

## **ABSTRACT**

HOLT, DANIEL LESTER. The Effects of Bus Stops on the Saturation Flow Rate of Signalized Intersections. (Under the direction of Dr. Joseph E. Hummer)

The total number of vehicle-miles traveled on our roadways has rapidly increased resulting in an increase in traffic congestion and a decrease in the operational integrity of the transportation system. To reduce these numbers of vehicle-miles, agencies attempt to influence and educate users on choosing the alternative mode of travel known as transit. For the potential users to conveniently use transit, agencies must conveniently locate bus stops so as to provide a high level of service. Though transit use has increased to provide approximately 8 billion passenger trips nationally, the number of vehicles and vehicle-miles traveled on our roadways has not decreased. With these bus stops usually located directly in the traffic stream, detrimental impacts to the traffic flow cannot be avoided as a bus stops and consequently blocks the traffic flow. Therefore, a realistic measure of the effect these transit vehicles have on the transportation system is needed. The 2000 Highway Capacity Manual's (HCM)  $F_{bb}$  adjustment factor equation found in Chapter 16 uses an average bus blockage time of 14.4 seconds. However, according to Chapter 27 of the 2000 HCM, when an average deceleration and acceleration time of 10 seconds for a bus to enter and exit a bus stop is applied to this 14.4 value, a total bus dwell time of only 4.4 seconds remains to actually serve its passengers. An additional review of Chapter 27 revealed that 15 seconds is a recommended average bus dwell time and along with the additional 10 seconds that accounts for the deceleration and acceleration time of a bus, Chapter 27 recommends a total bus blockage value of 25 seconds. With this disparity in bus blockage times, this research set out to formulate new analytical equations that more accurately estimate the effect of bus stops on

the saturation flow rate of a signalized intersection. These analytical equations were based on the assumption that the maximum impact of a bus stop occurs during the effective green time period. The near-side bus stop was shown to prohibit the progression of vehicles through the intersection, but that the effective green time and the cycle length were established as non-factors in evaluating this effect. However, the far-side bus stop does allow vehicle progression, but this progression is limited by the available vehicle storage space between the bus and the stop bar and the point in the signal cycle when the stop is performed. These equations were validated using CORISM simulation runs of a simple, saturated roadway network with a single bus route and bus stop that resulted in a simulated and an ideal saturation flow rate. A predicted saturation flow rate was then calculated to compare against the simulated saturation flow rate. Statistical testing and a sensitivity analysis conclusively showed that the magnitude of the proportion of right-turning vehicles at the intersection, the distance of the bus stop from the stop bar, and the actual number of bus stops have a direct effect on the value of the saturation flow rate. After a comparison of the adjustment factors from the derived equations against the HCM  $F_{bb}$  adjustment factor, it is found that the 14.4 value in the HCM  $F_{bb}$  equation does not accurately estimate the severity of the effects of a near-side bus stop and should be changed to the value of 25 seconds from Chapter 27 of the HCM. For the far-side bus stop, the new analytical equation developed here that is more sensitive to the parameters that can aid in estimating the effects of a far-side bus stop should be utilized to distinct it from the equation for a near-side bus stop.

**THE EFFECTS OF BUS STOPS ON THE  
SATURATION FLOW RATE OF SIGNALIZED INTERSECTIONS**

by

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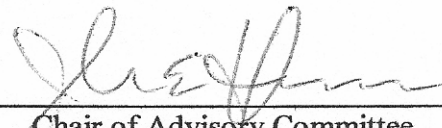
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### **Author's Biography**

The author was born in Sanford, North Carolina, on October 24, 1973, to the parents of James and Alice Holt. Growing up, the author participated in many social and recreational activities including the Webelos and Boy Scouts of America, local youth and young adult baseball, basketball, and soccer leagues and in activities associated with his church. Along with his parents, the experience of participating in these programs taught the author to set and achieve lofty goals and high achievements by committing 110% physical and mental effort towards them and never giving up in pursuit of them.

After relocating to Erwin, North Carolina in the late 1980s, the author graduated from Triton High School in 1992. Later that year, the author began the pursuit of his Bachelor's of Science degree in Civil Engineering at North Carolina State University. During the pursuit of this degree, the author also spent many hard-earned, but fun-filled, memorable years with the marching and pep band programs at NCSU as a playing member, as a Drum Major, and as the graduate assistant. It is these programs that took him to many exciting places throughout the United States while in support of the Wolfpack of N. C. State including giving him his first airline trip at the young age of 23.

During the summers between semesters while working toward his bachelor's degree, the author gained valuable experience working as an engineering assistant and an engineering technician with several construction and design units at the North Carolina Department of Transportation (NCDOT). While working with the band programs at N. C. State and with the many experienced professionals at NCDOT, the author graduated Cum Laude from N. C.

State University with his Bachelor's of Science degree in Civil Engineering in 1997.

However, the author desired more knowledge to continue his career as a civil engineer.

Later in 1997, with the aide of a graduate assistant and athletic scholarship with the N. C. State band program, the author began his pursuit of a Masters' of Science degree in Civil Engineering at N. C. State. While pursuing and completing his graduate degree, the author has continued his full-time, professional career as a transportation engineer with the Traffic Engineering Branch and now as a current member of the Chief Engineer's Office of the NCDOT. It was during this time that the author took and passed the Professionals' Engineering (PE) exam and is now a licensed professional civil engineer with the State of North Carolina.

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I wish to thank Dr. Joseph Hummer for his valuable guidance and persistence over the past six years that has helped make this possible. Through the pursuit of my academic and professional career as a transportation engineer, I cannot think of many advisors who have the persistence and belief in a topic to see a professional graduate student through to the end. Not only is this a testament to Dr. Hummer, but it is one to the staff and faculty of the Civil Engineering Department at N. C. State. To these individuals, Dr. John Stone, and Dr. Billy Williams, whose willingness and acceptance to come on at the end is truly appreciative and is something that I may not truly realize, I thank you.

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To my brother Dr. Darrin Holt, the path you carved was the road I took. Lucky for you, your path at N. C. State did finish before mine – contrary to some belief early on. However, between you and me, I think the professors in the Civil Engineering Department have had enough of the Holt boys. How many combined years was it? Anyhow, I sincerely thank you for your time and help and the homework and life advice you provided along the way. I can now say I have two degrees; maybe a little slow, but I’m catching up.

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Above all, I would be remiss if I did not think God. Things truly happen for a reason. Without him, none of this would be possible.

## Table of Contents

	Page
List of Tables .....	viii
List of Figures .....	x
Chapter 1: Introduction .....	1
Purpose and Scope .....	2
Report Outline .....	3
Chapter 2: Literature Review .....	4
Highway Capacity Manual Treatment .....	4
Curbside Bus Stop .....	7
Reserved Bus Lanes/Bus Bays .....	9
Queue Jumpers .....	10
Traffic Signal Bus Preemption .....	11
Transit Priority Traffic Signal Timing .....	12
Contra-Flow Bus Lanes .....	14
Chapter 3: Alternative Selection .....	17
Selection Summary .....	22
Chapter 4: Equation Formulation .....	23
Near-Side Bus Stop .....	23
Far-Side Bus Stop .....	25
Chapter 5: Simulation Approach and Results .....	31
Method of Analysis .....	31
Far-Side Bus Stop .....	34
Far-Side Simulation Results .....	37
Far-Side Statistical Testing .....	45
Comparison against the HCM Method for the Far-Side Bus Stop .....	53
Far-Side Equation: Sensitivity Analysis .....	54
Near-Side Bus Stop Experiment .....	58
Near-Side Simulation Results .....	59



Comparisons against the HCM Method for the Near-Side Bus Stop.....	64
Chapter 6: Conclusions and Recommendations .....	66
Future Work.....	68
List of References .....	70
Appendix A.....	71
Appendix B.....	81

## List of Tables

	Page
Table 1: Bus Blockage Adjustment Factor Values, 1994 HCM.....	6
Table 2: Alternative Evaluatin Matrix .....	18
Table 3: CORSIM Case Inputs – Far-Side Bus Cases.....	36
Table 4: Average Simulated and Predicted Flow Rates – Far-Side Bus Cases .....	39
Table 5: T-test Results of Dwell Time, 15 sec vs 30 sec.....	45
Table 6: T-test Results of Effective Green Time, 40 sec vs 60 sec .....	45
Table 7: T-test Results of Effective Green Time, 40 sec vs 80 sec .....	46
Table 8: T-test Results of Effective Green Time, 40 sec vs 100 sec .....	46
Table 9: T-test Results of Effective Green Time, 60 sec vs 80 sec .....	47
Table 10: T-test Results of Effective Green Time, 60 sec vs 100 sec .....	47
Table 11: T-test Results of Effective Green Time, 80 sec vs 100 sec .....	48
Table 12: T-test Results of the Proportion of Right-Turns, 0.00 vs 0.25 .....	48
Table 13: T-test Results of the Proportion of Right-Turns, 0.00 vs 0.50 .....	49
Table 14: T-test Results of the Proportion of Right-Turns, 0.25 vs 0.50 .....	49
Table 15: T-test Results of Bus Stop Location, 100 feet vs 250 feet.....	50
Table 16: T-test Results of Predicted vs Simulated Flow Rates for Accepted Cases.....	51
Table 17: T-test Results of Cases D, E, and F .....	52
Table 18: T-test Results of Cases G, H, I, and L .....	53
Table 19: T-test of Simulated Flow Rates vs HCM Flow Rates for Far-Side Stops .....	53
Table 20: T-test of Predicted Flow Rates vs HCM Flow Rates for Far-Side Stops .....	54
Table 21: Case Inputs for Sensitivity Analysis.....	56
Table 22: Inputs for Near-Side Cases .....	59
Table 23: Average of Simulated and Predicted Saturation Flow Rate Values - Near-Side Cases .....	60
Table 24: T-test of Predicted Flow Rates vs Simulated Flow Rates for Near-Side Stops....	62
Table 25: T-test Results of Dwell Time, 15 sec vs 30 sec.....	62
Table 26: T-test Results of Dwell Time, 15 sec vs 45 sec.....	63

Table 27: T-test Results of Dwell Time, 30 sec vs 45 sec .....	63
Table 28: T-test of Simulated Flow Rates vs HCM Flow Rates for Near-Side Stops.....	64
Table 29: T-test of Predicted Flow Rates vs HCM Flow Rates for Near-Side Stops.....	64
Table A1: Far-Side CORSIM Results, Cases 1 - 12.....	72
Table A2: CORSIM Results and Calculations, Case 14.....	73
Table A3: CORSIM Results and Calculations, Case 15.....	75
Table A4: CORSIM Results and Calculations, Case 16.....	77
Table A5: CORSIM Results and Calculations, Case 17.....	79
Table B1: Near-Side CORSIM Results, Repetitions 1 - 5.....	82
Table B2: Near-Side CORSIM Results, Repetitions 6 - 10.....	83

## List of Figures

	Page
Figure 1: Diagram of Time Period One ( $P_1$ ).....	27
Figure 2: Diagram of Time Period Two ( $P_2$ ).....	28
Figure 3: Diagram of All Three Time Periods.....	29
Figure 4: Simulated CORSIM Network .....	32
Figure 5: Avg. Predicted Saturation Flow Rates vs Avg. Simulated Saturation Flow Rates (Accepted Cases Only) .....	42
Figure 6: Avg. Predicted Saturation Flow Rates vs Avg. Simulated Saturation Flow Rates Only for Cases with Suffixes D, E, F.....	43
Figure 7: Avg. Predicted Saturation Flow Rates vs Avg. Simulated Saturation Flow Rates Only for Cases with Suffixes G, H, I, L.....	44
Figure 8: Plot of Sensitivity Analysis Results .....	57
Figure 9: Avg. Predicted Saturation Flow Rates vs Avg. Simulated Saturation Flow Rates	61

## **Chapter 1: Introduction**

In the past fifty years, the total number of vehicle-miles traveled on America's roadways has rapidly increased resulting in an increase in traffic congestion and a decrease in the operational integrity of the transportation system. In an attempt to reduce the number of vehicles and miles traveled, agencies attempt to influence and educate transportation users to choose alternative modes of travel. Their goal is to advocate public transportation and person-trips rather than vehicular trips to reduce the number of vehicle-miles, thereby decreasing the amount of traffic congestion. (1)

On a typical weekday, the transportation system may experience more than seven million workday commuters using public transportation with some additional thirty million persons depending on it to reach other destinations. Transit stops may accommodate an estimated eight billion passenger trips nationally. (2)

For these eight billion public transportation passengers, it is necessary for agencies to locate and design bus stop locations that provide good service, while trying to minimize any effects to traffic. Besides stopping traffic to serve passengers, transit vehicles are larger, slower, and less maneuverable than average automobiles and cause detrimental impacts to the traffic flow and the facility. The effects of these transit vehicles in the traffic flow can be observed as a reduction in corridor speed or as an increase in vehicular queues and delay. (1) Ultimately, better measures of the effects these transit vehicles and their stops have on the roadway are needed.

### **Purpose and Scope**

As it currently stands, the NCDOT does not have a formal policy concerning the construction design or placement of bus stops with respect to its location from intersections on state maintained roadways in the State of North Carolina. However, a joint effort between the City of Charlotte and the North Carolina Department of Transportation is currently underway to develop such a policy for state maintained roadways located within the authority of the City of Charlotte. As this joint effort continues, it is an objective of this research to provide recommendations for these agencies to consider in their development of a formal policy by indicating the potential effects to the transportation system of locating a bus stop near a signalized intersection.

As a result, the goal of the research is to analyze the effects of a bus stop on the saturation flow rate of a signalized intersection through the development of analytical equations with simple, available inputs that estimate those bus stop effects. The equations will be validated using a simulation of a simple, saturated roadway network with a single bus route and a single bus stop. As the literature review in Chapter 2 will show, previous research that investigated the implementation of alternative bus stop designs and treatment did not evaluate their effect to vehicular traffic during a saturated flow condition. In addition, keeping the simulation experiment simple allows the researcher to reduce the number and complexity of the simulation runs as well as minimize the number of factors in the experiment thereby creating credible and usable results. The validated equations produced by this research should provide insight into the effects that bus stops have on the

saturation flow rate. This, in turn, will allow traffic engineers to quantify the effects of bus stops on the highway system using standardized procedures.

### **Report Outline**

The process of evaluating the effect bus stops have on the saturation flow rate began with a literature review. This review involved the use of Internet databases, physical searches of personal, academic, professional, and other resource libraries, and communication with contacts in the transportation industry. After completion of this review, criteria were compiled to evaluate the types of bus stops contained in the literature review for evaluation in this research.

An evaluation matrix examined each alternative bus stop design based on the availability of analysis tools to evaluate the design, their effects on traffic capacity, the safety of the bus stop, and their use in North Carolina. After selecting the alternatives for analysis, analytical equations were developed to predict the effect of these bus stop alternatives on saturation flow at signalized intersections. A section of this document describes how the equations were developed and how the assumptions were made. Next, experimental runs were created using the CORSIM program to validate the performance of the equations. After completion of the CORSIM runs and after performing the appropriate statistical tests to assess the validity of the analytical equations, recommendations were made for a future analysis.

## **Chapter 2: Literature Review**

The intent of the literature review was to identify any research that has been performed regarding the effects of a bus stop as it relates to the operational performance of a signalized intersection. Once this research was identified, questions surrounding the validity of the results were compiled. These questions led to the creation of criteria used in evaluating this past research to formulate the scope, design, and limitations of the research.

### **Highway Capacity Manual Treatment**

Prior to the year 1965, approximately 1,600 intersection studies were completed for the Highway Capacity Manual (HCM) for use in level of service and capacity evaluations in the HCM. As a result of these studies, it was found that the proportion of heavy vehicles was a factor that influences an intersection's operational performance. It was concluded that the degree of this impact was dependent on the type of vehicle, its weight-power ratio, and its size and turning characteristics. It was also concluded that the effect of a bus and its stop on an intersection depended on the area of the city in which it was located (central business district, CBD, or suburban stop), the street geometrics and channelization, any on-street parking conditions, and the number of buses. (3) Much of this analysis structure survives in the current (2000) version of the HCM.

Under prevailing traffic conditions, the capacity of a signalized intersection is calculated and measured in terms of a saturation flow rate – the equivalent hourly rate at which queued vehicles traverse an intersection approach, assuming that the green signal



indication is available at all times and no lost times are experienced. This saturation flow is measured in terms of passenger cars per hour per lane (pcphpl). (4)

The calculation begins with the selection of an ideal saturation flow rate,  $S_o$ , currently estimated as 1,900 passenger cars per hour per lane (pcphpl). This ideal flow rate,  $S_o$ , is then adjusted for field conditions through the utilization of adjustment factors,  $F$ , as shown in the following equation: (4)

$$S = S_o F_w F_{hv} F_g F_p F_{bb} F_a F_{lu} F_{lt} F_{rt} F_{lpb} F_{rpb}, \quad (\text{Equation 16-4, 2000 HCM})$$

where,

$S$  = saturation flow rate for subject lane group;

$F_w$  = adjustment factor for lane width;

$F_{hv}$  = adjustment factor for heavy vehicles in traffic stream;

$F_g$  = adjustment factor for approach grade;

$F_p$  = adjustment factor for existence of a parking lane or parking activity;

$F_{bb}$  = adjustment factor for blocking effect of local buses;

$F_a$  = adjustment factor for area type;

$F_{lu}$  = adjustment factor for lane utilization;

$F_{lt}$  = adjustment factor for left turns in lane group;

$F_{rt}$  = adjustment factor for right turns in lane group;

$F_{lpb}$  = pedestrian adjustment for left-turn movements; and

$F_{rpb}$  = pedestrian-bicycle adjustment for right-turn movements.

Of these adjustment factors,  $F_{bb}$ , the bus blockage factor, accounts for the effect of a bus stop that is located within 250 feet, either upstream or downstream, of the signalized intersection. The adjustment value is based on the number of lanes in a lane group and the number of bus stops per hour. This blockage factor is referenced in the 1997, 1994, and 1985 versions of

the HCM with negligible numerical changes between the values that can be attributed to mathematical rounding. Table 1 shows the table for finding  $F_{bb}$  from the 1994 HCM.

**Table 1: Bus Blockage Adjustment Factor Values, 1994 HCM**

Number Of Lanes In Group, N	Number of Stops, $N_b$ 0	Number of Stops, $N_b$ 10	Number of Stops, $N_b$ 20	Number of Stops, $N_b$ 30	Number of Stops, $N_b$ 40
1	1	0.960	0.920	0.880	0.840
2	1	0.980	0.960	0.940	0.920
3	1	0.987	0.973	0.960	0.947

However, beginning with the 1994 HCM, an equation to directly calculate the value of the bus blockage factor was introduced: (4)

$$F_{bb} = (N - ((14.4N_b)/3600)) / N \quad (\text{Exhibit 16-7, 2000 HCM})$$

In this equation, 'N' represents the number of lanes in the lane group and ' $N_b$ ' represents the number of buses stopping per hour. This equation was also recommended for use when the number of bus stops per hour exceeded 40 in an hour. The 2000 HCM omits the table of bus blockage adjustment values and only a calculation utilizing the equation is now available.

