the analysis period (T) was

15 minutes. The incremental delay adjustment for actuated control (*k*) was taken as 0.5 for a fixed-time operation, since the intersections are saturated and they max out on all of their phases. The incremental delay adjustment for the filtering or metering by upstream signals (*I*) was taken as 0.314 for a 90% degree of saturation at the upstream signals.

For the morning peak-hour analysis at Westheimer at Wilcrest, the eastbound approach volume was 3,868 veh/hr with four lanes and an effective green (*g*) of 94 seconds. This yielded a degree of saturation of 103% for this approach, a uniform delay of 28.0 secs/veh, an incremental delay of 16.3 secs/veh, and a control delay of 37.8 secs/veh. For the afternoon peak-hour analysis at Westheimer at South Dairy Ashford, the westbound approach volume was 2,615 veh/hr with four lanes and an effective green (*g*) of 74 seconds. This yielded a degree of saturation of 84% for this approach, a uniform delay of 32.8 secs/veh, an incremental delay of 0.9 secs/veh, and a control delay of 33.7 secs/veh. The HCM default model worksheet is shown in Table C.1 in Appendix C.

5.2 HCM Delay Model Calibration

In order to calibrate the "default" HCM delay model, the delay field data was used. The weighted approach delay that the vehicle queue in front of the bus experienced at the approach was computed for each case and used to calibrate the HCM model. The control delay for each approach was estimated using the field data collected for the bus queue travel time and the queue length. Since the vehicles in the queue in front of the bus experienced an equal or greater delay than the bus, the control delay was estimated as the average time per vehicle in the queue. Therefore, the control delay was estimated from the field data as the weighted average of the bus queue travel time and the vehicle queue in front of the bus. In this manner, the vehicle control delay was estimated from the field data set as 23.7 secs/veh for the eastbound approach at Westheimer at Wilcrest during the morning peak-hour period, and 63.3 secs/veh for the westbound approach at Westheimer at South Dairy Ashford during the afternoon peak-hour period. The saturation flow rate and the progression factor in the HCM default model were adjusted, so that the HCM model control delay matched the field data results. The degree of saturation for the eastbound approach at Wilcrest in the morning peak hour period remained at 103%, while the degree of saturation for the westbound approach at South Dairy Ashford during the afternoon peak hour increased to 105%. Table 5.1 shows the results of the model calibration analysis. The HCM calibrated model worksheet is included as Table C.2 in Appendix C.

Table 5.1 HCM Delay Model Calibration

Analysis Period and Intersection Approach Direction	Model	Saturation Flow Rate (pcphpl)	Progression Factor	Control Delay (secs/veh)
AM Peak Hour Westheimer at Wilcrest Eastbound Approach	Default	1900	0.767	37.8
	Calibrated	1887	0.263	23.7
PM Peak Hour Westheimer at South Dairy Ashford Westbound Approach	Default	1900	1.000	33.7
	Calibrated	1420	1.000	94.2

5.3 HCM Delay Model Prediction Results

The calibrated HCM model was used to predict the impact of the DBL system on the other vehicles at each of the test intersections. This was done using 3.75 lanes instead 4 lanes for the approach on Westheimer at each intersection to account for the reduced number of lanes when the bus is present during the peak hour. Furthermore, the HCM model was used to assess the impact of the DBL system on streets with different lane geometry. This was accomplished by reducing the traffic volumes on Westheimer proportionately from four lanes to three and two lanes, and keeping all of the other parameters constant. The lane geometry analysis was a theoretical exercise, which in reality may yield larger impacts. Especially in the two-lane geometry case, the DBL system would be taking half of the capacity of the roadway and the impacts should be much greater than those reported here. A car occupancy of 1.2 people and bus occupancy of 40 people were used to compute the total system person-delay impacts. The total system impact results were normalized on a per lane basis to compare the impacts with different lane geometry. Table 5.2 shows the impacts of the DBL system to the other vehicles at the test intersections in seconds per vehicle and person-hours per lane.

Table 5.2 DBL System Impact on Other Vehicles

Analysis Period and Intersection	Delay Units	No Build	DBL System with 4 Lanes	DBL System with 3 Lanes	DBL System with 2 Lanes
AM Peak Hour Westheimer at Wilcrest	secs/veh (LOS)	18.4 (B)	34.5 (C)	39.4 (C)	48.0 (D)
	person-hour/lane	11.3	21.2	26.0	36.0
PM Peak Hour Westheimer at South Dairy Ashford	secs/veh (LOS)	64.9 (E)	76.6 (E)	81.6 (F)	89.0 (F)
	person-hour/lane	36.5	43.0	52.3	71.0

The impact on other vehicles is an increase from 18.4 secs/veh (LOS B) to 34.5 secs/veh (LOS C), which is 16.1 secs/veh, at Wilcrest in the morning peak-hour period, and from 64.9 sec /veh (LOS E) to 76.6 sec /veh (LOS E), which is 11.7 secs/veh, at South Dairy Ashford in the afternoon peak hour. However, the impact on other vehicles is much greater than the benefits of the system in person-hour delay. The benefits are 0.11 person-hours per lane and 0.19 person-hours per lane in the morning and afternoon peak hours, respectively; while the impacts are 9.9 person-hours and 6.5 person-hours per lane in the morning and afternoon peak hours, respectively. Table C.3 in Appendix C contains the calculations used to compute the DBL impact on other vehicles.

The impact on the delay of the other vehicles due to a decrease in number of lanes on Westheimer was that the vehicle delay increased during both peak hours. The intersection delay increased from 34.5 secs/veh with four lanes to 39.4 with three lanes, and to 48.0 secs/veh with two lanes during the morning peak hour. The vehicle delay increased from 76.6 secs/veh with four lanes to 81.6 secs/veh with three lanes, and to 89.0 secs/veh with two lanes.

The total system delay increased from 21.2 person-hours per lane with four lanes to 26.0 person-hours per lane with three lanes, and to 36.0 person-hours per lane with two lanes during the morning peak hour. The total system delay increased from 43.0 person-hours per lane with four lanes to 52.3 person-hours per lane with three lanes, and to 71.0 person-hours per lane with two lanes during the afternoon peak hour. Appendix C contains the spreadsheets used for the control delay calculations for different lane geometries.

To compare the DBL benefits with its impacts, the 60% driver compliance results were used as shown in Table 5.3. This shows that the marginal benefits are less than the impacts, as well as the total system benefits and impacts. This means that it would not be feasible to implement the DBL on Westheimer due to its high level of saturation.

Table 5.3 DBL Benefits and Impacts

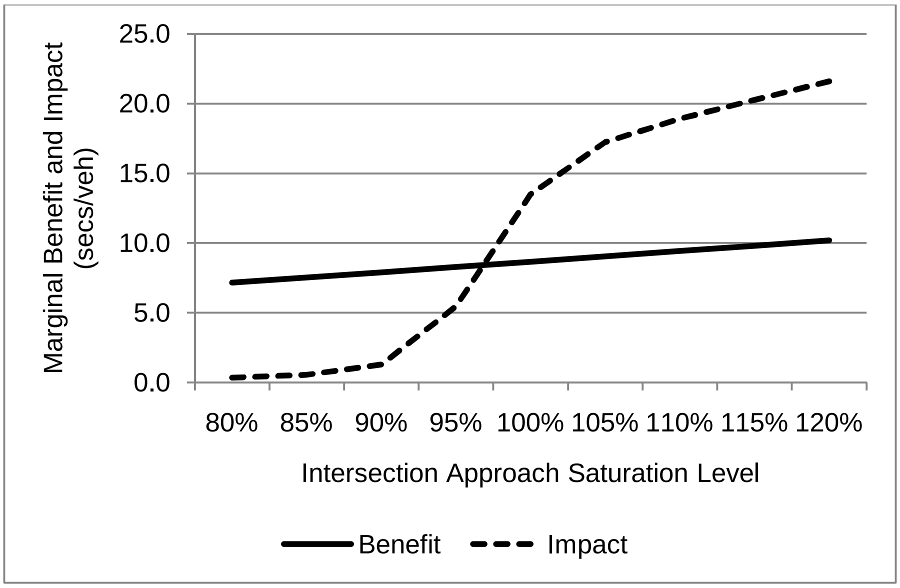
Time Period	Marginal		Total	
	Benefit (secs/bus)	Impact (secs/veh)	Benefit (person-hour)	Impact (person-hour)
AM Peak Hour	6.1	16.1	0.45	39.5
PM Peak Hour	10.3	11.7	0.77	26.2

The impact of the DBL system to bicycles in this test case was nil, since there is not a bike lane on Westheimer. The impact of the DBL system on on-street bikeways is a potential topic for further research. The impact of the DBL system on pedestrians was also nil, since the pedestrians have a sidewalk and cross the street at the signalized intersections on Westheimer.

