A MICROSIMULATION ANALYSIS OF HIGHWAY INTERSECTIONS NEAR HIGHWAY-RAILROAD GRADE CROSSINGS

A Thesis

by

JONATHAN MICHAEL TYDLACKA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Civil Engineering

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ABSTRACT

A Microsimulation Analysis of Highway Intersections Near
Highway-Railroad Grade Crossings. (August 2004)
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The purpose of this thesis was to perform microsimulation analyses on intersections near Highway-Railroad Grade Crossings (HRGCs) to determine if controlling mean train speed and train speed variability would improve safety and reduce delays. This research focused on three specific areas. First, average vehicle delay was examined, and this delay was compared for seven specific train speed distributions, including existing conditions. Furthermore, each distribution was associated with train detectors that were placed at the distance the fastest train could travel during the given warning time. Second, pedestrian cutoffs were investigated. These cutoffs represented an occasion when the pedestrian phases were truncated or shortened due to railroad signal preemption. Finally, vehicle emissions were analyzed using a modal emissions model.

A microscopic simulation model of the Wellborn Corridor in College Station, Texas was created using VISSIM. The model was run twenty times in each train speed distribution for each of three train lengths. Average vehicle delay was collected for three intersections, and delays were compared using the Pooled *t*-test with a 95% confidence interval. Comparisons were made between the distributions, and generally, distributions with higher mean train speeds were associated with lower average delay, and train length was not a significant factor.

Unfortunately, pedestrian cutoffs were not specifically controlled in this project; therefore, no statistical conclusions can be made with respect to the pedestrian cutoff problem. However, example cases were devised to demonstrate how these cutoffs could be avoided.

In addition, vehicle emissions were examined using the vehicle data from VISSIM as inputs for CMEM (Comprehensive Modal Emissions Model). For individual vehicles, as power (defined as the product of velocity and acceleration) increased, emissions increased. When comparing emissions from different train speed distributions, few significant differences were found. However, a scenario with no train was tested, and it was shown to have significantly higher emissions than three of the distributions with trains.

Ultimately, this thesis shows that average vehicle delay and vehicle emissions could be lowered by specific train speed distributions. Also, work could be done to investigate the pedestrian cutoff problem.

ACKNOWLEDGMENTS

I would like to thank Dr. Laurence Rilett for his help and guidance in the preparation of this thesis. His support and constant reassurance were instrumental to the completion of this project. In addition, I would like to thank Dr. Carroll Messer and Dr. Ming Zhang for providing their technical advice and for dedicating their time to serve as committee members.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

BACKGROUND

Safety problems can exist whenever a highway intersection exists near a Highway-Railroad Grade Crossing (HRGC). The potential for a collision exists because of the shared use of the same space by trains and motor vehicles at these HRGCs. One specific problem is that vehicles waiting at the traffic signal may be queued onto the tracks when a train is approaching. In order to clear these vehicles from the tracks, special operating procedures are necessary. One such procedure is traffic signal preemption.

According to the *Manual on Uniform Traffic Control Devices* (MUTCD), preemption is defined as the transfer of traffic signal operations from a normal mode to a special control mode (*1*). In this preemption mode, there are four steps. First, the train is detected and the active railroad warning devices, consisting of gates and flashing lights, are initiated. Next, the right-of-way must be transferred from the current phase to the phase that controls the critical approach (e.g. where vehicles could potentially queue across the railroad tracks). This is defined as the "right-of-way transfer time" (RTT). Third, this phase must have an adequate green clearance phase such that any queued vehicles are cleared from the tracks. This is the "queue clearance time". Finally, there must be a "separation time" which is the amount of time the tracks are clear before the train arrives at the intersection (*2*).

When the traffic signal controller is notified of preemption, the first action taken by the controller is to check which phases are currently active. If the active phase is the track clearance phase (the phase controlling the critical approach), then the RTT is essentially zero. However, if the active phase is not the track clearance phase, that phase must be terminated after a minimum green time has been exhausted. In addition, any pedestrian phases that were active at the onset of preemption will have to be served or terminated. This means that the pedestrian "WALK" interval (WALK) and pedestrian clearance interval (PCI) must be considered. The MUTCD states that during the transition to preemption control, "The shortening or omission of any pedestrian walk interval and/or pedestrian change interval shall be permitted" (*1*). Depending on the amount of warning time available, these intervals can be truncated at the onset of preemption, partially served for some of the interval, or fully served for the entire interval time.

This thesis follows the style and format of the *Transportation Research Board*.

If the WALK and PCI are truncated, the green time for the current vehicle phase at the onset of preemption will not be extended beyond the minimum. However, if the WALK and PCI are to be served partially or completely, the green time for the current vehicle phase at the onset of preemption must be extended so that the sum of the WALK plus PCI is less than or equal to the green interval (G). This relationship is shown in Equation 1 and in Figure 1.

$$WALK + PCI \leq G \qquad \textbf{Equation 1}$$

Where,

$WALK =$ Pedestrian WALK interval (sec);
$PCI =$ Pedestrian Clearance Interval (sec);
$G =$ Green Interval (Vehicle Phase) (sec);
$Y =$ Yellow Change Interval (Vehicle Phase) (sec); and
$R_C =$ All Red Clearance Interval (Vehicle Phase) (sec).

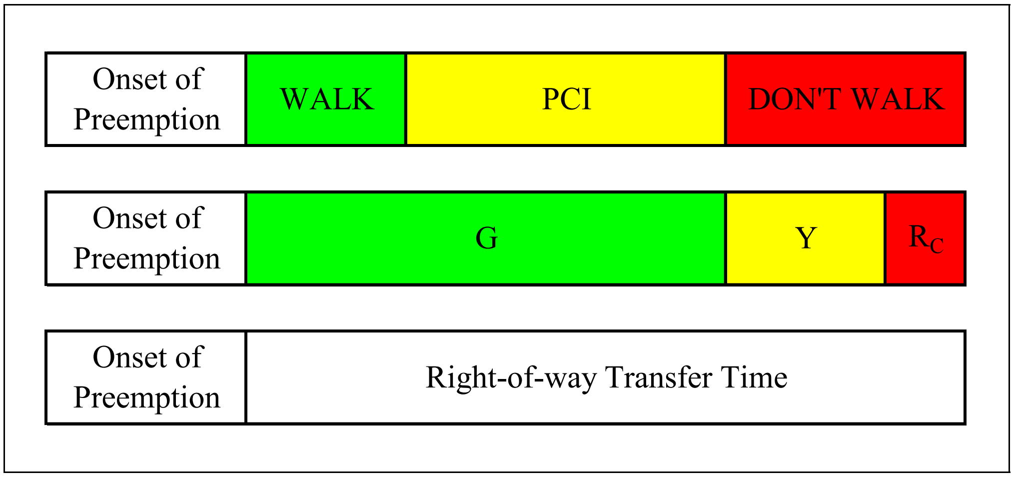


Figure 1. Right-of-way Transfer Time with Pedestrian Phases Served

Ultimately, many choices can be made as to the methods and intervals used for preemption. Ideally, one would choose those methods that provide the highest degree of safety with optimum efficiency, specifically with respect to the motorists and pedestrians. However, tradeoffs exist between safety and efficiency, and the chosen method will reflect these tradeoffs.

PROBLEM STATEMENT

Many solutions exist with respect to the specific preemption sequence that should be used at a given signalized highway intersection near a railroad grade crossing. If pedestrian signals are used at the signalized intersection, the solutions require that additional parameters be considered. When timing the preemption sequence for a controller, an engineer must make three decisions. First, what minimum green time should be used for the phases active when preemption begins? Also, assuming that pedestrian phasing is used, what should be done about the pedestrians? Should the full Pedestrian Clearance Interval (PCI) be used, or should this interval be truncated or omitted?

A dilemma is that if the pedestrian phase is served in its entirety, a much longer RTT will be necessary, and a longer delay will result for the motorists. However, if the pedestrian phase is truncated, the pedestrians are placed at risk because they will be in the crossing when the track clearance phase begins. When the pedestrian clearance interval is truncated or completely omitted, the pedestrian phase is not served in its entirety. This is referred to as a "pedestrian cutoff". Needless to say, this poses an unnecessary risk to pedestrians because they are in danger of being hit by a vehicle as they try to finish crossing the intersection.

One problem is that in order to decrease the likelihood of a pedestrian cutoff during a train preemption event, there may be corresponding increase in delay. If the train detectors are placed further from the crossing, more time could be given to the controller and the average number of pedestrian cutoffs could be reduced. However, as the detectors are placed further from the crossing, delay time may be increased. If one could test different strategies, specifically dealing with train detector placement, a solution might be found such that pedestrian cutoffs and delay are optimized. One possibility is that as the time given to pedestrian intervals at the onset of preemption is increased, the number of pedestrian cutoffs will decrease while the average intersection delay may increase.

RESEARCH OBJECTIVE

The primary objective of this research is to examine and quantify the impacts of both trains and the resulting traffic signal preemption at intersections near highway-railroad grade crossings. This research utilizes a microsimulation model to collect data from a model test-bed, which represents and approximates a real world test-bed. The research conducted as part of this thesis concentrates on three specific areas.

First, the issue of controlling train speeds is studied. This analysis looks into what could be done if the speeds of the trains could be controlled and if those agencies operating the traffic signals could have and use this information. By keeping the train speeds within a defined range, the detectors could be placed such that the warning time provided to the traffic signal controller not only meets the needs of the system, but also improves on the efficiency of the intersection. This improved efficiency could be in terms of lowered vehicle delay or increased safety through fewer pedestrian cutoffs.

Second, the issue of pedestrian cutoffs is examined. Pedestrian cutoffs are counted for each model run, and they are tabulated. However, the cutoffs are not specifically controlled in the analyses, so the cutoffs are not compared to the delay output. Instead, example scenarios are devised to be used in future pedestrian cutoff analyses.

Third, environmental effects of the motor vehicles are examined. In addition to the safety and delay problems caused by railroad preemption, the environment can be negatively affected by the emissions from the vehicles of the delayed motorists. This task includes an analysis of vehicle emissions such as Nitrogen Oxides (NOx), Hydrocarbons (HC), and Carbon Monoxides (CO). Specifically, train movements and train speeds are analyzed to see if they have an effect on emissions output from the motor vehicles in the model.

Although current preemption techniques perform well in clearing the tracks of vehicular traffic, some inefficiencies still exist. Particularly, delays could be lowered for the vehicles at the intersections. While there have been a number of approaches for remedying this problem, they have all put the onus on traffic operations and management. In this project, the focus was on controlling the trains directly.

ORGANIZATION

This thesis is divided into five sections. This section contains the background, problem statement, and research objectives. The next section contains a literature review. Specifically, rail preemption guidelines and vehicle emissions modeling are described in detail. Then, the methodology is outlined in the following section. Here, the test-bed is described, and the simulation methods are explained. Next, the following section includes the results of the sensitivity analysis with controlled train speeds. Specifically, efficiency is analyzed using vehicle delay and pedestrian cutoffs as measures of effectiveness. This section also contains the results of the emissions analysis. Vehicles emissions are compared to vehicle delay and pedestrian cutoffs for controlled train speeds. The final section consists of the summary and conclusions from this research.

LITERATURE REVIEW

RAIL PREEMPTION BACKGROUND

Preemption Standards

The main objective of signal preemption is safety. By law, the railroad active warning devices must provide a minimum of 20 seconds of warning time (*1*). This 20-second minimum is referred to as the Minimum Warning Time (MWT), and it is the minimum time that must be provided by the railroad active warning devices (flashing lights or gates with flashing lights) at the HRGC. However, the time available to the traffic signal controller at the highway intersection during preemption depends on the type of train warning system and type of preemption strategy in use at the intersection.

The *Manual on Uniform Traffic Control Devices* (MUTCD) suggests that preemption be implemented at a traffic signal when that signal is located within 200 feet of a HRGC (*1*,*3*). However, it is possible that vehicles may queue over the tracks even when the distance between the traffic signal and the HRGC is over 200 feet. Marshall and Berg developed a process to find the expected maximum length of queued vehicles for an intersection approach. Using a Poisson distribution to approximate random arrivals of vehicles, along with approach volume, cycle length, and assumed probability level as input values, they found that vehicles can extend over the tracks for intersections located farther from the tracks than 200 feet (*3*). Therefore, preemption may need to be considered at intersections located more than 200 feet from the HRGC.

Train Detection Technology

Basic track-based train detection systems utilize the tracks as conductors for an electrical circuit. In the absence of a train, the circuit is closed, but when a train enters the circuit, the axles short the circuit and cause the relay to de-energize. When the circuit is de-energized, the active warning devices are activated. Also, these warning devices operate in a fail-safe mode. Therefore, if the power were to be interrupted, the voltage would drop and the active warning devices would be activated by a backup power source (*4*,*5*).

Train detection systems that are not track-based also exist, and several technologies have been considered for use in train detection. Sonic detectors detect the train from the horn it sounds as it nears the crossing. GPS sensors can be used to detect the position, direction of travel, and speed of the train at any point as the train approaches the crossing. Even Doppler radar has been used to continually detect train location and train speed (*4*).

Train Warning Systems

Two common types of train warning systems are used today. One method uses the conventional system. In this system, trains activate the warning devices when they cross a detector at a fixed distance from the crossing. The detection circuit length is the distance that the fastest train at that crossing will travel during the minimum warning time (at least 20 seconds). This means that the detection circuit is extended to the distance that the fastest train can travel in the minimum warning time (MWT) (*4*). Because the majority of trains travel at speeds slower than the fastest train, they will have warning times that are greater than the minimum 20 seconds. This leads to a wide variety of warning times, which can lead to increased delay and added safety concerns for motorists.

The other type of train warning system utilizes a motion sensing system. This system is designed to determine the presence and direction of motion of the train. Consequently, if a train stops or changes direction within the circuit, the warning devices will deactivate (*5*).

Constant warning time (CWT) devices are an improvement on motion detection systems. With CWT devices, the length of the train detection circuit is again based on the fastest train. Using this system, the train's speed and distance from the intersection are measured, and the arrival time of the train is predicted based on the measured speed. The active warning devices are then activated accordingly to provide a constant warning time (*4*). A weakness, however, is that if the train changes speed after passing the detector, the warning time provided will not equal the designed warning time. This means that if the train accelerates, the warning time will be less than the design value. For example, consider a train which is traveling at 60 km/h (32.4 mph) when it is detected at 2881 feet from the crossing. Subsequently, the train accelerates at 0.37 ft/s/s (15 mph/min) just after passing the detector. The detection of this train will result in 7.0 fewer seconds of warning time as compared to the same train that does not change speeds past the detector. The early arrival of the train could cause serious safety concerns at the crossing.

Simultaneous Preemption and Advance Preemption

Two general types of traffic signal preemption techniques are commonly used: simultaneous preemption and advance preemption. With simultaneous preemption, the traffic signal controller is notified of the preemption at the same time as the railroad warning devices are activated (*2*). Therefore, the sum of the three components listed earlier ("right-of-way transfer time", "queue clearance time", "separation time") must be less than or equal to 20 seconds. On the other hand, a system utilizing advance preemption will notify the traffic signal controller prior to activating the railroad warning devices. The difference in time from when the traffic signal controller is notified and when the railroad warning devices are activated is called the advance preemption time (*2*). Typically, this advance preemption time is requested by the traffic engineer when the time calculated for the right-of-way transfer time, queue clearance time, and the separation time exceeds the 20-second minimum that is provided by the railroad.

PREEMPTION SEQUENCE

All currently manufactured controllers have the same basic preemption sequencing, in accordance with currently accepted practices (*5*). This sequence is shown in Figure 2.

1. Entry Into Preemption
2. Termination of the Current Phase
3. Track Clearance Green Time
4. Preemption Hold Interval
5. Return to Normal Operations

Figure 2. Preemption Sequence

Entry into Preemption

As the train enters the detection circuit, the circuit is de-energized. Then, the traffic signal controller will enter into preemption. However, some controllers will wait for a specified lag time to verify that the preemption call is still active (*6*).

Termination of the Current Phase

The right-of-way transfer time (RTT) is the maximum amount of time needed for the worst-case condition before the track clearance interval can be started. The RTT consists of the time for the traffic signal controller to react to a preemption call, any green time for the current phase, pedestrian walk and clearance time, and yellow change and red clearance intervals for the opposing traffic (*6*). The RTT may be calculated using Equation 2 and Equation 1.

$$RTT = \tau + G + Y + R \qquad \textbf{Equation 2}$$

$$G \geq WALK + PCI \qquad \textbf{Equation 1}$$

Where,

RTT = Right-of-way Transfer Time (sec);
τ = Time for the Signal Controller to React to a Preemption Call (sec);
G = Green time for the current vehicle phase (sec);
Y = Yellow Change Interval (sec);
R_C = All Red Clearance Interval (sec);
$WALK$ = Pedestrian Walk Interval (sec); and
PCI = Pedestrian Clearance Interval (sec).

This time is based on the worst-case scenario in which a preemption notification is received by the controller just after a conflicting phase begins. In this case, the minimum green is served for the conflicting vehicle phase, and the WALK and PCI are truncated, omitted, or served, depending on the controller settings. After the vehicle green ends, the vehicle yellow interval and the all red clearance interval are served. The sum of the four intervals (τ, G, Y, R) is the RTT.

If the pedestrian intervals are served, the green interval for the vehicle phase is extended so that the sum of the WALK and PCI is less than the vehicle green time. Typically, at the onset of preemption, the WALK is truncated and the PCI is omitted. Although a full WALK interval is not necessary for pedestrians to safely cross the intersection, the full pedestrian clearance interval is necessary if the pedestrians are to be given time to safely cross. Therefore, when the pedestrian intervals are truncated or omitted, pedestrians are put at risk.

Track Clearance Green Time

Following the right-of-way clearance, the tracks must then be cleared of vehicles. Typically, the time required for this is considered to be the queue clearance time. In order to ensure a certain degree of safety, the tracks and the area adjacent to the tracks must be cleared of vehicles before the train arrives. This area is outlined as the Minimum Track Clearance Distance (MTCD). The *Manual on Uniform Traffic Control Devices* (MUTCD) defines the minimum track clearance distance (MTCD) as the length along a highway (measured from either the stop line, warning device, or 3.7 m (12 ft) perpendicular to the track centerline) to 1.8 m (6 ft) beyond the tracks, measured perpendicular to the far rail, along the centerline or edge line of the highway, as appropriate, to obtain the longer distance (*1,7*). The MTCD is illustrated in Figure 3. The queue clearance time is based on the time it takes a design vehicle to start up and clear the MTCD. Therefore, the green interval of the track clearance phase is typically equal to the queue clearance time.