In the 2000 HCM equation for bus blockage, the value of 14.4 (seconds) represents the average bus blockage time per bus stop. Of the available bus characteristics that can impact a facility's traffic flow, the blockage time is perhaps the most critical. Simply defined, the blockage time is the amount of time a bus blocks a travel lane. The capacity reduction to the intersection is directly correlated to the amount of blockage time. A portion of the blockage time is the time necessary to serve the passengers and is known as the dwell

time. Though a field calculation of dwell time is possible, in the absence of field data, Chapter 27 of the 2000 HCM recommends commonly-accepted values of dwell times from 15 to 60 seconds. The remainder of the blockage time is what is necessary for the bus to decelerate to a stop and to accelerate from a stop. Chapter 27 of the HCM recommends typical values of five seconds for deceleration and five seconds for acceleration for a total of ten additional seconds. (4) When this additional ten seconds is applied to the 14.4 value in Chapter 16, it is unrealistic to assert that approximately 4.4 seconds is available to serve the passengers at a bus stop.

A review of the differing bus blockage and dwell times from Chapters 16 and 27 reveal an additional discrepancy in the  $F_{bb}$  adjustment factors from Table 1. If an HCM-recommended dwell time of fifteen seconds is coupled with the additional ten seconds from the bus maneuvers to equate a total bus blockage time of twenty-five seconds and as the number of bus stops ( $N_b$ ) increase from zero to one per minute, with all other factors held constant and ideal, the total  $F_{bb}$  adjustment factor increases from zero to forty-two percent. However, using a bus blockage time of only 14.4 seconds per stop, the HCM adjustment factor approaches, at most, a twenty-four percent adjustment as the value of  $N_b$  approaches one per minute. Therefore, this research will question whether the value of 14.4 is appropriate.

### **Curbside Bus Stop**

A common design of most bus stops is the curbside bus stop. With these types of stops, the bus performs its stop in the actual travel lane. Typically, this stop is either located upstream of the stop bar (i.e., the near-side stop) or is located some distance downstream of

the stop bar (i.e., the far-side stop). Located either upstream or downstream, it is the stopping of the bus in the travel lane that is the curbside's bus stop greatest impact to the traffic flow. To analyze the impact to traffic operations, a portion of Transit Cooperative Research Program (TCRP) Project A-10 was set aside to study how bus stops influenced both roadway and pedestrian traffic for both the curbside and bus bay types of bus stops on suburban arterials. (5) The TCRP project visited and collected data at fourteen sites located in Arizona, Michigan, and California. These field studies indicated that through vehicles with the far-side bus stop encountered more delay than those with a near-side bus stop. The project noted that buses stopping at near-side stops, particularly at signalized intersections, overlapped with the red phases of the traffic signal which resulted in less delay.

During the computer simulation portion of the study, researchers concentrated their investigations on using such factors as vehicle speeds and maximum queue lengths behind a stopped bus. The researchers calibrated the models by comparing field studies for travel time and queue lengths with the data generated by the computer model. In the outputs, a relationship between vehicle speed differences and bus dwell times was discovered for dwell times of twenty, forty, and sixty seconds. In its conclusions, the study reported that the bus bay stop, where an exclusive lane or turnout is provided to remove a bus from the traffic stream to perform its stop, showed advantages over curbside stops in increased average vehicle speeds at simulated traffic volumes of 250 and 350 vehicles per hour (vph). (5) The results of this research indicated, as expected, that when a bus stop is out of the main travel lane the impact to traffic operations is minimized. However, factors related to such details as the amount of effective green time, the percentage of turning vehicles and the

roadway geometry were not identified as being significant in their field studies or in their computer modeling. In addition, though a plot of the speed difference versus the total traffic volume was presented, the impact to the saturation flow was unknown.

### **Reserved Bus Lanes/Bus Bays**

A bus bay is a designated area adjacent to a roadway that allows for the loading and unloading of passengers while removing the transit vehicle from the adjacent traffic flow. The removal of buses from the traffic flow allows the facility to maintain a consistent traffic flow without significant interruption (5). Transportation analysts with the *IBI Group* in Toronto, Ontario, Canada, researched the impacts of bus bays on a surface street corridor in Toronto. The research team wanted to conduct a corridor study to evaluate whether bus bays are successful in improving bus and corridor performance. Rather than physically implementing bus bays into an existing transportation system, they chose simulation with the TRANSYT-7F program, a macroscopic simulation and signal-optimization program, to model traffic conditions. The decision to use TRANSYT-7F resulted from its history of analyzing transit priority measures and its estimates of delay based on the principles associated with the theory of deterministic queuing.

The experiments employed basic study cases that evaluated the ‘before/after’ conditions of transit and traffic flow operations during AM and PM peak hour of traffic volume. The ‘before’ case consisted of the shared-lane scenario (where a bus and automobile utilize the same lane) with a curbside bus stop. The ‘after’ case simulated the existence of a bus bay that separated the transit vehicle from the adjacent traffic flow. To validate the simulations, field studies, involving the floating car study method, were

conducted to collect data on traffic signal delay, total vehicular travel time, and bus stop dwell time. Using field validation, the local saturation flow rate was calculated.

The research results showed that the average delay and travel time for the adjacent traffic increased by 28% and 15%, respectively, with a 15% decrease in average speed, as the bus dwell time increased to serve the increased bus ridership. Likewise, buses experienced a 14% reduction in average delay and a 9% reduction in average travel time with an 11% improvement in average speed. As can be seen by these results, the improvements in bus operation were exceeded by the degradation impacts to the adjacent traffic stream. However, it was unclear whether the increased bus ridership and dwell time was attributed to a possible traffic shift to other surface street routes with the implementation of bus bays or whether users actually switched to the transit mode. (6)

As the research noted, the use of the TRANSYT-7F program resulted in unreliable capacity estimates as the degree of saturation approached 100%. However, it is at the saturated condition where the greatest detrimental impact of a bus stop on an intersection's capacity should be measured. Therefore, for this research, a computer simulation program will be selected that will allow saturated traffic conditions to be analyzed so that the detrimental impact to an intersection's capacity can be quantified.

### **Queue Jumpers**

A portion of TCRP Project A-10 also studied the queue jumper, a unique type of bus bay, in a transit-priority design that provides the bus the ability to bypass queued vehicles at a signalized intersection to reach a far-side bus stop. This bypass maneuver is accomplished through the use of a near-side right-turn and bus lane that continues to the far-side of the

intersection. This exclusive lane allows for a direct movement to a far-side bus stop. A queue jumper removes a bus from the traffic flow and allows it to make its stop while being removed from the traffic flow. A queue jumper study was performed to develop possible recommendations for queue jumper designs at far-side bus stops. The potential benefits of a queue jumper for buses are measured in terms of travel time savings and an increase in speed. To estimate the advantages of a queue jumper, the travel time savings were converted to speeds. The research indicated that the bus benefits of a queue jumper were noticed once traffic volumes exceeded 250 vph. (5) A queue jumper is an example of a transit-priority design that improves the efficiency and operation of the transit vehicle. By removing a transit vehicle from the main traffic flow via an exclusive lane, its impact to saturation flow rate has already been minimized. Therefore, this bus stop design would not be a good treatment to analyze for its effect on the saturation flow rate.

### **Traffic Signal Bus Preemption**

Khasnabis, Karnati, and Rudraraju discuss traffic signal preemption techniques that provide preferential treatment for bus progression through signalized intersections. (7) This priority is achieved via green extension, red truncation, or red interruption. Green extension increases the green time by a specified amount. Red truncation terminates a red phase with the injection of a short green phase that is not a part of the normally-programmed green phase. The lack of contiguity with using a red truncation calls for additional time to be incorporated into the clearance phase. With each technique, an increase in green time, a reduction in delay, a reduction in queue lengths, and an increase in vehicle capacity are the anticipated results.

To analyze this signal preemption, the researchers chose the NETSIM software. The primary objective of the research was to develop a procedure for assessing the operational impacts of implementing the signal preemption. To perform the research, a series of signalized intersections on a primary bus route in Ann Arbor, Michigan was selected for data collection and validation. To minimize the complexity of the data collection, a number of signalized intersections were excluded based on their complex phasing and actuated signal operations.

At the outset, it was suggested that bus preemption may adversely impact side street traffic operations as the preferential allocation of effective green time for the main street increases vehicular delay and queue length on remaining approaches not given preferential treatment. However, the paper indicated that no preemption technique was validated in its entirety with this research nor should it be used to evaluate the results of bus preemption on intersections, and that further research is necessary to estimate a net savings in vehicular delay. (7)

### **Transit Priority Traffic Signal Timing**

The Southwest Region University Transportation Center presented research into modifying the existing transportation infrastructure in lieu of the higher cost of physically reconstructing a transportation infrastructure. (8) To offset an increased traffic demand and congestion, the encouragement of high occupancy vehicles (HOV) such as surface street buses, as an alternative in meeting travel demand, was introduced. This research noted that one method of promoting the use of mass transit by increasing its operational efficiency in the transportation infrastructure was through the use of traffic signal timing adjustment. This



research team believed that the signal timing adjustments should be re-focused on the entire transportation system and not just at a single point, i.e. the transit vehicle.

To model and simulate the impacts of implementing any signal timing priority scheme, the TRAF-NETSIM software, a microscopic simulation program that analyzes individual vehicles as they interact with other vehicles, was chosen. The simulation used signal timing methods such as green extension or red truncation over a run time of sixty minutes to evaluate any effect from a signal adjustment. The researchers simulated traffic volumes that ranged, in increments of 10%, from 0% to 100% of saturated flow. In each simulation run, a transit priority cycle was inserted in lieu of the normal signal timing plan once every ten minutes to simulate a ten-minute bus headway. After completing these NETSIM runs, an increase in travel delay was observed along with a degree of uncertainty as to whether the bus benefits of the transit priority signal timing scheme outweighed the delay increase incurred by the remaining vehicles.

The NETSIM outputs indicated that once the level of saturation reached 100%, priority signal timing schemes yield no significant advantage. The results further noted limited success utilizing the green extension treatment method with a near-side bus stop. However, the research indicated that priority methods might have success with far-side bus stops since the measure of effectiveness is no longer a direct function of the bus dwell time. The researchers further noted that the use of the green extension method could allow traffic to operate under its normal signal timing scheme. The results showed a positive effect in that transit vehicles gain a significant share of trips through the use of a priority signal timing scheme. Therefore, if an arterial operates with a generous amount of excess capacity, the

cycle length, transit delay, and vehicular delay can in fact decrease. However, it should be noted that the runs involved with this research concentrated on off-peak times of operation. Therefore, the researchers indicated that an emphasis on peak hour operations when traffic corridors are operating at their highest possible degree of saturation needs to be performed.

(8)

### **Contra-Flow Bus Lanes**

In order to improve surface street traffic operations, Rouphail presented research involving the use of contra-flow bus lanes and the programming of traffic signal settings to minimize passenger delays rather than using the conventional signal timing method of minimizing vehicular delays. (9) The research intent was to evaluate the relationship between bus performance and signal priority techniques. A contra-flow bus lane provides a bus an exclusive lane to travel and perform its operation in the opposite direction of the adjacent traffic flow. The advantage of a contra-flow bus lane is that any bus blockage of traffic flow is eliminated and the adjacent traffic flow is not impeded, although cars lose the use of one lane.

The research reflected actual field observations on a typical Chicago, Illinois, downtown street where a contra-flow bus lane was installed in 1980. The conclusions indicated that bus operation dramatically improved with the dedication of an exclusive lane to bus traffic. This improvement was observed by an increase in the overall bus speed on the route. This separation of bus traffic from the normal traffic flow was viewed as a means of minimizing vehicular delays that are attributed to bus stops.

To evaluate the effectiveness of the contra-flow bus lanes and a traffic signal timing priority scheme designed to minimize passenger delays, the researchers chose the TRANSYT-7F program. In using this program, six scenarios were developed for analysis. However, with the density of the pedestrian traffic in the study area, the default saturation flow rate in TRANSYT-7F was revised.

The TRANSYT-7F model results showed that the degree of operational improvement was dependent on whether the buses operated in mixed traffic conditions or in exclusive contra-flow lanes. In addition, the research noted that the total number of vehicle-miles for the nonbus traffic did decrease after the implementation of the contra-flow bus lane. The research noted that some of the improvements in nonbus traffic could be attributed to the increased bus ridership. Though a ridership increase and a lower total of vehicle-miles traveled with the implementation of the contra-flow bus lane has a positive impact on a congested arterial, the impact of these bus treatment measures on the saturation flow rate was still not known. (9)

The literature review uncovered several research projects that looked at different strategies and bus stop treatments at intersections to improve bus performance while also attempting to reduce the magnitude of traffic congestion on our nation's roadways. The analysis for each of these strategies typically resulted in an improvement and enhancement of the bus ridership and operations. However, as buses and vehicles predominately share the same travel lanes, the magnitude of the bus operation improvement was usually at a cost to the vehicular portion of the traffic stream. Whether it was an increase in bus ridership that resulted in an increased bus dwell time where a travel lane is blocked or where a traffic

signal network was optimized for bus vehicles to improve or maintain its service, it is the vehicular traffic that is negatively impacted. This impact to vehicular operations was not accurately estimated or, at times, even noted in the research analysis. Though certain research reported the degradation to adjacent vehicles in terms of speed or delay, a more basic measure of the impact a bus stop has on an intersection, its saturation flow rate was not quantified. Though computer software such as TRANSYT-7F was used to evaluate traffic operations, at the time the computer software included flaws in its modeling that can inaccurately report the level of operations, especially at saturated conditions. In addition, most of the research and computer software had its handling of bus operations and its effects on the traffic stream rooted in the Highway Capacity Manual. In using the manual, it is observed that the handling and characteristics of buses and bus stops from the average or typical bus blockage time to the equations to use differ even between the chapters of the same manual.

With the clear discrepancies in the average bus blockage times found in Chapters 16 and 27 of the Highway Capacity Manual, 14.4 and 25 seconds respectively, and the lack of any conclusive analysis in the literature review of the impacts that an alternative bus stop design and treatment have on an intersection's saturation flow rate, this research will focus its efforts on developing analytical equations that serve to more accurately estimate and quantify the bus blockage adjustment factor for use in the calculation of an intersection's saturation flow rate.

### **Chapter 3: Alternative Selection**

Upon completion of the literature review, a list of bus treatments that have the potential for further analysis was compiled. This list was narrowed in an evaluation matrix that uses criteria that arose during the literature review that measure the scope of the impacts. The first criterion measures the potential use and application of the bus stop on roadways in the State of North Carolina. The second criterion measures the ability of computer software such as CORSIM, TRANSYT, Synchro, and HCM to analyze an intersection containing a bus stop. The next criterion measures the effects the bus stop treatment has on the vehicular safety of the adjacent traffic volume. This criterion measures the expectation of a transit vehicle performing a stop and how this expectation alters driver behavior. The remaining criteria measure the use of a particular type of bus stop and its effect on the capacity of a signalized intersection and the effect it can produce on transit operations in terms of whether transit can deliver a high quality of service to its users. Each bus stop treatment was assigned a categorical score - positive, negative, or neutral benefit – based on its comparison to a signalized intersection without a bus stop. Presented in Table 2 is an evaluation matrix that shows the score for each bus stop treatment in each criteria category that was used in selecting the more promising alternatives for further analysis.

**Table 2: Alternative Evaluation Matrix**

<b>Criteria</b> <b>Strategy</b>	<b>Use In</b> <b>North</b> <b>Carolina</b>	<b>Available</b> <b>Analysis</b> <b>Tools</b>	<b>Safety</b>	<b>Effects on</b> <b>Traffic</b> <b>Capacity</b>	<b>Effects on</b> <b>Transit</b> <b>Operations</b>
<b>Near Side Stop</b>	++	++	--	--	-
<b>Far Side Stop</b>	++	++	--	--	-
<b>Bus Bay</b>	+	++	+	+	+
<b>Queue Jumper</b>	-	+	-	N	++
<b>Contraflow Bus Lane</b>	--	++	+	++	++
<b>Signal Preemption (Bus)</b>	+	+	N	--	+
<b>Signal Priority (Timing)</b>	+	+	N	--	+

**Legend**

++ = very positive effect

+ = somewhat positive effect

N = neutral effect

- = somewhat negative effect

-- = very negative effect

Alternatives that create only marginal results as well as those that would create a complex experimental design beyond the constraints of the research were not selected. After considering the results of the literature review and the evaluation matrix, two alternatives emerged as promising for further analysis. In the following sections, the two alternatives selected for further analysis are discussed with the remaining sections examining those alternatives that were not selected.

**Curbside bus stops**, both near-side and far-side, appropriately satisfied the evaluation criteria established in that they had strong effects in all categories and were

selected as the most promising alternatives for further analysis. These common types of bus stops are perhaps the easiest and most convenient for passengers and transit vehicles to use. However, these curbside stops are perhaps the most detrimental to the traffic flow.

As a curbside stop occurs in the traffic flow lane, they impede traffic progression and reduce the number of vehicles that an intersection can process. With the relative ease and ability to model these types of stops, obtaining credible results and conclusions can be accomplished within the constraints of the research.

Though not a common bus design treatment on North Carolina's roadways due to the right-of-way necessary for it, a **bus bay** bus stop is a condition where a transit vehicle uses an exclusive travel lane or turnout to perform its stop. A major advantage of the bus bay is the opportunity it provides for a bus to perform a stop while removed from the traffic flow. This opportunity assists in minimizing the impact the stop has on the adjacent traffic flow. With the stop performed outside of the traffic flow, the surrounding vehicles can continue their normal traffic progression.

Though the bus bay allows a stop to occur outside the traffic flow, a degree of concern is introduced when the transit vehicle exits and re-enters the traffic stream. Due to the nature of the transit vehicle, the amount of time and space necessary for it to decelerate and accelerate before and after the stop may alter the behavior of the adjacent traffic flow. However, with an overall positive benefit to the traffic flow of a bus bay, it was not selected for further analysis.