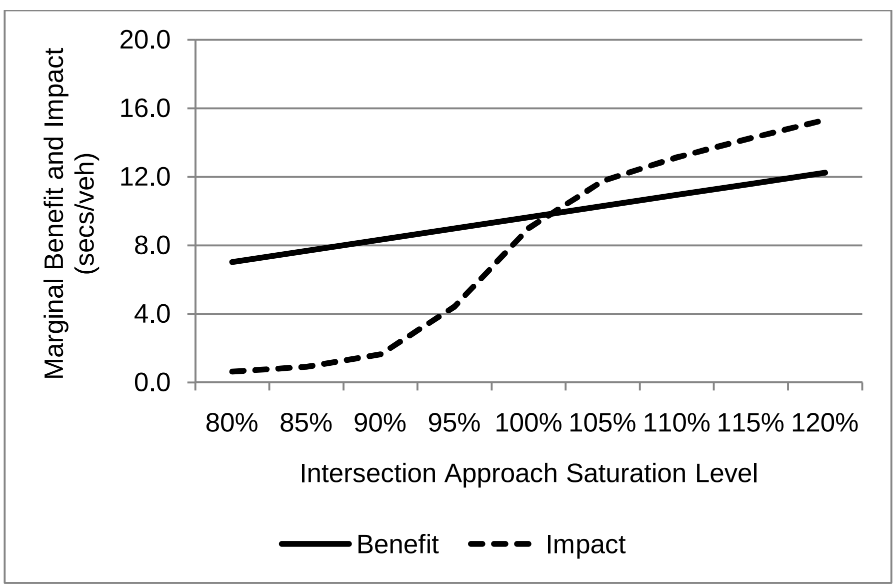
5.4 Sensitivity Analysis

A sensitivity analysis of the DBL benefits was performed to determine at what saturation level the DBL system becomes feasible in terms of marginal benefits and total system benefits. This was accomplished using the DBL linear regression model for the benefits, and the HCM delay model for the impacts on other vehicles for the morning and afternoon peak hour periods.

The intersection approach saturation levels were varied from 80% to 120%, which would include the DBL operating conditions. The DBL benefits were computed for a constant driver compliance level of 60%. The results of the marginal benefits and impacts are shown in Figure 5.1.



(a)



(b)

Figure 5.1 DBL Marginal Benefits and Impacts vs Saturation Level (a) AM Peak (b) PM Peak

The straight lines on Figure 5.1 represent the marginal benefits of the DBL system, which show an increasing trend as the saturation level increases. The "s" curves in these figures represent the DBL impact on other vehicles, which also show an increasing trend as saturation levels increase. Note that the impact curves are steepest between the 90% saturation level and the 105% saturation level, which means that the rate of impact increase is the greatest in this interval. The results indicate that the DBL marginal benefits would outweigh the impacts on other vehicles at or below where the "s" curves intersect the straight lines; the 97% and the 102% saturation levels for the morning and afternoon peak hours, respectively. In general, the DBL system is beneficial up to the 97% saturation level, and the threshold to minimize the impact on other vehicles is the 90% saturation level.

The DBL total system benefits and impacts are shown in Table 5.4. The benefits do not converge with the impacts, even at the 80% saturation level. The frequency of buses would need to increase from four to ten buses per hour for the benefits to be greater or equal than the impacts at the 80% saturation level. The frequency of buses would need to be greater than ten buses per hour for the benefits to be greater than the impacts at higher saturation levels.

Table 5.4 DBL Total System Benefits and Impacts versus Saturation Level

Intersection Approach Saturation Level (%)	DBL Total System Benefits (person-hr)		DBL Total System Impacts (person-hr)	
	AM Peak	PM Peak	AM Peak	PM Peak
80	0.32	0.59	0.8	1.3
85	0.31	0.56	1.3	1.9
90	0.30	0.54	2.9	3.5
95	0.29	0.51	12.9	9.6
100	0.28	0.48	32.7	19.9
105	0.26	0.46	42.8	26.5
110	0.25	0.43	48.3	30.1
115	0.24	0.41	53.1	33.3
120	0.23	0.38	58.0	36.5

5.5 Lane Change Flow Ratio

The HCM 2010 has a new methodology to predict the probability of a lane change maneuver. The probability of a lane change maneuver is the joint probability of having a motivation to change lanes and the opportunity to change the lanes. A variable that is common to these two probability distributions is the ratio of the approach flow rate to maximum flow rate that would allow any lane changes. The maximum flow rate that would allow any lane changes corresponds to headway of 3.7 seconds, or a saturation rate of 973 veh/hr, per the HCM. The existing flow rates on Westheimer at the two test approaches are much higher than the maximum saturation flow rate for lane-changing maneuvers. They are 1,659 veh/hr on the eastbound direction at Wilcrest in the morning peak period, and 1,353 veh/hr on the westbound direction at South Dairy Ashford in the afternoon peak period. This means that it would be very difficult to change lanes when the DBL system is activated. However, as the platoon is released from the upstream major intersection, the platoon disperses and there are more opportunities for lane-changing maneuvers as the distances between major intersections along a corridor increase. It would take a platoon ¾ miles to disperse enough to begin a lane-changing maneuver. The spacing of the major intersections along this corridor is approximately two miles, and typically the coordinated platoon does not stop at the minor intersections. Currently, vehicles that are trapped behind the bus when the bus stops are able to change lanes once the platoon on the adjacent lanes passes through. The distance required to make a lane-changing maneuver is 825 feet according to AASHTO.[16] Therefore, it is required that there is a clear sight distance to the DBL sign of at least this distance. The total distance for the platoon to disperse and a vehicle be able to make the lane-changing maneuver is approximately 9/10th of a mile.

5.6 HCM Transit Level of Service

A transit level of service (LOS) was computed for the test segment on Westheimer Road in the eastbound direction during the morning peak hour and in the westbound direction during the afternoon peak hour. This was performed for the "before" and "after" DBL system conditions using the HCM methodology. The computation of the average bus operating speed contains a term to account for the bus running time losses, which accounts for the bus delay due to traffic signals and other factors when operating on city streets. The bus running time losses have a typical value of 0.5 to 1.0 minutes/mile for exclusive bus lanes, and 0.7 to 1.5 minutes/mile for mixed traffic outside the central business district (CBD). The existing running time losses for the test section are 1.36 and 1.08 minutes/mile for the morning and afternoon peak hours, respectively. The existing test section is a mixed traffic situation and its bus running time losses are within the HCM typical range. The DBL system would lower the bus running time losses to 1.28 and 0.942 minutes/mile for the morning and afternoon peak hours, respectively. This translates to a reduction in bus travel time of 2.7% during the morning peak hour and 5.6% during the afternoon peak hour.

The transit LOS scores for the segment for the "before" conditions were 4.75 and 4.67 for the morning and afternoon peak hours, respectively. These scores correspond to LOS "E," which includes transit scores of 4.25 to 5.00. The transit LOS scores for the segment for the "after" conditions were 3.86 and 3.79 for the morning and afternoon peak hours, respectively. These scores correspond to LOS "D," which includes transit scores of 3.50 to 4.25. The computations for these results are included in Tables D.1, D.2, D.3, and D.4 in Appendix D.

5.7 Generalized DBL System Applications

The field data collection and analysis documented in this dissertation have confirmed previous theoretical research findings, which identified roughly the optimum saturation conditions for the DBL operation. The findings of this research effort have determined that the

DBL system is feasible for saturation levels of less than 97%. In general, the DBL would be ideal for streets with saturation levels of less than 90%, as documented in section 5.4 Sensitivity Analysis and illustrated in Figure 5.1 DBL Marginal Benefits and Impacts versus Saturation Level (a) AM Peak (b) PM Peak of this dissertation. Therefore, based on these findings it was determined that the DBL system was not adequate for the Westheimer corridor, because its saturation level is over 100%.