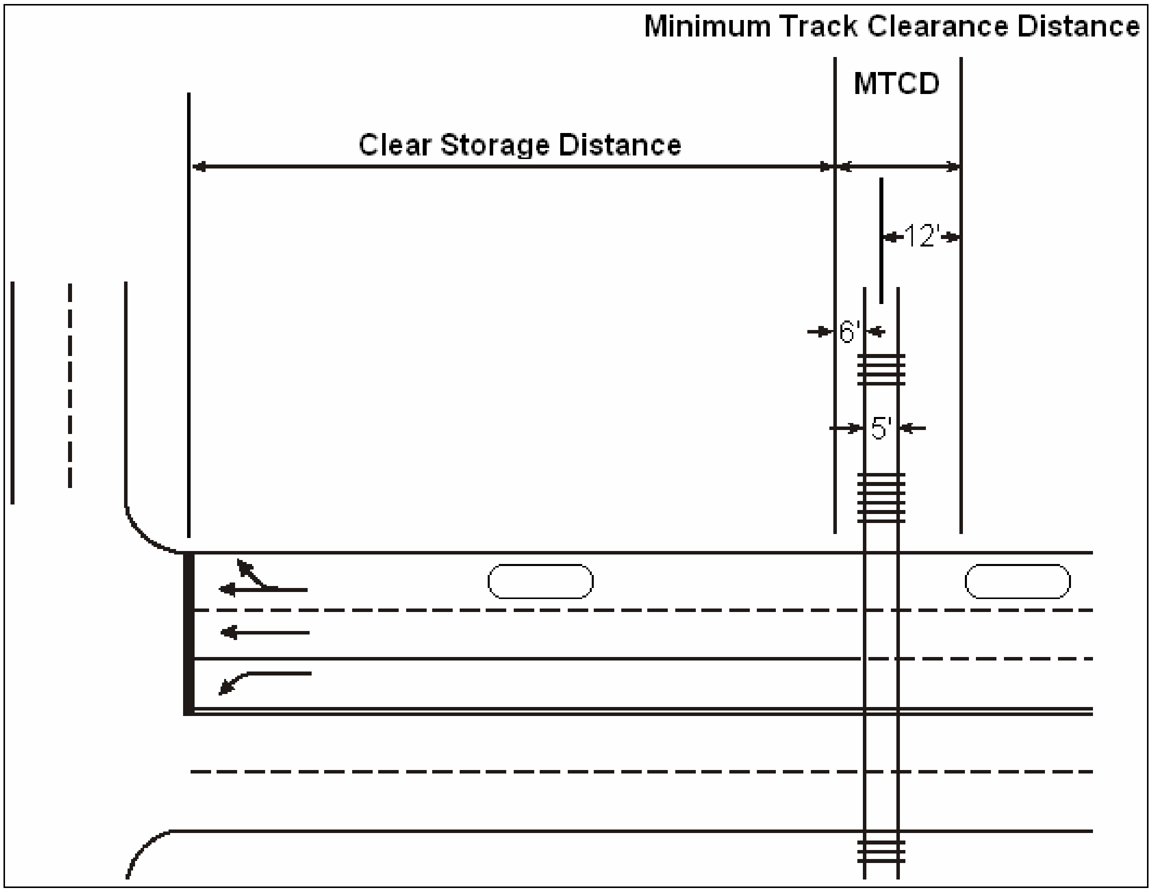


Figure 3. Minimum Track Clearance Distance, MTCD (Adapted from *7*)

The minimum track clearance green time must be at least equal to the queue clearance time, which is the time required for a vehicle stopped on the tracks to start up and move off of the tracks (*2*). This ensures that drivers have green time provided as long as they are attempting to clear their vehicles from the tracks.

The track clearance green time may be calculated using numerous methods. One such procedure is that used by the Texas Department of Transportation. First, the distance "L" is measured (in feet) from the warning device on the far side of the tracks to the edge or shoulder of the road at the highway intersection. The distance, L, is the MTCD for this procedure. Then, the minimum track clearance green time is found by consulting Table 1. The desired track green provides time for vehicles in front of the warning device to enter the intersection after the onset of preemption, while the minimum green time is based on the time necessary for a vehicle stopped on the tracks to clear the tracks and move to safety (*8*). Figure 4 illustrates the clearance distance, L.

Table 1. Track Clearance Green Time (*6,8*)

L (feet)	Mimimum Time (seconds)	Desirable Time (seconds)
25	6	10
50	7	10
75	9	10
100	10	12
125	11	14
150	12	17
175	14	19
200	15	21
>200	As Determined	As Determined

For this procedure, all vehicles are assumed to be through-moving passenger cars with a vehicle length of 25 feet, and their departure headways are assumed to be consistent with Greenshields. The track clearance times are factored up by a multiplier of 1.5 for each truck expected to be in the clearance distance, L, and by 1.3 for each left-turning vehicle expected (*6*).

When the track clearance green time ends, the separation time is then provided. This time acts as a safety buffer between the vehicles leaving the tracks and the train arriving at the crossing. After this separation time ends, the train arrives at the crossing.

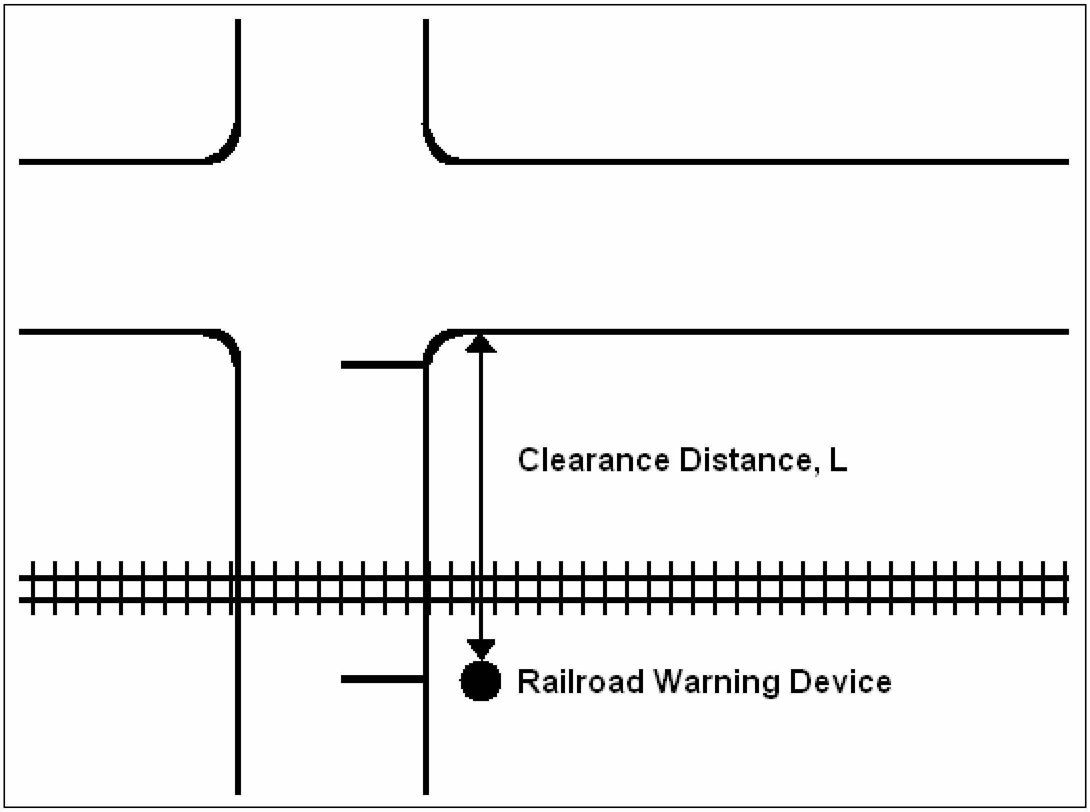


Figure 4. Clearance Distance, L (Adapted from *6*)

Preemption Hold Interval

Once the green, yellow, and red clearance times for the track clearance phase have expired, the preemption signaling proceeds to a hold interval. The hold interval occurs when the train is near or in the highway-railroad grade crossing, and it is intended to allow movements that do not conflict with the train to proceed through the intersection (*6*).

Several types of preemption hold operations are used. First, the controller may have all directions display *flashing red*, where all signals display a flashing red ball so that each signal face approximates STOP sign. Next, *steady all red* may be used. Here, all signals display a solid red ball. Also, a *yellow/red flash* operation may be used. In this mode, all phases which do not conflict with one another will display flashing yellow, while the remaining phases will flash red (*5*,*6*).

A more flexible mode is the *limited service* operation. In this mode, all phases that have movements conflicting with the train remain red, while the controller cycles through the non-conflicting movements. This mode may also allow for the service of non-conflicting pedestrian movements. Finally, the *rest in green* operation may be used. This holds green the primary movements that do not conflict with the grade crossing. This is usually the two through phases on the street that runs parallel to the tracks (*5*,*6*)

Return to Normal Operations

After the train exits the detection circuit at the grade crossing, the circuit is energized, and the active warning devices are deactivated. Then, the preemption call to the controller is removed. Now, the controller services specific return phases which are typically phases that were obstructed by the movement of the train (*6*). Then, the controller will return to normal operations.

VEHICLE EMISSIONS MODELING

Currently, four predominant methods exist for mobile source emissions modeling. The standard in the United States is MOBILE6, which utilizes an aggregate approach. However, in California, the standard is the similar EMFAC model. Also, there is a more disaggregate model called the Comprehensive Modal Emissions Model (CMEM). Finally, a new method, called the Portable Emission Measurement System (PEMS), is available.

MOBILE6

Typical mobile source emissions modeling, including MOBILE6 modeling, utilizes estimations of vehicle miles of travel (VMT) and operational characteristics of vehicles in the geographic area of interest. Then, the necessary information, including average link speed and VMT, is usually obtained from traffic demand models. Finally, this data is used as input for an emissions model to produce average emissions per unit length for a given vehicle type over a specified time period (*9*,*10*,*11*).

MOBILE6 is capable of calculating the average in-use fleet emissions factors for carbon monoxide (CO), hydrocarbons (HC), and nitrous oxides (NO_X), and this can be done for cars, trucks, buses, and motorcycles that run on either gasoline, diesel, or natural gas (*12*). The emissions factors are based on relationships between emissions rates and average vehicle speeds, and one such relationship for freeways and arterial roadways is shown in Equation 3 (*11*).

These emissions factors are derived from a driving cycle known as the Federal Test Procedure (FTP), and the FTP does not include speeds above 57 mph nor does it include acceleration rates above 3.3 mph/s. Since these events are common in today's traffic, it is perceivable that the FTP does not reflect the current driving behavior. It should be noted, however, that there current efforts to revise the FTP (*9*,*10*).

$$CR_{iypjf} = (B_{iyp} + OC)C_{iypjf} + T_{iyp} + F_{iy} + R_{iy} + S_{iy} + H_{iy} + D_{iy}$$

Equation 3

$$\forall i = 1,N;\ y = 1,Y;\ p = 1,P;\ j = 1,J;\ f = 1,M$$

Where,

CR_{iypjf} = Composite Emission Rate for Vehicle Class *i*, Model Year *y*, Pollutant *p*, Speed Index *j*, and Facility Type *f* (g/mi);

B_{iyp} = Base Emission Rate for Vehicle Class *i*, Model Year *y*, and Pollutant *p* (g/mi);

OC = Off-cycle Emissions Offset (A Function of Base Emission Rate);

C_{iypjf} = Composite Correction Factor for Vehicle Class *i*, Model Year *y*, Pollutant *p*, Speed Index *j*, and Facility Type *f*;

T_{iyp} = Start Emissions for Vehicle Class *i*, Model Year *y*, and Pollutant *p* (g/mi);

F_{iy} = Refueling Factor for Vehicle Class *i* and Model Year *y* (*p* = HC);

R_{iy} = Running Loss Factor for Vehicle Class *i* in Model Year *y* (*p* = HC);

S_{iy} = Resting Loss Factor for Vehicle Class *i* and Model Year *y* (*p* = HC);

H_{iy} = Hot Soak Emission Factor for Vehicle Class *i* and Model Year *y* (*p* = HC);

D_{iy} = Diurnal Emission Factor for Vehicle Class *i* and Model Year *y* (*p* = HC);

N = Number of Vehicle Classes;

Y = Number of Model Years;

P = Number of Pollutant Types;

J = Number of Average Speed Values Used in Analysis; and

M = Number of Facility Types.

Presently, MOBILE6 is designed to calculate aggregate regional emissions using average driving characteristics. Although it is capable of producing regional emissions inventories, the model is limited by the use of average speeds and currently outdated driving cycles. These aggregate characteristics make MOBILE6 unsuitable for accurately evaluating microscopic traffic flow improvements such as signal coordination and other operational improvements (*9*,*10*).

CMEM

CMEM is an emissions model based on the mode of operation of the vehicle. It was developed at the University of California, Riverside, and it utilizes a physical, power-demand modal modeling approach in order to predict vehicle emissions (*9*,*13*). Specifically, the prediction of emissions is based the various modes of vehicle operation, such as cruise, idle, acceleration, and deceleration.

As compared to the MOBILE6 model, which predicts emission based on average speeds, CMEM utilizes an alternate approach that looks at the specific modes. This approach may be beneficial in that it can more accurately portray emissions from specific modes of driving. Previous research has shown that a vehicle in acceleration mode is has higher emission rates as compared to a vehicle in cruise mode (*14*). Similarly, increasing individual vehicle power (defined as the product of speed and acceleration) has been shown to increase vehicle emissions (*11*).

In this model, the emissions process is dissected into components corresponding to physical phenomena that are associated with vehicle operation and emissions production (*9*). Unlike descriptive modal models in which emissions are observed and then assigned to statistical bins, CMEM is a deterministic model that utilizes causal parameters to predict emissions. These parameters vary with vehicle type, engine, and emission technology, and some of them may be stated as vehicle specifications by the manufacturer (*9*,*13*). Using these parameters, over 300 vehicles were tested, and their emissions were collected for the following three test cycles: a complete 3-bag FTP test, a high speed cycle, and a modal emission cycle developed by the research team (*13*).

CMEM is capable of predicting engine-out emissions, tailpipe emissions, and fuel consumption for numerous types of light-duty vehicles (LDVs). Also, it implicitly employs all factors in the vehicle operating environment that affect emissions, and some of these include vehicle technology, fuel type, and operating modes (*9*,*10*).

PEMS

PEMS is an on-board emission measurement system that is relatively new. This system provides empirical emissions output estimates for a specific vehicle based on sample of tailpipe emissions and theoretical exhaust flow data. Although the accuracy of this type of system is currently uncertain, PEMS still may be desired for many emissions testing and emissions predicting applications. Unfortunately, the typically high costs associated with these systems tend to inhibit their use.

Other means of on-board emissions measurement include instrumented vehicles. Along with being expensive, instrumented vehicle studies, are only able to test one vehicle, so their focus is specific to a single vehicle model (*14*). Some other emissions models utilize a dynamometer to test the vehicles. Here, the vehicle is driven in a laboratory, and emissions are collected for various driving cycles. Although a specific driving cycle may be used, the dynamometer tests can still have shortcomings, such as an under-representation of short-term events that cause high emissions (i.e. high accelerations) (*14*). On the other hand, the PEMS model allows versatility in that the testing equipment may be applied to any LDV, and the vehicle may be tested in everyday traffic conditions on a roadway.

Several commercial applications of the PEMS model are currently available. One such model is the OEM-2100 portable on-board mass emissions exhaust emissions monitoring system developed by Clean Air Technologies, Inc. This system measures second-by-second mass emissions from a sample probe in the tailpipe. Specifically, HC, CO, CO_2, and NO_X are measured in grams per second. These data are combined with theoretical exhaust flow data to produce an estimate of total tailpipe emissions. The theoretical exhaust flow data are calculated from engine parameters obtained from the On-board diagnostic (OBD) system, which provides engine and vehicle operation data. If the vehicle is older than a 1996 model, more direct monitoring may be necessary, as the OBD protocols were not standardized until 1996 (*11*).

METHODOLOGY

In the previous section, railroad preemption fundamentals and emissions modeling techniques were described with some detail. In this section, the test-bed used for this research will be described, and specific detail will be used to describe the current signal control operations and preemption operations of the intersections in the test-bed. Also, the creation of the VISSIM VAP logic will be discussed, and the simulation design will be explained.

TEST-BED

The test-bed for this project is the "Wellborn Corridor" in College Station, Texas. This corridor includes an urban arterial roadway, Wellborn Rd., which runs parallel to a single Union Pacific two-way railroad line. Both the road and tracks run through the campus of Texas A&M University, and there are a relatively large number of pedestrians and vehicles that cross the rail line at various highway-railroad at-grade crossings. In addition, there are approximately 20-25 trains per day using this corridor, and the passage of each train causes the traffic signal to be preempted at each highway intersection with a nearby rail crossing. The section of interest in the corridor includes four signalized highway intersections, each near a HRGC, and they are (from north to south): Old Main Dr., Joe Routt Blvd., George Bush Dr., and Holleman Dr. Each of these intersections operates with constant warning time (CWT) systems for train detection, and the minimum warning time (MWT) is 20 seconds for each intersection except for George Bush Dr., where the MWT is 35 seconds. See Figure 5 for a map of the corridor.

In order to create a working model in the VISSIM program, large amounts of field data, which included intersection layout, traffic volumes, and traffic signaling data, were collected and compiled. Then, this data was coded into the VISSIM program to create the model for the corridor. This task included creating the layout for the model, inserting additional field data, and creating the VAP files, which would control the traffic signals.

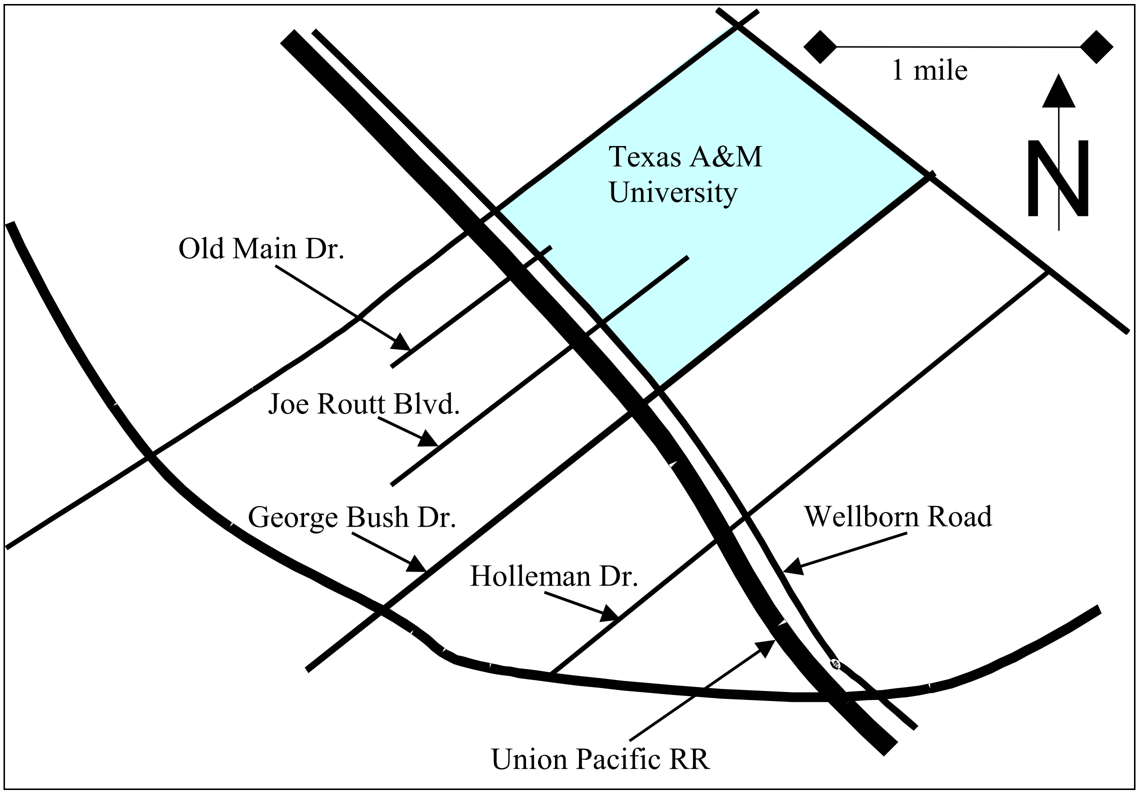


Figure 5. Map of Wellborn Corridor

Traffic Volumes

The traffic volume data for this project came from multiple sources. Vehicle and pedestrian volumes were obtained for the George Bush Dr. and Old Main Dr. intersections from a traffic count done in September 2001 by the Texas A&M ITE Student Chapter. Their counts did not include the Holleman Dr. intersection, so the vehicle and pedestrian counts were taken for this project at the Holleman Dr. intersection on March 5, 2002. Due to construction at the time the counts were done, traffic volumes were not counted at Joe Routt Blvd. Therefore, they were obtained through the use of some older count data available from the City of College Station. Although the data for the Joe Routt Blvd. intersection was about two or three years older than the other data, the volumes seemed to be reasonable, and they were deemed acceptable. All of the counts were taken during weekdays when the university classes were in session; therefore, the student population was near its peak. Although all of the counts included both AM and PM peak volumes, this project looked only at the AM peak period from 7:15-8:15. The AM peak vehicle and pedestrian volumes used in the model can be found in Figure 6.