An uncommon design in North Carolina, a **queue jumper** is a type of bus stop that is similar to that of a bus bay. An exclusive transit lane is provided that, much like an auxiliary

turn lane, allows a bus to bypass a standing queue, if it exists, and to progress through the intersection to perform a stop in an extension of this exclusive lane on the far-side of the intersection. Though the frequency of implementing this type of stop is low, it does provide benefits to transit similar to a bus bay. By utilizing an exclusive lane to bypass a vehicle queue, a bus can avoid delay in performing its stop. In addition, the exclusive transit lane allows the normal traffic progression to continue without impedance from a stopped bus. As is the case with a bus bay stop, the deceleration and acceleration associated with the bus exiting and re-entering the traffic stream can provide some impacts to traffic operations. Though the initial exiting and re-entering of the bus into the traffic stream will degrade traffic operations, the traffic progression is not forced to endure additional effects that result from a stopped bus. With an overall positive impact to the adjacent traffic flow, a queue jumper was not selected for further analysis.

Extremely uncommon in North Carolina, a **contra-flow** bus lane is an exclusive transit lane that allows transit vehicles to perform their stops while traveling in the opposite direction of the vehicular traffic flow on a one-way street. The potential for this design to provide a positive benefit to transit operations and the surrounding traffic flow may be substantial where it can be implemented. As a bus performs its functions outside of the traffic flow, the acceleration and deceleration characteristics and the dwell time that accompanies each stop is not a direct impact to the adjacent traffic flow. However, a degree of concern exists where these contra-flow lanes intersect and interact with the normal traffic flow. Also, a contra-flow lane does reduce the number of lanes available for cars, and there may be serious safety impacts. Though this type of transit treatment has been and can be



analyzed in a computer simulation program, with its significant potential of providing positive benefits to the surrounding traffic operations, its effect on the saturation flow rate will be minimal. Therefore, a contra-flow bus lane was not selected for further analysis.

Where implementing physical treatments for a bus and a bus stop are not feasible, the use of **traffic signal preemption** is a possibility. The objective of this or any other type of preemption technique is to provide some kind of preferential treatment to ease the movement of a particular vehicle or approach. This preferential treatment is usually achieved at the expense of the other users of the network. Various preemption techniques may involve extending the green time for an approach or by truncating a phase to induce a red signal indication to allow for a preferential movement. However, the measures of the benefits or costs to an intersection's capacity and traffic progression are difficult to quantify. These preemption techniques are difficult to analyze in a computer simulation program as a complex experiment design is needed. For these reasons, this technique was not selected for further analysis.

The last alternative studied in the literature review was **transit priority in traffic signal timing**. As noted by Rouphail (4), the standard in developing a traffic signal timing plan is to use the minimal amount of green time necessary to process the maximum amount of vehicles possible while vehicular delay is minimized to the maximum extent possible. If this standard is followed, in theory, the capacity of the intersection and its traffic progression are optimized. However, when a signal timing plan is developed with its focus to ensure that a transit vehicle experiences the least amount of delay possible while adhering to its

published stop schedule, the magnitude and severity of the impacts to the surrounding traffic flow and approaches are secondary considerations.

### **Selection Summary**

Based on the criteria that were compiled after the literature review, two alternatives, the near-side and far-side bus stops, were selected for further analysis and experimentation with a computer simulation program. These alternatives have the potential to produce a significant impact to an intersection's saturation flow rate. As for the remaining alternatives that were not selected, they either already have a positive benefit to the surrounding traffic flow (bus bay, queue jumper, contra-flow lane) or they focus on improving bus operations and not necessarily improving the adjacent traffic flow (signal preemption, signal timing) and would be difficult to study.

## Chapter 4: Equation Formulation

The Highway Capacity Manual (4) is the pre-eminent traffic operations analysis reference in use in the United States. In reviewing the HCM, we see that the bus blockage time includes the time to serve the passengers, or dwell time, and the deceleration and acceleration time involved in entering and exiting the bus stop. According to Chapter 27 of the HCM, a typical dwell time value,  $D_w$ , for an outlying (suburban) stop is approximately fifteen seconds with an accepted value of five seconds for the deceleration and five seconds for the acceleration time (ten seconds total) for the bus at the bus stop. Given a typical outlying stop, the typical bus blockage time would be twenty-five seconds ( $D_w + \text{deceleration} + \text{acceleration}$ , or  $15 + 5 + 5$ ). This pause in vehicle movement has its maximum impact on the saturation flow rate when it occurs during the effective green time period of the traffic signal cycle.

### Near-Side Bus Stop

When a near-side bus stop is assumed with random bus arrivals, the chance that a bus stop occurs during the effective green time ( $g$ ) is equal to the  $g/C$  ratio, or the effective green time to total cycle length time ( $C$ ) ratio. With the  $g/C$  ratio applied to the value of the total bus blockage time ( $BT$ ) for all buses that stop ( $N_b$ ) in a given time frame (e.g., one-hour), the proportion of the green time blocked for that one-hour time period is expressed in the following equation:

$$\text{Proportion Blocked} = N_b * BT * g/C$$

For example, if a cycle length of 100 seconds has an effective green time of 40 seconds and a bus blockage time of 25 seconds with 6 bus stops occurring, the following proportion of one hour of green that is blocked by the bus given these arbitrary values is as follows:

$$\begin{aligned} N_b * BT * g/C &= 6 \text{ bus/hour} * 25 \text{ sec/bus} * (40/100) \text{ sec/sec} \\ &= 60 \text{ sec blocked/hour} \end{aligned}$$

Given the units that remain and that the equation is for the proportion of one hour of green that is blocked, to find the proportion of a real hour that is blocked, we need to divide by the g/C ratio times 3,600 seconds, or 1,440 seconds, as follows:

$$\text{Proportion of hour blocked} = \frac{6 \text{ bus/hr} * 25 \text{ sec/bus} * (40/100) \text{ sec/sec}}{(40/100) \text{ sec/sec} * 3600 \text{ sec/hr}} = \frac{60 \text{ sec blocked}}{1440 \text{ sec of green time}}$$

The result of this example is that 0.04167, or 4.167%, of the hour is blocked by the bus. It is clearly observed that the g/C ratio factors out and is of no consequence in evaluating the effect of a near-side bus stop on the saturation flow rate. In the equation for the bus blockage adjustment factor,  $F_{bb}$  in the HCM, the value of 14.4 represents an average bus blockage time, in seconds. Noting Chapter 27 of the HCM and the recommended value of the blockage time for a typical bus stop of 25 seconds, the value of 14.4 can be questioned.

Accounting for the fact that a lane group may contain more than one lane, the saturation flow rate adjustment factor for bus blockage,  $F_{bb}$ , for a lane group with N number of lanes can be calculated as follows:

$$F_{bb} = (N - (N_b * (\text{Dwell Time} + 10))) / 3600 / N$$

### **Far-Side Bus Stop**

Though the effective green time and bus stop positioning are of no consequence for a near-side bus stop location, these same statements, assumptions, and conclusions cannot be made for the far-side bus stop location. As the near-side scenario prohibits vehicles from progressing through the intersection while a bus stop is in progress, the far-side stop allows for the movement of vehicles through the intersection to continue. However, the limitations of this continued progression is based upon two distinct factors – the amount of vehicle storage between the bus stop and the stop line and the point within the signal cycle when the stop is made.

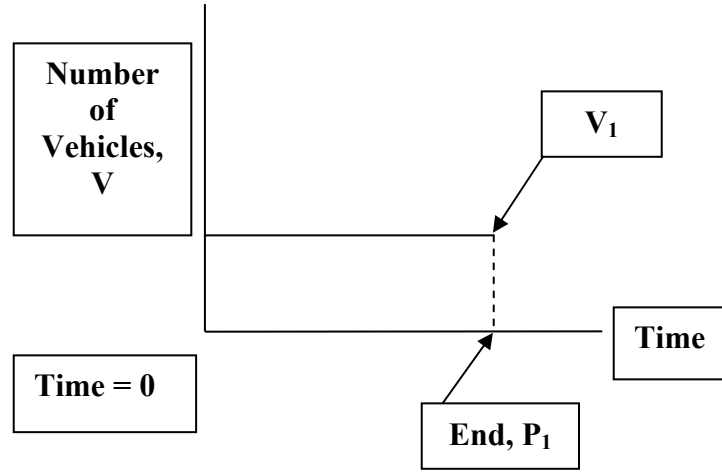
In developing an equation for the far-side bus stop, the bus could stop during three distinct time periods ( $P_1$ ,  $P_2$ , and  $P_3$ ). The critical detail in deriving this equation is the distance of the far-side bus stop from the stop bar of the signalized intersection. Each of the three time periods were measured relative to when the bus passed the stop bar. For each period, an average number of vehicles ( $V_1$ ,  $V_2$ , and  $V_3$ ) that could use the shared through-right turn lane during each time period are calculated to achieve a total number of vehicles for each signal cycle with a bus stop for all three time periods ( $V_T$ ).

The first time period ( $P_1$ ) applies when the bus moves past the stop bar early in the green phase starting when the effective green ( $g$ ) equals zero. The ideal number of vehicles is the amount that can traverse the intersection during the effective green time of the intersection given no buses stopping during the signal cycle. Given an average vehicle headway ( $h$ ), this magnitude can be expressed as the effective green time ( $g$ ) divided by the headway ( $h$ ), or  $g/h$ . As a bus approaches a stop to serve its passengers, no vehicles can use

the lane. Therefore, given the value of the bus blockage time (BT) and the vehicle headway (h), the number of vehicles that are blocked can be calculated by dividing the blockage time (BT) by the headway (h), or  $BT/h$ . However, vehicles can move past the stop bar as the far-side bus stop is performed to fill the distance between the stop bar and the bus stop or to make right-turns. Therefore, the number of vehicles that can get past the stop bar while the bus is stopped is the number of storage spaces between the stop bar and the back of the bus ( $St$ ) divided by the proportion of through vehicles in the traffic stream ( $1 - P_{rt}$ ), where  $P_{rt}$  is the proportion of right-turns in the shared lane,  $St / (1 - P_{rt})$ . Finally, we need to adjust for time lost between when the bus finishes its stop and when the vehicles start flowing again. This can be expressed as  $(L + h)/h$ , where 'L' is the lost time in seconds. Putting all of these parts together, the average number of vehicles ( $V_1$ ) processed during the first time period ( $P_1$ ) is computed by the following equation:

$$V_1 = g/h - BT/h + St/(1-P_{rt}) - (L + h)/h$$

The first time period ends at that time at which a stopped bus would start again, but no more vehicles could be processed past the stop bar because the signal had turned red. This time is  $(g - BT - (L + h))$  which leads to the assumption that  $BT + L + h < g$ . A diagram of  $V_1$  and  $P_1$  is presented in Figure 1.



**Figure 1: Diagram of Time Period One (P<sub>1</sub>)**

The second time period (P<sub>2</sub>) begins with the bus passing the stop bar at some point in time greater than the value of  $(g - BT - (L + h))$ , or the end of P<sub>1</sub>. During P<sub>2</sub>, the storage spaces behind the bus are filled so no more vehicles are processed by the travel lane, and the bus does not start moving soon enough to allow vehicles to get beyond the stop bar because the signal turns red. The number of vehicles that can be processed during a green phase when a bus stops during P<sub>2</sub> increases linearly during P<sub>2</sub> from the number processed during P<sub>1</sub> to the number processed during time period three, P<sub>3</sub> ( $g/h$ , see below). The average number of vehicles ( $V_2$ ) processed when a bus stops during P<sub>2</sub> can be computed as:

$$V_2 = (V_1 + V_3) / 2 =$$

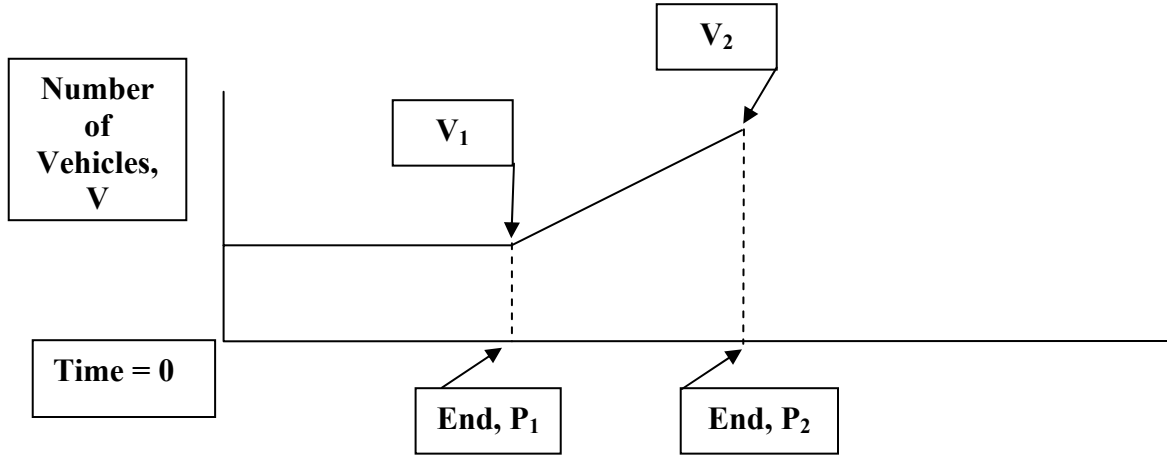
$$(g/h - BT/h + St/(1 - P_{rt}) - (L + h)/h + g/h) / 2$$

P<sub>2</sub> holds from the end of P<sub>1</sub> at  $(g - BT - (L + h))$ , until the bus stop is no longer an issue to the vehicles in the travel lane. This occurs at the time  $(g - (St * h)/(1 - P_{rt}))$ . At that time and for the rest of the effective green period, the storage spaces behind the stopped bus will not fill up. Thus, the calculation of the length of P<sub>2</sub> is as follows:

$$P_2 = \text{End of } P_2 - \text{End of } P_1 = g - ((St * h)/(1 - P_{rt})) - (g - BT - (L + h)) =$$

$$BT - (St * h)/(1 - P_{rt}) + L + h$$

A diagram of  $V_2$  and  $P_2$  is presented in Figure 2.



**Figure 2: Diagram of Time Period Two ( $P_2$ )**

This leads to another assumption that  $BT + L + h > (St * h)/(1 - P_{rt})$ . During time period three ( $P_3$ ), the bus stops so late in the green phase that the storage spaces are not filled before the signal turns red.

With the bus stop no longer an issue, the number of vehicles that can be processed in  $P_3$  by the travel lane is simply the ideal value of  $g/h$ . With the limit of the three distinct time periods equal to the value of the effective green time, the length of  $P_3$  is calculated by subtracting the beginning of  $P_3$  from the effective green time,  $g$ , as follows:

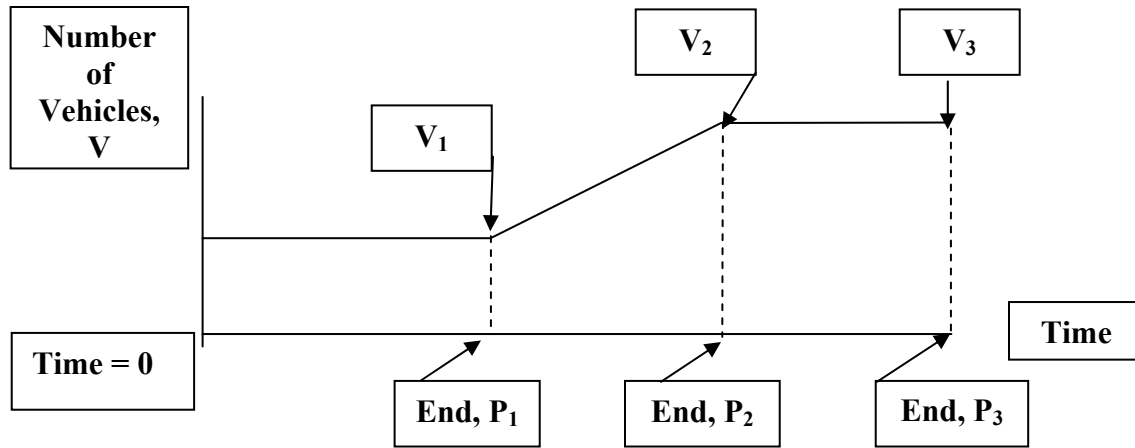
$$P_3 = \text{End of } P_3 - \text{End of } P_2 = g - (g + (St * h)/(1 - P_{rt})) = (St * h)/(1 - P_{rt})$$



With all time periods derived, the equation to obtain the average number of vehicles processed during a green phase ( $V_T$ ) with a bus stop is as follows:

$$V_T = (1 / g) * (V_1 * P_1 + V_2 * P_2 + V_3 * P_3)$$

In the preceding equation,  $P_1$ ,  $P_2$ ,  $P_3$ , and  $g$  are calculated in seconds. Graphically, these three distinct time periods are shown in Figure 3:



**Figure 3: Diagram of All Three Time Periods**

For example, if an effective green time of 40 seconds, a blockage time of 20 seconds, a vehicle headway and lost time of 2 seconds each, a proportion of right turns at 0.50 (50%), and 4 storage spaces are allowed behind a stopped bus, the average number of vehicles expected for that cycle is computed as follows:

$$\begin{aligned} \square V_1 * P_1 &= (40/2 - 20/2 + 4/(1-0.50) - (2+2)/2) * (40-20-2-2) \\ &= (20 - 10 + 8 - 2) * (40 - 20 - 4) = 256 \text{ veh-sec} \end{aligned}$$

$$\square V_1 * P_1 = (g/h - BT/h + St/(1-Prt) - (L + h)/h + g/h) * (BT - (St * h)/(1 - P_{rt}) + L + h)$$

$$= ((40/2 - 20/2 + 4/(1-0.50) - ((2+2)/2) + 40/2) * (20 - (4*2)/(1-0.50) + 2 + 2)$$

$$= ((40 - 10 + 8 - 2)/2) * (20 - 16 + 4) = 144 \text{ veh-sec}$$

$$\square V_3 * P_3 = (g/h) * ((St * h)/(1 - P_{rt})) = 40/2 * ((4*2)/(1-0.50))$$

$$= 20 * 16 = 320 \text{ veh-sec}$$

$$\square V_T = (1 / g) * V_1 * P_1 + V_2 * P_2 + V_3 * P_3$$

$$V_T = 40 * (256 + 144 + 320) = 18 \text{ vehicles per cycle containing a bus}$$

With the average number of vehicles calculated, to obtain the saturation flow rate adjustment for that cycle, the average number of vehicles ( $V_T$ ) is divided by the ideal number of vehicles that can be processed by the intersection,  $g/h$ , which are 20 vehicles for this example.

Therefore, the adjustment factor is  $18/20$  or  $0.90$ . This adjustment factor accompanied by an adjustment factor for any cycles in an hour of analysis that does not contain a bus stop will yield a total adjustment factor for the saturation flow rate for a given hour.