As an example of two potential applications of the DBL to other corridors in the Houston area, two candidate corridors have been identified as the Bellaire Blvd. and the Gessner Road corridors. METRO has already implemented a signature bus line on Bellaire Blvd, and has plans to implement more signature bus lines on other corridors, such as Gessner Road. The METRO signature line service features peak-hour express bus service on arterial streets with signal transit priority and next-bus information signs at the bus stops. In accordance with the HCM generalized capacity guidelines, and current traffic volume counts from the city of Houston, the existing saturation levels of these two corridors were determined. The Bellaire Blvd. corridor is currently operating at approximately 83% saturation, while the Gessner Road corridor is currently operating at approximately 88% saturation. These two corridors are good candidates for the application of the DBL system, since their current saturation levels are below 90%, as determined in section 5.4 and illustrated in Figure 5.1 of this dissertation. The current levels of saturation on the Bellaire Blvd. and Gessner Road corridors would also allow for some traffic growth before they reach the capacity saturation level in the future.

CHAPTER 6

CONCLUSIONS

In conclusion, the main contributions of this dissertation consist of providing an effective sign design for the implementation of dynamic bus lane system, providing two probabilistic models to estimate the benefits of the system during the morning and afternoon peak hours, and providing the traffic saturation levels when the system should be implemented.

The literature review conducted for the DBL system revealed that the idea for the operation of this system had been around for 15 years, and that there was a demonstration project in Lisbon which showed potential benefits of 20% in reduced bus travel times. A similar system has been in implemented for a tram in Melbourne, Australia, but with savings of 1% and 10% in reduced bus travel times. There has also been research in California which has explored compliance issues with the US Manual on Uniform Traffic Control Devices, and developed formulae to compute the capacity and the benefits of the system, as well as rough domains for the optimum operation of the system. The literature research also found that there is the need to implement such a system in the US and outside the United States as evidenced by projects using bus-only intermittent use of highway shoulders in Minneapolis and Paris; and that the use of intermittent high-occupancy vehicle lanes on arterial streets has been implemented in Seattle. A triple-left turn lane system using the same concept of a large dynamic message has been implemented successfully by the author in Sugar Land, Texas in 2010. The concept for the DBL system has been in a developmental stage for several years, but there is no literature evidence that it has been implemented for permanent operation anywhere in the world yet.

Two simple linear regression models were constructed using the bus queue travel time before it reached the bus stop as the response variable, and the vehicle queue in front of the bus as the predictor variable. One model was developed for the morning peak hour, and another model was developed for the afternoon peak hour. These models predict that the bus travel time would be reduced by 2.7% and 5.6% during the morning and afternoon peak hours, respectively. These results are much lower than those reported elsewhere.

The HCM methodology was used to assess the impact of the DBL system on other vehicles. Generally, the impact was that the DBL would cause the intersection level of service to drop one level. However, the total system impact on other vehicles is much greater than the DBL benefits in terms of person-hour delay. The impacts are larger than the benefits by factors of 50 and 90 in the morning and afternoon peak hours, respectively. The HCM model showed that the impact on the delay of the other vehicles due to a decrease in number of lanes was that the intersection level of service also dropped by one level.

A sensitivity analysis of the saturation levels versus the DBL benefits and impacts showed that the DBL system would perform ideally at or below the 90% saturation level. Also, it was found that because of the high level of traffic saturation on Westheimer, it would be very difficult to change lanes when the DBL system is activated. However, as the platoon is released from the upstream major intersection, the platoon disperses and there will be more opportunities for lane-changing maneuvers as the distances between major intersections along a corridor increase. The spacing between major intersections should be at least $9/10^{th}$ of a mile to allow for lane-changing maneuvers. The transit levels of service were improved for the test section from by one level for both peak hours.

In conclusion, the marginal impacts of the DBL system outweigh the benefits for this test section of Westheimer. The person-hour delay impacts were much greater than the benefits by an order of magnitude. The most significant factor attributable to the high level of impacts on vehicle and person delay is the high level of traffic saturation on this section of Westheimer. Even though the transit level of service would be improved, it is not advisable to implement the DBL system on Westheimer. It is advisable to implement it on other arterial streets with lower saturation levels. The following step-by-step procedure is recommended to determine whether the DBL system is feasible to implement on another arterial street:

1. Select an arterial street where the traffic saturation level is preferably below 90%, and absolutely below 97%
2. Estimate the average vehicle queue in front of the bus stop during the peak hours. Apply a reduction factor to the result to account for driver compliance
3. Estimate the average queue caused by right-turning vehicles during the peak hours, if any
4. Compute the difference between the average vehicle queue and the average right-turn queue.
5. Compute the DBL marginal benefits using the linear regression models presented in this dissertation
6. Compute the DBL marginal impacts using the HCM methodology with the study intersection approach with and without a ¼ traffic lane less than the existing conditions
7. If the marginal benefits are larger than the marginal impacts, then the DBL system is feasible; otherwise, it is not

The safety impacts of the DBL system have not been investigated as part of this research effort, and it is a potential topic for further research. This research effort should consider driveway density, speed, lane-changing maneuvers, driver comprehension, and driver attention factors. The impact of the DBL system on streets with bikeways is another potential topic for further research.

APPENDIX A

TRAVEL TIME DATA

Table A.1 AM Peak Bus Stopped Time (Seconds)

Westheimer, South Dairy Ashford to Wilcrest Eastbound Direction (7:00-9:00 AM) – April 2010							
Bus Stop #	Bus Stop Location	Run Number and Beginning Time					Mean Stopped Time (sec)
		1	2	3	4	5	
		6:55:00 AM	7:13:28 AM	7:36:03 AM	8:00:04 AM	8:27:30 AM	
1	South Dairy Ashford	0	27	46	91	60	44.8
2	Shadow View (No signal)	22	0	17	19	0	11.6
3	Shadow Briar	36	25	61	18	0	28.0
4	Westminster Plaza (No signal)	0	0	0	0	25	5.0
5	Gray Falls/W. Houston Center	21	62	34	0	0	23.4
6	Kirkwood	0	0	89	74	0	32.6
7	Crescent Park	68	0	25	26	0	23.8
8	Woodland Park	20	61	14	0	49	28.8
9	Hayes	17	29	76	14	25	32.2
10	Wilcrest	0	112	27	88	27	50.8
End of Run Time		7:02:28 AM	7:24:23 AM	7:47:15 AM	8:09:25 AM	8:35:17 AM	Total 281
Duration of Run (minutes)		7.47	10.90	11.20	9.35	7.78	9.34

Table A.2 PM Peak Bus Stopped Time (Seconds)

Westheimer, South Dairy Ashford to Wilcrest Westbound Direction (4:30-6:30 PM) – April 2010							
Bus Stop #	Bus Stop Location	Run Number and Beginning Time					Mean Stopped Time (sec)
		1	2	3	4	5	
		4:42:40 PM	5:05:20 PM	5:39:14 PM	5:59:03 PM	6:19:13 PM	
1	Wilcrest	62	56	16	27	34	39.0
2	Hayes	0	23	13	73	56	33.0
3	Woodland Park	17	17	70	18	14	27.2
4	Crescent Park (No signal)	13	17	12	14	16	14.4
5	Kirkwood	86	74	9	0	0	33.8
6	Gray Falls/W. Houston Center	0	21	21	80	13	27.0
7	Westminster Plaza (No signal)	15	20	0	0	0	7.0
8	Shadow Briar	8	0	51	14	0	14.6
9	Shadow View (No signal)	0	0	0	12	0	2.4
10	South Dairy Ashford	101	110	149	144	184	137.6
End of Run Time		4:52:23 PM	5:15:30 PM	5:49:52 PM	6:10:01 PM	18:28:09 AM	Total 336
Duration of Run (minutes)		9.72	10.20	10.60	11.00	8.93	10.09

Table A.3 AM Peak Passenger Car Stopped Time (Seconds)

Westheimer, South Dairy Ashford to Wilcrest Eastbound Direction (7:00-9:00 AM) – April 2010											
Int. #	Intersection Name	Run Number and Beginning Time									Mean Stopped Time (sec)
		1	2	3	4	5	6	7	8	9	
		7:00:18 AM	7:09:19 AM	7:19:30 AM	7:34:24 AM	7:54:44 AM	8:12:08 AM	8:23:04 AM	8:39:35 AM	8:49:32 AM	
1	South Dairy Ashford	0	55	49	58	57	50	56	50	54	47.7
3	Shadow Briar	0	0	0	0	0	0	0	0	0	0.0
5	Gray Falls	0	0	0	78	48	141	0	0	0	29.7
6	Kirkwood	0	0	17	136	0	0	0	0	0	17.0
7	Crescent Park	0	0	0	88	0	0	0	0	0	9.8
8	Woodland Park	0	0	95	79	0	0	0	0	0	19.3
9	Hayes	0	0	75	152	63	0	0	0	0	32.2
10	Wilcrest	0	0	0	0	0	0	0	0	0	0.0
End of Run Time		7:03:41 AM	7:14:05 AM	7:27:07 AM	7:46:57 AM	8:04:03 AM	8:19:30 AM	8:31:58 AM	8:44:04 AM	8:53:47 AM	
Duration of Run (minutes)		3.38	4.77	7.62	12.60	9.32	7.37	4.90	4.48	4.25	Mean 6.52