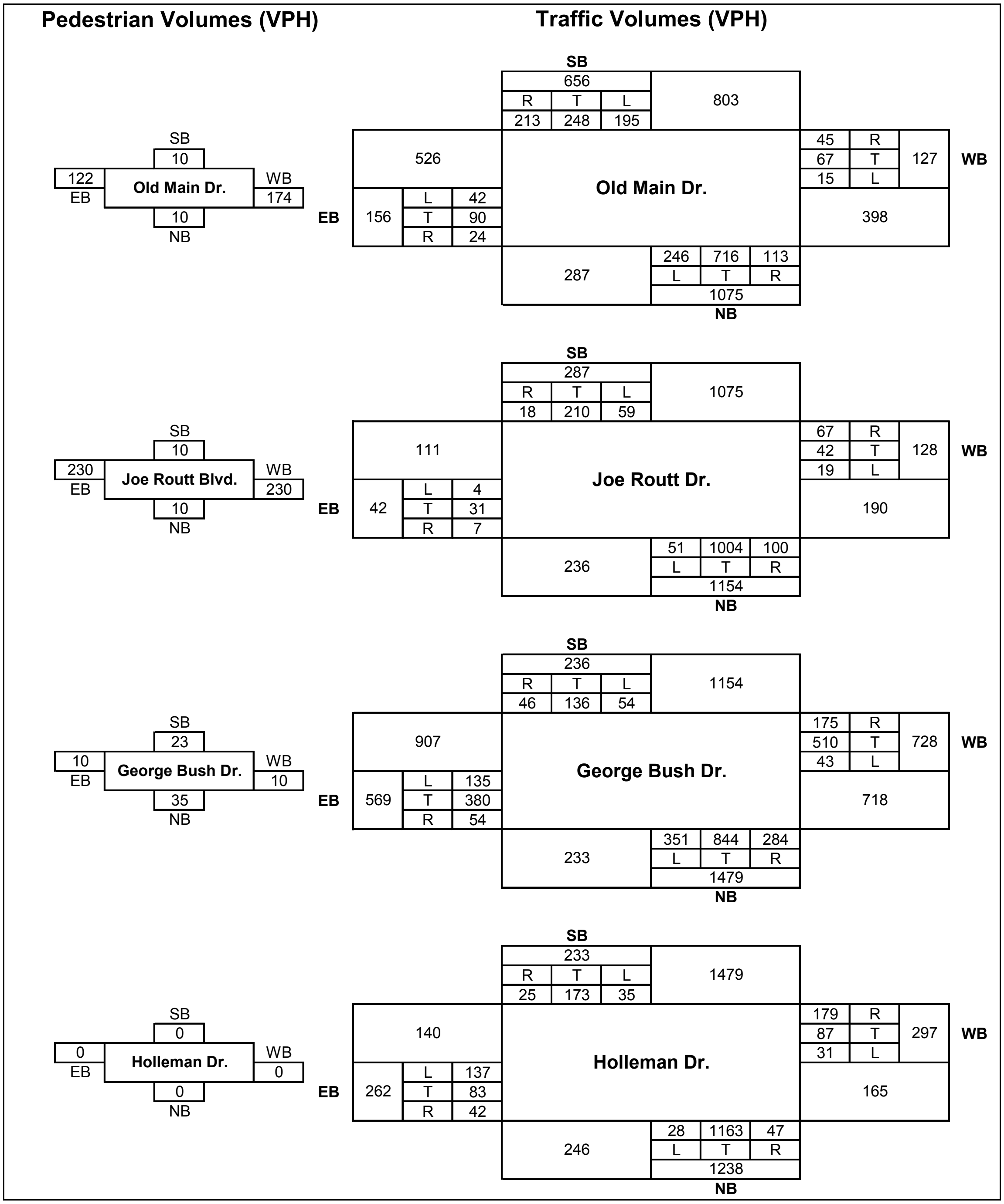


Figure 6. AM Peak Vehicle and Pedestrian Volumes

Traffic Signal Operations

The Wellborn Corridor currently utilizes coordinated signaling along Wellborn Rd. Additionally, the phasing includes protected and permissive left turns. The coordinated timings for each intersection were collected from the signal controllers, and it was noted that the controllers operate in a semi-actuated coordinated mode. This means that the main street (Wellborn Rd.) runs in coordinated mode, and the cross streets are served only after the main street phases are served and if there is a call for service on the cross street.

All of the intersections operate with a cycle length of 120 seconds, and each one runs in semi-actuated coordinated mode during the AM Peak hour. Figure 7 illustrates the intersection layout and phase assignments, where the symbol ϕ denotes the phase.

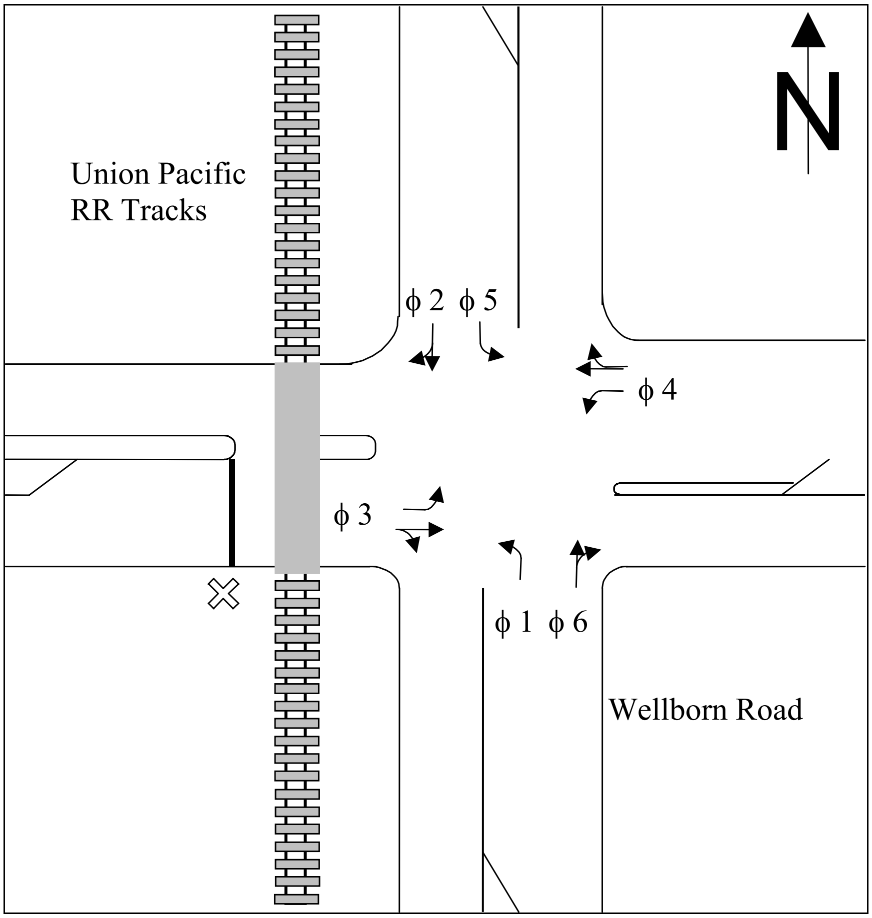


Figure 7. Intersection Layout and Phase Assignments

DEVELOPING VAP CODE FOR VISSIM

In order to perform the analyses, the VISSIM 3.70 microsimulation package was used to model the corridor. VISSIM was chosen because it can effectively simulate multi-modal systems, which, in this case, includes rail, vehicle, and pedestrian traffic. VISSIM allows the user to operate traffic signals with three different types of controls. They are pre-timed signal control, NEMA Standard Signal Control Emulator (which can operate in fully actuated, coordinated, or semi-actuated coordinated modes), and vehicle actuated signal control (VAP) (*15*).

For the traffic signal operations in the model, the VAP logic file component of VISSIM was used. The VAP file method was chosen because, unlike the other available methods, it allows unique signal controls operations (i.e. railroad preemption) to be used in simulation. Another advantage of using the VAP file method is that one file can control the normal phasing and preemption phasing for an intersection. Also, the same file can also be used to collect the pedestrian cutoff data and to model the CWT train warning system. Therefore, a VAP signal logic file was written for each intersection. One such file for the George Bush Dr. intersection is included in Appendix A.

Coordinated Traffic Signals with Protected-Permitted Phasing

The coordinated logic is relatively simple. First, the main street (Wellborn Rd.) does not have actuated through phases, so the through phases (phases 2 and 6) are green during preset intervals in the cycle. The corresponding pedestrian phases are actuated, and when they are active, the WALK interval is extended to utilize the additional guaranteed green time for the through phases. For the actuated cross street phases and main street left-turn phases, the logic was set up to provide green time for these phases if and when the controller receives a call for the appropriate phase. Like the main street phases, these cross street phases could only be served during set intervals of the cycle; however, they could be skipped if the controller receives no call. For the cross streets, the pedestrian signals are served along with the vehicle phases, and if a pedestrian is detected without a vehicle also detected, both phases are served. Additionally, whenever a pedestrian phase is served for the cross streets, the corresponding vehicle green time is extended to the minimum time required for the pedestrians to safely cross the roadway. This semi-actuated coordinated signaling was replicated in the VAP logic files that VISSIM uses for its signal controllers.

The protected-permissive phasing is only used on the main street approaches, as the cross streets use a different phasing. Primarily, the protected-permitted phasing requires the use of two signals for the left-turn approaches. One signal is for protected and one for permitted. This was done in the VISSIM model as well, and the setup in the model worked as follows: First, the protected left turn phases were set to green when the protected phases were supposed to be green, and then the same protected left turn phases were each set to green when the corresponding, non-conflicting through phases began. The only problem was that when the cars in the model saw the green signal for permissive left-turns, special yielding considerations (priority rules) had to be set up to stop the vehicles from proceeding with the turn if another car or a pedestrian blocked the path to successful completion of the turn. The VISSIM priority rules criteria that the turning cars followed included a minimum headway of 115 feet and a minimum gap time of 8 seconds. The minimum gap time was based on the critical gap time for a left turn, and the critical gap is the gap in opposing traffic for which the number of drivers rejecting the gap is equal to the number of drivers accepting the gap. The *Highway Capacity Manual* reports a critical gap value of 5.5 seconds for left-turning vehicles at a two-way stop-controlled intersection (*16*). Also, a study with data collected in Houston, Texas found a critical gap value of 4.5 seconds for left-turning vehicles without a protected signal (*17*). Although these values were not specifically determined for unprotected left turns under protected-permissive phasing, each of these values was originally used as the minimum gap time. However, the turning vehicles in the model were accepting gaps that were too small, so a larger minimum gap value of 8 seconds was used to correct this problem. After many visual inspections and careful checking of the vehicle movements, this model setup was deemed to be acceptable for the intended simulation.

The main street phases use protected-permissive left turns, but the cross streets do not use this type of phasing. The cross streets are served using a split phasing setup. After the main street through phases are served and a call has been received for each cross street approach, both approaches are served separately in the order predetermined in the controller. The through phase and left turn phase are served together for one cross street approach, and then the other approach is served similarly.

Preemption Sequence

The preemption sequence used in this model approximates the sequence used by the City of College Station. For example, the sequence used at George Bush Dr. utilizes an advance preemption time of 15 seconds, so the MWT is 35 seconds. Here, the city uses a minimum green time of 5 seconds for any phases that are green when the preemption call is read by the controller. This was also done in the model. Next, the city uses 5 seconds of clearance time after the green time ends for those same phases. Due to rounding approximations, this clearance time was 6 seconds in the model. Finally, the city uses 13 seconds for the track clearance green interval, which allows time for vehicles to clear the tracks before the train arrives. This track clearance green time of 13 seconds was also used in the VISSIM model.

Once the preemption sequence ends, the controller enters a "dwell" state. Here, it cycles through the phases that do not have movements conflicting with the train. For this state, the George Bush Dr. intersection was observed during five train preemption events.

From the observations of the George Bush Dr. intersection during preemption, it was noted that the controller first serves the westbound left (WBL) phase with a green arrow, while the other westbound through (WB) movements are held with a display of a red ball. Following the WBL phase, the controller then serves the southbound through (SB) and southbound left (SBL) movements simultaneously. Finally, the SBL phase ends and the northbound through (NB) and SB phases are served simultaneously. Following the NB and SB phases, the controller serves the WBL phase and continues to cycle through the three aforementioned blocks. The WBL block is served for a minimum time of 8 seconds, but it may be extended to as long as 26 seconds, if the appropriate traffic demand exists. Also, the second block (SBL and SB) is served for a minimum of 10 seconds and can be extended to 20 seconds. Finally, the third block (SB and NB) has a set duration of 60 seconds. It should be noted that each block is served in each cycle of the three blocks. Traffic demand may extend the time for a block, but demand is not used to decide if a block should be served. For example, if no vehicles are present at the WBL and SBL detectors, these phases will still be served during the preemption dwell state, and NB and SB vehicles will be delayed while these phases are served. Although improvements could be made to this preemption dwell sequence, the VISSIM model reflects similar phasing as is used in the field. Figure 8 includes a diagram showing each of the three blocks of preemption dwell phasing.

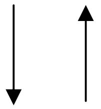
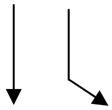
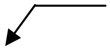
60 seconds	SB NB	
10-20 seconds	SB SBL	
8-26 seconds	WBL	
End of Track Clearance Phase		

Figure 8. Preemption Dwell Phasing

Pedestrian Cutoffs

Pedestrian cutoffs can result from the preemption of traffic signals near highway-railroad intersections. For the purposes of this thesis, a pedestrian cutoff occurs when a pedestrian phase is truncated during the preemption sequence for a signalized highway intersection. Due to constraints in the VISSIM model, a pedestrian cutoff (in the model) occurs when a pedestrian phase is still active when the track clearance phase of the preemption sequence begins. A pedestrian phase is considered active if it is operating in either the "WALK" interval or the flashing "DON'T WALK" interval. If a pedestrian cutoff occurs, a safety hazard exists because a pedestrian could be stranded in the path of vehicles trying to clear the tracks as a train approaches.

In order to quantify these cutoffs using the VISSIM model, counters were added in the VAP logic where the cutoffs would occur. The signaling logic is set up so that when a train is detected, the current vehicle phase terminates once it has reached a minimum green time for preemption. When the phase terminates, the signal displays yellow, followed by red. Then, phase 3 is set to green for the track clearance phase. It should be noted that the pedestrian phasing is different. When the preemption call is received by the controller, the current pedestrian phase is set to yellow and then red (representing flashing "DON'T WALK" and solid "DON'T WALK"). In the VISSIM VAP logic, a phase cannot display red directly following green without some period of transition (yellow interval) unless the yellow interval is set to zero (*15*). Because the yellow interval was defined as the PCI, it could not be set to zero for the entire simulation. This means that the that the green "WALK" interval is cut off where it is, but the signal must go through the entire "yellow" interval or PCI (varies from 10 to 19 seconds throughout the model) before it actually displays red. Hence, the 10 to 19-second flashing "DON'T WALK" signal is not shortened when the train is detected in the model.

A single method for counting pedestrian cutoffs was used in this model. This method involves counting when the PCI (flashing "DON'T WALK") actually overlaps with the track clearance phase. This situation involves a conflict between the two phases, and more importantly, it illustrates an important safety problem. Ultimately, pedestrians could still be crossing when the track clearance phase begins. In this case, the pedestrians could be directly in the path of vehicles trying to clear the tracks. Figures 9-12 illustrate this scenario. In the electronic version of this thesis, a corresponding video file may be viewed to further demonstrate the pedestrian cutoff scenario. This can be done by simply clicking the mouse button on any one of Figures 9-12, and the video will open in a media player.

Figure 9 shows the intersection just after preemption has begun. Here, the vehicle signals are red for all directions including the road running parallel to the railroad tracks, but the corresponding pedestrian phases are still in the clearance interval. Consequently, pedestrians (shown at the bottom of the figure) are still trying to cross the intersection.

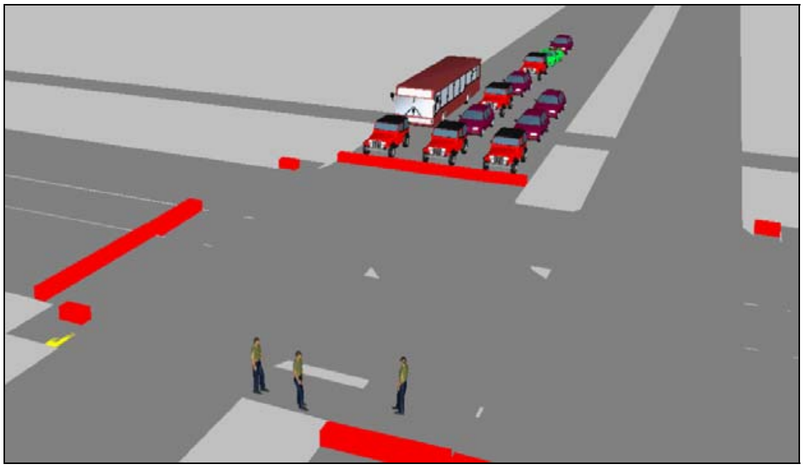


Figure 9. Illustration of the Pedestrian Cutoff Scenario, Part 1

Figure 10 shows the intersection just after the track clearance phase turned green. The vehicles near the tracks are beginning to move, but the pedestrians are still trying to cross.