## **Chapter 5: Simulation Approach and Results**

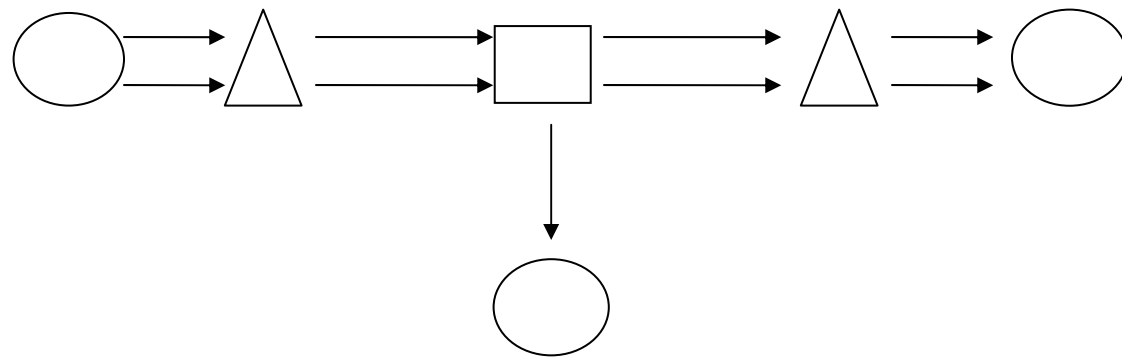
This chapter will address the process involved in creating and performing the simulation runs that provide the data used to validate the equations derived in the last chapter. The research relied upon CORSIM v. 5.1, a microscopic, stochastic simulation package developed by the Federal Highway Administration (FHWA). With its established track record, the ability to obtain and analyze results quickly, the ease in estimating parameters, the ability to control the surrounding parameters, the ability to view simulations in TRAFVU, and its ability to avoid the logistical difficulties that are encountered in performing field experiments, the CORSIM simulation package was a good choice for this research. Appropriate steps to ensure that CORSIM provides credible estimates of the impact of bus stops on the saturation flow rate were followed.

When a traffic signal indication turns green, a separation between vehicles, or headway, is introduced, measured in terms of seconds between consecutive vehicles crossing the stop bar. If a consistent headway and a continuous green signal indication are observed for a specified time period, e.g., a one-hour time period, a maximum theoretical flow rate is expected. Any interruption in the green time will result in a capacity reduction. (4)

### **Method of Analysis**

The research used CORSIM to model a saturated roadway network with one isolated, pre-timed signalized intersection (Figure 4). Typical values regarding traffic signal timing and roadway operations were assumed when needed. The entry number of vehicles per hour was selected to maintain a continuous stream of vehicles and a steady vehicular queue to

reflect a saturated traffic condition. Efforts were made to view the simulations in TRAFVU as well as examining the CORSIM output to verify the existence of a saturated flow condition for each case simulated.

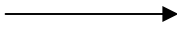


#### **Legend**

Signalized intersection = 

Dummy Node = 

Source/Sink Node = 

Travel Lane = 

**Figure 4: Simulated CORISM Network**

Each case simulated had two travel lanes: an exclusive through lane (CORSIM Lane 2) and a combination through-right turn lane (CORSIM Lane 1) that contained the curbside bus stop. After the simulation runs were performed, data regarding the vehicle discharge for the combination through-right turn lane was retrieved. By applying the amount of effective green time and its proportion of the 60-minute simulation time period against the vehicle discharge per hour for the combination travel lane (Lane 1), a ‘simulated’ saturation flow rate

is calculated. The discharge value for the combination lane already accounts for the effects of the proportion of right-turns as well as the effects of the bus stops. For Lane 2, using the proportion of the time period that is the effective green time and to the discharge value, we can obtain a saturation flow rate. The inverse of this saturation flow rate ( $3600 \text{ seconds} / \text{ideal flow rate}$ ) is calculated to obtain the headway per vehicle. Since Lane 2 did not contain any turn lanes, turning vehicles, or heavy vehicles and with all the remaining details of Lane 2 having adjustment factors equal to 1.00, this calculated flow rate value is referred to as the 'ideal' saturation flow rate per lane for each case.

The research consisted of two basic experiments – far-side and near-side bus stops. For the far-side bus stop experiment, each simulation run was composed of a 60-minute time period that is preceded by a warm-up (equilibrium) period not to exceed fifteen minutes. The selection of a 60-minute time simplifies the subsequent calculations and allowed the simulations to achieve stable operations. To obtain the saturation flow rate, output referencing the vehicle discharge per lane, the average queue per lane, and the number of buses serviced during the time period is utilized. Though additional performance data are found in the CORSIM output, this research will only rely on select output that is used to directly calculate the saturation flow rate.

In the experimental design, CORSIM requires the selected simulation time period be evenly divisible by the traffic signal cycle length. If this situation does not exist, CORSIM will revise the cycle length to a value that satisfies this constraint. To avoid any artificial revision by the CORSIM program, an appropriate cycle length was selected. Chapter 16 of

the 2000 HCM (pg. 16-160) suggests that to produce statistically significant values, a minimum of fifteen complete signal cycles should be observed. Though CORSIM has the ability to model actuated traffic signals, since each simulation contained a traffic volume that sustained saturated conditions, actuated signals would behave like pre-timed traffic signals anyway. Therefore, with each simulation having a 60-minute (3,600-second) time period, a fixed cycle length of either 100 or 150 seconds that results in 24 to 36 complete signal cycles per hour was used.

If a left-turn maneuver were introduced, to obtain any significant data, an opposing traffic volume would need to be introduced into the simulation, thereby complicating the research greatly. Therefore, with only traffic volumes simulated in a one-way direction, no left-turning vehicles or maneuvers are included in this research. The remaining design details listed below remained constant for all models. These values were also selected to minimize any additional adjustment of the saturation flow rate:

- ❑ a 90-degree intersection
- ❑ free flow speed of 30 miles per hour
- ❑ yellow and all red time of 4 seconds and 0 seconds, respectively
- ❑ lost time of 2 seconds
- ❑ 0% grade

### **Far-Side Bus Stop**

Cases 1 – 12 modeled a basic roadway network with no buses with cases 13 to 17 modeling the far-side bus stop. With the high number of cases, only two repetitions of each case were needed to provide adequate sample sizes. The two repetitions will use a different set of random number seeds that were chosen from a spreadsheet of 8-digit random numbers that was created in Microsoft Excel. The roadway network contained an exclusive through

lane and a combination through-right turn lane and one pre-timed, signalized intersection. The number of vehicles per hour necessary to sustain a saturated flow condition was selected from a range of 1,000 to 2,500 vehicles per hour (vph). A 150-second signal cycle length was selected that results in 24 complete signal cycles per simulation time period. Noting that the effect of the far-side stop depends on the portion of the green phase in which the bus arrives at the stop, four levels of effective green time (40, 60, 80, and 100 seconds) were used. Three levels of right-turn percentage (0%, 12.5%, and 25% of the approach volume) were selected. According to Chapter 16 of the HCM, the bus blockage factor measures the effect of bus stops that occur within a 250-foot distance of the stop line. Therefore, bus stop locations approximately 100 feet and 250 feet downstream of the stop line were modeled. We could not make the bus stop any closer to the stop bar without the bus blocking part of the cross street, which is not allowed in CORSIM. With the variability of the effective green time and the restrictions on the far side analytical equation noted previously, only two levels of bus dwell time (15 and 30 seconds) were modeled. Using a bus headway of 5 minutes allows each bus and bus stop to remain independent of the preceding and proceeding one. Table 3 summarizes the input for each far-side bus stop case.

**Table 3: CORISM Case Inputs - Far-Side Bus Cases**

<b>40-Second Effective Green</b>	<b>Case</b>														
	1	2	3	14a	14b	14c	14d	14e	14f	14g	14h	14i	14j	14k	14l
Right Turn % By Approach (veh)	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25
Dwell Time (sec)	0	0	0	15	15	15	30	30	30	15	15	15	30	30	30
Bus Headway (minutes)	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5
Bus Stop Distance from Stop Bar (feet)	0	0	0	100	100	100	100	100	100	250	250	250	250	250	250
Vehicles per hour (vph)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
<b>60-Second Effective Green</b>	<b>Case</b>														
	4	5	6	15a	15b	15c	15d	15e	15f	15g	15h	15i	15j	15k	15l
Right Turn % By Approach (veh)	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25
Dwell Time (sec)	0	0	0	15	15	15	30	30	30	15	15	15	30	30	30
Bus Headway (minutes)	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5
Bus Stop Distance from Stop Bar (feet)	0	0	0	100	100	100	100	100	100	250	250	250	250	250	250
Vehicles per hour (vph)	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
<b>80-Second Effective Green</b>	<b>Case</b>														
	7	8	9	16a	16b	16c	16d	16e	16f	16g	16h	16i	16j	16k	16l
Right Turn % By Approach (veh)	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25
Dwell Time (sec)	0	0	0	15	15	15	30	30	30	15	15	15	30	30	30
Bus Headway (minutes)	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5
Bus Stop Distance from Stop Bar (feet)	0	0	0	100	100	100	100	100	100	250	250	250	250	250	250
Vehicles per hour (vph)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
<b>100-Second Effective Green</b>	<b>Case</b>														
	10	11	12	17a	17b	17c	17d	17e	17f	17g	17h	17i	17j	17k	17l
Right Turn % By Approach (veh)	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25	0	12.5	25
Dwell Time (sec)	0	0	0	15	15	15	30	30	30	15	15	15	30	30	30
Bus Headway (minutes)	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5
Bus Stop Distance from Stop Bar (feet)	0	0	0	100	100	100	100	100	100	250	250	250	250	250	250
Repetition 1, Vehicles per hour (vph)	2500	2500	2500	2500	2400	2400	2500	2400	2400	2500	2450	2400	2500	2500	2400
Repetition 2, Vehicles per hour (vph)	2500	2500	2500	2500	2400	2400	2500	2400	2400	2500	2500	2400	2500	2450	2400



Given the prevailing traffic conditions that will be created in the CORSIM models, the major simulation issue to be addressed was the selection of the number of vehicles per hour that was necessary to sustain a saturated traffic condition. To ensure that each case sustains this condition, each case was coded with an estimated number of vehicles per hour and was subsequently viewed in TRAFVU to verify that a continuous vehicular queue existed that kept the stop bar busy. An additional check of the CORSIM output for the average vehicle queue per lane was done to verify the saturated condition. A check of the number of bus stops serviced during the simulation time period was also performed. It was necessary for a sufficient number of buses ( $N_b$  greater than 10) to be serviced so the effect on the saturation flow rate is meaningful. Therefore, with the primary objective of sustaining a saturated traffic flow condition, a balance between the number of vehicles per hour and the average vehicle queue per lane to achieve a saturation flow condition with a sufficient number of buses serviced had to be maintained. As a result, the value for the number of vehicles per hour fluctuated between certain cases and, at times, specific runs.

### **Far-Side Simulation Results**

At the completion of the CORISM runs, the vehicle discharge per lane, the average dwell time, the number of bus stops, and the average vehicle queue per lane was retrieved from each model output for use in the analysis and is presented in Tables A1 – A5 in Appendix A. We then used the vehicle discharge and the effective green time proportion to calculate the simulated (Lane 1) and ideal (Lane 2) saturation flow rates. The ideal flow rate from Lane 2 was then used with the analytical equation developed earlier to find a predicted

saturation flow rate for each case. With two repetitions per case, an average simulated and an average predicted saturation flow rate for each case was calculated (Table 4).

**Table 4: Average Simulated and Predicted Flow Rates - Far Side Bus Cases**

<b>40-Second Effective Green</b>	<b>Case</b>											
	<b>14a</b>	<b>14b</b>	<b>14c</b>	<b>14d</b>	<b>14e</b>	<b>14f</b>	<b>14g</b>	<b>14h</b>	<b>14i</b>	<b>14j</b>	<b>14k</b>	<b>14l</b>
<b>Avg. Simulated Saturation Flow Rate, <math>u_1</math>, (pcphpl)</b>	1721	1646	1648	1648	1575	1628	1881	1772	1703	1863	1782	1691
<b>Avg. Predicted Saturation Flow Rate, <math>u_2</math>, (pcphpl)</b>	1683	1667	1630	1554	1569	1558	1847	1795	1764	1764	1780	1747
<b>Difference, <math>u_1 - u_2</math>, (pcphpl)</b>	38	-21	18	94	6	70	34	-23	-61	99	2	-56
<b>Difference<sup>2</sup>, <math>(u_1 - u_2)^2</math>, (pcphpl)<sup>2</sup></b>	1444	441	324	8836	36	4900	1156	529	3721	9801	4	3136
<b>60-Second Effective Green</b>	<b>Case</b>											
	<b>15a</b>	<b>15b</b>	<b>15c</b>	<b>15d</b>	<b>15e</b>	<b>15f</b>	<b>15g</b>	<b>15h</b>	<b>15i</b>	<b>15j</b>	<b>15k</b>	<b>15l</b>
<b>Avg. Simulated Saturation Flow Rate, <math>u_1</math>, (pcphpl)</b>	1655	1664	1623	1646	1572	1580	1806	1743	1682	1791	1731	1651
<b>Avg. Predicted Saturation Flow Rate, <math>u_2</math>, (pcphpl)</b>	1709	1700	1651	1658	1559	1574	1866	1781	1720	1780	1778	1736
<b>Difference, <math>u_1 - u_2</math>, (pcphpl)</b>	-54	-36	-28	-12	13	6	-60	-38	-38	11	-47	-85
<b>Difference<sup>2</sup>, <math>(u_1 - u_2)^2</math>, (pcphpl)<sup>2</sup></b>	2916	1296	784	144	169	36	3600	1444	1444	121	2209	7225
<b>80-Second Effective Green</b>	<b>Case</b>											
	<b>16a</b>	<b>16b</b>	<b>16c</b>	<b>16d</b>	<b>16e</b>	<b>16f</b>	<b>16g</b>	<b>16h</b>	<b>16i</b>	<b>16j</b>	<b>16k</b>	<b>16l</b>
<b>Avg. Simulated Saturation Flow Rate, <math>u_1</math>, (pcphpl)</b>	1794	1730	1606	1775	1688	1689	1864	1722	1631	1858	1771	1625
<b>Avg. Predicted Saturation Flow Rate, <math>u_2</math>, (pcphpl)</b>	1740	1762	1680	1602	1618	1568	1816	1807	1739	1746	1794	1735
<b>Difference, <math>u_1 - u_2</math>, (pcphpl)</b>	54	-32	-74	173	70	121	48	-85	-108	112	-23	-110
<b>Difference<sup>2</sup>, <math>(u_1 - u_2)^2</math>, (pcphpl)<sup>2</sup></b>	2916	1024	5476	29929	4900	14641	2304	7225	11664	12544	529	12100
<b>100-Second Effective Green</b>	<b>Case</b>											
	<b>17a</b>	<b>17b</b>	<b>17c</b>	<b>17d</b>	<b>17e</b>	<b>17f</b>	<b>17g</b>	<b>17h</b>	<b>17i</b>	<b>17j</b>	<b>17k</b>	<b>17l</b>
<b>Avg. Simulated Saturation Flow Rate, <math>u_1</math>, (pcphpl)</b>	1803	1667	1629	1751	1678	1637	1847	1729	1643	1857	1739	1643
<b>Avg. Predicted Saturation Flow Rate, <math>u_2</math>, (pcphpl)</b>	1804	1774	1749	1710	1633	1623	1907	1817	1714	1788	1787	1706
<b>Difference, <math>u_1 - u_2</math>, (pcphpl)</b>	-1	-107	-120	41	45	14	-60	-88	-71	69	-48	-63
<b>Difference<sup>2</sup>, <math>(u_1 - u_2)^2</math>, (pcphpl)<sup>2</sup></b>	1	11449	14400	1681	2025	196	3600	7744	5041	4761	2304	3969

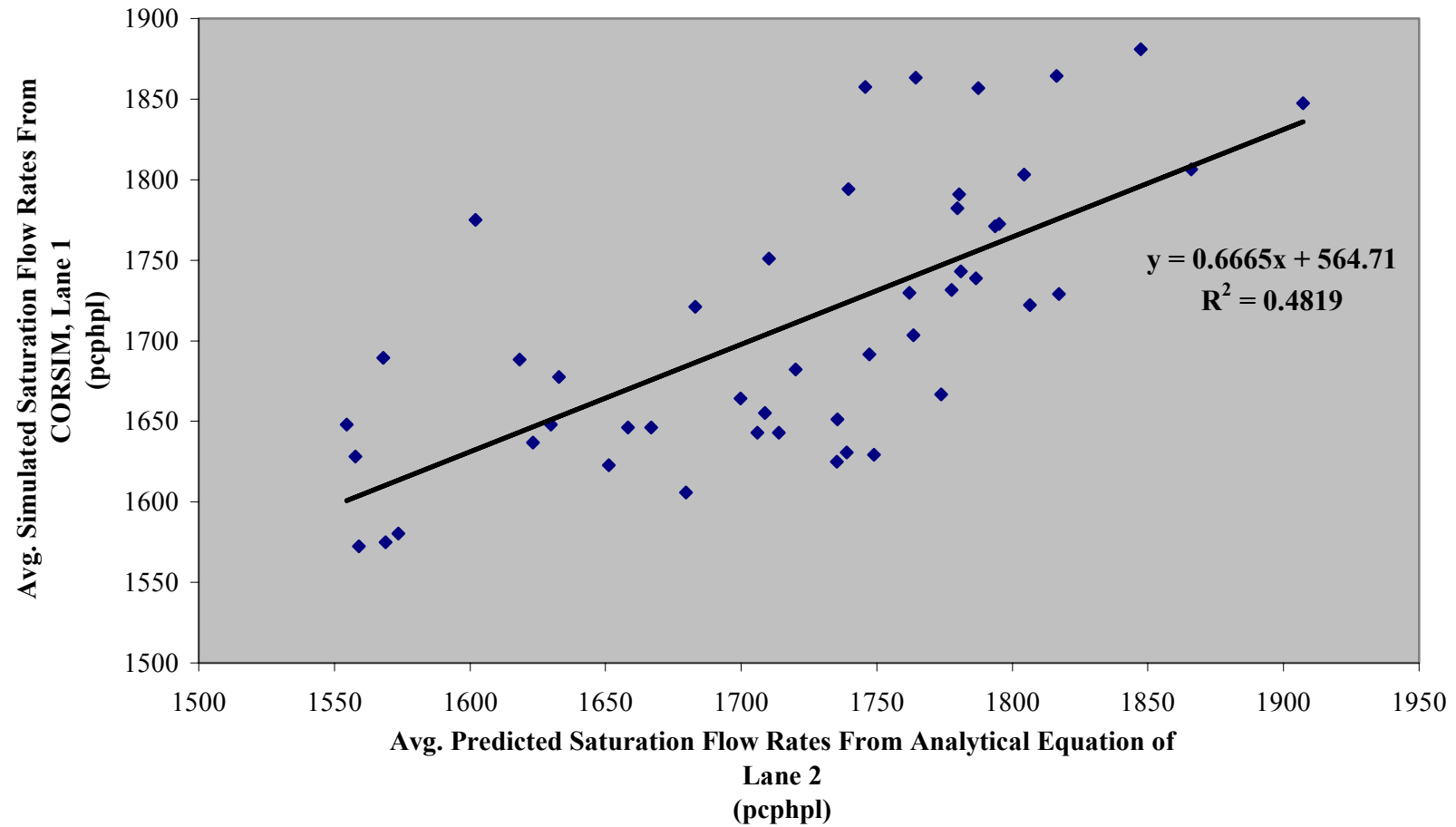
As was noted in Chapter 4, there are two assumptions that must be satisfied for the far-side equation to be valid. In calculating the predicted flow rate, we note that each run with a suffix of 'g, h, i, and l' did not satisfy these assumptions as the middle term of the equation (the duration of  $P_2$ ) had negative values. It appears that these cases had bus stops that were so far away from the intersection with dwell times that were so short that they did not affect the intersection saturation flow rate. With the bus stop no longer a factor on the saturation flow rate, the value for the average number of vehicles with a bus stop that could be processed by the travel lane for these cases were equated to the average number of vehicles that are processed in  $P_3$  (g/h). As a result, these runs were not selected as acceptable cases for further analysis regarding the far-side analytical equation. More explanation will be provided on those cases later in this chapter.