Table A.4 PM Peak Passenger Car Stopped Time (Seconds)

Westheimer, South Dairy Ashford to Wilcrest Westbound Direction (4:30-6:30 PM) – April 2010									
Int. #	Intersection Name	Run Number and Beginning Time							Mean Stopped Time (sec)
		1	2	3	4	5	6	7	
		4:49:30 PM	5:01:53 PM	5:12:21 PM	5:31:53 PM	5:49:15 PM	6:04:21 PM	6:19:15 PM	
1	Wilcrest	42	48	0	62	60	53	46	44.4
3	Hayes	0	0	0	0	0	0	0	0.0
5	Woodland Park	0	0	0	0	0	0	0	0.0
6	Crescent Park	0	0	0	0	0	0	0	0.0
7	Kirkwood	0	0	0	0	21	0	0	3.0
8	Gray Falls	0	0	0	0	0	0	0	0.0
9	Shadow Briar	0	0	0	0	0	0	0	0.0
10	South Dairy Ashford	38	52	165	152	183	159	129	125.4
End of Run Time		4:54:25 PM	5:07:13 PM	5:21:40 PM	5:39:20 PM	5:56:59 PM	6:11:30 PM	6:26:21 PM	
Duration of Run (minutes)		4.92	5.33	6.32	7.45	7.73	7.15	7.10	Mean 6.57

APPENDIX B

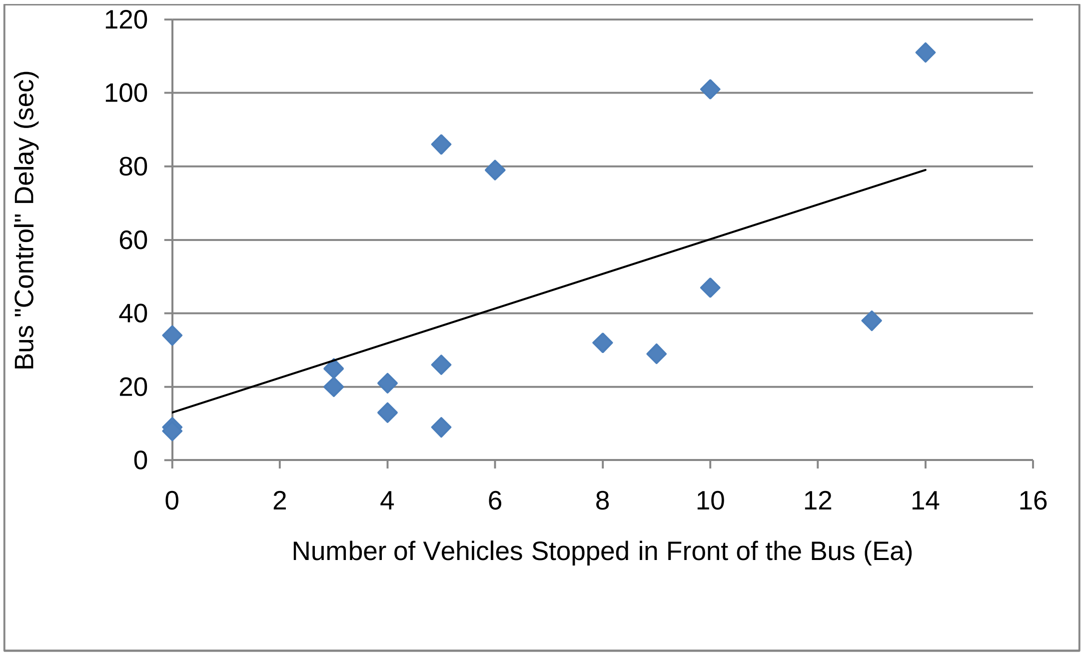
STATISTICAL ANALYSIS DATA

Table B.1 Variable Frequency Distribution Data

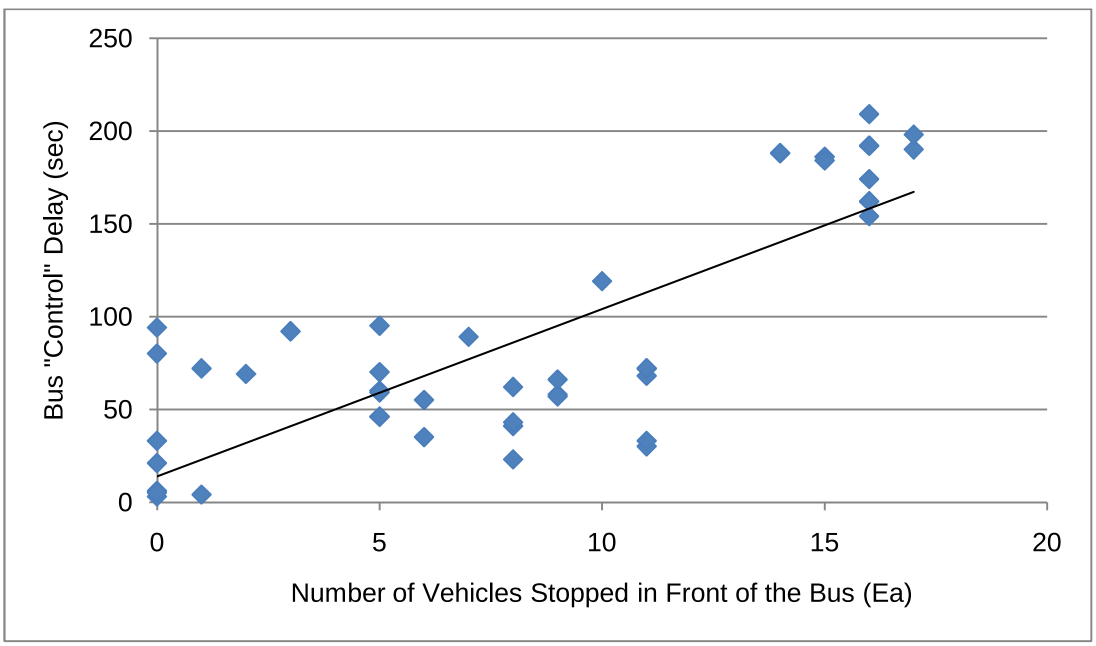
AM Peak				
Bus Delay Bins *Yi*	Frequency		Vehicle Queue Bins *Xi*	Frequency
0	3		0	3
10	2		2	0
20	3		4	4
30	7		6	4
40	2		8	1
50	0		10	3
			12	0
			14	2
			16	0
Chi Square Test =	0.08615		Chi Square Test =	0.12624
Chi Square =	0.584		Chi Square =	2.204
PM Peak				
Bus Delay Bins *Yi*	Frequency		Vehicle Queue Bins *Xi*	Frequency
0	7		0	9
20	8		4	4
40	11		8	13
60	17		12	13
80	5		16	14
100	5		20	5
120	5		24	0
140	0		28	0
Chi Square Test =	0.00497		Chi Square Test =	0.0195
Chi Square =	2.20413		Chi Square =	1.6103

Table B.2 Variable Relationship Tests

Regression Slope	Residual Mean Sum of Squares MSE	Predictor Variance $\sum(X_i - X)^2$	Slope t-Statistic	t-Statistic for 90% Confidence	Is slope t greater or equal than t for 90% confidence?
AM Peak Hour Model					
2.24	49.3	307	1.75	1.75	Yes
PM Peak Hour Model					
4.95	275	5,588	22.3	1.67	Yes