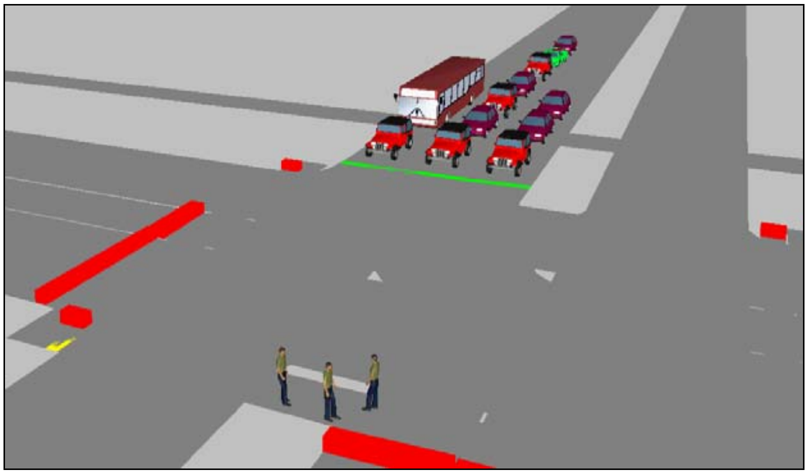


Figure 10. Illustration of the Pedestrian Cutoff Scenario, Part 2

Figure 11 shows the intersection after the lead vehicles have moved away from the tracks. A possible collision exists between the pedestrian and the lead vehicles as the pedestrian attempts to cross the intersection. Furthermore, this collision may difficult for the driver to avoid as he tries to clear the tracks for his own safety.

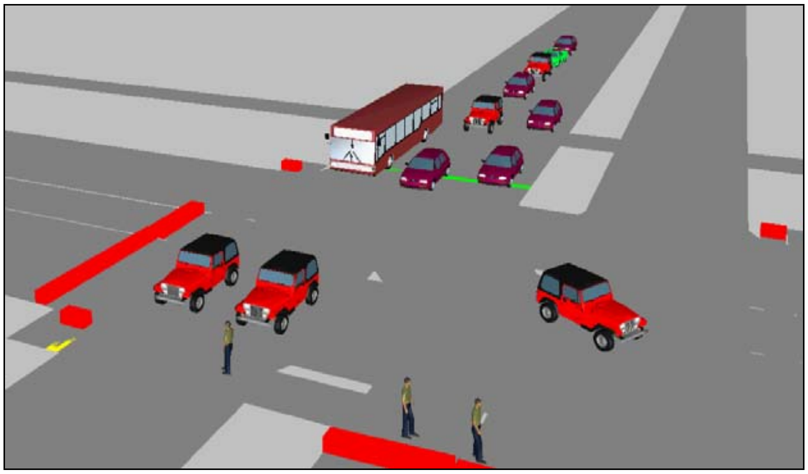


Figure 11. Illustration of the Pedestrian Cutoff Scenario, Part 3

Figure 12 shows the intersection just after the train has arrived. The track clearance phase had already ended, and the signals are just about to begin dwell phasing.

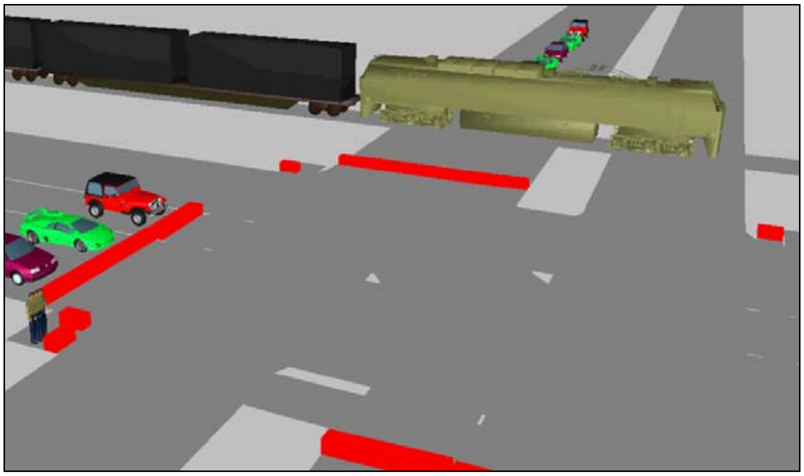


Figure 12. Illustration of the Pedestrian Cutoff Scenario, Part 4

For the purposes of this thesis, it is recognized that a pedestrian cutoff has occurred when the pedestrian clearance timer is less than the PCI. When the track clearance phase begins, the pedestrian clearance timer is checked to see if it is less than the PCI for the corresponding pedestrian phase. If it is less, a conflict of phases occurs. This conflict is recorded as a pedestrian cutoff. Similarly, if the timer is greater than or equal to the PCI value, a pedestrian cutoff is not recorded. This methodology is explained in Equation 4.

$$\begin{array}{ll} Timer < PCI & \text{Pedestrian Cutoff} \\ Timer \geq PCI & \text{No Pedestrian Cutoff} \end{array} \qquad \textbf{Equation 4}$$

Where,

$Timer$ = Pedestrian Clearance Timer (Started at Onset of PCI) (sec); and
PCI = Pedestrian Clearance Interval (Fixed Value) (sec).

For this method, those instances where the four-second pedestrian “WALK” interval was cut short were not specifically counted. Mainly, this is because pedestrians can legally enter the intersection only until the signal display starts showing the flashing “DON’T WALK” signal at the beginning of the PCI. So, if the ‘WALK’ interval is cut short, the pedestrians in the model will not enter into the intersection while the signal displays flashing “DON’T WALK”. Also, since the phase must contain the full PCI (flashing “DON’T WALK”) in VISSIM, there will still be an overlap of conflicting phases in most cases. This is because the maximum time from train detection until the track clearance phase begins is only 11 seconds. This includes a minimum green for the vehicle phase (5 sec maximum), a vehicle yellow interval (4-5 sec), and a red clearance interval (2 sec). Within this model, the pedestrian clearance intervals range from 10 to 19 seconds. The 11 seconds is less than all PCI values except for one. So, for almost all cases, a conflicting overlap will result when the pedestrian “WALK” display is shortened. Consequently, even though the cutoff of the “WALK” display itself is not counted, the resulting overlap will be counted.

The only time this is not true is at the Old Main Dr. intersection when preemption begins exactly one second after the NB and SB vehicle phases begin along with their corresponding pedestrian phases. In this rare instance, the “WALK” intervals will be truncated, but the PCI will finish before the track clearance phase begins. Because the pedestrians were given adequate time to cross the intersection before the track clearance phase had begun, this instance was not counted as a pedestrian cutoff in the model.

Constant Warning Time (CWT) System

In order to accurately model the CWT system in VISSIM, the system in the model must be set up so that it performs just as the CWT devices perform in the field. The train speed and distance must be measured and an arrival time (to the crossing) must be predicted for the train. Using this predicted arrival time, a constant warning time is provided. This is true for any train speed less than or equal to the speed of the fastest train; however, the warning time will not be constant if the train accelerates, decelerates, or stops between the detector and the crossing. For the Wellborn Corridor in this model, the fastest train was found to be 65 km/h, and a warning time of 35 seconds was provided at the George Bush Dr. crossing. In addition to the 35-second CWT file for the George Bush Dr. intersection, additional files were created for the 20-second CWT systems being used at the other three intersections.

For the 35-second CWT file, the VAP logic for the traffic signals included additional arguments to provide the constant warning time of 35 seconds to the controller. The following describes the arguments used in the VAP code. First, when a train is detected, a train detection timer begins. In addition, the detector records the speed of the train using the velocity function. Recognizing that 35 seconds of warning time must be provided, a variable (“Sec_til_pre” or seconds until preemption) represents how long the controller must wait until preemption is initiated. This is shown in Equation 5. Once the train detection timer is equal to or greater than the variable Sec_til_pre, preemption begins. As preemption begins, a preemption timer starts. Finally, when the train is detected at the crossing, the warning time is set equal to the preemption timer.

$$t_{ij} = \frac{d_j}{v_{ij}} - 36 \qquad \textbf{Equation 5}$$

Where,

t_{ij} = Seconds Until Preemption is to Begin for Train i at Location j (sec);
d_j = Distance from the Train Detector to the Crossing (m);
v_{ij} = Velocity of Train i at the Detector of Location j (m/sec); and
36 = Time Subtracted to Reserve 35 Seconds of Warning Time (sec).

In Equation 5, 36 seconds is subtracted from the dividend in order to reserve 35 seconds for the warning time. The reason that 35 seconds is not subtracted is that VISSIM rounds up the final value for Sec_til_pre; therefore, this methodology better represents the warning time.

SIMULATION DESIGN

Using the information from the preceding sections, a model was created, and VAP code was written for each intersection in the model. After the model was created, it was developed further. First, the model was run several times as visual inspections were done. Next, slight changes to the priority rules were made to accommodate right-turn on red (RTOR) movements as well as pedestrian movements. Specifically, yielding criteria was set up so that vehicles would not turn onto a street if a pedestrian occupied the crosswalk. Also, yielding criteria were set up for protected-permissive left turns, as described earlier. Then, the calibrated model was simulated for 30 trial runs, and volumes were collected for each vehicle movement. Each intersection has 12 movements as shown in Figure 13, and three intersections were analyzed.

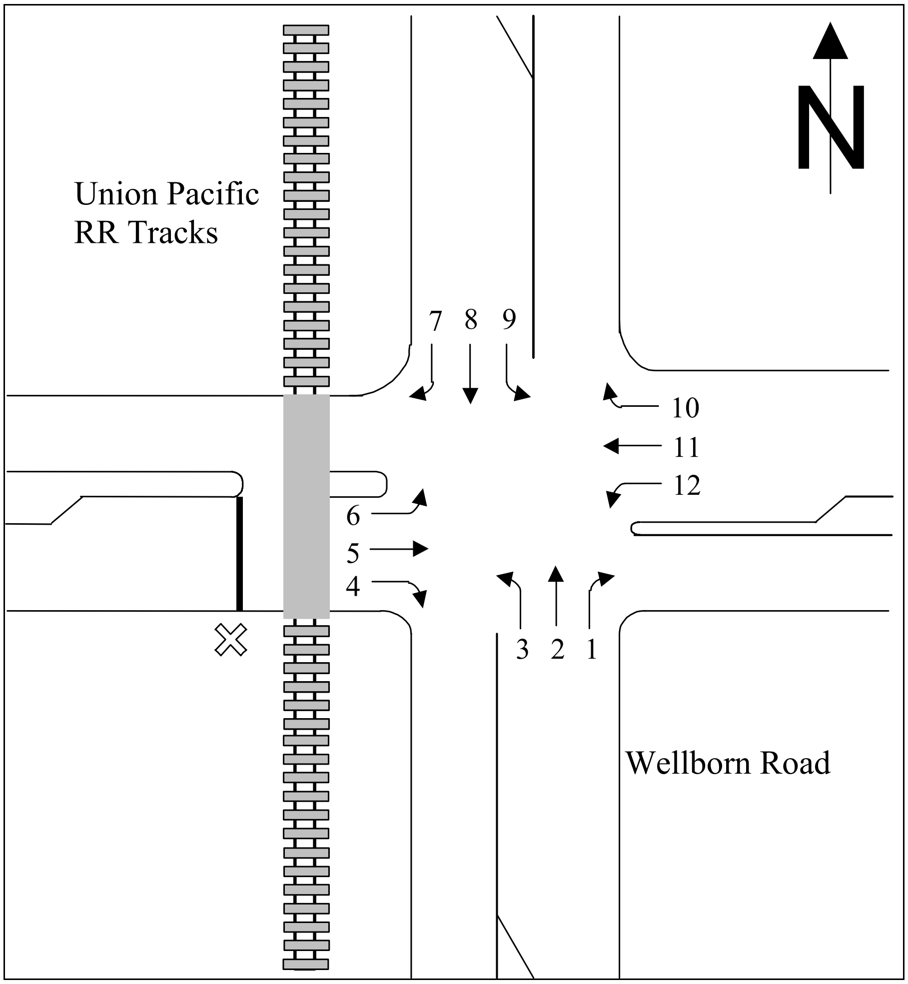


Figure 13. Turning Movements at Each Intersection

The twelve volumes were collected from Old Main Dr., Joe Routt Dr., and George Bush Dr., and they were averaged for the 30 runs. The average model volumes were compared against the actual volumes for all 36 volume movements, and the results are shown in Figure 14. The actual and model volumes were similar, and for most movements, the difference was less than 5 percent. Thus, after numerous visual inspections and the preliminary volume analysis, the simulation model was considered to be valid for the corridor being studied.

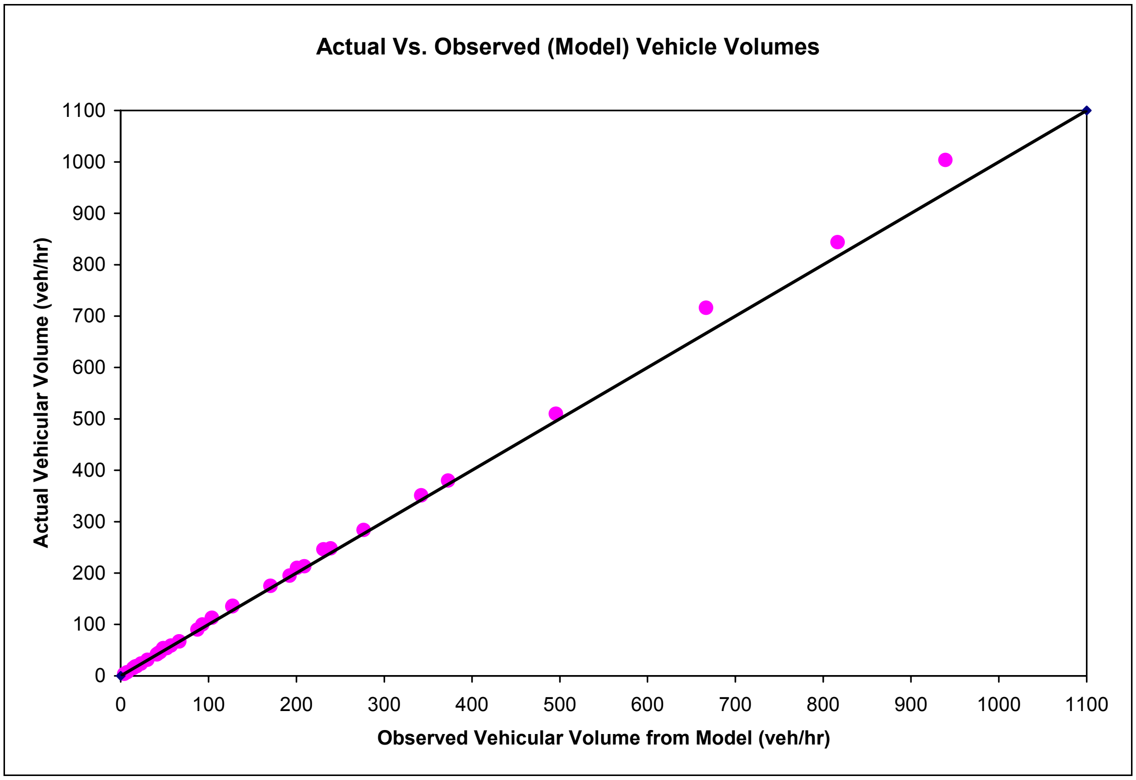


Figure 14. Comparison of Actual and Observed Vehicle Volumes

The actual train speeds distribution was approximated in the VISSIM model using a data set of 683 actual train speeds collected by a detector at the George Bush Dr. crossing. The distribution of actual average train speeds at the George Bush Dr. intersection is shown in Figure 15. This distribution has a mean train speed of 39.0 km/h and a standard deviation of 8.2 km/h. Additionally, these speeds were assumed to be valid for all intersections in the model. For the purpose of the model runs, only one train was sent into the network during each run, and this train was always northbound.

Then, the model was to be run for three different northbound train events, where each event represented a different train length. The train lengths were taken from the train length data collected from the Wellborn Corridor, and the average train length (μ = 1363 m) and the standard deviation of the length (σ = 564 m) were used to find three representative train lengths as shown in Table 2.

Table 2. Train Lengths

μ = 1363m σ = 564 m	Length 1	Length 2	Length 3
Formula	μ - σ	μ	μ + σ
Length	799 m	1363 m	1927 m

Running the Model for Existing Conditions

Each train length event was simulated for 20 runs. Each run consisted of a train entering and exiting all four HRGCs during the peak AM period, and each run lasted for one hour of simulation time. The train speeds were randomly chosen from the real-world train speed distributions collected in the field. All traffic signals were set up to approximate the current operations in the corridor, and all other parameters were modeled after real-world conditions in the corridor. As output from the model, average intersection delay and the number of occurrences of a pedestrian cutoff is reported.

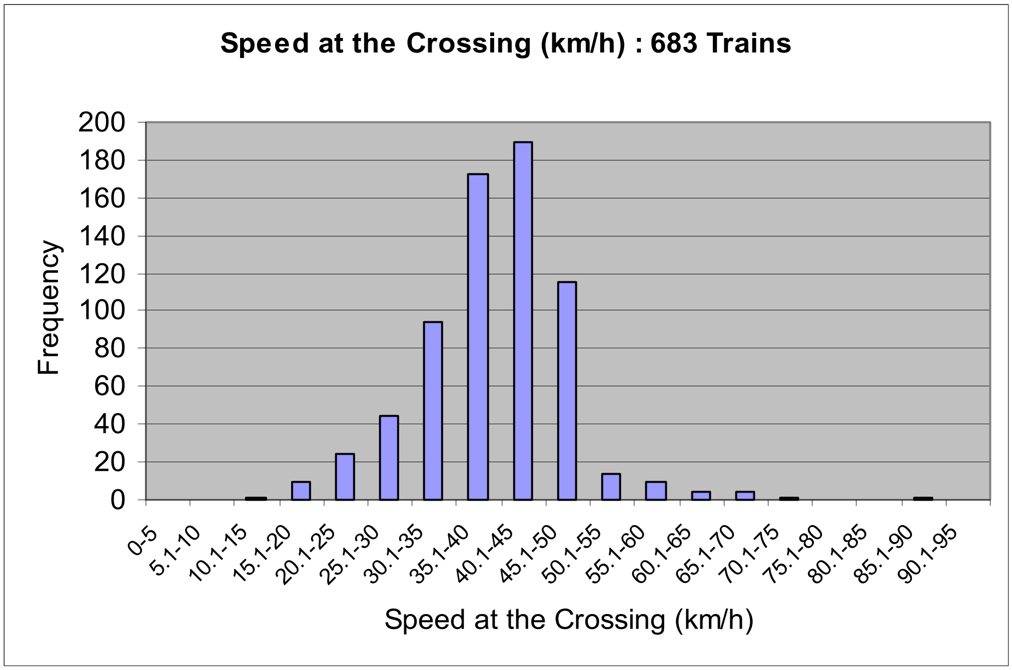


Figure 15. Actual Train Speeds at George Bush Dr.

Run Model with Different Train Speeds

For this analysis, train speeds were chosen from distributions with specific means and standard deviations. The means and corresponding standard deviations used in this analysis are included in Table 3.

Table 3. Means and Standard Deviations for Train Speeds

Mean (km/h)	35	50	65
Standard Deviation (km/h)	5 & 10	5 & 10	5 & 10

One mean speed and one standard deviation were used to produce a train speed distribution, and 6 distributions were tested. For each speed distribution, the train detectors were moved accordingly to minimize delay and improve safety. Specifically, the detectors were moved to the distance that the fastest train in the speed distribution can travel during the specified warning time for the crossing. Each distribution was tested with twenty simulations for each of the three train events, and the measure of effectiveness includes average intersection delay as well as the number of pedestrian cutoffs.