A further review of the predicted saturation flow rate values from the far-side analytical equation revealed lower than expected values for each 'd, e, and f' cases. Though the middle terms for these cases were positive, a further review of the first vehicle term for  $P_1$  of the far-side equation reveals lower than expected values. With all other first term values for the equation remaining relatively higher and more consistent for the other cases, each 'd, e, and f' case was not selected for further analysis. More explanation will be provided on those cases later in this chapter.

With the remaining cases that do satisfy the equation assumptions and expectations, a scatter plot of the average predicted flow rate (x-axis) and the average simulated flow rate (y-axis) of the accepted cases (Figure 5) was created with a 'best-fit' trend line equation in form of ' $y = mx + b$ ' derived to evaluate if any relationship between the predicted and simulated

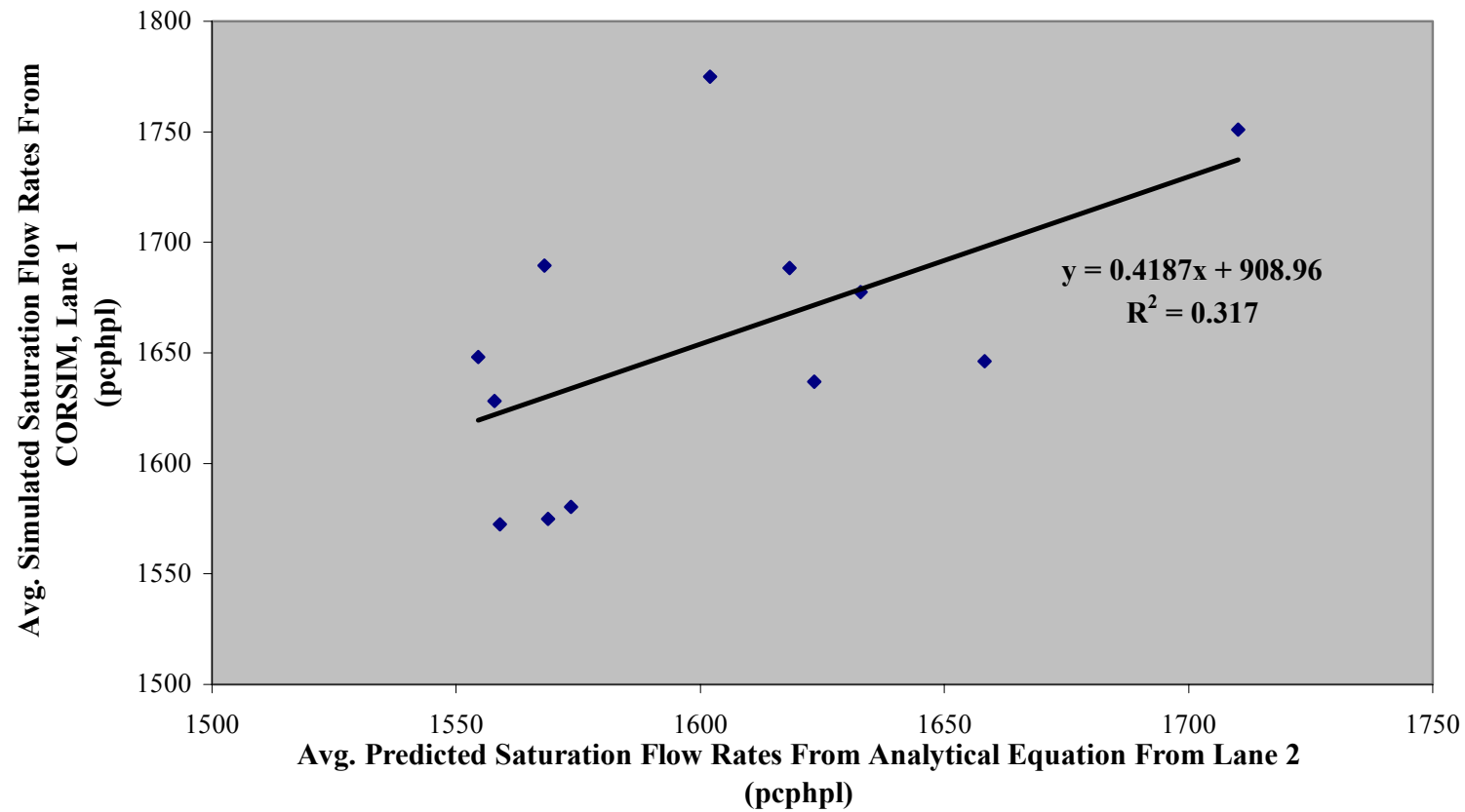
flow rates exists. In addition, to evaluate their applicability with the remaining cases that were selected for further analysis, a scatter plot of the average predicted and average simulated saturation flow rate values for all 'd, e, and f' cases (Figure 6) and 'g, h, i, and l' cases (Figure 7) was created with a 'best-fit' trend line equation,  $y = mx + b$ , provided to evaluate if the relationship among these cases matched the relationship among the acceptable cases.

**Far-Side Bus Stop**  
**Avg. Predicted Saturation Flow Rates vs**  
**Avg. Simulated Saturation Flow Rates**  
**(Accepted Cases Only)**

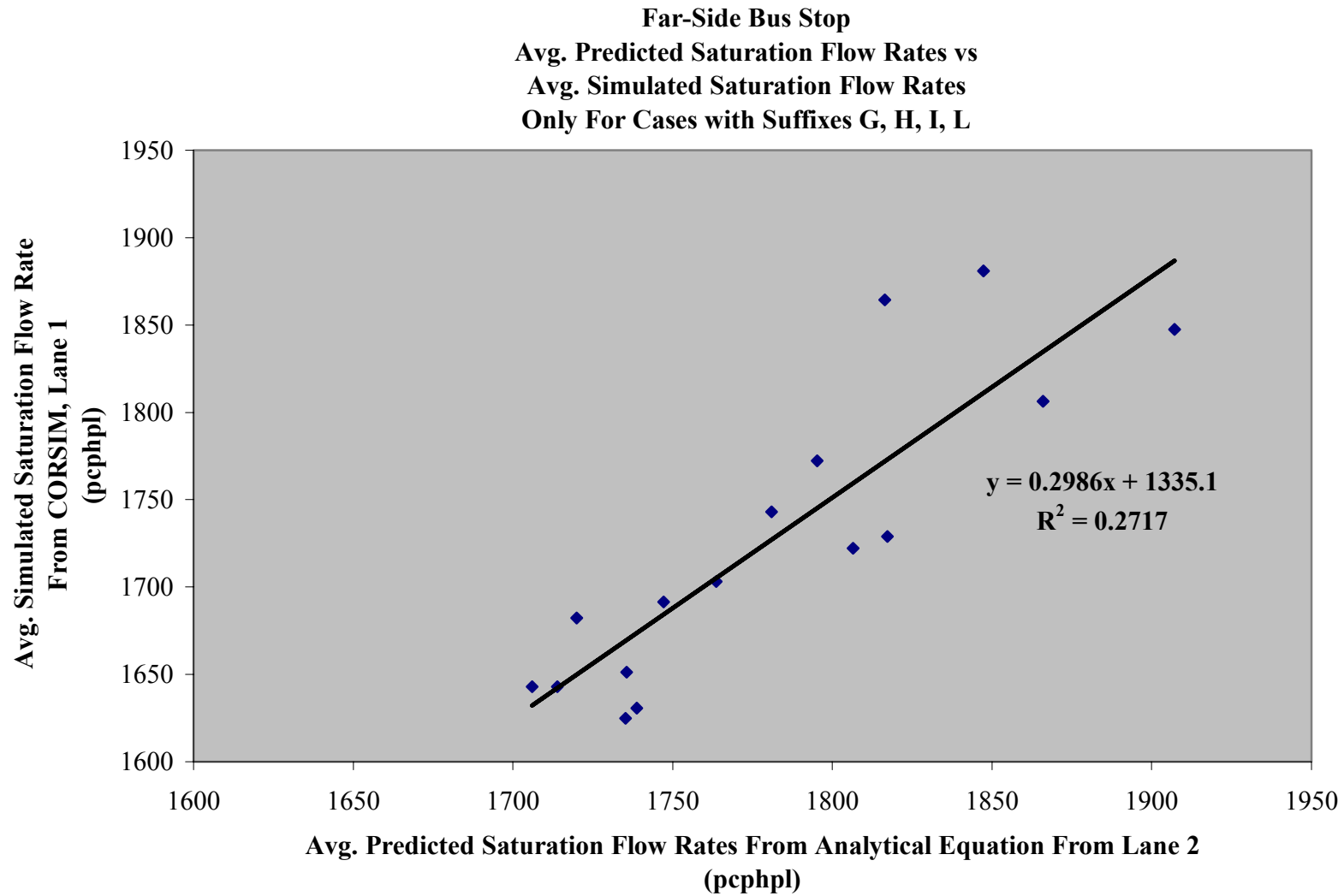


**Figure 5**

**Far-Side Bus Stop**  
**Avg. Predicted Saturation Flow Rates vs Avg. Simulated Saturation Flow Rates**  
**Only For Cases with Suffixes D, E, F**



**Figure 6**



**Figure 7**



### Far-Side Statistical Testing

To examine the output data in detail, the Lane 1 (simulated) saturation flow rates for each case were grouped by each parameter that is varied in the far-side experiment (dwell time, effective green time, proportion of right-turns by approach, and bus stop location). An average saturation flow rate was calculated for each group and was tested using the 'T-test' against every other group. Table 5 through 15 shows the T-test results.

**Table 5: T-test Results of Dwell Time, 15 sec vs 30 sec**

<b>Output Dwell Time (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
15	$u_1$	48	1717	87.20
30	$u_2$	48	1703	93.52
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            0.768 T-critical value        1.99 Null Hypothesis?      Accepted				

**Table 6: T-test Results of Effective Green Time, 40 sec vs 60 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
40	$u_1$	24	1713	99.56
60	$u_2$	24	1679	76.90
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -2.048 T-critical value        -2.014 Null Hypothesis?      Rejected				

**Table 7: T-test Results of Effective Green Time, 40 sec vs 80 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
40	$u_1$	24	1713	99.56
80	$u_2$	24	1729	93.47
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -0.580 T-critical value        -2.014 Null Hypothesis?      Accepted				

**Table 8: T-test Results of Effective Green Time, 40 sec vs 100 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
40	$u_1$	24	1713	99.56
100	$u_2$	24	1719	86.96
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -0.194 T-critical value        -2.014 Null Hypothesis?      Accepted				

**Table 9: T-test Results of Effective Green Time, 60 sec vs 80 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
60	$u_1$	24	1679	76.90
80	$u_2$	24	1729	93.47
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -2.048 T-critical value       -2.014 Null Hypothesis?      Rejected				

**Table 10: T-test Results of Effective Green Time, 60 sec vs 100 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
60	$u_1$	24	1679	76.90
100	$u_2$	24	1719	86.96
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -1.674 T-critical value       -2.014 Null Hypothesis?      Accepted				

**Table 11: T-test Results of Effective Green Time, 80 sec vs 100 sec**

<b>Effective Green (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
80	$u_1$	24	1729	93.47
100	$u_2$	24	1719	86.96
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            0.419 T-critical value        2.014 Null Hypothesis?      Accepted				

**Table 12: T-test Results of the Proportion of Right-Turns, 0.00 vs 0.25**

<b>Right Turn Proportion By Approach</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
0.00	$u_1$	32	1785	84.91
0.25	$u_2$	32	1701	70.89
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            4.318 T-critical value        2.00 Null Hypothesis?      Rejected				

**Table 13: T-test Results of the Proportion of Right-Turns, 0.00 vs 0.50**

<b>Right Turn Proportion By Approach</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
0.00	$u_1$	32	1785	84.91
0.50	$u_2$	32	1644	48.62
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            8.131 T-critical value        2.00 Null Hypothesis?      Rejected				

**Table 14: T-test Results of the Proportion of Right-Turns, 0.25 vs 0.50**

<b>Right Turn Proportion By Approach</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
0.25	$u_1$	32	1701	70.89
0.50	$u_2$	32	1644	48.62
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            3.698 T-critical value        2.00 Null Hypothesis?      Rejected				

**Table 15: T-test Results of Bus Stop Location, 100 Feet vs 250 Feet**

<b>Bus Stop Location (feet)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
100	$u_1$	48	1669	75.43
250	$u_2$	48	1751	85.50
Null Hypothesis $u_1 - u_2 = 0$ T-statistic            -4.996 T-critical value       -1.99 Null Hypothesis?     Rejected				

The results of the T-tests showed that most parameters, when statistically tested against other values, resulted in an acceptance of the null hypothesis that the two average flow rates involved in the test were similar. However, a few test results did conclude otherwise. Foremost, testing the proportions of right turns resulted in a rejection of the null hypothesis,  $H_0$ , in all test cases (Tables 12 – 14). Therefore, it can be stated conclusively that as the proportion of right-turns changed the magnitude of the simulated saturation flow rate changed as well. Secondly, the bus stop location T-test (Table 15) reveals that the distance of the bus stop from the stop bar affected the saturation flow rate value as well. The effective green time tests indicated a rejection of the null hypothesis for those tests that involved the 60-second effective green time.

The scatter plot (Figure 5) of the accepted cases yielded a trend line equation of  $y = 0.6665x + 564.71$  with an R-square value of 0.4819. The mid-level  $R^2$  value indicates that the data points were mildly scattered, but overall, a relationship between the points is clearly evident. In addition, with a slope edging close to one and an intercept fairly close to zero considering the magnitude of the saturation flow rate values, the equation shows that the

predicted and simulated values matched very well. When these simulated and predicted flow rate values are compared using a two-tailed, paired T-test with a 0.05 level of confidence, the null hypothesis,  $H_0$ , that stated the simulated and predicted flow rate values are equal, was accepted (Table 16). As a result, the statistical test confirmed that the means are statistically similar at a 0.05 confidence level.

**Table 16: T-Test Results of Predicted vs Simulated Flow Rates for Accepted Cases**

Statistical Terms	Values
Null Hypothesis, $H_0$	$\mu_1 - \mu_2 = 0$
$\bar{X}_d$	9.26
$S_d^2$	5177
$S_d$	71.95
T-statistic	0.814
Degrees of Freedom	39
Confidence Level	0.05
T-critical value	2.02
Null Hypothesis?	Accepted

In reviewing the simulation runs, it was observed that for more than one bus trip, the bus is seen crossing the stop bar of the intersection in Lane 2 (the exclusive through lane), halting in Lane 2 for any processed vehicles in Lane 1 to clear the bus stop area, and proceeding to crossover into Lane 1 to perform its stop with no queued vehicles in the storage between it and the stop bar. This bus behavior and maneuver is potentially the explanation that led to the lower predicted saturation flow rate values for the ‘d, e, and f’ cases. When the average predicted and average simulated saturation flow rate values for these cases are shown on a scatter plot (Figure 6), the resulting trend line equation,  $y = 0.4187x + 908.96$ , and  $R^2$  value of 0.317 indicates that the flow rate values matched

fairly well, though not as well as the accepted cases as shown in Figure 5. In addition, when a paired T-test (Table 17) is performed for the predicted and simulated saturation flow rate values for these cases, the null hypothesis that the values of the flow rates are equal was rejected.

**Table 17: T-test Results of Cases D, E, and F**

<b>Statistical Terms</b>	<b>Values</b>
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	53.50
$S_d^2$	4649
$S_d$	68.19
T-statistic	3.844
Degrees of Freedom	23
Confidence Level	0.05
T-critical value	2.07
Null Hypothesis?	Rejected

When the average predicted and average simulated saturation flow rate values for cases 'g, h, i, and l' are shown on a scatter plot (Figure 7), the resulting trend line equation,  $y = 0.2986x + 1335.1$ , with a slope near zero, a y-intercept fairly distant from zero, and a  $R^2$  value of 0.2717, indicates that the flow rate values are widely scattered and did not match well. When a paired T-test (Table 18) is performed for the predicted and simulated saturation flow rate values for these cases, the null hypothesis that the values of the flow rates are equal was rejected.



**Table 18: T-test Results of Cases G, H, I, and L**

<b>Statistical Terms</b>	<b>Values</b>
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	123.575
$S_d^2$	6146.2
$S_d$	78.40
T-statistic	8.917
Degrees of Freedom	31
Confidence Level	0.05
T-critical value	2.04
Null Hypothesis?	Rejected

### **Comparison against the HCM Method for the Far-Side Bus Stop**

With the results shown in Table 16 indicating that the predicted flow rate values for the acceptable cases are statistically similar to the simulated saturation flow rates, a comparison of the flow rates calculated with the current HCM method against the simulated flow rates from the CORSIM runs and the predicted flow rates resulting from the revised  $F_{bb}$  analytical equation was performed (Table 19 and 20, respectively).