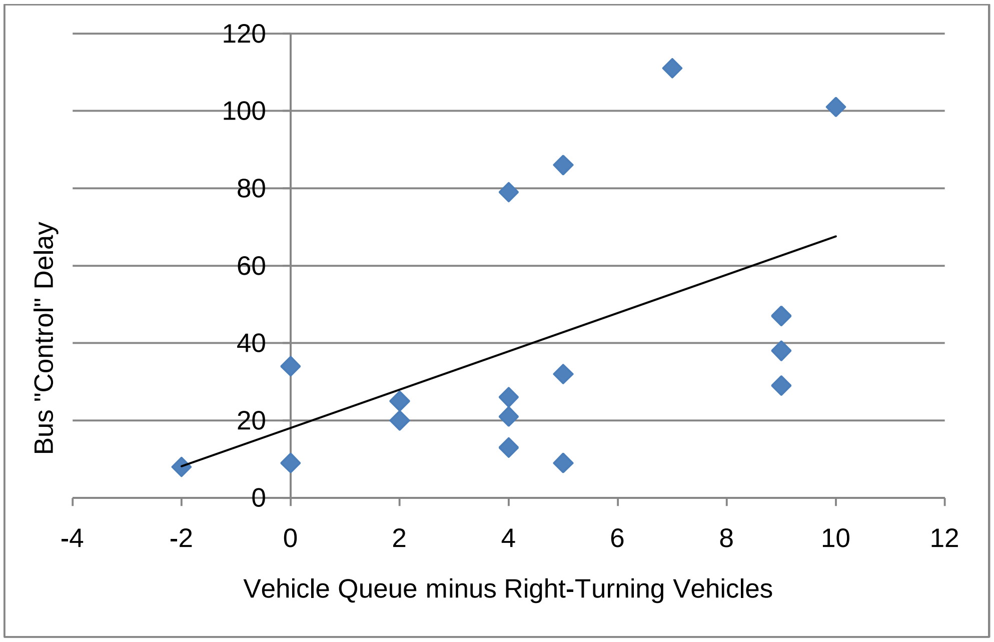


(a)

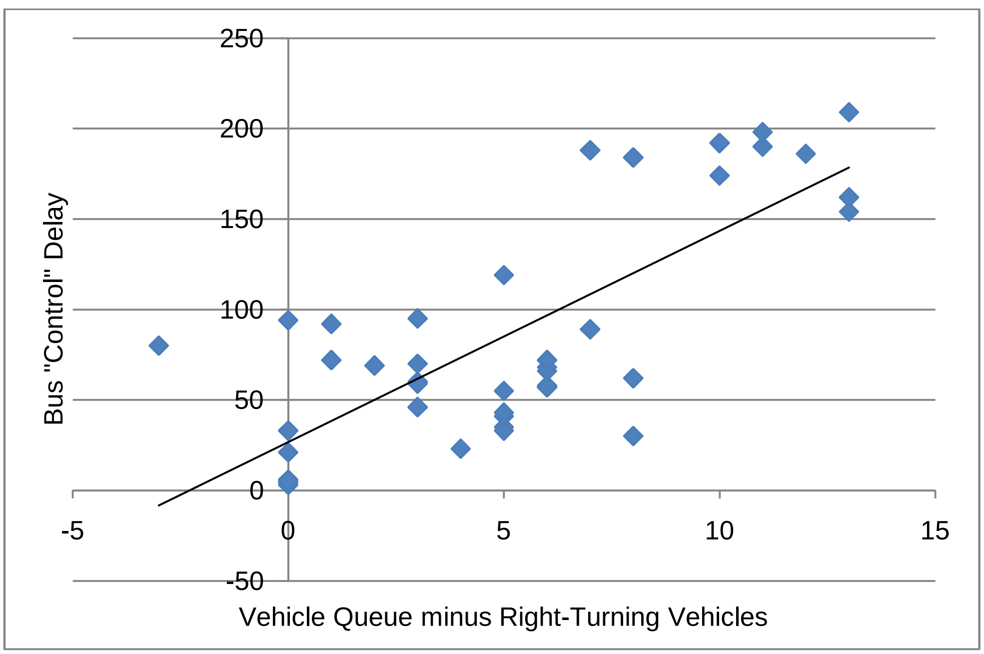


(b)

Figure B.1 Simple Linear Regression Model #2 (a) AM Peak (b) PM Peak



(a)



(b)

Figure B.2 Simple Linear Regression Model #3 (a) AM Peak (b) PM Peak

Table B.3 Interval Estimation for the Bus Queue Travel Time

Time Period	Compliance Level	Confidence Level	Vehicle Queue	Predicted Bus Queue Travel Time (sec)	Student Statistic	Standard Deviation of Predicted Bus Queue Travel Time (sec)	Predicted Bus Queue Travel Time Error (sec)	Predicted Bus Queue Travel Time Lower Bound (sec)	Predicted Bus Queue Travel Time Upper Bound (sec)
AM Peak	0%	86.30%	5.80	17.0	1.571	2.87	4.50	12.5	21.5
PM Peak			6.10	32.2	1.510	5.72	8.64	23.6	40.9
AM Peak	100%	86.30%	1.30	6.9	1.571	3.39	5.32	1.6	12.2
PM Peak			2.60	14.9	1.510	5.77	8.72	6.2	23.6
AM Peak	0%	76.70%	5.80	17.0	1.243	2.87	3.56	13.4	20.6
PM Peak			6.10	32.2	1.206	5.72	6.90	25.3	39.1
AM Peak	80%	76.70%	2.20	8.9	1.243	3.21	3.99	4.9	12.9
PM Peak			3.30	18.4	1.206	5.75	6.94	11.4	25.3
AM Peak	0%	63.20%	5.80	17.0	0.928	2.87	2.66	14.3	19.7
PM Peak			6.10	32.2	0.908	5.72	5.19	27.1	37.4
AM Peak	60%	63.20%	3.10	10.9	0.928	3.06	2.84	8.1	13.8
PM Peak			4.00	21.9	0.908	5.74	5.21	16.6	27.1
AM Peak	0%	45.00%	5.80	17.0	0.612	2.87	1.75	15.2	18.7
PM Peak			6.10	32.2	0.602	5.72	3.44	28.8	35.7
AM Peak	40%	45.00%	4.00	13.0	0.612	2.96	1.81	11.2	14.8
PM Peak			4.70	25.3	0.602	5.73	3.45	21.9	28.8
AM Peak	0%	26.00%	5.80	17.0	0.338	2.87	0.97	16.0	18.0
PM Peak			6.10	32.2	0.334	5.72	1.91	30.3	34.2
AM Peak	20%	26.00%	4.90	15.0	0.338	2.89	0.98	14.0	16.0
PM Peak			5.40	28.8	0.334	5.72	1.91	26.9	30.7

APPENDIX C

CAPACITY ANALYSIS DATA

Table C.1 HCM Default Model

Wilcrest AM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	*person-hr*
EB	3868	4,159	4	1	6460	94	150	0.627	4,048	1.027	1.000	28.0	16.3	37.8	157,064	
EB LT	112	120	1	0.95	1534	24	150	0.160	245	0.491	0.491	57.4	2.2	53.6	6,454	
WB	1469	1,580	4	1	6460	84	150	0.560	3,618	0.437	0.437	19.2	0.1	19.3	30,550	
WB LT	110	118	1	0.95	1534	14	150	0.093	143	0.826	0.826	66.8	15.6	82.4	9,749	
NB	396	426	2	1	3230	24	150	0.160	517	0.824	0.824	61.0	4.8	65.8	28,009	
NB LT	137	147	2	0.95	3069	24	150	0.160	491	0.300	0.300	55.6	0.5	56.1	8,261	
SB	456	490	2	1	3230	34	150	0.227	732	0.670	0.670	52.9	1.5	54.4	26,688	
SB LT	304	327	2	0.95	3069	34	150	0.227	696	0.470	0.470	50.2	0.7	50.9	16,645	
TOTALS		7,368													283,421	94.5
d_i =	38.5	secs/veh														
S. Dairy Ashford PM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	
EB	1229	1,254	4	1	6460	64	150	0.427	2,756	0.455	0.455	30.6	0.2	23.6	29,641	
EB LT	235	240	1	0.95	1534	24	150	0.160	245	0.977	0.977	62.7	27.0	83.2	19,943	
WB	2615	2,668	4	1	6460	74	150	0.493	3,187	0.837	0.837	32.8	0.9	33.7	89,936	
WB LT	207	211	1	0.95	1534	34	150	0.227	348	0.607	0.607	52.0	2.5	54.5	11,510	
NB	656	669	3	1	4845	34	150	0.227	1,098	0.610	0.610	52.0	0.8	52.8	35,373	
NB LT	153	156	1	0.95	1534	24	150	0.160	245	0.636	0.636	58.9	3.9	62.8	9,811	
SB	1200	1,224	3	1	4845	44	150	0.293	1,421	0.862	0.862	50.1	2.4	52.5	64,291	
SB LT	318	324	1	0.95	1534	44	150	0.293	450	0.721	0.721	47.5	3.2	50.7	16,440	
TOTALS		6,748													276,945	92.3
d_i =	41.0	secs/veh														