Examine Vehicle Emissions Due to Train Operations

Emissions produced by vehicles on the roadway can vary for a particular vehicle depending on the movement characteristics of the vehicle. The movement of the trains causes blockage of the HRGC as well as the preemption of normal operations of the traffic signal controller for the nearby highway intersection. These factors have an effect on the vehicle operations in the area, and it is expected that individual vehicle emissions are greater during a train preemption event as compared to normal operations. Therefore, the first part of this analysis involved running the model with and without a train. Individual vehicle characteristics (namely speed) were collected, and these values were used as inputs for an emissions model.

The Comprehensive Modal Emissions Model, Version 2.0 (CMEM) was used for the emissions analysis. Individual vehicle characteristics were used as inputs, and CMEM was used to produce vehicle emissions as a function of vehicle power. The emissions data includes Nitrogen Oxides (NOx), Hydrocarbons (HC), and Carbon Monoxides (CO). Next, the individual emissions were aggregated for the entire corridor, and the corridor was analyzed for total emissions with and without a train movement.

The final part of this analysis incorporated the analysis with different train speeds described earlier. The model was run, and data was collected for existing conditions with train movements. Then, the model was run with the different train speed distributions and alternate detector placements. A before and after analysis was performed to test whether the aggregate vehicle emissions were lower for the test cases with controlled speeds as compared to the real-world case. It was hypothesized that emissions would lower for the test cases in which the train speeds are explicitly controlled and the detectors are placed accordingly.

Collecting Data from VISSIM

The data collected from the simulation runs included average vehicle delay, d_{ij}, for each movement at each intersection; however, this data was summarized to produce delay per intersection, d_j. The average delay for each intersection was found from Equation 6.

Equation 6

$$d_j = \frac{\sum_{i=1}^{N} V_{ij} d_{ij}}{\sum_{i=1}^{N} V_{ij}}$$

Where,

d_j = Average Delay at Intersection j (sec/veh);
V_{ij} = Volume of Movement i at Intersection j (veh/hr);
d_{ij} = Average Delay for Movement i at Intersection j (sec/veh); and
N = Number of Movements.

RESULTS

As described earlier, the duration of each simulation was 3600 seconds of simulation time. However, the analysis time was different. From observation of the model, it was noted that the traffic volumes and therefore, the model, were at a steady state after 600 seconds. Because it was necessary for the model network to be at a steady-state before the train event was to begin, the train began its journey at 601 seconds. Also, the end of the analysis time was found in a similar fashion. For the slowest train speed and longest train length scenario, the model did not reach steady-state until 2400 seconds. This worst-case scenario was used so that the analysis period could be the same for all simulations. Consequently, the analysis period for each simulation run was 30 minutes of simulation time from 601 seconds until 2400 seconds.

Each train speed distribution was run for 20 simulations for each of the three representative train lengths. Table 4 lists the test conditions.

Output data was collected from the model for three of the four intersections (Old Main Dr., Joe Routt Dr., and George Bush Dr.). It should be noted that simulated data was not collected for the Holleman Dr. intersection because there were not any observed pedestrian volumes at this intersection. The output data for the three intersections consisted of average vehicle delay and vehicle movement characteristics (time, velocity, etc.).

Table 4. Illustration of Simulation Runs

Train Length	Name of Dist.	Train Speed Distribution	Fastest Train*	Detector Location from Crossing
Short Train				
	Existing	μ=39.0 km/h, σ=8.2 km/h	65 km/h	361 m [1]; 632 m [2]
	35-5	μ=35.0 km/h, σ=5.0 km/h	50 km/h	278 m [3]; 486 m [4]
	35-10	μ=35.0 km/h, σ=10.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-5	μ=50.0 km/h, σ=5.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-10	μ=50.0 km/h, σ=10.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-5	μ=65.0 km/h, σ=5.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-10	μ=65.0 km/h, σ=10.0 km/h	95 km/h	528 m [3]; 924 m [4]
Average Train				
	Existing	μ=39.0 km/h, σ=8.2 km/h	65 km/h	361 m [1]; 632 m [2]
	35-5	μ=35.0 km/h, σ=5.0 km/h	50 km/h	278 m [3]; 486 m [4]
	35-10	μ=35.0 km/h, σ=10.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-5	μ=50.0 km/h, σ=5.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-10	μ=50.0 km/h, σ=10.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-5	μ=65.0 km/h, σ=5.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-10	μ=65.0 km/h, σ=10.0 km/h	95 km/h	528 m [3]; 924 m [4]
Long Train				
	Existing	μ=39.0 km/h, σ=8.2 km/h	65 km/h	361 m [1]; 632 m [2]
	35-5	μ=35.0 km/h, σ=5.0 km/h	50 km/h	278 m [3]; 486 m [4]
	35-10	μ=35.0 km/h, σ=10.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-5	μ=50.0 km/h, σ=5.0 km/h	65 km/h	361 m [3]; 632 m [4]
	50-10	μ=50.0 km/h, σ=10.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-5	μ=65.0 km/h, σ=5.0 km/h	80 km/h	444 m [3]; 778 m [4]
	65-10	μ=65.0 km/h, σ=10.0 km/h	95 km/h	528 m [3]; 924 m [4]

*: 99th Percentile Train Speed

[1]: Existing Location for Old Main Dr. and Joe Routt Blvd.

[2]: Existing Location for George Bush Dr.

[3]: Moved to Accommodate Fastest Train at Old Main Dr. and Joe Routt Blvd.

[4]: Moved to Accommodate Fastest Train at George Bush Dr.

AVERAGE VEHICLE DELAY

Delay Data

Average delay was used as the main measure of effectiveness for this research. For each train speed distribution and train length, average delay was collected for each of the three intersections for all 20 simulations. Then, the 20 runs were averaged, and four separate average delay times were found for each train speed distribution for the entire 30-minute period (one for each intersection analyzed and one average of the intersections). The summarized collected average delay data for the 30-minute period follows in Tables 5-7.

Table 5. Average Vehicle Delay (Short Train Length)

Train Speed Distributions	Delay Entire Network (sec/veh)	Delay Old Main Dr. (sec/veh)	Delay Joe Routt Blvd. (sec/veh)	Delay George Bush Dr. (sec/veh)
Existing	26.8	21.5	20.6	33.6
35-5	26.4	21.6	20.5	32.8
35-10	28.0	22.4	20.9	35.5
50-5	25.4	(19.9)	19.6	32.2
50-10	25.3	20.0	(19.2)	32.1
65-5	(25.1)	20.6	19.3	(31.1)
65-10	25.6	21.4	19.9	31.4

(): Minimum Average Delay for Network/Intersection

In Table 5, the average delay for the 35-5 distribution is similar to that of the existing conditions. However, the delay for the 35-10 distribution is slightly larger than the delay for the existing conditions. For the remainder of the distributions, the average delay was lower than for the existing conditions, and the delay generally decreases as the mean train speed increases.

For the short train length, the train speed distribution that was associated with the minimum delay for the entire network was found to be the 65-5 distribution. This distribution was also associated with the lowest average delay for the George Bush Dr. intersection.

Table 6. Average Vehicle Delay (Average Train Length)

Train Speed Distributions	Delay Entire Network (sec/veh)	Delay Old Main Dr. (sec/veh)	Delay Joe Routt Blvd. (sec/veh)	Delay George Bush Dr. (sec/veh)
Existing	29.4	23.5	21.2	37.7
35-5	29.7	24.2	21.0	38.2
35-10	30.8	23.6	21.8	40.3
50-5	26.1	(20.8)	19.9	33.0
50-10	26.3	21.1	(19.5)	33.3
65-5	(26.0)	21.6	19.6	(32.3)
65-10	26.3	22.2	19.6	32.6

(): Minimum Average Delay for Network/Intersection

For the average train length, each delay was higher than the corresponding delay from the short train length with the exception of one case (the 65-10 distribution at the Joe Routt Blvd. intersection). Once again, the delay for the existing distribution and the 35-5 distribution were similar, and the delay for the 50-5, 50-10, 65-5, 65-10 distributions were lower than the delay for the existing conditions. This was true for all three intersections and for the entire network.

In Table 6, the minimum delay for the entire network and the George Bush Dr. intersection was found with the 65-5 distribution. Just as for the short train length, the general rule is that as the mean train speed increases, the delay decreases.

Table 7. Average Vehicle Delay (Long Train Length)

Train Speed Distributions	Delay Entire Network (sec/veh)	Delay Old Main Dr. (sec/veh)	Delay Joe Routt Blvd. (sec/veh)	Delay George Bush Dr. (sec/veh)
Existing	31.7	24.3	21.9	41.9
35-5	32.9	27.3	22.2	42.4
35-10	34.1	27.0	23.2	44.8
50-5	28.9	(22.4)	20.2	38.0
50-10	29.0	23.1	20.6	37.4
65-5	(27.2)	23.2	(19.4)	(34.0)
65-10	(27.2)	22.9	19.6	34.1

(): Minimum Average Delay for Network/Intersection

Table 7 helps illustrate that for the long train length, each delay was higher than the corresponding delay from the average train length with the exception of two cases (the 65-5 and 65-10 distributions at the Joe Routt Blvd. intersection). Furthermore, each delay was higher than the corresponding delay from the short train length with the exception of one case (the 65-10 distribution at the Joe Routt Blvd. intersection). This shows that as the train length increases, the delay also increases. This is justified by the fact that longer trains will occupy the railroad crossings for longer periods of time, causing added delay to motorists.

Once again, the delay for the 50-5, 50-10, 65-5, 65-10 distributions were lower than the delay for the existing conditions, and this was true for all three intersections and for the entire network. The minimum delay for the entire network was found with the 65-5 and 65-10 distributions, and the minimum delay for the Joe Routt Blvd. and George Bush Dr. intersections were found with the 65-5 distribution. Just as for the other train lengths, the delay decreases as the mean train speed increases.

Statistical Testing

In order to prove if any differences exist in the data, the *t*-Test statistical test was used. Specifically, the Pooled *t*-Test was used to determine if a significant difference in means existed between two average delays. Equations 7 and 8 describe the Pooled *t*-Test (*18*).

Equation 7

$$T_0 = \frac{\overline{X}_1 - \overline{X}_2 - \Delta_0}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}$$

Where,

S_p = Pooled Estimator of the population standard deviation, σ;
n_1, n_2 = Number of Observations from Populations 1 and 2, Respectively;
S_1^2, S_2^2 = Sample Variances from Populations 1 and 2, Respectively;
T_0 = Test Statistic;
$\overline{X}_1$, $\overline{X}_2$ = Sample Means from Populations 1 and 2, Respectively; and
Δ_0 = Difference in Population Means, $\Delta_0 = \mu_1 - \mu_2 = 0$.

Equation 8

$$H_0 : \mu_1 - \mu_2 = 0$$
$$H_1 : \mu_1 - \mu_2 \neq 0$$

Rejection Criteria: $t_0 > t_{\alpha/2, n_1+n_2-2}$ or $t_0 < -t_{\alpha/2, n_1+n_2-2}$

Where,

H_0 = Null Hypothesis;
H_1 = Alternate Hypothesis;
μ_1, μ_2 = Means of Population 1 and 2, Respectively;
$n_1 - n_2 - 2$ = 38, Degrees of Freedom; and
$t_{\alpha/2, n_1+n_2-2}$ = 2.02, for 95% Confidence.

The average delay was compared between the existing conditions and each of the specified train speed distributions for all three train lengths. These comparisons were carried out for each of the three intersections analyzed and for the entire network (an average of the three intersections). In addition, the delay was compared for the same distributions with different train lengths. The results of the Pooled *t*-Test for average vehicle delay are included in Appendix B.

As another method of displaying the delay results, confidence intervals were used. Specifically, 95% confidence intervals on the difference in means ($\mu_1 - \mu_2$) were used in this analysis. The confidence intervals were computed for specific pairs of sample means. The train speed distribution for existing conditions was compared to each other train speed distribution. This was done for all three train length scenarios for the George Bush Dr. intersection as well as the entire network. The George Bush Dr. intersection was analyzed because this is where the most traffic occurs; therefore, this is where the largest impact on delay is expected. Comparisons for the two other intersections and for the remaining pairs of sample means were not analyzed with confidence intervals, but they were analyzed with the Pooled *t*-Test. Furthermore, confidence intervals were found for delay comparisons between the same speed distributions with different train lengths. Equation 9 illustrates how the confidence interval was computed (*18*).

Equation 9

$$\overline{X}_1 - \overline{X}_2 - t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

$$\le \mu_1 - \mu_2 \le \overline{X}_1 - \overline{X}_2 + t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

Where,

S_p = Pooled Estimator of the population variance, σ^2;

S_1^2, S_2^2 = Sample Variances from Populations 1 and 2, Respectively;

$\overline{X}_1$, $\overline{X}_2$ = Sample Means from Populations 1 and 2, Respectively;

μ_1, μ_2 = Means of Population 1 and 2, Respectively;

n_1, n_2 = Number of Observations from Populations 1 and 2, Respectively;

$n_1 - n_2 - 2$ = 38, Degrees of Freedom; and

$t_{\alpha/2,n_1+n_2-2}$ = 2.02, for 95% Confidence.

In terms of determining whether two sample means were statistically different, this analysis gave the same results as the Pooled *t*-Test, as expected. Here, if the confidence interval included zero, the means were not different at the 95% confidence level. Furthermore, if both parts of the interval were greater than zero, a reduction in delay (from sample mean 1 to sample mean 2) was found. Figures 16 and 17 illustrate the confidence interval delay comparisons between existing distributions and the test distributions for the average train length. Similar figures for the short and long train lengths are found in Appendix C.

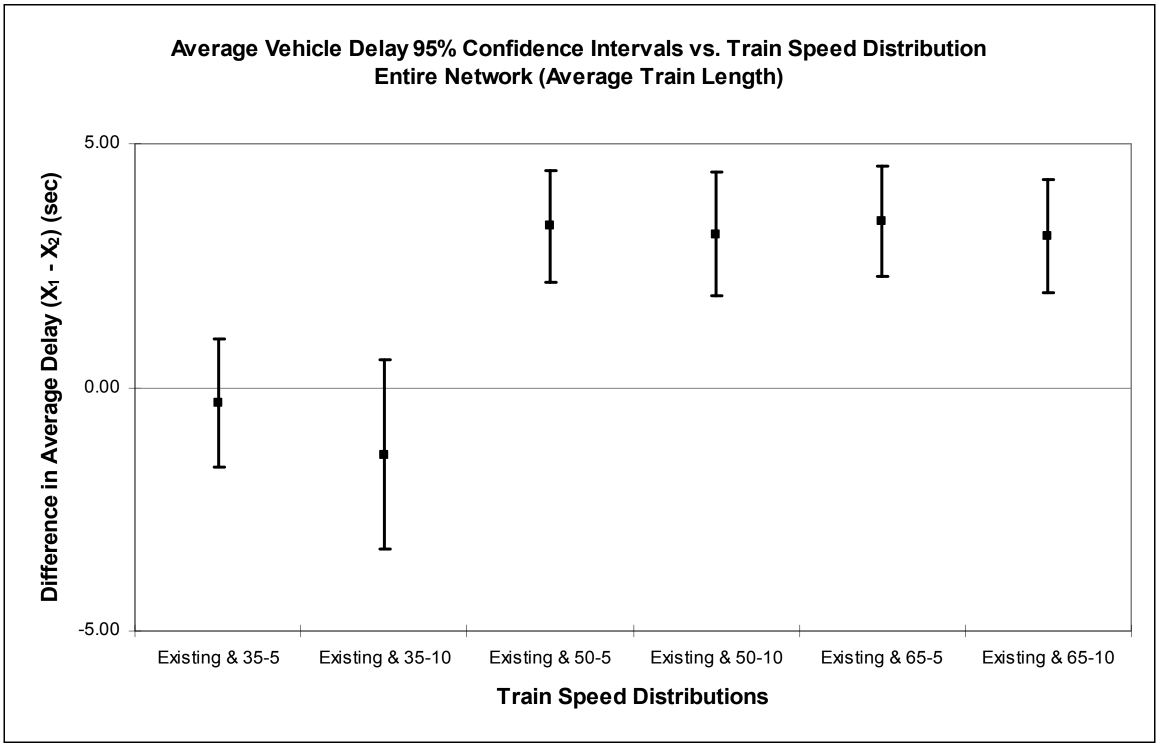


Figure 16. 95% Confidence Intervals on $\mu_1 - \mu_2$ for the Existing Distribution (Entire Network, Average Train Length)

The confidence intervals help show that when comparing existing conditions to the specific train speed distributions for the average train length, delay was significantly lower for the distributions with means of 50 km/h and 65 km/h. Delay did not change significantly for the 35-5 and 35-10 distributions. This is not surprising because both the mean and standard deviation of these distributions are similar to the mean and standard deviation of train speeds for existing conditions (39.0 and 8.2 km/h, respectively). The distributions for which there was a delay reduction saw the delay reduced for all three train length cases; so, for the comparisons of existing conditions and specific train speed distributions, train length was generally not a significant factor.

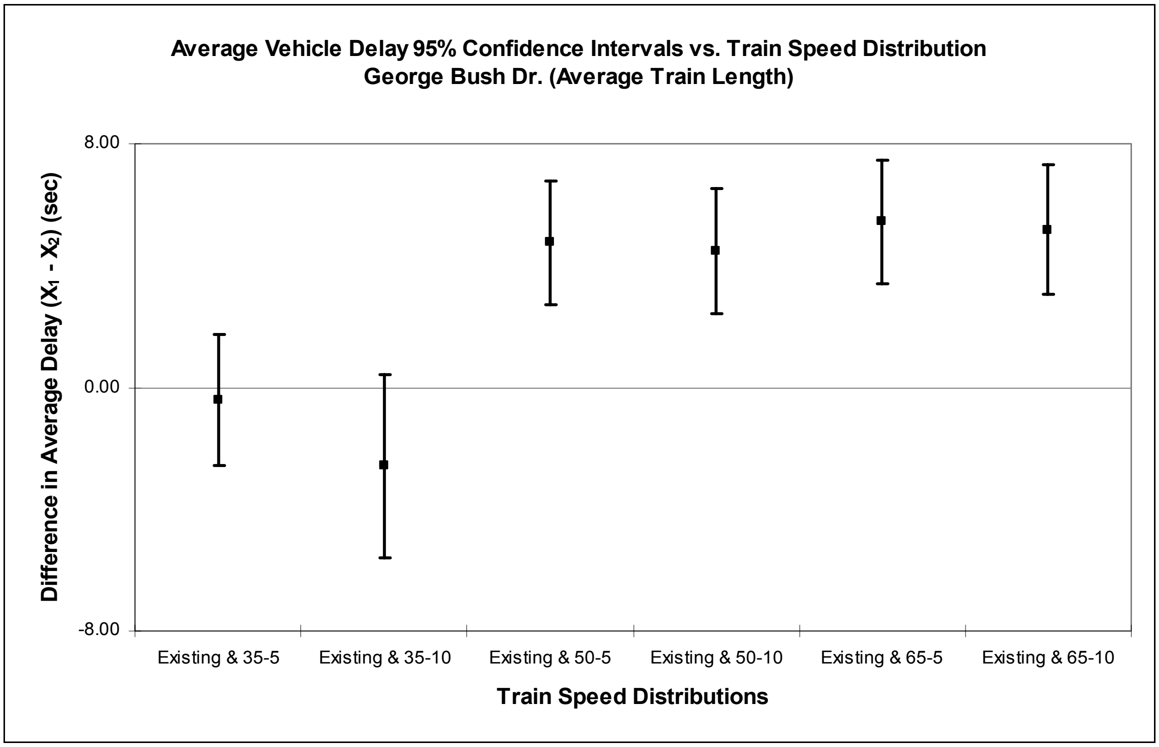


Figure 17. 95% Confidence Intervals on $\mu_1 - \mu_2$ for the Existing Distribution (George Bush Dr., Average Train Length)

In addition to the comparisons made between existing conditions and the specified train speed distributions, comparisons were also made between the specified distributions themselves.