**Table 19: T-test of Simulated Flow Rates vs HCM Flow Rates for Far-Side Stops**

<b>Statistical Terms</b>	<b>Values</b>
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	-17.551
$S_d^2$	7008.334
$S_d$	83.716
T-statistic	-2.054
Degrees of Freedom	95
Confidence Level	0.05
T-critical value	-1.99
Null Hypothesis?	Rejected

**Table 20: T-test of Predicted Flow Rates vs  
HCM Flow Rates for Far-Side Stops**

<b>Statistical Terms</b>	<b>Values</b>
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	31.69
$S_d^2$	3343
$S_d$	57.82
T-statistic	4.651
Degrees of Freedom	71
Confidence Level	0.05
T-critical value	2.02
Null Hypothesis?	Rejected

As Tables 19 and 20 show, the current HCM  $F_{bb}$  adjustment for bus stops does not produce statistically similar results as compared to both the simulated flow rates from CORSIM and the predicted flow rates from the analytical equation. Therefore, when the results of this test are coupled with the majority of the other statistical tests that show a similarity between the simulated flow rates from CORSIM and the predicted flow rates from the analytical equation, the analytical equation is shown to more accurately estimate the adjustment for the effect of the far-side bus stop.

#### **Far-Side Equation: Sensitivity Analysis**

Looking at the results of the scatter plots and the statistical testing, it can be stated that the magnitude of certain parameters can affect the predicted saturation flow rate values that result from the far-side analytical equation. According to the statistical testing, varying

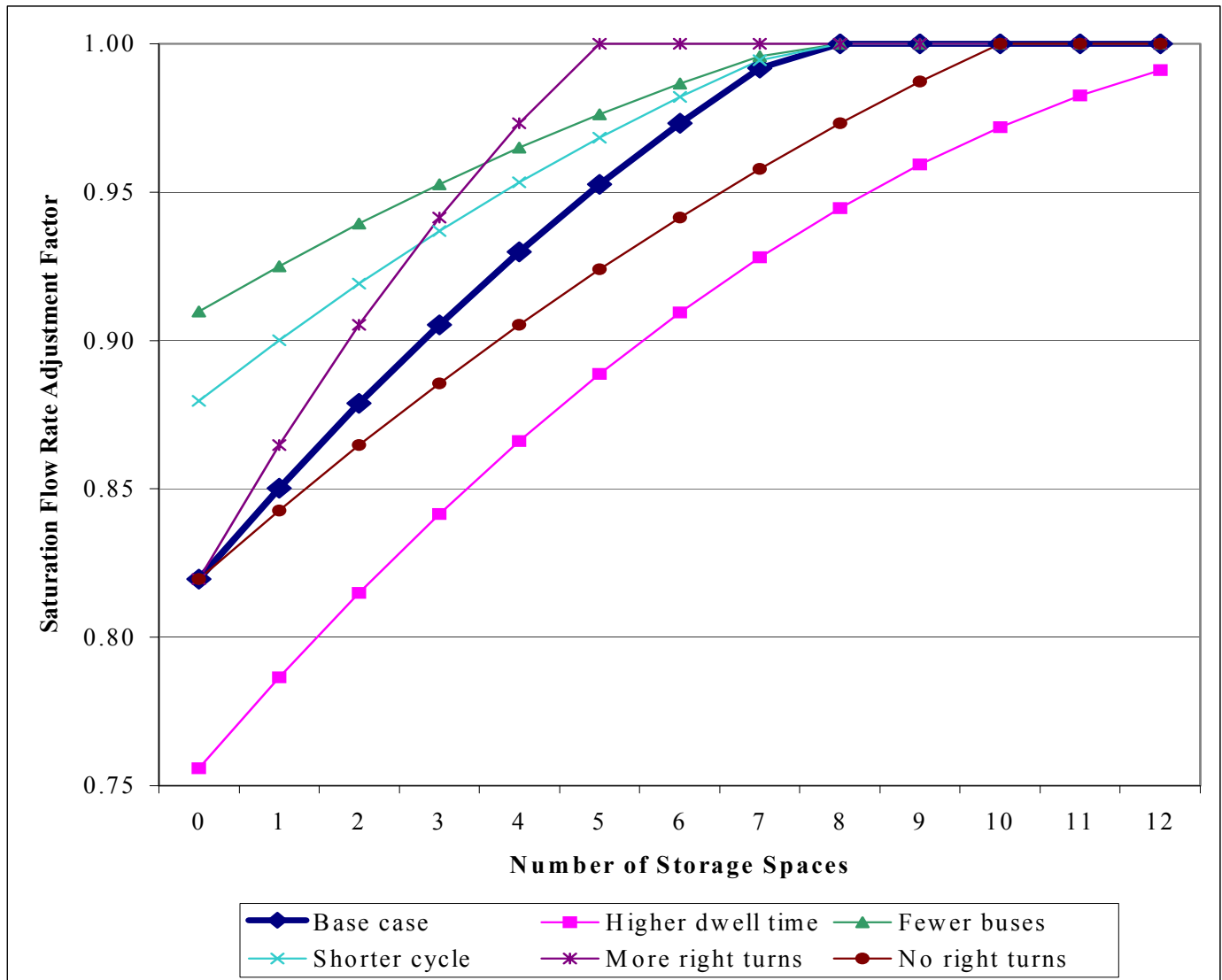
the magnitude of the  $P_{rt}$  and the bus stop location, which translates into the number of storage spaces, has an affect on the resulting value of the equation. After reviewing the 'g, h, i, and l' cases models, it was concluded that a short dwell time and a longer distance, i.e., more vehicle storage spaces, from the stop bar to the bus stop, made the effects of the bus stop irrelevant to the saturation flow rate. To analyze this irrelevance, it was decided that a sensitivity analysis to evaluate when the values of these parameters are of no relevance to the saturation flow rate, i.e., a saturation flow rate adjustment factor equal to 1.00, would be performed.

As a base case, an effective green time of 40 seconds was selected with a 150 second cycle length, a proportion of right-turns of 0.25, a bus dwell time of 15 seconds, and 12 bus stops ( $N_b$ ). Each successive case will vary a selected parameter from this base case. With the objective of this analysis to only gauge the sensitivity of the equation's variables, no CORSIM simulation was necessary. Therefore, the ideal saturation flow rate of 1,900 pcphpl from the 2000 HCM was used. A collection of cases that varies the dwell time, the proportion of right-turns, the cycle length, and the number of bus stops in an hour are created. For each case, the resulting saturation flow rate adjustment factor was calculated for the number of possible vehicle storage spaces that range from 1 to 12 to determine the point at which the bus stop location had minimal to no effect on the saturation flow rate. Table 21 presents the parameters used for each sensitivity case.

**Table 21: Case Inputs for Sensitivity Analysis**

<b>Case Name</b>	<b>Effective Green Time (sec)</b>	<b>Cycle Length (sec)</b>	<b>Proportion Right-Turns <math>P_{rt}</math></b>	<b>Dwell Time (sec)</b>	<b>Bus Stops (<math>N_b</math>)</b>
Base	40	150	0.25	15	12
Higher dwell time	40	150	0.25	30	12
Fewer bus stops	40	150	0.25	15	6
Shorter cycle length	40	100	0.25	15	12
More right-turns	40	150	0.50	15	12
Less right-turns	40	150	0.00	15	12

The sensitivity analysis calculated a saturation flow rate adjustment factor for each vehicle storage space in each case. These calculated flow rate adjustment factors are seen in Figure 8.



**Figure 8: Plot of Sensitivity Analysis Results**

As Figure 8 shows, the far-side equation is shown to be more sensitive to its parameters.

Therefore, with the sensitivity of its parameters and the additional statistical testing of the results of the analytical equation, it is concluded that using the analytical equation to estimate the effects of a far-side bus stop should be pursued.

### **Near-Side Bus Stop Experiment**

Cases 18, 19a, 19b, 19c simulated the near-side bus stop. With only four cases, to obtain statistically significant results, each case was repeated ten times with different random number seeds applied for each repetition. As was done for the far-side scenario, these random number seeds were selected from a Microsoft Excel spreadsheet. Case 18 served as the base condition in which all the necessary input parameters are held constant with no bus route or bus stop. A cycle length of 100 seconds was selected for all four cases that result in 36 signal cycles per hour of simulation time. As was previously noted in the equation formulation for the near-side bus stop, as the effective green time is not a significant factor in evaluating the effects of bus stops, it is not necessary to simulate more than one level of effective green. Therefore, an effective green time value of 40 seconds was selected. A right-turn percentage of 10% of the traffic volume for the approach was selected. For cases 19a – 19c, a single, near-side bus stop is located upstream of and at the stop bar. Bus dwell time values of 15 seconds (case 19a), 30 seconds (case 19b), and 45 seconds (case 19c) were simulated. A bus headway of 5 minutes was selected to allow each bus and bus stop to remain independent of the preceding and proceeding one.

Again, the major simulation issue to address was the selection of the number of vehicles per hour that sustains a saturated traffic condition. To verify that each case sustained this condition, each simulation run was coded with an estimated number of vehicles per hour and was subsequently viewed in TRAFVU to verify that a continuous vehicular queue existed that kept the stop bar busy. An additional check of the CORSIM output for the average vehicle queue per lane was done to verify the saturated condition. For cases 19a,

19b, and 19c, another check of the number of bus stops serviced during the simulation time period was done. It was necessary for a sufficient number of buses ( $N_b$  greater than 10) to be serviced so the effects on the saturation flow rate can be measured. Therefore, with the primary objective of sustaining a saturated traffic flow condition, a balance between the number of vehicles per hour and the average vehicle queue per lane to achieve a saturation flow condition with a sufficient number of buses serviced was accomplished. Table 22 summarizes the input for each near-side bus stop case.

**Table 22: Inputs for Near-Side Cases**

<b><u>Case</u></b>	<b><u>18</u></b>	<b><u>19a</u></b>	<b><u>19b</u></b>	<b><u>19c</u></b>
<b>Effective green (g), sec</b>	40	40	40	40
<b>Green time (g), sec</b>	38	38	38	38
<b>Cycle length (sec)</b>	100	100	100	100
<b>Rt. Turn % by approach</b>	5	5	5	5
<b>Dwell time, sec</b>	0	15	30	45
<b>Bus headway (minute)</b>	0	5 minutes	5 minutes	5 minutes
<b>Vehicles per hour, vph</b>	1500	1400	1400	1400

### **Near-Side Simulation Results**

At the completion of the CORISM runs, the vehicle discharge per lane, the average simulated dwell time, the number of bus stops, and the average vehicle queue per lane was retrieved from the outputs for analysis and is presented in Tables B1 and B2 in Appendix B.

After utilizing the vehicle discharge and the effective green time proportion to calculate the simulated (Lane 1) and ideal (Lane 2) saturation flow rates, transforming the ideal flow rate to a predicted flow rate value using the equation developed in Chapter 4 was done.

The average simulated dwell time and the number of bus stops that was obtained from the CORSIM output was used in the analytical equation. In addition, the adjustment factor for the proportion of right-turns for the shared travel lane that occurs in each case for Lane 1 was calculated and applied. With the average simulated and average predicted saturation flow rates at hand (Table 23), a scatter plot (Figure 9) of the average predicted saturation flow rate (x-axis) against the average simulated saturation flow rate (y-axis) was created and a ‘best-fit’ trend line equation in form of ‘ $y = mx + b$ ’ was derived to evaluate if any relationship between the flow rates exists.

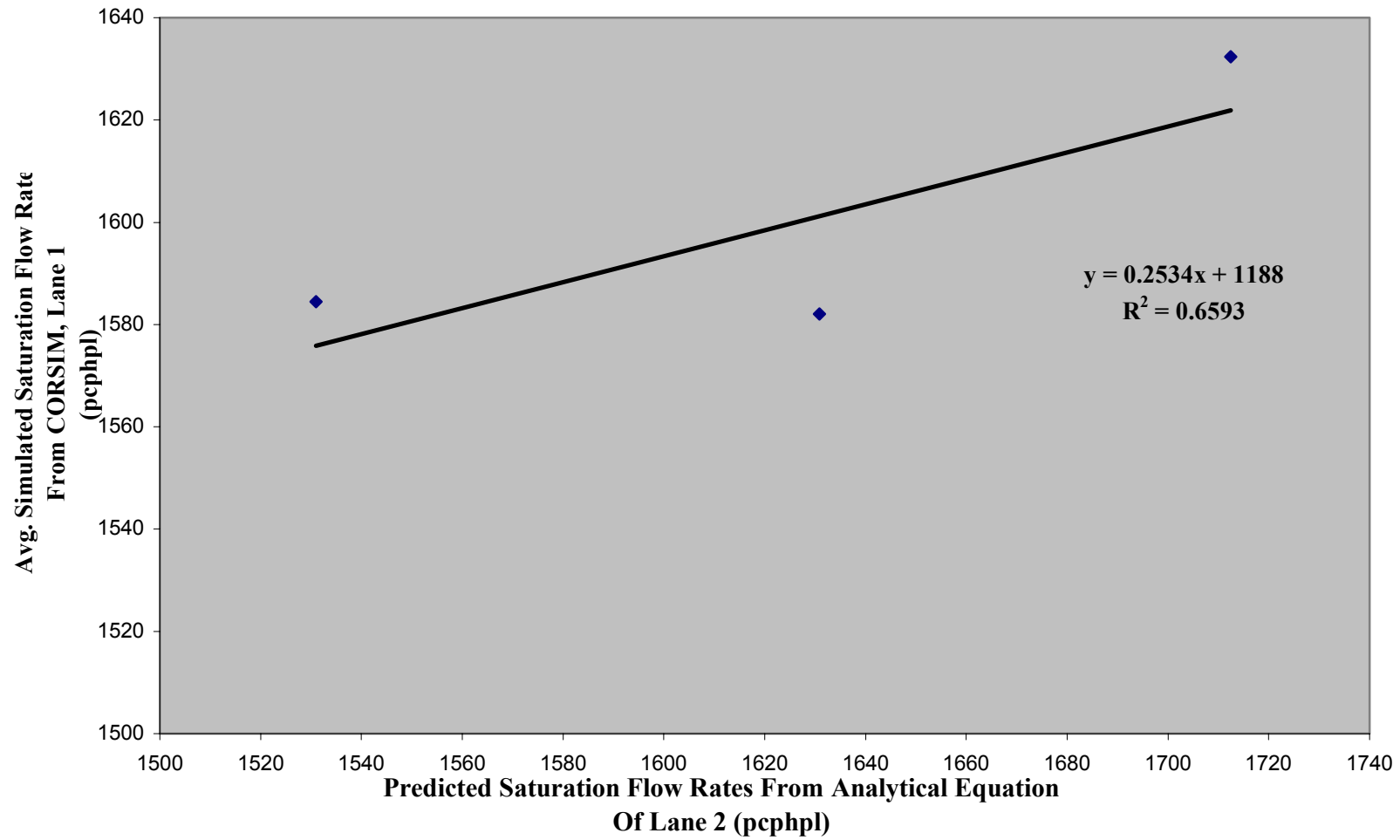
**Table 23: Average of Simulated and Predicted Saturation Flow Rate Values – Near Side Cases**

	Case		
	19a	19b	19c
<b>Dwell Time (sec)</b>	15	30	45
<b>Avg. Simulated Saturation Flow Rate, <math>u_1</math>, (pcphpl)</b>	1632	1582	1584
<b>Avg. Predicted Saturation Flow Rate, <math>u_2</math>, (pcphpl)</b>	1712	1631	1531
<b>Difference, <math>u_1 - u_2</math>, (pcphpl)</b>	-80	-49	53
<b>Difference<sup>2</sup>, <math>(u_1 - u_2)^2</math>, (pcphpl)<sup>2</sup></b>	6400	2401	2809

Similar to the far-side results, with a slope near zero and a y-intercept fairly distant from zero, the trend line equation and the  $R^2$  value for the near-side bus stops,  $y = 0.2534x + 1188$  and 0.6593 respectively, shows that the near-side results of the predicted and simulated saturation flows did not match well. However, a high  $R^2$  value did indicate that the values were not widely scattered. The simulated and predicted saturation flow rate values for all repetitions were then compared using a paired T-test (Table 24).



**Near-Side Bus Stop**  
**Avg. Predicted Saturation Flow Rates vs**  
**Avg. Simulated Saturation Flow Rates**



**Figure 9**

**Table 24: T-test of Predicted Flow Rates vs Simulated Flow Rates for Near-Side Stops**

Statistical Terms	Values
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	25.08
$S_d^2$	8352
$S_d$	91.39
T-statistic	1.503
Degrees of Freedom	29
Confidence Level	0.05
T-critical value	2.05
Null Hypothesis?	Accepted

When both sets of flow rates were evaluated in a two-tailed, paired T-test with a 0.05 confidence level, the null hypothesis,  $H_0$ , that the means of the saturation flow rate values are essentially equal was accepted.

Additional statistical tests compared the average simulated saturation flow rates by bus dwell time (15 seconds, 30 seconds, and 45 seconds) in Tables 25 – 27.

**Table 25: T-test Results of Dwell Time, 15 sec vs 30 sec**

Input Dwell Time (sec)	Population Number	N (number of samples)	Mean, Lane 1 (pcphpl)	Standard Deviation (s)
15	$u_1$	10	1632	48.00
30	$u_2$	10	1582	49.28
Null Hypothesis $u_1 - u_2 = 0$				
Degree of Freedom 18				
Confidence Level 0.05				
T-statistic 2.31				
T-critical value 2.10				
Null Hypothesis? Rejected				

**Table 26: T-test Results of Dwell Time, 15 sec vs 45 sec**

<b>Input Dwell Time (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
15	$u_1$	10	1632	48.00
45	$u_2$	10	1584	81.11
Null Hypothesis $u_1 - u_2 = 0$ Degree of Freedom 18 Confidence Level 0.05 T-statistic 1.61 T-critical value 2.10 Null Hypothesis? Accepted				

**Table 27: T-test Results of Dwell Time, 30 sec vs 45 sec**

<b>Input Dwell Time (sec)</b>	<b>Population Number</b>	<b>N (number of samples)</b>	<b>Mean, Lane 1 (pcphpl)</b>	<b>Standard Deviation (s)</b>
30	$u_1$	10	1582	49.28
45	$u_2$	10	1584	81.11
Null Hypothesis $u_1 - u_2 = 0$ Degree of Freedom 18 Confidence Level 0.05 T-statistic -0.08 T-critical value -2.10 Null Hypothesis? Accepted				

In performing T-tests comparing the average flow rates for each bus dwell time, the null hypotheses of equal means was accepted except for the comparison of the 15-second dwell time against the 30-second dwell time. It is possible that the dwell time does not matter above 30 seconds for near-side bus stops with the cycle length and green time tested because the stop is simply completed during the red phase.

### Comparison against the HCM Method for Near-Side Bus Stop Cases

With the results shown in Table 24 indicating that the predicted flow rate values are statistically similar to the simulated saturation flow rates, a comparison of the flow rates calculated with the current HCM  $F_{bb}$  equation against the simulated flow rates from the CORSIM runs and the predicted flow rates resulting from the revised  $F_{bb}$  analytical equation was performed (Table 28 and 29, respectively).