Table C.2 HCM Model Calibration

Wilcrest AM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	*person-hr*
EB	3868	4,159	4	1	6460	94	150	0.627	4,048	1.027	1.000	28.0	16.3	23.7	98,370	32.8
EB LT	112	120	1	0.95	1534	24	150	0.160	245	0.491	0.491	57.4	2.2	17.3	2,083	
WB	1469	1,580	4	1	6460	84	150	0.560	3,618	0.437	0.437	19.2	0.1	5.2	8,175	
WB LT	110	118	1	0.95	1534	14	150	0.093	143	0.826	0.826	66.8	15.6	33.2	3,926	
NB	396	426	2	1	3230	24	150	0.160	517	0.824	0.824	61.0	4.8	20.9	8,880	
NB LT	137	147	2	0.95	3069	24	150	0.160	491	0.300	0.300	55.6	0.5	15.1	2,226	
SB	456	490	2	1	3230	34	150	0.227	732	0.670	0.670	52.9	1.5	15.5	7,579	
SB LT	304	327	2	0.95	3069	34	150	0.227	696	0.470	0.470	50.2	0.7	13.9	4,551	
TOTALS		7,368													135,791	45.3
d_i =	18.4	secs/veh														
S. Dairy Ashford PM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	
EB	1229	1,254	4	1	5165	64	150	0.427	2,204	0.569	0.569	32.6	0.3	25.3	31,741	
EB LT	235	240	1	0.95	1227	24	150	0.160	196	1.222	1.000	63.0	113.7	170.1	40,780	
WB	2615	2,668	4	1	5165	74	150	0.493	2,548	1.047	1.000	38.0	25.3	63.3	168,996	56.3
WB LT	207	211	1	0.95	1227	34	150	0.227	278	0.760	0.760	54.2	6.1	60.3	12,729	
NB	656	669	3	1	3874	34	150	0.227	878	0.762	0.762	54.2	2.0	56.2	37,652	
NB LT	153	156	1	0.95	1227	24	150	0.160	196	0.795	0.795	60.6	10.1	70.7	11,042	
SB	1200	1,224	3	1	3874	44	150	0.293	1,136	1.078	1.000	53.0	40.8	93.8	114,854	
SB LT	318	324	1	0.95	1227	44	150	0.293	360	0.902	0.902	50.9	11.4	62.4	20,238	
TOTALS		6,748													438,031	146.0
d_i =	64.9	secs/veh														

Table C.3 DBL Impact on Other Vehicles

Wilcrest AM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	*person-hr*
EB	3868	4,159	3.75	1	6056	94	150	0.627	3,795	1.096	1.000	28.0	44.8	52.1	216,899	72.3
EB LT	112	120	1	0.95	1534	24	150	0.160	245	0.491	0.491	57.4	2.2	17.3	2,083	
WB	1469	1,580	4	1	6460	84	150	0.560	3,618	0.437	0.437	19.2	0.1	5.2	8,175	
WB LT	110	118	1	0.95	1534	14	150	0.093	143	0.826	0.826	66.8	15.6	33.2	3,926	
NB	396	426	2	1	3230	24	150	0.160	517	0.824	0.824	61.0	4.8	20.9	8,880	
NB LT	137	147	2	0.95	3069	24	150	0.160	491	0.300	0.300	55.6	0.5	15.1	2,226	
SB	456	490	2	1	3230	34	150	0.227	732	0.670	0.670	52.9	1.5	15.5	7,579	
SB LT	304	327	2	0.95	3069	34	150	0.227	696	0.470	0.470	50.2	0.7	13.9	4,551	
TOTALS		7,368													254,320	84.8
d_i =	34.5	secs/veh														
S. Dairy Ashford PM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	
EB	1229	1,254	4	1	5165	64	150	0.427	2,204	0.569	0.569	32.6	0.3	25.3	31,741	
EB LT	235	240	1	0.95	1227	24	150	0.160	196	1.222	1.000	63.0	113.7	170.1	40,780	
WB	2615	2,668	3.75	1	4843	74	150	0.493	2,389	1.117	1.000	38.0	54.8	92.8	247,603	82.5
WB LT	207	211	1	0.95	1227	34	150	0.227	278	0.760	0.760	54.2	6.1	60.3	12,729	
NB	656	669	3	1	3874	34	150	0.227	878	0.762	0.762	54.2	2.0	56.2	37,652	
NB LT	153	156	1	0.95	1227	24	150	0.160	196	0.795	0.795	60.6	10.1	70.7	11,042	
SB	1200	1,224	3	1	3874	44	150	0.293	1,136	1.078	1.000	53.0	40.8	93.8	114,854	
SB LT	318	324	1	0.95	1227	44	150	0.293	360	0.902	0.902	50.9	11.4	62.4	20,238	
TOTALS		6,748													516,638	172.2
d_i =	76.6	secs/veh														

Table C.4 DBL Impact on Other Vehicles with Three Lane Approaches on Westheimer

Wilcrest AM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	*person-hr*
EB	2901	3,119	2.75	1	4441	94	150	0.627	2,783	1.121	1.000	28.0	56.2	63.5	198,208	66.1
EB LT	112	120	1	0.95	1534	24	150	0.160	245	0.491	0.491	57.4	2.2	17.3	2,083	
WB	1102	1,185	3	1	4845	84	150	0.560	2,713	0.437	0.437	19.2	0.2	5.2	6,179	
WB LT	110	118	1	0.95	1534	14	150	0.093	143	0.826	0.826	66.8	15.6	33.2	3,926	
NB	396	426	2	1	3230	24	150	0.160	517	0.824	0.824	61.0	4.8	20.9	8,880	
NB LT	137	147	2	0.95	3069	24	150	0.160	491	0.300	0.300	55.6	0.5	15.1	2,226	
SB	456	490	2	1	3230	34	150	0.227	732	0.670	0.670	52.9	1.5	15.5	7,579	
SB LT	304	327	2	0.95	3069	34	150	0.227	696	0.470	0.470	50.2	0.7	13.9	4,551	
TOTALS		5,933													233,632	77.9
d_i =	39.4	secs/veh														
S. Dairy Ashford PM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	
EB	922	941	3	1	3874	64	150	0.427	1,653	0.569	0.569	32.6	0.5	25.4	23,911	
EB LT	235	240	1	0.95	1227	24	150	0.160	196	1.222	1.000	63.0	113.7	170.1	40,780	
WB	1961	2,001	2.75	1	3551	74	150	0.493	1,752	1.142	1.000	38.0	66.5	104.5	209,208	69.7
WB LT	207	211	1	0.95	1227	34	150	0.227	278	0.760	0.760	54.2	6.1	60.3	12,729	
NB	656	669	3	1	3874	34	150	0.227	878	0.762	0.762	54.2	2.0	56.2	37,652	
NB LT	153	156	1	0.95	1227	24	150	0.160	196	0.795	0.795	60.6	10.1	70.7	11,042	
SB	1200	1,224	3	1	3874	44	150	0.293	1,136	1.078	1.000	53.0	40.8	93.8	114,854	
SB LT	318	324	1	0.95	1227	44	150	0.293	360	0.902	0.902	50.9	11.4	62.4	20,238	
TOTALS		5,767													470,413	156.8
d_i =	81.6	secs/veh														