Although the results varied depending on the comparison being made, generally, delay decreased as mean train speed increased. Particularly, the delay for train speeds with a mean of 35 km/h was higher than the delay for the distributions with the other mean speeds for nearly all cases. Figure 18 illustrates this point for the 35-5 distribution.

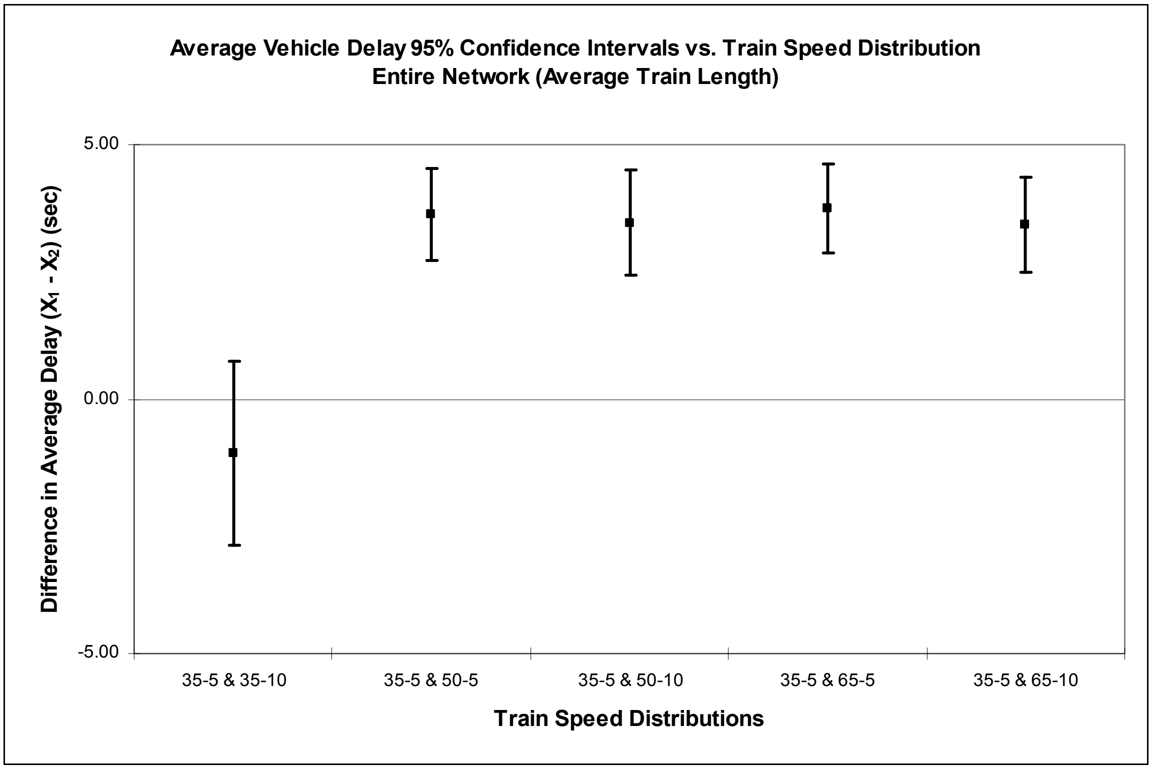


Figure 18. 95% Confidence Intervals on $\mu_1 - \mu_2$ for the 35-5 Distribution (Entire Network, Average Train Length)

On the other hand, the comparisons with higher mean train speeds showed that there was no significant difference in delay. Specifically, the differences in delay were not significant for the distributions with mean speeds of 50 km/h when compared to the distributions with mean speeds of 65 km/h. Also, this result was common for all train lengths, so once again, train length was generally not a factor for these comparisons across speed distributions. Figure 19 includes confidence interval comparisons for the 50-5 and 50-10 distributions against the 65-5 and 65-10 distributions.

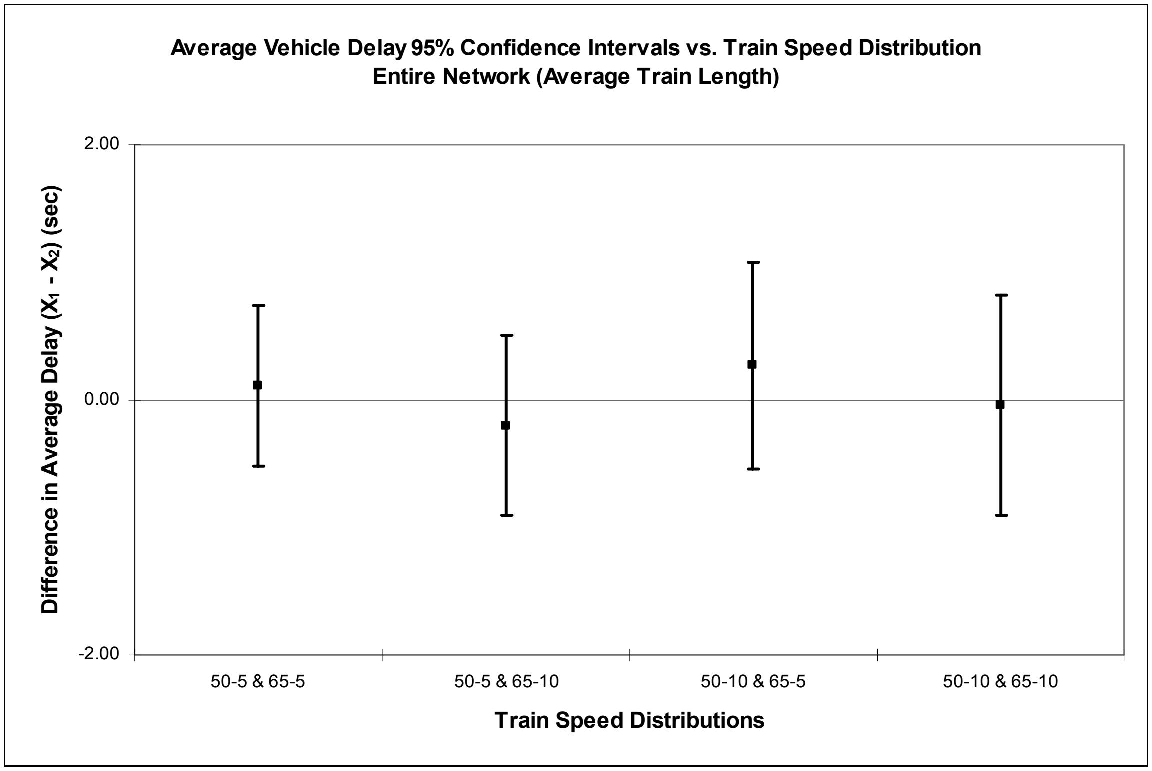


Figure 19. 95% Confidence Intervals on $\mu_1 - \mu_2$ for the 50-5 and 50-10 Distributions (Entire Network, Average Train Length)

In another comparison, the delays from train speed distributions with the same mean speed (and therefore different standard deviations of speed) were compared. In these cases, only the distributions with the slowest mean speed (35 km/h) proved to have significantly different delays, and this was only for the short train length case. Specifically, the 35-5 distribution had a statistically significant lower delay as compared to the 35-10 distribution. There were no other significant differences in delay for the comparisons involving the same mean speed with different standard deviations of speed. Figure 20 includes the confidence interval comparison for the pairs of distributions with the same mean speed for the short train length.

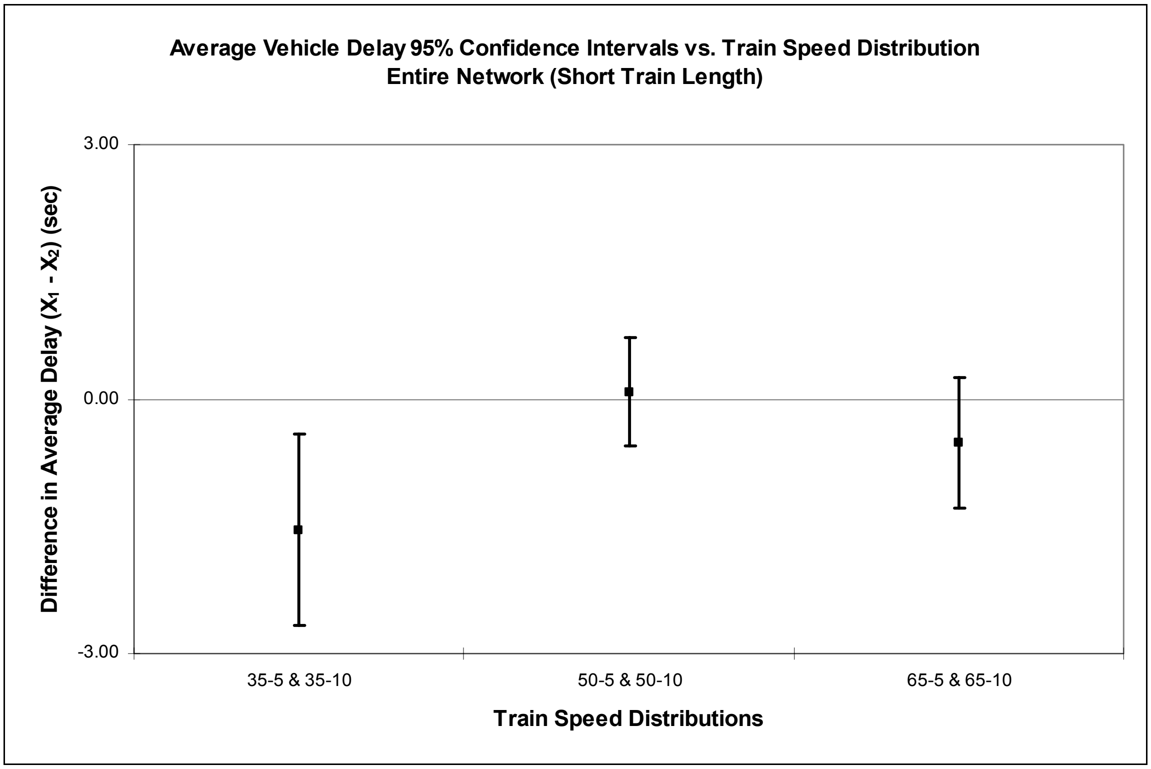


Figure 20. 95% Confidence Intervals on $\mu_1 - \mu_2$ for the 35-5, 50-5, and 65-5 Distributions (Entire Network, Average Train Length)

Finally, each train speed distribution was compared against the same distribution for different train lengths. Specifically, the three train length comparisons were short vs. average, average vs. long, and short vs. long. Figure 21 shows the comparisons for the short vs. long train length for the entire network, and the remaining comparisons are included in Appendix C.

Figure 21 displays the difference in delay from the short train length to the long train length, and this difference is negative for all speed distributions. This means that delay was higher for the cases with the long train as compared to the cases with the short train. Similar relationships were found for the other length comparisons, so the general rule is that as train length increases, average vehicle delay also increases.

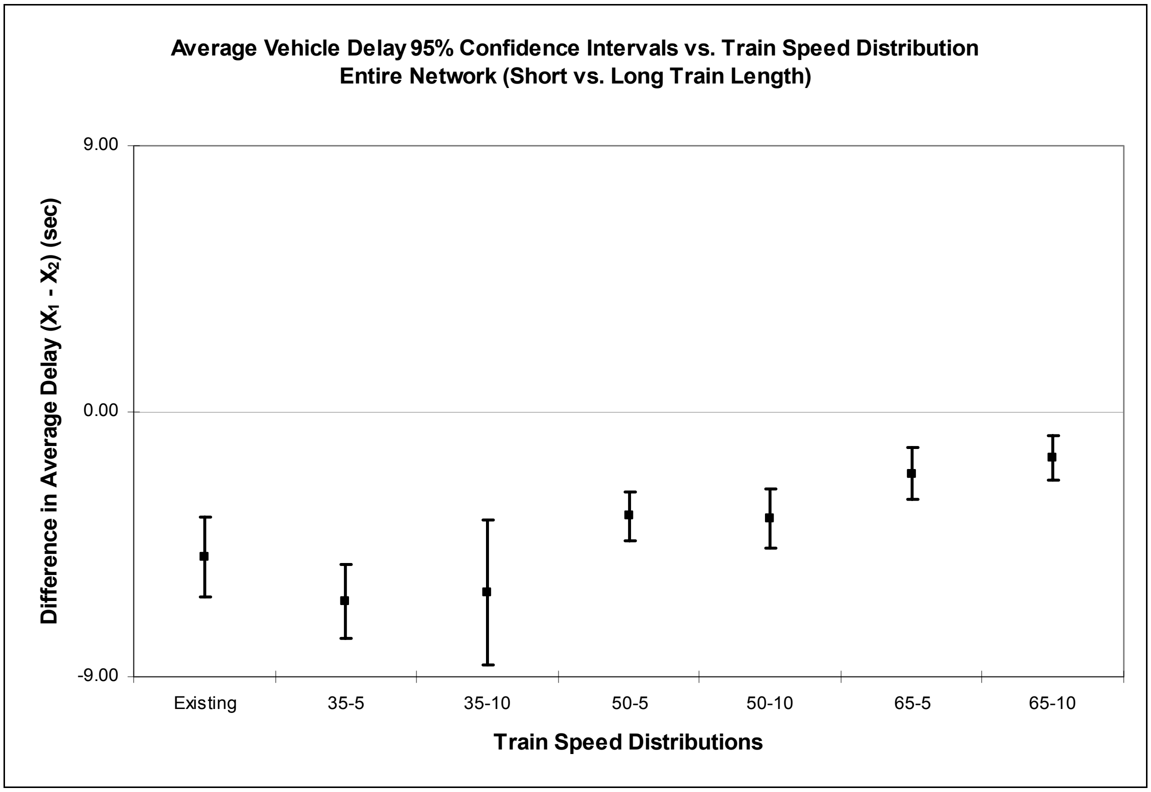


Figure 21. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions (Entire Network, Short vs. Long Train Length)

PEDESTRIAN CUTOFFS

Pedestrian Cutoff Data

Pedestrian cutoff events were monitored during each simulation run, and pedestrian cutoffs did occur in some simulation runs. However, the preemption strategies used in this research did not specifically control the pedestrian phases as the train approached, so the pedestrian cutoffs that were recorded were not correlated with train speed or vehicle delay. Figure 22 helps illustrate this point for the case of existing train speeds, and Appendix D includes additional illustrations.

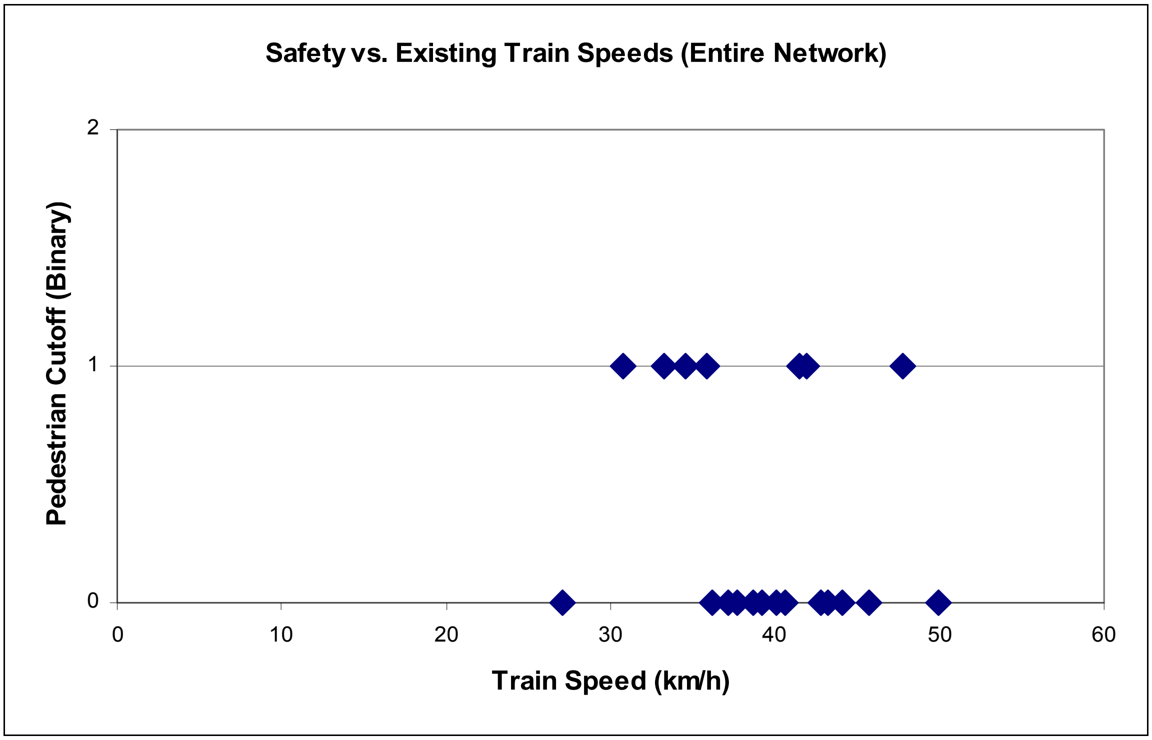


Figure 22. Pedestrian Cutoffs vs. Train Speed for Existing Train Speeds

The "normal preemption" used in this research merely activates the track clearance phase at a set time after the train is detected; it does not alter the start or end time of the pedestrian phases. In the model, a pedestrian cutoff occurred when the pedestrian phase was active exactly at the time that preemption began for that intersection. Since the timing of the pedestrian phase is not altered, a test on pedestrian cutoffs can be approximated by controlling the start time of preemption. This preemption start time is linearly related to the time that the train is sent into the network, so by sending the train into the network earlier or later, a test for pedestrian cutoffs can be performed.

Pedestrian Cutoff Examples

The event of a pedestrian cutoff can occur within a certain time interval. Specifically, this is during the time when the pedestrian phase is active, and this means that the pedestrian phase is in WALK mode or in the PCI (Flashing DON'T WALK). If the train causes the controller to initiate preemption within this time interval, a pedestrian cutoff will occur. Figures

23-24 show how a pedestrian cutoff can occur for each of three pedestrian phases at the George Bush Dr. intersection.