**Table 28: T-test of Simulated Flow Rates vs HCM Flow Rates for Near-Side Stops**

Statistical Terms	Values
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	-183.69
$S_d^2$	5009.08
$S_d$	70.77
T-statistic	-14.22
Degrees of Freedom	29
Confidence Level	0.05
T-critical value	-2.05
Null Hypothesis?	Rejected

**Table 29: T-test of Predicted Flow Rates vs HCM Flow Rates for Near-Side Stops**

Statistical Terms	Values
Null Hypothesis, $H_0$	$u_1 - u_2 = 0$
$X_d$	-158.62
$S_d^2$	5593.90
$S_d$	74.79
T-statistic	-11.62
Degrees of Freedom	29
Confidence Level	0.05
T-critical value	-2.05
Null Hypothesis?	Rejected

The results of Tables 28 and 29 show that the current HCM adjustment equation for bus stops does not produce statistically similar results to the simulated flow rates or those flow rates calculated using the revised analytical equation. Therefore, when the results of this test are coupled with the initial test (Table 24) that shows a similarity between the simulated flow rates from CORSIM and the predicted flow rates from the analytical equation, it can be conclusively stated that the analytical equation more accurately estimates the adjustment for the effect of the near-side bus stop.

## Chapter 6: Conclusions and Recommendations

The goal of the research was to analyze the effects of a bus stop on the saturation flow rate of a signalized intersection through the development of analytical equations with simple, available inputs that estimated those bus stop effects. After reviewing the Highway Capacity Manual (HCM), the  $F_{bb}$  adjustment factor equation was found to use an average bus blockage time of 14.4 seconds. However, a review Chapter 27 of the 2000 HCM revealed that, with the absence of any field data, a total bus blockage value that equates to an average bus dwell time of fifteen seconds plus an additional ten seconds to account for the deceleration and acceleration to enter and exit a stop, or twenty-five seconds, was recommended. Based on these differing bus blockage times and on a derivation of the  $F_{bb}$  equation that determined the parameters that are of no consequence for the near-side bus stop, CORSIM research was performed for the near-side bus stop in which the expression of dwell time plus ten seconds was used in the  $F_{bb}$  equation. After comparing the simulated saturation flow rates from CORSIM with the predicted saturation flow rates calculated using the analytical equation, it was concluded that these flow rate values for the near-side bus stop were similar. An additional comparison of the predicted flow rate values was done against the HCM adjustment for  $F_{bb}$ . This comparison conclusively showed that the HCM adjustment did not estimate the bus stop effects as accurately as did the revised analytical equation. Therefore, based on the results of these comparisons, as the research replaced the value of 14.4 in the analytical equation for a near-side bus stop, it is recommended that the value of 14.4 seconds be replaced in the HCM  $F_{bb}$  equation by the value of twenty-five seconds to be more consistent with Chapter 27. As a note, since the dwell time was an

important factor in the replacement of the 14.4 value, if one expects dwell times to be longer, one should use the actual dwell time rather than the assigned fifteen second value.

In reviewing the far-side bus stop, the derivation of an equation was performed by breaking the stop down into three distinct time periods. Using an average vehicle headway, an analytical equation dependent upon the effective green time, the bus dwell time, the proportion of right-turns at the intersection, and the number of storage spaces between the bus and the stop bar was derived. As was done for the near-side bus stop, CORSIM simulation runs were done for a far-side bus stop. Data retrieved from the CORSIM output was used in the analytical equation to calculate a predicted saturation flow rate. A comparison of the simulated flow rates from CORSIM with the predicted flow rates from the analytical equation indicated that the parameters for the proportion of right-turns and the bus stop location have a direct affect the intersection's saturation flow rate value. Using these selected parameters along with a number of bus stops and a dwell time for each stop, a sensitivity analysis clearly indicated that differing values of these parameters do have a significant effect on the results of the far-side analytical equation. With the very limited amount of parameters utilized in the current HCM  $F_{bb}$  equation ( $N$  and  $N_b$ ) and its unrealistic value for the average bus blockage time (14.4), its sensitivity to the effects of the far-side bus stop on the intersection is questionable. Therefore, it is recommended that the separate analytical equation created here by the researchers should replace the current HCM equation in evaluating the effects of the far-side bus stop.

### **Future Work**

Although significant strides and results were achieved by this research, as the promotion of the use of transit as a mode of travel continues to increase, the treatment and design of the bus stops where passengers are to be served will continue to be an issue to both the transit professional and the traffic engineer. Therefore, considerable effort will still be needed to more accurately estimate the effect bus stops have on the saturation flow rate at signalized intersections. Initially, it was felt by the researcher that the amount of CORSIM simulations performed were sufficient. However, as the  $R^2$  values that were derived for each plot of the analytical equations indicated a widespread diversity of the simulated and predicted flow rates, to produce data that are more concentrated along a resulting trend line, perhaps more simulations should be done. Though the justification to use a pretimed traffic signal in a saturated traffic condition was done by the researcher, as public agencies continue the trend of constructing actuated traffic signals that are optimized to process the maximum amount of vehicular traffic volume possible, research that uses these developed analytical equations with an actuated traffic signal will be necessary. In addition, where transit vehicles are a major factor in the traffic stream, it could be beneficial to expand this research to evaluate traffic conditions where the traffic signal timing is focused on maintaining the transit schedule. In analyzing the placement of bus stops relative to the intersection, only those stops that occurred in a through movement direction, from upstream to downstream, were examined by the researcher. However, if a bus stop is located in the direction of travel for an auxiliary turning vehicle, its effect on the vehicles wishing to resume travel in this direction may prove beneficial. In reviewing the analytical equations that were derived by



the researcher, the recommendations were centered on the replacement of the bus blockage time in the HCM  $F_{bb}$  adjustment factor with a more consistent value found in Chapter 27 of the 2000 HCM (25 seconds). However, it is worth noting that, in particular with the far-side bus stop, the vehicles adjusted for the lost time and the start-up time when a vehicle moves and as the bus departs its stop were included as terms in the analytical equation. One of the issues that arose after the completion of this research was whether this lost time and start-up time was already accounted for in the bus blockage time. Further research to evaluate this inclusion is recommended; though, it is important to note that as the values for these two factors are relatively low, their effects on the saturation flow rate are probably minimal as well. As this research concentrated its focus on the bus stop effects of vehicle operations, the effect that alternative bus stop designs and treatments may have on transit procedures and operations was not reviewed. As traffic engineers begin to develop policies toward bus stop placement, it would be informative for research that evaluated the effects that these bus stops have on transit procedures and operations are available. Lastly, though the CORSIM software has a high quality track record in estimating transportation effects, it is field data, validation, and calibration that serve to provide CORSIM the parameters and defaults it uses. Therefore, utilizing field data for the validation and calibration of the developed analytical equations may provide significant insight that could be used to fine tune these equations to more accurately estimate the effects of bus stops on the saturation flow rate of signalized intersections.

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## **Appendix A**

**Table A1: Far-Side CORSIM Results, Cases 1 - 12**

<b>Run #1 Case #</b>	<b>Effective Green Time (sec)</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Discharge Lane 1 (vph)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vph)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (veh)</b>	<b>Avg. Queue Lane 2 (veh)</b>	<b>No. of Bus Trips (veh)</b>
1	40	38	0.253	474	1871	478	1887	22	22	0
2	40	38	0.253	498	1966	482	1903	33	35	0
3	40	38	0.253	494	1950	534	2108	13	14	0
4	60	58	0.387	714	1847	704	1821	34	35	0
5	60	58	0.387	670	1733	724	1872	47	52	0
6	60	58	0.387	659	1704	709	1834	58	59	0
7	80	78	0.520	937	1802	966	1858	10	10	0
8	80	78	0.520	909	1748	995	1913	10	11	0
9	80	78	0.520	838	1612	974	1873	32	35	0
10	100	98	0.653	1275	1952	1232	1886	9	9	0
11	100	98	0.653	1132	1733	1227	1878	40	44	0
12	100	98	0.653	1075	1645	1214	1858	59	58	0
<b>Run #2 Case #</b>	<b>Effective Green Time (sec)</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Discharge Lane 1 (vph)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vph)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (veh)</b>	<b>Avg. Queue Lane 2 (veh)</b>	<b>No. of Bus Trips (veh)</b>
1	40	38	0.253	469	1851	483	1907	23	23	0
2	40	38	0.253	444	1753	483	1907	30	33	0
3	40	38	0.253	475	1875	537	2120	13	14	0
4	60	58	0.387	722	1867	727	1880	24	24	0
5	60	58	0.387	664	1717	733	1896	37	41	0
6	60	58	0.387	647	1673	727	1880	46	48	0
7	80	78	0.520	963	1852	933	1794	9	9	0
8	80	78	0.520	907	1744	989	1902	9	11	0
9	80	78	0.520	850	1635	981	1887	30	33	0
10	100	98	0.653	1259	1927	1243	1903	9	9	0
11	100	98	0.653	1195	1829	1291	1976	11	14	0
12	100	98	0.653	1066	1632	1224	1873	61	61	0

**Table A2: CORSIM Results and Calculations, Case 14**

Run #1 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles per hr	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>rt</sub> Right Turn Adjustment	Storage Behind Stop (number of vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway Lane 2 (sec)	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
14a	40	38	24	0.253	0.000	1.000	3.000	450	1776	471	1859	1.936	43	45
14b	40	38	24	0.253	0.250	0.963	3.000	437	1725	477	1883	1.912	46	50
14c	40	38	24	0.253	0.500	0.925	3.000	419	1654	473	1867	1.928	53	55
14d	40	38	24	0.253	0.000	1.000	3.000	427	1686	460	1816	1.983	59	60
14e	40	38	24	0.253	0.250	0.963	3.000	388	1532	477	1883	1.912	57	61
14f	40	38	24	0.253	0.500	0.925	3.000	411	1622	470	1855	1.940	58	61
14g	40	38	24	0.253	0.000	1.000	11.000	476	1879	473	1867	1.928	34	33
14h	40	38	24	0.253	0.250	0.963	11.000	457	1804	465	1836	1.961	39	42
14i	40	38	24	0.253	0.500	0.925	11.000	436	1721	485	1914	1.880	39	40
14j	40	38	24	0.253	0.000	1.000	11.000	470	1855	467	1843	1.953	32	32
14k	40	38	24	0.253	0.250	0.963	11.000	457	1804	468	1847	1.949	40	42
14L	40	38	24	0.253	0.500	0.925	11.000	435	1717	476	1879	1.916	43	44
Run #2 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles per hr	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>rt</sub> Right Turn Adjustment	Storage Behind Stop (number of vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway Lane 2 (sec)	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
14a	40	38	24	0.253	0.000	1.000	3.000	422	1666	481	1899	1.896	39	41
14b	40	38	24	0.253	0.250	0.963	3.000	397	1567	499	1970	1.828	40	43
14c	40	38	24	0.253	0.500	0.925	3.000	416	1642	475	1875	1.920	44	46
14d	40	38	24	0.253	0.000	1.000	3.000	408	1611	481	1899	1.896	43	45
14e	40	38	24	0.253	0.250	0.963	3.000	410	1618	484	1911	1.884	41	44
14f	40	38	24	0.253	0.500	0.925	3.000	414	1634	484	1911	1.884	40	42
14g	40	38	24	0.253	0.000	1.000	11.000	477	1883	463	1828	1.970	30	31
14h	40	38	24	0.253	0.250	0.963	11.000	441	1741	480	1895	1.900	34	37
14i	40	38	24	0.253	0.500	0.925	11.000	427	1686	481	1899	1.896	40	40
14j	40	38	24	0.253	0.000	1.000	11.000	474	1871	466	1839	1.957	29	30
14k	40	38	24	0.253	0.250	0.963	11.000	446	1761	481	1899	1.896	33	35
14L	40	38	24	0.253	0.500	0.925	11.000	422	1666	481	1899	1.896	41	41

**Table A2: CORSIM Results and Calculations, Case 14 (Cont'd)**

Run #1 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$	$P_1$	$V_2$	$P_2$	$V_3$	$P_3$							
			(vehicles)	(sec)	(vehicles)	(sec)	(vehicles)	(sec)							
14a	13.6	11	15	22	18	12	21	6	16.4	13	19	0.905	0.956	1.000	1682
14b	19.1	11	13	17	17	15	21	8	16.0	13	19	0.891	0.956	0.963	1616
14c	14.2	11	17	22	19	7	21	12	18.6	13	20	0.953	0.956	0.925	1646
14d	30.5	11	6	5	13	29	20	6	13.1	13	17	0.838	0.956	1.000	1522
14e	31.2	10	7	5	14	27	21	8	14.2	14	18	0.867	0.960	0.963	1571
14f	32.4	10	8	4	14	25	21	12	15.5	14	18	0.897	0.960	0.925	1539
14g	14.0	12	22	22	22	-3	21	21	20.7	12	21	1.000	0.952	1.000	1867
14h	14.7	11	26	21	23	-10	20	29	20.4	13	20	1.000	0.956	0.963	1767
14i	15.8	11	33	20	27	-22	21	41	21.3	13	21	1.000	0.956	0.925	1771
14j	27.8	11	15	8	18	10	20	21	18.7	13	20	0.961	0.956	1.000	1771
14k	27.8	11	19	8	20	3	21	29	20.1	13	20	0.991	0.956	0.963	1762
14L	27.3	11	27	9	24	-11	21	42	20.9	13	21	1.000	0.956	0.925	1738
Run #2 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$	$P_1$	$V_2$	$P_2$	$V_3$	$P_3$							
			(vehicles)	(sec)	(vehicles)	(sec)	(vehicles)	(sec)							
14a	16.4	11	13	20	17	15	21	6	15.9	13	19	0.887	0.956	1.000	1684
14b	15.8	11	15	20	19	12	22	7	17.4	13	20	0.906	0.956	0.963	1718
14c	18.0	11	15	18	18	10	21	12	17.7	13	19	0.931	0.956	0.925	1614
14d	30.5	11	6	6	14	29	21	6	13.5	13	18	0.836	0.956	1.000	1587
14e	31.6	11	6	4	14	28	21	8	14.4	13	18	0.852	0.956	0.963	1567
14f	27.8	11	10	8	16	20	21	11	16.2	13	19	0.892	0.956	0.925	1576
14g	16.9	11	21	19	21	-1	20	22	20.3	13	20	1.000	0.956	1.000	1828
14h	15.3	11	26	21	23	-9	21	28	21.1	13	21	1.000	0.956	0.963	1824
14i	16.4	11	32	20	27	-21	21	42	21.1	13	21	1.000	0.956	0.925	1756
14j	28.5	12	15	8	18	11	20	22	18.6	12	20	0.956	0.952	1.000	1758
14k	29.5	12	18	7	20	6	21	28	20.4	12	21	0.984	0.952	0.963	1797
14L	31.1	11	25	5	23	-7	21	42	21.1	13	21	1.000	0.956	0.925	1756

**Table A3: CORSIM Results and Calculations, Case 15**

Run #1 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	$F_{rt}$ Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2	Saturation Flow Rate Lane 2 (pcphpl)	Headway Lane 2 (sec)	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
15a	60	58	24	0.387	0.000	1.000	3.000	623	1611	726	1878	1.917	66	67
15b	60	58	24	0.387	0.250	0.963	3.000	648	1676	724	1872	1.923	55	59
15c	60	58	24	0.387	0.500	0.925	3.000	640	1655	715	1849	1.947	72	73
15d	60	58	24	0.387	0.000	1.000	3.000	627	1622	730	1888	1.907	72	72
15e	60	58	24	0.387	0.250	0.963	3.000	606	1567	708	1831	1.966	70	72
15f	60	58	24	0.387	0.500	0.925	3.000	607	1570	718	1857	1.939	76	77
15g	60	58	24	0.387	0.000	1.000	11.000	704	1821	722	1867	1.928	46	47
15h	60	58	24	0.387	0.250	0.963	11.000	683	1766	714	1847	1.950	51	56
15i	60	58	24	0.387	0.500	0.925	11.000	660	1707	717	1854	1.941	64	65
15J	60	58	24	0.387	0.000	1.000	11.000	698	1805	716	1852	1.944	49	50
15k	60	58	24	0.387	0.250	0.963	11.000	667	1725	711	1839	1.958	57	60
15L	60	58	24	0.387	0.500	0.925	11.000	639	1653	724	1872	1.923	67	67
Run #2 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	$F_{rt}$ Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2	Saturation Flow Rate Lane 2 (pcphpl)	Headway Lane 2 (sec)	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
15a	60	58	24	0.387	0.000	1.000	3.000	657	1699	725	1875	1.920	47	48
15b	60	58	24	0.387	0.250	0.963	3.000	639	1653	733	1896	1.899	49	54
15c	60	58	24	0.387	0.500	0.925	3.000	615	1591	726	1878	1.917	62	63
15d	60	58	24	0.387	0.000	1.000	3.000	646	1671	740	1914	1.881	48	50
15e	60	58	24	0.387	0.250	0.963	3.000	610	1578	724	1872	1.923	59	62
15f	60	58	24	0.387	0.500	0.925	3.000	615	1591	727	1880	1.915	61	62
15g	60	58	24	0.387	0.000	1.000	11.000	693	1792	721	1865	1.931	38	38
15h	60	58	24	0.387	0.250	0.963	11.000	665	1720	717	1854	1.941	46	50
15i	60	58	24	0.387	0.500	0.925	11.000	641	1658	721	1865	1.931	58	58
15J	60	58	24	0.387	0.000	1.000	11.000	687	1777	721	1865	1.931	40	39
15k	60	58	24	0.387	0.250	0.963	11.000	672	1738	732	1893	1.902	42	46
15L	60	58	24	0.387	0.500	0.925	11.000	638	1650	727	1880	1.915	59	59