Table C.5 DBL Impact on Other Vehicles with Two Lane Approaches on Westheimer

Wilcrest AM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	*person-hr*
EB	1934	2,080	1.75	1	2826	94	150	0.627	1,771	1.174	1.000	28.0	80.5	87.8	182,649	60.9
EB LT	112	120	1	0.95	1534	24	150	0.160	245	0.491	0.491	57.4	2.2	17.3	2,083	
WB	734.5	790	2	1	3230	84	150	0.560	1,809	0.437	0.437	19.2	0.2	5.3	4,183	
WB LT	110	118	1	0.95	1534	14	150	0.093	143	0.826	0.826	66.8	15.6	33.2	3,926	
NB	396	426	2	1	3230	24	150	0.160	517	0.824	0.824	61.0	4.8	20.9	8,880	
NB LT	137	147	2	0.95	3069	24	150	0.160	491	0.300	0.300	55.6	0.5	15.1	2,226	
SB	456	490	2	1	3230	34	150	0.227	732	0.670	0.670	52.9	1.5	15.5	7,579	
SB LT	304	327	2	0.95	3069	34	150	0.227	696	0.470	0.470	50.2	0.7	13.9	4,551	
TOTALS		4,498													216,078	72.0
d_i =	48.0	secs/veh														
S. Dairy Ashford PM																
Direction	*V*	*v*	*N*	f_{LT}	*s*	*g*	*C*	*g/C*	*c*	*X*	*min(X,1.0)*	*d1*	*d2*	*d*	*dv*	
EB	614.5	627	2	1	2583	64	150	0.427	1,102	0.569	0.569	32.6	0.7	25.6	16,082	
EB LT	235	240	1	0.95	1227	24	150	0.160	196	1.222	1.000	63.0	113.7	170.1	40,780	
WB	1308	1,334	1.75	1	2260	74	150	0.493	1,115	1.197	1.000	38.0	91.5	129.5	172,786	57.6
WB LT	207	211	1	0.95	1227	34	150	0.227	278	0.760	0.760	54.2	6.1	60.3	12,729	
NB	656	669	3	1	3874	34	150	0.227	878	0.762	0.762	54.2	2.0	56.2	37,652	
NB LT	153	156	1	0.95	1227	24	150	0.160	196	0.795	0.795	60.6	10.1	70.7	11,042	
SB	1200	1,224	3	1	3874	44	150	0.293	1,136	1.078	1.000	53.0	40.8	93.8	114,854	
SB LT	318	324	1	0.95	1227	44	150	0.293	360	0.902	0.902	50.9	11.4	62.4	20,238	
TOTALS		4,787													426,162	142.1
d_i =	89.0	secs/veh														

APPENDIX D

TRANSIT ANALYSIS DATA

Table D.1 AM Peak “Before” Transit Level of Service

“Before” DBL System Conditions Eastbound Direction (7:00-8:00 am)

Step 1.Compute transit vehicle running time[1]

$$S_{Rt} = \min\left(S_R, \frac{61}{1+e^{-1.00+\left(\frac{1185N_{ts}}{L}\right)}}\right) = \min\left\{\frac{11{,}100}{6.52} x \frac{60}{5280}, \frac{61}{1+e^{-1.00+\left[\frac{1185(10)}{11{,}100}\right]}}\right\} = \min(19.2, 29.5)$$

$$= 19.3 \text{ mph}$$

Step 2.Determine delay at intersections

$$\sum d_{ts} = 281\ sec$$

$$t_{Rt} = \frac{3{,}600L}{5{,}280 S_{Rt}} + \sum d_{ts} = (6.52x60) + 281 = 672\ sec$$

$$d_t = t_l 60\left(\frac{L}{5{,}280}\right) = \left(\frac{281 - 11x10}{60x2.1}\right)(60)\left(\frac{11{,}100}{5{,}280}\right) = 1.36(60)\left(\frac{11{,}100}{5{,}280}\right) = 171\ sec/veh$$

Step 3.Determine travel speed

$$S_{Tt,seg} = \frac{3{,}600L}{5{,}280(t_{Rt} + d_t)} = \frac{3{,}600(11{,}100)}{5{,}280(672 + 171)} = 8.98\ mph$$

Step 4.Determine transit wait-ride score

$$T_{Ptt} = \left(a_1 \frac{60}{S_{Tt,seg}}\right) + 2T_{ex} - T_{at} = 1.00\left(\frac{60}{8.98}\right) + 2(3) - \frac{1.3(1.0)}{10} = 12.55 \frac{min}{mi}$$

$$F_{tt} = \frac{(e-1)T_{btt} - (e+1)T_{Ptt}}{(e-1)T_{Ptt} - (e+1)T_{btt}} = \frac{(-0.4-1)(4.0) - (-0.4+1)(12.55)}{(-0.4-1)(12.55) - (-0.4+1)(4.0)} = 0.447$$

$$F_h = 4.00e^{-1.434/(v_s+0.001)} = 4.00e^{-1.434/(4+0.001)} = 2.8$$

$$S_{w-r} = F_h F_{tt} = 2.8(0.447) = 1.25$$

[1] Methodology and variables are defined in the HCM 2010 (Reference #1)

Table D.1 - *Continued*

Step 5.Determine pedestrian LOS score for link

$$F_w = -1.2276 \ln\left(W_v + 0.5W_1 + 50p_{pk} + W_{b_uR}f_b + W_{aR}f_{sw}\right)$$

$$= -1.2276 \ln[5 + 0.5(0) + 50(0) + 5(6 - 0.5x5)] = -4.2$$

$$F_v = 0.0091 \frac{v_m}{4N_{th}} = 0.0091 \frac{3{,}980}{4(4)} = 2.26$$

$$F_s = 4\left(\frac{S_R}{100}\right)^2 = 4\left[\frac{\frac{3{,}600x11{,}100}{5{,}280x672}}{100}\right]^2 = 0.0507$$

$$I_{p,link} = 6.0468 + F_w + F_v + F_s = 6.0468 - 4.2 + 2.26 + 0.0507 = 4.16$$

Step 6.Determine transit LOS score for segment

$$I_{t,seg} = 6.0 - 1.50S_{w-r} + 0.15I_{p,link} = 6.0 - 1.50(1.25) + 0.15(4.16) = 4.75$$

Step 7.Determine LOS

LOS = “E”

Table D.2 PM Peak “Before” Transit Level of Service

“Before” DBL System Conditions Westbound Direction (5:00-6:00 pm)

Step 1.Determine transit vehicle running time

$$S_{Rt} = \min\left(S_R, \frac{61}{1+e^{-1.00+\left(\frac{1185N_{ts}}{L}\right)}}\right) = \min\left\{\frac{11{,}100}{6.57} x \frac{60}{5280}, \frac{61}{1+e^{-1.00+\left[\frac{1185(10)}{11{,}100}\right]}}\right\} = \min(19.2{,}29.5)$$

$$= 19.2 \text{ mph}$$

Step 2.Determine delay at intersections

$$\sum d_{ts} = 336\ sec$$

$$t_{Rt} = \frac{3{,}600L}{5{,}280S_{Rt}} + \sum d_{ts} = (6.57x60) + 336 = 730\ sec$$

$$d_t = t_l 60\left(\frac{L}{5{,}280}\right) = \left(\frac{336 - 20x10}{60x2.1}\right)(60)\left(\frac{11{,}100}{5{,}280}\right) = 1.08(60)\left(\frac{11{,}100}{5{,}280}\right) = 136\ sec/veh$$

Step 3.Determine travel speed

$$S_{Tt,seg} = \frac{3{,}600L}{5{,}280(t_{Rt}+d_t)} = \frac{3{,}600(11{,}100)}{5{,}280(730+136)} = 8.74\ mph$$

Step 4.Determine transit wait-ride score

$$T_{Ptt} = \left(a_1 \frac{60}{S_{Tt,seg}}\right) + 2T_{ex} - T_{at} = 1.00\left(\frac{60}{8.74}\right) + 2(3) - \frac{1.3(1.0)}{10} = 12.73\frac{min}{mi}$$

$$F_{tt} = \frac{(e-1)T_{btt} - (e+1)T_{Ptt}}{(e-1)T_{Ptt} - (e+1)T_{btt}} = \frac{(-0.4-1)(4.0) - (-0.4+1)(12.73)}{(-0.4-1)(12.73) - (-0.4+1)(4.0)} = 0.447$$

$$F_h = 4.00e^{-1.434/(v_s+0.001)} = 4.00e^{-1.434/(4+0.001)} = 2.8$$

$$S_{w-r} = F_h F_{tt} = 2.8(0.447) = 1.25$$

Table D.2 - *Continued*

Step 5.Determine pedestrian LOS score for link

$$F_w = -1.2276\ln\left(W_v + 0.5W_1 + 50p_{pk} + W_{b_uR}f_b + W_{aR}f_{sw}\right)$$

$$= -1.2276\ln[5 + 0.5(0) + 50(0) + 5(6 - 0.5x5)] = -4.2$$

$$F_v = 0.0091\frac{v_m}{4N_{th}} = 0.0091\frac{2{,}822}{4(4)} = 1.76$$

$$F_s = 4\left(\frac{S_R}{100}\right)^2 = 4\left[\frac{\frac{3{,}600x11{,}100}{5{,}280x730}}{100}\right]^2 = 0.043$$

$$I_{p,link} = 6.0468 + F_w + F_v + F_s = 6.0468 - 4.2 + 1.76 + 0.043 = 3.65$$

Step 6.Determine transit LOS score for segment

$$I_{t,seg} = 6.0 - 1.50S_{w-r} + 0.15I_{p,link} = 6.0 - 1.50(1.25) + 0.15(3.65) = 4.67$$