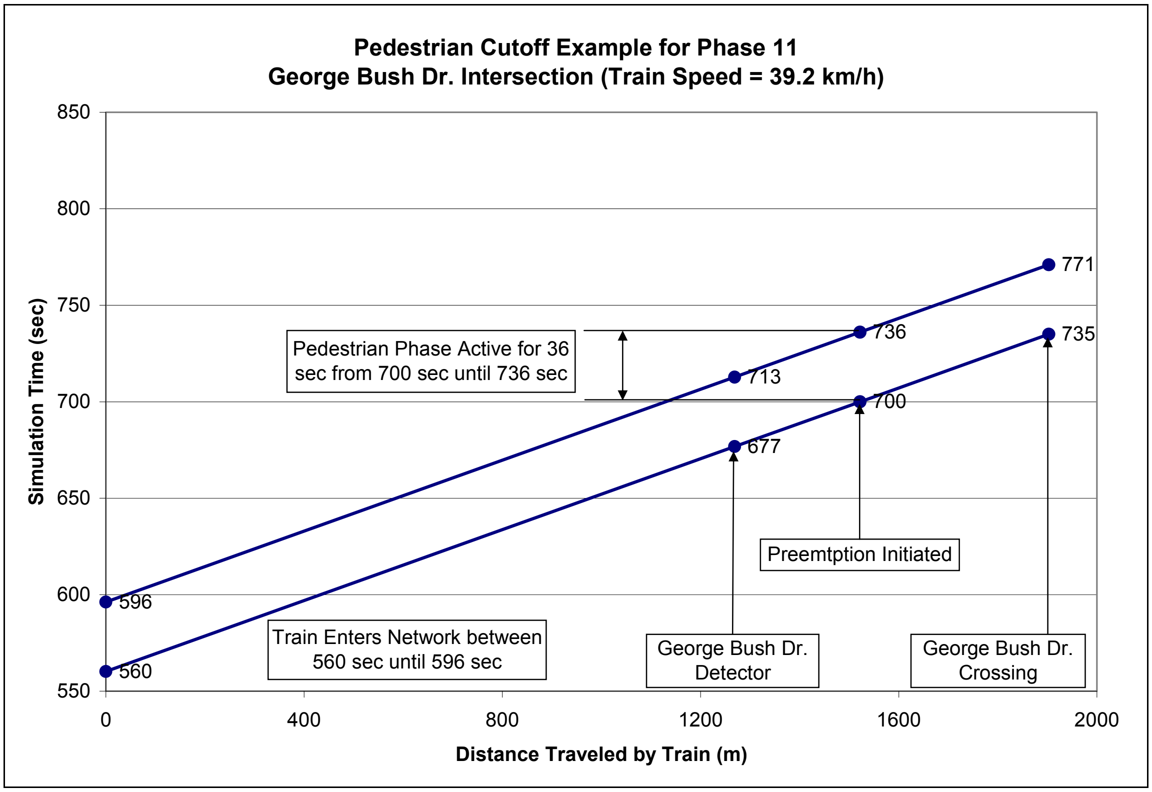


Figure 23. Pedestrian Cutoff Example for Pedestrian Phase 11

Figure 23 helps illustrate a pedestrian cutoff for phase 11. This cutoff will occur if the train enters the network between 560 and 596 seconds. If the train, with a constant speed of 39.2 km/h, enters the network at 560 seconds, it will initiate preemption at 700 seconds. Preemption will be initiated just as the pedestrian phase begins, so a pedestrian cutoff will result.

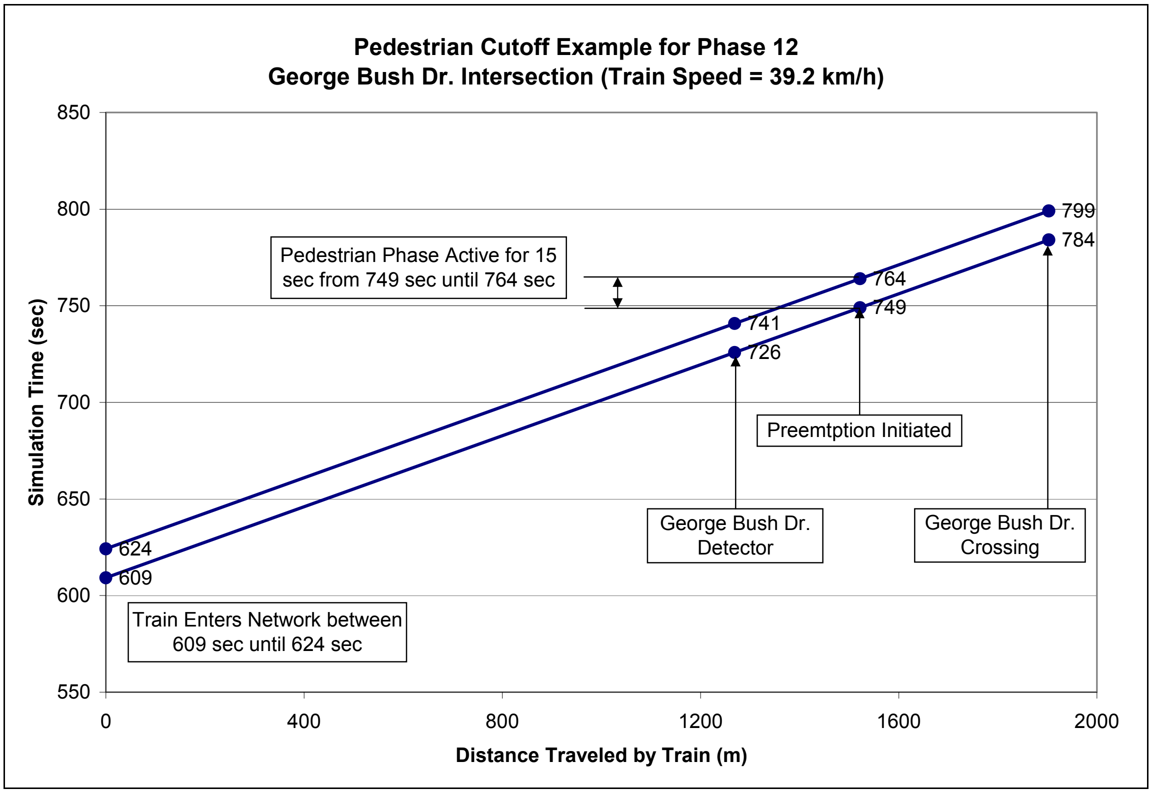


Figure 24. Pedestrian Cutoff Example for Pedestrian Phase 12

As shown in Figure 24, a pedestrian cutoff for phase 12 will occur in this case if the train enters the network at a simulation time of 609 seconds. With its constant speed of 39.2 km/h, the train will cause the controller to start preemption at 749 seconds, just as the pedestrian phase is activated.

Although controlling when the train enters the detection zone may not be feasible, the start of the pedestrian phase could be altered in future tests. If the start of the pedestrian phase could be altered, the pedestrian cutoff could be avoided without controlling the entrance time of the train.

In addition, future research could utilize continuous detection and/or detection further upstream from the crossing. Continuous detection would be able to detect if the train accelerates, decelerates, or stops after is enters the detection circuit. Furthermore, the detection from a further distance would give more time to the traffic signal controller. This would allow for the start time of pedestrian phases to be altered before preemption starts so that a pedestrian cutoff is avoided.

VEHICLE EMISSIONS

Individual Vehicle Emissions

Vehicle emissions can vary for a particular vehicle depending on the velocity and acceleration characteristics of the vehicle. Specifically, as the power of the vehicle (product of velocity and acceleration) increases, the emissions increase linearly. For the purposes of this thesis, power is defined in units of $km^2/h^2/s$.

Using data obtained from the microsimulation runs, time and velocity values were obtained for 14 different vehicles. These vehicles were chosen for their diverse velocity characteristics so that many values for the product of velocity and acceleration were evaluated. The velocity values were used as input to the CMEM model to produce vehicle acceleration values and emissions values for the design vehicle. The design vehicle used for all emissions analyses in this thesis is defined in CMEM as a Category 10 vehicle. This is a normal emitting car that is a tier 1 vehicle with a low power/weight ratio and a mileage less than 50,000 (*13*). Additionally, values for secondary load and soak time were defined to be zero.

The output from CMEM included vehicle velocity and acceleration values per second as well as CO, HC, and NOx emissions and fuel usage each given in g/s. Figures 25-28 illustrate the effect of power on vehicle emissions and fuel usage. As shown in the figures, the production of emissions and the usage of fuel each increase as power increases for the design vehicle. It should be noted that as accelerations increase in both magnitude and frequency, the average power level of the design vehicle will be higher. Therefore, it may be possible to say that as these vehicles are forced to accelerate more, they can be expected to produce higher emissions when compared to the same vehicles that are not forced to accelerate as much.

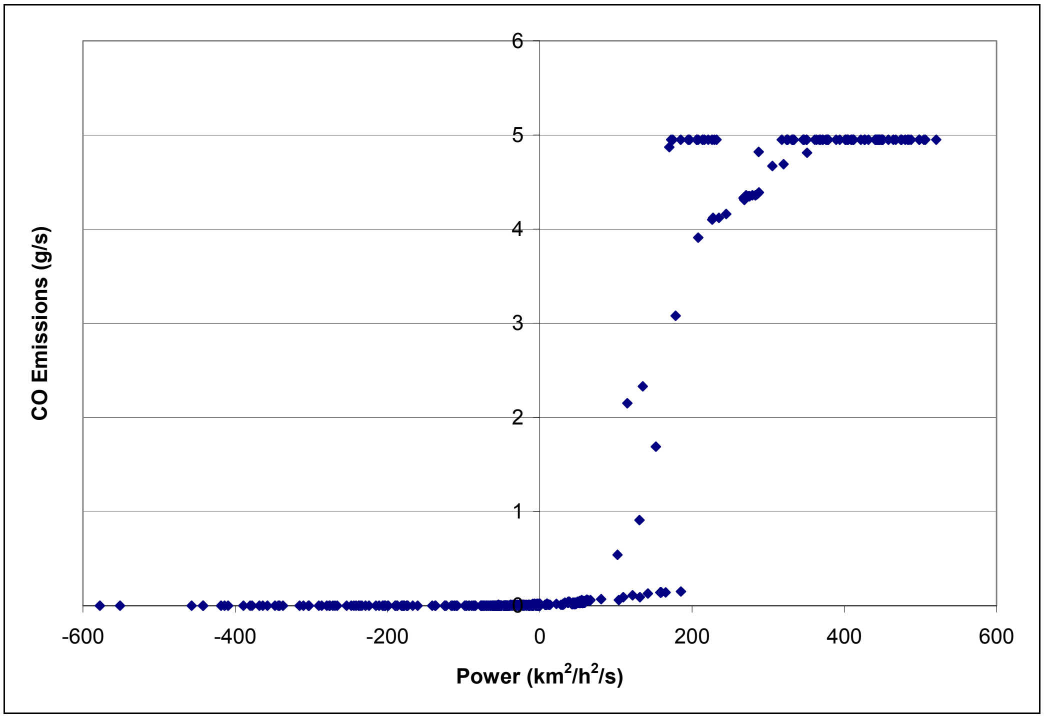


Figure 25. CO Emissions vs. Vehicle Power

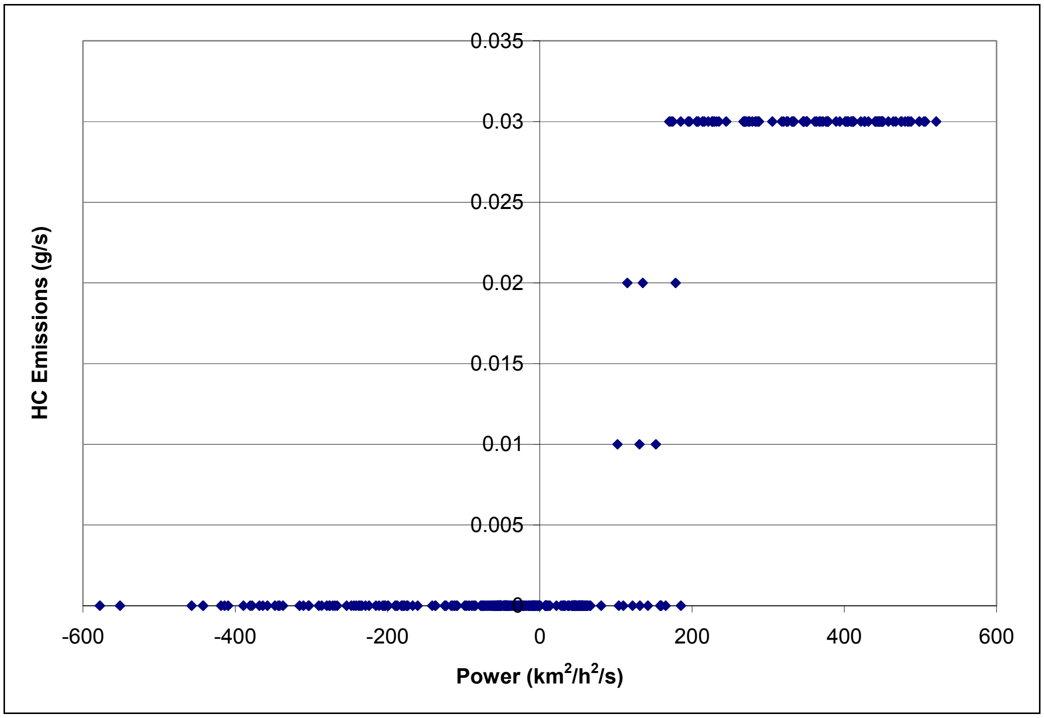


Figure 26. HC Emissions vs. Vehicle Power

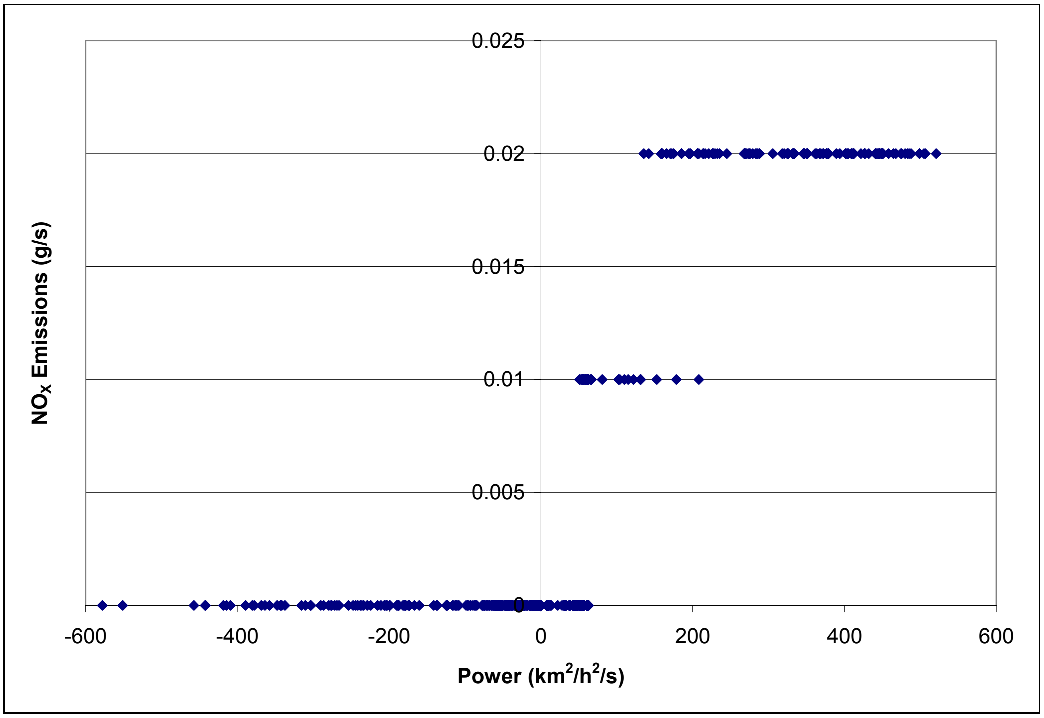


Figure 27. NO_X Emissions vs. Vehicle Power

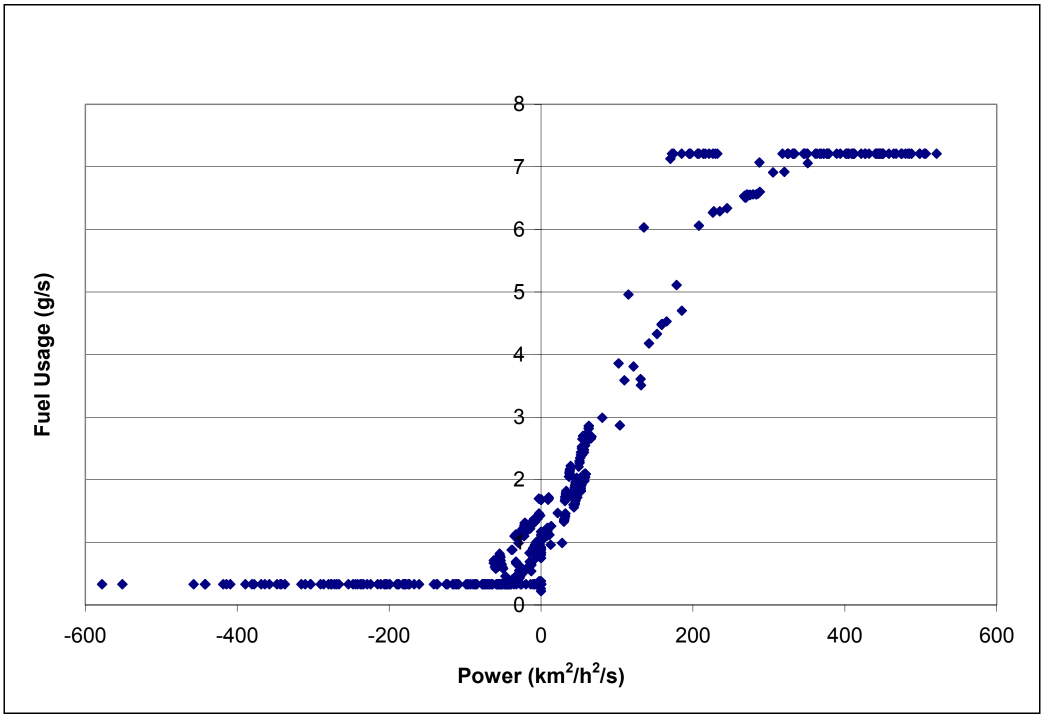


Figure 28. Fuel Usage vs. Vehicle Power

Total Network Vehicle Emissions

In this analysis, the vehicle emissions for the entire network were compared between the train speed distributions. The vehicle data from ten simulation runs were used to conduct ten runs with the CMEM software. This data was collected using the same 30-minute analysis period that was applied in the delay analysis. Output of CO, HC, NOx, and fuel usage was obtained. Each CMEM output was found for each train speed distribution for the average train length. Then, the results were averaged for each output and for each train speed distribution. Table 8 includes a summary of the average emissions. Finally, the average emissions were compared for each train speed distribution, and the fuel usage was compared in the same manner.