**Table A3: CORSIM Results and Calculations, Case 15 (Cont'd)**

Run #1 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$ (vehicles)	$P_1$ (sec)	$V_2$ (vehicles)	$P_2$ (sec)	$V_3$ (vehicles)	$P_3$ (sec)							
15a	17.5	11	23	39	27	16	31	6	25.0	13	28	0.908	0.956	1.000	1704
15b	13.1	11	26	43	29	9	31	8	27.4	13	29	0.943	0.956	0.963	1700
15c	14.4	10	27	42	29	7	31	12	28.3	14	30	0.965	0.960	0.925	1651
15d	30.0	9	17	26	24	28	31	6	21.6	15	28	0.882	0.964	1.000	1665
15e	33.6	10	15	22	23	30	31	8	21.1	14	27	0.872	0.960	0.963	1536
15f	31.3	9	19	25	25	24	31	12	23.5	15	28	0.910	0.964	0.925	1563
15g	14.0	12	33	42	32	-3	31	21	31.1	12	31	1.000	0.952	1.000	1867
15h	14.7	11	36	41	33	-10	31	29	30.8	13	31	1.000	0.956	0.963	1777
15i	14.7	11	43	41	37	-24	31	43	30.9	13	31	1.000	0.956	0.925	1715
15J	26.0	12	26	30	29	9	31	21	28.3	12	30	0.959	0.952	1.000	1776
15k	27.3	11	29	29	30	3	31	29	30.0	13	30	0.990	0.956	0.963	1753
15L	26.2	11	38	30	34	-12	31	42	31.2	13	31	1.000	0.956	0.925	1732
Run #2 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$ (vehicles)	$P_1$ (sec)	$V_2$ (vehicles)	$P_2$ (sec)	$V_3$ (vehicles)	$P_3$ (sec)							
15a	18.0	10	23	38	27	16	31	6	24.8	14	29	0.914	0.960	1.000	1713
15b	15.3	11	25	41	29	12	32	8	26.9	13	29	0.931	0.956	0.963	1699
15c	16.4	11	27	40	29	9	31	12	27.9	13	30	0.951	0.956	0.925	1651
15d	27.8	11	18	28	25	26	32	6	22.4	13	28	0.863	0.956	1.000	1651
15e	31.2	10	17	25	24	27	31	8	22.0	14	27	0.877	0.960	0.963	1581
15f	27.6	10	21	28	26	20	31	11	24.6	14	29	0.911	0.960	0.925	1584
15g	14.2	11	33	42	32	-3	31	21	31.1	13	31	1.000	0.956	1.000	1865
15h	14.4	10	36	42	34	-10	31	28	30.9	14	31	1.000	0.960	0.963	1785
15i	14.2	11	44	42	37	-24	31	42	31.1	13	31	1.000	0.956	0.925	1725
15J	27.3	11	26	29	28	10	31	21	28.2	13	30	0.957	0.956	1.000	1785
15k	26.7	11	30	29	31	3	32	28	30.8	13	31	0.989	0.956	0.963	1803
15L	28.4	11	36	28	34	-10	31	42	31.3	13	31	1.000	0.956	0.925	1739



**Table A4: CORSIM Results and Calculations, Case 16**

Run #1 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>RT</sub> Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway (sec) Lane 2	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
16a	80	78	24	0.520	0.000	1.000	3.000	931	1790	984	1892	1.902	11	11
16b	80	78	24	0.520	0.250	0.963	3.000	896	1723	1012	1946	1.850	11	12
16c	80	78	24	0.520	0.500	0.925	3.000	833	1602	965	1856	1.940	41	44
16d	80	78	24	0.520	0.000	1.000	3.000	930	1788	987	1898	1.897	11	11
16e	80	78	24	0.520	0.250	0.963	3.000	855	1644	972	1869	1.926	26	31
16f	80	78	24	0.520	0.500	0.925	3.000	815	1567	962	1850	1.946	47	50
16g	80	78	24	0.520	0.000	1.000	11.000	977	1879	943	1813	1.985	10	10
16h	80	78	24	0.520	0.250	0.963	11.000	882	1696	953	1833	1.964	30	36
16i	80	78	24	0.520	0.500	0.925	11.000	838	1612	976	1877	1.918	35	37
16J	80	78	24	0.520	0.000	1.000	11.000	964	1854	956	1838	1.958	10	10
16k	80	78	24	0.520	0.250	0.963	11.000	924	1777	986	1896	1.899	12	14
16L	80	78	24	0.520	0.500	0.925	11.000	840	1615	980	1885	1.910	33	35
Run #2 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>RT</sub> Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway (sec) Lane 2	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
16a	80	78	24	0.520	0.000	1.000	3.000	935	1798	973	1871	1.924	10	10
16b	80	78	24	0.520	0.250	0.963	3.000	903	1737	1005	1933	1.863	10	11
16c	80	78	24	0.520	0.500	0.925	3.000	837	1610	973	1871	1.924	42	45
16d	80	78	24	0.520	0.000	1.000	3.000	916	1762	985	1894	1.901	10	10
16e	80	78	24	0.520	0.250	0.963	3.000	901	1733	1004	1931	1.865	13	15
16f	80	78	24	0.520	0.500	0.925	3.000	942	1812	970	1865	1.930	45	48
16g	80	78	24	0.520	0.000	1.000	11.000	962	1850	946	1819	1.979	10	10
16h	80	78	24	0.520	0.250	0.963	11.000	909	1748	999	1921	1.874	9	11
16i	80	78	24	0.520	0.500	0.925	11.000	858	1650	979	1883	1.912	32	35
16J	80	78	24	0.520	0.000	1.000	11.000	968	1862	940	1808	1.991	10	10
16k	80	78	24	0.520	0.250	0.963	11.000	918	1765	985	1894	1.901	9	11
16L	80	78	24	0.520	0.500	0.925	11.000	850	1635	971	1867	1.928	39	41

**Table A4: CORSIM Results and Calculations, Case 16 (Cont'd)**

Run #1 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, V <sub>T</sub> (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM F <sub>bb</sub> Adjustment Factor	F <sub>rt</sub> Adjustment	Predicted Sat. Flow (pcphpl)
			V <sub>1</sub>	P <sub>1</sub>	V <sub>2</sub>	P <sub>2</sub>	V <sub>3</sub>	P <sub>3</sub>							
			(vehicles)	(sec)	(vehicles)	(sec)	(vehicles)	(sec)							
16a	17.5	12	34	59	38	16	42	6	35.2	12	39	0.919	0.952	1.000	1738
16b	13.5	12	38	63	41	10	43	7	38.7	12	41	0.947	0.952	0.963	1775
16c	13.6	11	38	62	40	6	41	12	38.7	13	40	0.972	0.956	0.925	1669
16d	35.5	12	24	41	33	34	42	6	29.4	12	36	0.849	0.952	1.000	1611
16e	28.4	11	29	48	35	25	42	8	32.0	13	37	0.894	0.956	0.963	1609
16f	31.6	11	29	44	35	24	41	12	32.5	13	37	0.903	0.956	0.925	1546
16g	14.0	12	42	62	41	-4	40	22	40.3	12	40	1.000	0.952	1.000	1813
16h	14.7	11	46	61	43	-10	41	29	40.7	13	41	1.000	0.956	0.963	1764
16i	14.7	11	54	61	48	-24	42	42	41.7	13	42	1.000	0.956	0.925	1736
16j	26.5	12	36	50	39	9	41	22	37.8	12	39	0.962	0.952	1.000	1769
16k	27.0	12	41	49	41	3	42	28	41.1	12	42	0.988	0.952	0.963	1803
16L	28.4	11	47	48	44	-10	42	42	41.9	13	42	1.000	0.956	0.925	1743
Run #2 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, V <sub>T</sub> (vehicles)	Number of Cycles without Bus	Overall Average per Cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM F <sub>bb</sub> Adjustment Factor	F <sub>rt</sub> Adjustment	Predicted Sat. Flow (pcphpl)
			V <sub>1</sub>	P <sub>1</sub>	V <sub>2</sub>	P <sub>2</sub>	V <sub>3</sub>	P <sub>3</sub>							
			(vehicles)	(sec)	(vehicles)	(sec)	(vehicles)	(sec)							
16a	15.0	12	35	61	38	13	42	6	35.8	12	39	0.930	0.952	1.000	1741
16b	15.0	12	37	61	40	11	43	7	37.8	12	40	0.940	0.952	0.963	1749
16c	12.5	11	39	64	40	5	42	12	39.5	13	41	0.977	0.956	0.925	1691
16d	38.0	12	23	38	33	36	42	6	28.7	12	35	0.841	0.952	1.000	1593
16e	30.5	12	28	46	36	27	43	7	32.2	12	38	0.876	0.952	0.963	1628
16f	26.2	11	32	50	37	19	41	12	34.4	13	38	0.921	0.956	0.925	1590
16g	15.0	12	42	61	41	-3	40	22	40.4	12	40	1.000	0.952	1.000	1819
16h	15.5	12	47	61	45	-8	43	27	42.7	12	43	1.000	0.952	0.963	1849
16i	13.6	11	55	62	48	-25	42	42	41.8	13	42	1.000	0.956	0.925	1741
16j	29.5	12	34	47	37	12	40	22	36.4	12	38	0.953	0.952	1.000	1722
16k	29.5	12	39	47	41	6	42	28	40.3	12	41	0.979	0.952	0.963	1784
16L	27.3	11	47	49	44	-11	41	42	41.5	13	41	1.000	0.956	0.925	1727

**Table A5: CORSIM Results and Calculations, Case 17**

Run #1 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>rt</sub> Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway (sec) Lane 2	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
17a	100	98	24	0.653	0.000	1.000	3.000	1185	1814	1251	1915	1.880	24	24
17b	100	98	24	0.653	0.250	0.963	3.000	1080	1653	1246	1907	1.888	50	53
17c	100	98	24	0.653	0.500	0.925	3.000	1040	1592	1230	1883	1.912	64	63
17d	100	98	24	0.653	0.000	1.000	3.000	1136	1739	1241	1899	1.895	37	37
17e	100	98	24	0.653	0.250	0.963	3.000	1087	1664	1212	1855	1.941	63	66
17f	100	98	24	0.653	0.500	0.925	3.000	1054	1613	1199	1835	1.962	67	65
17g	100	98	24	0.653	0.000	1.000	11.000	1251	1915	1255	1921	1.874	13	14
17h	100	98	24	0.653	0.250	0.963	11.000	1164	1782	1221	1869	1.926	17	21
17i	100	98	24	0.653	0.500	0.925	11.000	1076	1647	1204	1843	1.953	61	60
17J	100	98	24	0.653	0.000	1.000	11.000	1184	1812	1184	1812	1.986	49	49
17k	100	98	24	0.653	0.250	0.963	11.000	1126	1723	1205	1844	1.952	46	49
17L	100	98	24	0.653	0.500	0.925	11.000	1068	1635	1213	1857	1.939	61	61
Run #2 Case #	Effective Green Time (sec)	Green Time (sec)	Number of Cycles	Proportion of Hour-Green	Right Turn Proportion By Lane	F <sub>rt</sub> Right Turn Adjustment	Storage Behind Stop (vehicles)	Discharge Lane 1 (vehicles)	Saturation Flow Rate Lane 1 (pcphpl)	Discharge Lane 2 (vehicles)	Saturation Flow Rate Lane 2 (pcphpl)	Headway (sec) Lane 2	Avg. Queue Lane 1 (vehicles)	Avg. Queue Lane 2 (vehicles)
17a	100	98	24	0.653	0.000	1.000	3.000	1171	1792	1202	1840	1.957	52	52
17b	100	98	24	0.653	0.250	0.963	3.000	1098	1681	1303	1994	1.805	10	11
17c	100	98	24	0.653	0.500	0.925	3.000	1089	1667	1324	2027	1.776	11	13
17d	100	98	24	0.653	0.000	1.000	3.000	1152	1763	1228	1880	1.915	45	45
17e	100	98	24	0.653	0.250	0.963	3.000	1105	1691	1243	1903	1.892	21	27
17f	100	98	24	0.653	0.500	0.925	3.000	1085	1661	1272	1947	1.849	15	19
17g	100	98	24	0.653	0.000	1.000	11.000	1163	1780	1237	1893	1.901	43	42
17h	100	98	24	0.653	0.250	0.963	11.000	1095	1676	1246	1907	1.888	53	57
17i	100	98	24	0.653	0.500	0.925	11.000	1071	1639	1217	1863	1.933	42	44
17J	100	98	24	0.653	0.000	1.000	11.000	1242	1901	1244	1904	1.891	14	14
17k	100	98	24	0.653	0.250	0.963	11.000	1146	1754	1252	1916	1.879	17	21
17L	100	98	24	0.653	0.500	0.925	11.000	1079	1652	1197	1832	1.965	50	51

**Table A5: CORSIM Results and Calculations, Case 17 (Cont'd)**

Run #1 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$ (vehicles)	$P_1$ (sec)	$V_2$ (vehicles)	$P_2$ (sec)	$V_3$ (vehicles)	$P_3$ (sec)							
17a	12.0	11	48	84	50	10	53	6	48.3	13	51	0.958	0.956	1.000	1835
17b	16.9	11	46	79	49	13	53	8	47.0	13	50	0.948	0.956	0.963	1740
17c	15.6	10	48	80	50	8	52	11	48.7	14	51	0.972	0.960	0.925	1692
17d	28.4	11	39	68	46	27	53	6	41.4	13	48	0.901	0.956	1.000	1712
17e	28.8	10	39	67	45	25	52	8	41.3	14	47	0.917	0.960	0.963	1637
17f	28.7	9	40	67	46	21	51	12	42.7	15	48	0.939	0.964	0.925	1594
17g	14.0	12	55	82	54	-3	53	21	53.4	12	53	1.000	0.952	1.000	1921
17h	13.6	11	57	82	55	-11	52	28	51.9	13	52	1.000	0.956	0.963	1799
17i	14.7	11	64	81	57	-24	51	43	51.2	13	51	1.000	0.956	0.925	1705
17j	27.6	10	45	68	48	10	50	22	46.7	14	49	0.970	0.960	1.000	1758
17k	28.0	9	50	68	50	3	51	29	50.0	15	51	0.991	0.964	0.963	1760
17L	26.7	11	58	69	55	-12	52	43	51.6	13	52	1.000	0.956	0.925	1717
Run #2 Case #	Output Dwell Time (sec)	No. of Bus Trips (bus vehicles)	Far-Side Analytical Equation - Time Period Results						Average per Cycle w/ Bus, $V_T$ (vehicles)	Number of Cycles without Bus	Overall Average per cycle (vehicles)	Predicted Saturation Flow Rate Adjustment	HCM $F_{bb}$ Adjustment Factor	$F_{rt}$ Adjustment	Predicted Saturation Flow Rate (pcphpl)
			$V_1$ (vehicles)	$P_1$ (sec)	$V_2$ (vehicles)	$P_2$ (sec)	$V_3$ (vehicles)	$P_3$ (sec)							
17a	12.7	9	46	83	48	11	51	6	46.2	15	49	0.964	0.964	1.000	1774
17b	17.0	12	48	79	52	14	55	7	48.9	12	52	0.942	0.952	0.963	1807
17c	15.5	12	51	81	54	9	56	11	52.2	12	54	0.963	0.952	0.925	1806
17d	32.7	9	36	63	44	31	52	6	39.5	15	47	0.909	0.964	1.000	1708
17e	32.0	12	38	64	45	28	53	8	41.1	12	47	0.889	0.952	0.963	1628
17f	30.5	11	41	66	48	23	54	11	44.3	13	50	0.917	0.956	0.925	1652
17g	14.5	12	54	82	53	-3	53	21	52.6	12	53	1.000	0.952	1.000	1893
17h	13.3	9	59	83	56	-10	53	28	53.0	15	53	1.000	0.964	0.963	1836
17i	15.5	12	64	81	58	-23	52	43	51.7	12	52	1.000	0.952	0.925	1723
17j	29.5	12	46	67	50	13	53	21	48.0	12	50	0.954	0.952	1.000	1817
17k	28.9	11	50	67	52	5	53	28	51.3	13	52	0.983	0.956	0.963	1814
17L	27.8	11	57	68	54	-11	51	43	50.9	13	51	1.000	0.956	0.925	1695

## **Appendix B**

**Table B1: Near-Side CORSIM Results, Repetitions 1 - 5**

<b>Run #1 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.1	713	1876	713	1876	31	33	0
19a	38	0.38	0.1	651	1713	733	1929	22	23	12
19b	38	0.38	0.1	622	1637	722	1900	27	29	12
19c	38	0.38	0.1	669	1761	718	1889	22	24	12
<b>Run #2 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	684	1800	737	1939	30	31	0
19a	38	0.38	0.10	612	1611	721	1897	27	29	12
19b	38	0.38	0.10	607	1597	724	1905	28	30	12
19c	38	0.38	0.10	586	1542	730	1921	32	34	11
<b>Run #3 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	707	1861	708	1863	31	32	0
19a	38	0.38	0.10	631	1661	719	1892	23	25	12
19b	38	0.38	0.10	611	1608	729	1918	25	27	12
19c	38	0.38	0.10	604	1589	729	1918	30	32	12
<b>Run #4 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	668	1758	711	1871	42	44	0
19a	38	0.38	0.10	627	1650	716	1884	21	23	12
19b	38	0.38	0.10	590	1553	723	1903	33	36	11
19c	38	0.38	0.10	570	1500	729	1918	41	44	11
<b>Run #5 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	704	1853	702	1847	30	31	0
19a	38	0.38	0.10	627	1650	731	1924	21	23	12
19b	38	0.38	0.10	606	1595	737	1939	24	26	12
19c	38	0.38	0.10	604	1589	721	1897	28	31	11

**Table B2: Near-Side CORSIM Results, Repetitions 6 - 10**

<b>Run #6 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.1	697	1834	699	1839	37	38	0
19a	38	0.38	0.1	619	1629	721	1897	34	35	12
19b	38	0.38	0.1	589	1550	723	1903	38	40	12
19c	38	0.38	0.1	617	1624	697	1834	38	41	12
<b>Run #7 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	683	1797	711	1871	37	39	0
19a	38	0.38	0.10	596	1568	711	1871	41	44	12
19b	38	0.38	0.10	560	1474	731	1924	44	46	11
19c	38	0.38	0.10	595	1566	713	1876	42	45	11
<b>Run #8 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	700	1842	720	1895	36	38	0
19a	38	0.38	0.10	609	1603	723	1903	32	34	11
19b	38	0.38	0.10	621	1634	719	1892	27	30	12
19c	38	0.38	0.10	565	1487	721	1897	41	43	11
<b>Run #9 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	697	1834	715	1882	27	28	0
19a	38	0.38	0.10	638	1679	723	1903	20	21	12
19b	38	0.38	0.10	613	1613	716	1884	28	29	12
19c	38	0.38	0.10	582	1532	718	1889	43	46	12
<b>Run #10 Case #</b>	<b>Green Time (sec)</b>	<b>Proportion of Hour-Green</b>	<b>Right Turn Proportion By Lane</b>	<b>Discharge Lane 1 (vehicles)</b>	<b>Saturation Flow Rate Lane 1 (pcphpl)</b>	<b>Discharge Lane 2 (vehicles)</b>	<b>Saturation Flow Rate Lane 2 (pcphpl)</b>	<b>Avg. Queue Lane 1 (vehicles)</b>	<b>Avg. Queue Lane 2 (vehicles)</b>	<b>No. of Bus Trips (bus vehicles)</b>
18	38	0.38	0.10	698	1837	710	1868	11	12	0
19a	38	0.38	0.10	593	1561	719	1892	36	38	11
19b	38	0.38	0.10	593	1561	716	1884	37	40	11
19c	38	0.38	0.10	629	1655	717	1887	33	36	12