Step 7.Determine LOS

LOS = “E”

Table D.3 AM Peak “After” Transit Level of Service

“After” DBL System Conditions Eastbound Direction (7:00-8:00 am)

Step 1.Determine transit vehicle running time

$$S_{Rt} = \min\left(\mathrm{S_R}, \frac{61}{1+\mathrm{e}^{-1.00+\left(\frac{1185\mathrm{N_{ts}}}{\mathrm{L}}\right)}}\right) = \min\left\{\frac{11{,}100}{6.52}\mathrm{x}\frac{60}{5280}, \frac{61}{1+\mathrm{e}^{-1.00+\left[\frac{1185(10)}{11{,}100}\right]}}\right\} = \min(19.2{,}29.5)$$

$$= 19.3\ \mathrm{mph}$$

Step 2.Determine delay at intersections

$$\sum d_{ts} = 281\ sec$$

$$t_{Rt} = \frac{3{,}600L}{5{,}280S_{Rt}} + \sum d_{ts} = (6.52x60) + 281 = 672\ sec$$

$$d_t = t_l 60\left(\frac{L}{5{,}280}\right) = \left(\frac{281 - 10.1 - 11x10}{60x2.1}\right)(60)\left(\frac{11{,}100}{5{,}280}\right) = 1.28(60)\left(\frac{11{,}100}{5{,}280}\right) = 161\ sec/veh$$

Step 3.Determine travel speed

$$S_{Tt,seg} = \frac{3{,}600L}{5{,}280(t_{Rt} + d_t)} = \frac{3{,}600(11{,}100)}{5{,}280(672 + 161)} = 9.44\ mph$$

Step 4.Determine transit wait-ride score

$$T_{Ptt} = \left(a_1\frac{60}{S_{Tt,seg}}\right) + 2T_{ex} - T_{at} = 1.00\left(\frac{60}{9.085}\right) + 2(3) - \frac{1.3(1.0)}{10} = 12.47\frac{min}{mi}$$

$$F_{tt} = \frac{(e-1)T_{btt} - (e+1)T_{Ptt}}{(e-1)T_{Ptt} - (e+1)T_{btt}} = \frac{(-0.4-1)(4.0) - (-0.4+1)(12.47)}{(-0.4-1)(12.47) - (-0.4+1)(4.0)} = 0.659$$

$$F_h = 4.00e^{-1.434/(v_s+0.001)} = 4.00e^{-1.434/(4+0.001)} = 2.8$$

$$S_{w-r} = F_h F_{tt} = 2.8(0.659) = 1.84$$

Table D.3 - *Continued*

Step 5.Determine pedestrian LOS score for link

$F_w = -1.2276 \ln\left(W_v + 0.5W_1 + 50p_{pk} + W_{b_uR}f_b + W_{aR}f_{sw}\right)$

$$= -1.2276 \ln[5 + 0.5(0) + 50(0) + 5(6 - 0.5x5)] = -4.2$$

$F_v = 0.0091 \frac{v_m}{4N_{th}} = 0.0091 \frac{3,980}{4(4)} = 2.26$

$F_s = 4\left(\frac{S_R}{100}\right)^2 = 4\left[\frac{\frac{3,600x11,100}{5,280x672}}{100}\right]^2 = 0.0507$

$I_{p,link} = 6.0468 + F_w + F_v + F_s = 6.0468 - 4.2 + 2.26 + 0.0507 = 4.16$

Step 6.Determine transit LOS score for segment

$I_{t,seg} = 6.0 - 1.50S_{w-r} + 0.15I_{p,link} = 6.0 - 1.50(1.84) + 0.15(4.16) = 3.86$

Step 7.Determine LOS

LOS = “D”

Table D.4 PM Peak “After” Transit Level of Service

“After” DBL System Conditions Westbound Direction (5:00-6:00 pm)

Step 1.Determine transit vehicle running time

$$S_{Rt} = \min\left(S_R, \frac{61}{1+e^{-1.00+\left(\frac{1185N_{ts}}{L}\right)}}\right) = \min\left\{\frac{11{,}100}{6.57} x \frac{60}{5280}, \frac{61}{1+e^{-1.00+\left[\frac{1185(10)}{11{,}100}\right]}}\right\} = \min(19.2, 29.5)$$

$$= 19.2 \text{ mph}$$

Step 2.Determine delay at intersections

$$\sum d_{ts} = 336\ sec$$

$$t_{Rt} = \frac{3{,}600L}{5{,}280S_{Rt}} + \sum d_{ts} = (6.57x60) + 336 = 730\ sec$$

$$d_t = t_l 60\left(\frac{L}{5{,}280}\right) = \left(\frac{336 - 17.3 - 20x10}{60x2.1}\right)(60)\left(\frac{11{,}100}{5{,}280}\right) = 0.942(60)\left(\frac{11{,}100}{5{,}280}\right) = 119\ sec/veh$$

Step 3.Determine travel speed

$$S_{Tt,seg} = \frac{3{,}600L}{5{,}280(t_{Rt} + d_t)} = \frac{3{,}600(11{,}100)}{5{,}280(730 + 119)} = 8.91\ mph$$

Step 4.Determine transit wait-ride score

$$T_{Ptt} = \left(a_1 \frac{60}{S_{Tt,seg}}\right) + 2T_{ex} - T_{at} = 1.00\left(\frac{60}{8.91}\right) + 2(3) - \frac{1.3(1.0)}{10} = 12.6 \frac{min}{mi}$$

$$F_{tt} = \frac{(e-1)T_{btt} - (e+1)T_{Ptt}}{(e-1)T_{Ptt} - (e+1)T_{btt}} = \frac{(-0.4-1)(4.0) - (-0.4+1)(12.6)}{(-0.4-1)(12.6) - (-0.4+1)(4.0)} = 0.657$$

$$F_h = 4.00e^{-1.434/(v_s+0.001)} = 4.00e^{-1.434/(4+0.001)} = 2.8$$

$$S_{w-r} = F_h F_{tt} = 2.8(0.657) = 1.84$$

Table D. 4 - *Continued*

Step 5.Determine pedestrian LOS score for link

$$F_w = -1.2276\ln\left(W_v + 0.5W_1 + 50p_{pk} + W_{b_uR}f_b + W_{aR}f_{sw}\right)$$

$$= -1.2276\ln[5 + 0.5(0) + 50(0) + 5(6 - 0.5x5)] = -4.2$$

$$F_v = 0.0091\frac{v_m}{4N_{th}} = 0.0091\frac{2,822}{4(4)} = 1.76$$

$$F_s = 4\left(\frac{S_R}{100}\right)^2 = 4\left[\frac{\frac{3,600x11,100}{5,280x730}}{100}\right]^2 = 0.043$$

$$I_{p,link} = 6.0468 + F_w + F_v + F_s = 6.0468 - 4.2 + 1.76 + 0.043 = 3.65$$

Step 6.Determine transit LOS score for segment

$$I_{t,seg} = 6.0 - 1.50S_{w-r} + 0.15I_{p,link} = 6.0 - 1.50(1.84) + 0.15(3.65) = 3.79$$

Step 7.Determine LOS

LOS = “D”

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BIOGRAPHICAL INFORMATION

Isaac F. Joskowicz graduated with a Bachelor of Science and a Master of Science in Civil Engineering from the University of Houston in 1981 and 1986, respectively. During his entire career, Mr. Joskowicz has worked as a traffic engineering consultant to the Harris County Metropolitan Transit Authority (Houston METRO), the City of Houston, Harris County, the Texas Department of Transportation, as well as other governmental entities and private clients in the Houston region, Texas, the United States, and abroad. He is a registered professional engineer in the state of Texas, a certified professional traffic operations engineer, and a fellow member of the Institute of Transportation Engineers.

Some of Mr. Joskowicz's major projects in his 30-year professional career include the US 59 freeway reconstruction, the METRO computerized traffic signal system, the Anzalduas international bridge, the City of Houston and METRO congestion mitigation and air quality programs, the City of Houston traffic signal timing optimization program, the METRO Main Street light rail system, the IH 10 freeway reconstruction, the Grand Parkway Segment E, the West Alabama reversible lane signal system, the Sugar Land triple-left system, the US 290 freeway reconstruction., and the METRO bus signal priority implementation.

Mr. Joskowicz led a volunteer research effort to investigate the effects of flexible work hours on city-wide traffic for the City of Houston. He has also been a lecturer in transportation engineering at the University of Houston since 1991.