Table 8. Average Emissions and Fuel Use (Average Train Length)

Train Speed Distributions	CO (kg/km)	HC (g/km)	NO_X (g/km)	Fuel Use (kg/km)
No Train	279.1	2122	2781	822.7
Existing	190.4	1452	1849	568.7
35-5	230.5	1757	2348	687.6
35-10	262.9	2006	2712	779.7
50-5	236.3	1796	2358	698.0
50-10	201.9	1536	2022	597.4
65-5	237.3	1803	2367	697.8
65-10	185.0	1408	1861	546.1

Once again, 95% confidence intervals for the difference in means were used to statistically test the data. Equation 10 shows how the confidence intervals were found. As before, if the confidence interval included zero, the means were not different at the 95%

confidence level. Furthermore, if both parts of the interval were greater than zero, then a significant reduction in delay (from population mean 1 to population mean 2) was found. Figure 29 shows the confidence intervals for the difference in means of CO Emissions, and only those confidence intervals including a significant difference were shown. Similar plots for HC emissions, NO_X emissions, and fuel use are included in Appendix E.

Equation 10

$$\overline{X}_1 - \overline{X}_2 - t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \le \mu_1 - \mu_2 \le \overline{X}_1 - \overline{X}_2 + t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

Where,

S_p = Pooled Estimator of the population variance, σ^2;

S_1^2, S_2^2 = Sample Variances from Populations 1 and 2, Respectively;

$\overline{X}_1$, $\overline{X}_2$ = Sample Means from Populations 1 and 2, Respectively;

μ_1, μ_2 = Means of Population 1 and 2, Respectively;

n_1, n_2 = Number of Observations from Populations 1 and 2, Respectively;

$n_1 - n_2 - 2$ = 18, Degrees of Freedom; and

$t_{\alpha/2,n_1+n_2-2}$ = 2.10, for 95% Confidence.

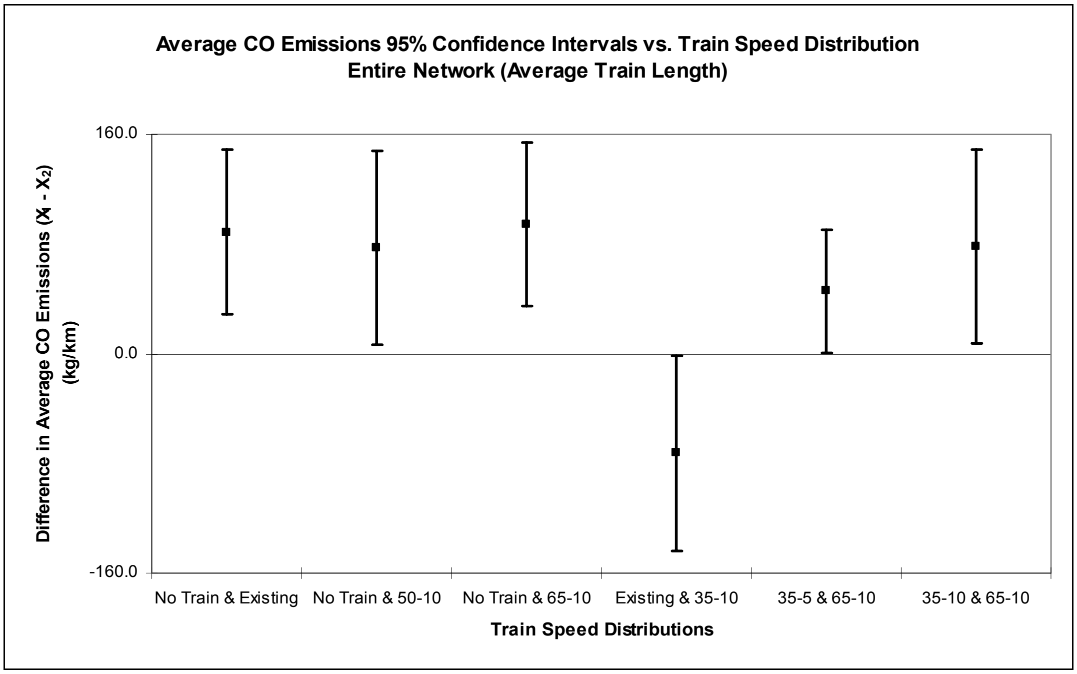


Figure 29. 95% Confidence Intervals on $\mu_1 - \mu_2$ for CO Emissions

The previous plot shows the only six comparisons in which there was a statistically significant difference in means for the CO emissions. The results for the other emissions output and for fuel use (included in Appendix C) show strikingly similar results. In fact, they provide the same statistically different pairs with the exception of one additional pair in the NO_X results.

The only significant increase in CO emissions shown is the comparison of existing conditions to the 35-10 distribution. This is justified by the fact that the 35-10 distribution has a slower mean train speed than the existing conditions. A train with a slower speed will occupy the crossing for a longer time, and this could cause a prolonged stammer in traffic flow. As a result, a higher than normal amount of short burst accelerations could cause increased emissions output and fuel use.

Similarly, the 65-10 distribution produced lower CO emissions as compared to both the 35-5 and 35-10 distributions. Once again, the faster train speeds in the 65-10 distribution mean that the crossings were occupied for less time and that emissions output and fuel use could be lower as a result.

The most interesting comparisons show that emissions were actually lower for distributions with trains as compared to the distribution without trains. In fact, emissions and fuel use were higher for the no train case compared to all of the distributions with trains. Specifically, three distributions with trains (existing conditions, 50-10, and 65-10) had emissions that were significantly lower than the case with no train at the 95% confidence level.

SUMMARY AND CONCLUSIONS

SUMMARY

The purpose of this thesis was to test the effects of different train movements on nearby motor vehicle operations. In particular, different train speeds were analyzed to see if they had an effect on average intersection delay, pedestrian cutoffs, and vehicle emissions.

After completion of the microsimulation model in VISSIM, the model was run for different train speed distributions with each distribution corresponding to a specific train detector placement. Data collected from VISSIM included average vehicle delay, green time distribution, and the vehicle record, which included the vehicle characteristics such as vehicle number and speed. The average delay was used to find average delay per intersection as well as for the entire network. Also, the green time distribution was used to determine the number of pedestrian cutoffs that occurred in the simulations. Finally, the vehicle record files were used as input for the CMEM software that was used to find vehicle emissions for the entire network.

CONCLUSIONS

Average Vehicle Delay

In this thesis, there were seven train speed distributions, including the existing conditions. Each one had a specific mean and standard deviation, but each distribution also had train detectors moved to the location that the fastest train could travel within the required warning time for the crossing. After running each distribution 20 times for each of three train lengths (short, average, and long), the average vehicle delay results showed some significant differences.

Four distributions had significantly lower delays compared to the existing conditions. These were the 50-5, 50-10, 65-5, and 65-10 distributions, and this result was expected because these distributions generally had train speeds that were greater than the speeds in the existing conditions. These results were the same for all train length scenarios. On the other hand, the 35-5 and 35-10 distributions did not have delays that were significantly different from the existing conditions. For these distributions, the speeds were similar to those in the existing conditions, so a difference in delay would not be expected. Again, these results were the same for all train length scenarios.

Comparisons were also made between the individual distributions. As a general rule, delay decreased as mean train speed increased, and train length was not a factor. Particularly, the delay for the distributions with a mean train speed of 35 km/h was higher than the delay for almost all other distributions. Conversely, the distributions with a mean speed of 50 km/h did not have significantly higher delays when compared to the distributions with mean train speeds of 65 km/h.

Next, the distributions with the same mean speeds were compared. This tested the possible significance of the standard deviation of the train speed. However, the only difference found was in the slow mean speed of 35 km/h, where the 35-5 distribution had a lower delay than the 35-10 distribution. Furthermore, this was only for the short train length, and no other differences were found in these comparisons.

Finally, each distribution was compared against the same distribution for different train lengths. Here, the delays for each distribution were compared between the short, average, and long train lengths. As expected, the longer train lengths were associated with the longer delays in almost all comparisons.

Ultimately, average vehicle delay was lower for the cases in which train speeds were higher. In particular, the lowest delay for both the George Bush Dr. intersection and the entire network for all three train length cases were found in the 65-5 distribution. This is, of course, including the consideration that the detectors were moved further out from the crossing to accommodate the faster trains in this distribution. So, given the fact that the detection zone is longer for the faster trains, the resulting average vehicle delay is still lower.

Pedestrian Cutoffs

Unfortunately, no statistical conclusions can be made with respect to the pedestrian cutoff problem. The preemption used in this thesis did not alter the start of the pedestrian phase, so cutoffs could not be controlled directly. Instead, example scenarios were created to demonstrate how pedestrian cutoffs could be controlled. In these examples, it was shown that if the entrance time of the train were altered, the event of a pedestrian cutoff could be controlled. This then led to the reasoning that the cutoffs may be controlled by delaying or omitting the start time of the pedestrian phase since the arrival time of the train could not realistically be controlled.

Vehicle Emissions

As an introduction to the output from the CMEM software, emissions and fuel use were plotted for a few individual vehicles for various power levels. Generally, as power increased, emissions production and fuel use increased. The purpose of this part of the analysis was to show that high accelerations can lead to high emissions rates.

The next part of the analysis involved finding the total network vehicle emissions using the CMEM software. This included the total vehicular emissions and fuel use for all three intersections analyzed. Specifically, output from CMEM included CO, HC, NO_X, and fuel use units of g/km. The lowest emissions for CO and HC and for fuel use were with the 65-10 distribution, and the lowest emissions for NO_X were with the existing conditions. However, these two distributions did not have significantly different emissions or fuel use values. Only the 35-10 distribution was different from the existing conditions, and it showed higher emissions and fuel use.

Among the more interesting and surprising results are the comparisons between the distributions with trains and those without trains. Three distributions with trains (existing conditions, 50-10, and 65-10) each had lower emissions than the distribution without a train. Although this was not an expected result, it can be justified.

The traffic signal controllers in the simulations without a train tended to operate in a manner such that delay would be minimized for the intersection; however, they did not specifically provide efficient progression. Therefore, stop-and-go traffic could exist during the high volume AM peak period used in the simulation. This stop-and-go traffic includes many short burst accelerations that could lead to increased emissions output and fuel use.

On the other hand, the controllers in the simulations with a train movement tend to operate differently. Specifically, during a train movement, the controller is not operating to minimize overall intersection delay. This is because two or more approaches cannot be completely served. Instead of serving each approach to minimize total intersection delay, the controller serves the approaches that are not obstructed by the passage of the train. During this time, the volume of vehicles being served is lower, and the number of phases being served is also lower. Lower volumes and fewer phases to serve could mean that there are fewer stops and therefore less stop-and-go traffic. During the passage of the train, it seems that most vehicles will either be stopped completely (as they wait for the passage of the train), or they will be moving freely (without the stop-and-go traffic). If this is the case, emissions could actually be lower for simulations with a train movement as compared to the simulations without a train.

Although the results from the emissions analysis may have been counterintuitive, they seem to be plausible. It was found that the 65-10 distribution produced the lowest emissions, but the only significantly significant difference involving the existing conditions was that the 35-10 distribution produced higher emissions and fuel use. And the fact that the 65-10 distribution produced significantly lower emissions than both the 35-5 and 35-10 distributions helps support the claim that the 65-10 distribution is the best for the emissions analysis. However, the interesting outcome is that emissions were significantly lower for some distributions with train events as compared to the distributions without trains.

FUTURE RESEARCH

One of the omissions of this thesis is a direct and controlled analysis of pedestrian cutoffs as compared to average vehicle delay and vehicle emissions. Therefore, future research would include testing alternate preemption strategies that would provide additional warning time to the controller and control the start of the pedestrian phase. If the start of the pedestrian phase is delayed or omitted appropriately, the frequency of pedestrian cutoffs may be reduced.

Furthermore, pedestrian volumes may be altered to test the effectiveness of the alternate preemption strategies. For example, volumes may be set to zero to see the resulting delay and emissions output. Then, pedestrian volumes may be set to large numbers (i.e. 200 pedestrians per hour) so that there is always a call to the pedestrian phase. Again delay and emissions could be analyzed with the resulting pedestrian cutoffs.

Finally, additional analyses could be done to further examine vehicle emissions output for high volume, congested arterials near HRGCs. Specifically, emissions output with and without train movements could be researched further.

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APPENDIX A

VAP CODE FOR GEORGE BUSH DR. INTERSECTION

```
/****************** Semi-Actuated-Coordinated ****************************/
/****************** WITH PEDESTRIANS ********************************/

/**********************************************/
/***** GEORGE BUSH DR. AT WELLBORN RD. *****/
/**********************************************/

PROGRAM SCJ3_Semi_Act_Coord_Peds;

ARRAY
tamber[8] = [4,4,4,4,4,4,4,0],  /*Yellow interval for each phase*/
Recall[8] = [0,1,0,0,0,1,0,0],  /*A value of 1 gives an automatic call for that phase*/
Passage[8] = [2,4.5,4,3,4,4.5,3.0,0],  /*Passage gap for each phase*/
MaxGreen[8] = [21,65,23,20,14,60,26,0],  /*Values adhere to coordinated timing*/
MinGreen[8] = [7,10,8,8,7,10,8,0],  /*Minimum green time for each phase*/
PedGreen[4] = [4,4,4,4],  /*Pedestrian WALK time for each of 4 pedestrian phases*/
PedClr[4] = [19,18,19,18],  /*Pedestrian clearance interval for each phase*/
RedClear[8] = [2,2,2,2,2,2,2,0],  /*All-red clearance interval for each phase*/
/*** Phase 7 is the WBL phase that is served during preemption dwell***/

/*** New Arrays ***/

/*PedRecall[8] = [0,1,0,0,0,1,0,0],*/

PreempMin[1] = [5],  /*Minimum green time for a phase at the onset of preemption*/
SelPedClr[4] = [19,18,19,18],  /*Pedestrian clearance intervals during preemption*/
RetPedClr[4] = [19,18,19,18],  /*Pedestrian clearance intervals during preemption*/
TrackClrTime[1] = [13],  /*Track clearance green time (to clear vehicles from the tracks)*/
DwellPedGreen[2] = [4,4],  /*Pedestrian WALK interval during preemption*/
DwellRECALL[7] = [0,1,0,0,1,1,1],  /*During preemption, value of 1 is an automatic call for that phase*/
MinDwellGreen[7] = [0,60,0,0,10,60,8],  /*Minimum green time for each phase during preemption*/
MaxDwellGreen[7] = [0,60,0,0,20,60,26];  /*Maximum green time for each phase during preemption*/

/*********************************************************************/
/** Compute Conditionals ************************************************/
/*********************************************************************/

SUBROUTINE Compute_Conditionals;

/*******************************/
/**** DEFINE CONDITIONALS ****/
/*******************************/

Call1 := presence(21) or occupancy(21) OR RECALL[1];
Call3 := presence(23) or occupancy(23) OR RECALL[3];
Call4 := presence(24) or occupancy(24) OR RECALL[4];
Call5 := presence(25) or occupancy(25) OR RECALL[5];
Call7 := presence(43) or occupancy(43) OR RECALL[7];

GapOut1 := headway(21) > Passage[1];
GapOut3 := headway(23) > Passage[3];
GapOut4 := headway(24) > Passage[4];
GapOut5 := headway(25) > Passage[5];
GapOut7 := headway(43) > Passage[7];

MinOver1 := t_green(1) >= MinGreen[1];
MinOver3 := t_green(3) >= MinGreen[3];
MinOver4 := t_green(4) >= MinGreen[4];
MinOver5 := t_green(5) >= MinGreen[5];
MinOver7 := t_green(7) >= MinGreen[7];

MaxOut1 := t_green(1) >= MaxGreen[1];
MaxOut3 := t_green(3) >= MaxGreen[3];
MaxOut4 := t_green(4) >= MaxGreen[4];
MaxOut5 := t_green(5) >= MaxGreen[5];
MaxOut7 := t_green(7) >= MaxGreen[7].
```

```
/********* Semi-Actuated Coordinated with Ped - Normal Mode ***************/
/**********************************************************************/
/** CorrectionCompute_Conditionals ***************************************/
/**********************************************************************/

SUBROUTINE CorrectionCompute_Conditionals;

MinGreen[1] := 7;
MinGreen[5] := 7;

IF (FirstAfterDwell = 0) THEN
        FirstAfterDwell := 1;
END;

/*PedRecall[2] := 0;*/
/*PedRecall[6] := 0;*/

/********************************/
/**** DEFINE CONDITIONALS ****/
/********************************/

Call1 := presence(21) or occupancy(21) OR RECALL[1];
Call3 := presence(23) or occupancy(23) OR RECALL[3];
Call4 := presence(24) or occupancy(24) OR RECALL[4];
Call5 := presence(25) or occupancy(25) OR RECALL[5];
Call7 := presence(43) or occupancy(43) OR RECALL[7];

GapOut1 := headway(21) > Passage[1];
GapOut3 := headway(23) > Passage[3];
GapOut4 := headway(24) > Passage[4];
GapOut5 := headway(25) > Passage[5];
GapOut7 := headway(43) > Passage[7];

MinOver1 := t_green(1) >= MinGreen[1];
MinOver3 := t_green(3) >= MinGreen[3];
MinOver4 := t_green(4) >= MinGreen[4];
MinOver5 := t_green(5) >= MinGreen[5];
MinOver7 := t_green(7) >= MinGreen[7];

MaxOut1 := t_green(1) >= MaxGreen[1];
MaxOut3 := t_green(3) >= MaxGreen[3];
MaxOut4 := t_green(4) >= MaxGreen[4];
MaxOut5 := t_green(5) >= MaxGreen[5];
MaxOut7 := t_green(7) >= MaxGreen[7].

SUBROUTINE Ring1;

/*********************************/
/*********** RING #1 ************/
/*********************************/

/* PEDESTRIAN PHASE */

CallPed12 := presence(29) or occupancy(29);
CallPed10 := presence(27) or occupancy(27);
CallPed11 := presence(28) or occupancy(28);

IF CallPed12 THEN
        Call12 :=1;
END;

IF CallPed10 THEN
        Call10 :=1;
END;
```

```
IF CallPed11 THEN
        Call11 :=1;
END;

IF t_green(1) THEN
        IF ((T = 21) OR MinOver1 AND (GapOut1 or MaxOut1)) THEN /*NEED =, NOT >= DUE TO PREEMPT RELEASE*/
                sg_red(1);
                start(Phase1ClearTimer);
                NextRing1Phase := 2;
        END;
END;

IF t_green(2) THEN
        IF (Call3 or Call12) THEN
                IF ((T >= 59) AND (T < (88 - MinGreen[3]))) THEN
                        sg_red(2);
                        start(Phase2ClearTimer);
                        NextRing1Phase := 3;
                END;
        ELSE
                IF (Call4 or Call10) THEN
                        IF ((T >= 59) AND (T < (114 - MinGreen[4]))) THEN
                                sg_red(2);
                                start(Phase2ClearTimer);
                                NextRing1Phase := 4;
                        END;
                ELSE
                        IF (Call1 or Call5) THEN
                                IF ((T >= 59) AND ((T < (21 - MinGreen[1])) OR (T > 65))) THEN
                                        sg_red(2);
                                        start(Phase2ClearTimer);
                                        NextRing1Phase := 1;
                                        NextRing2Phase := 5; /*** Maybe not necessary. ***/
                                END;
                        END;
                END;
        END;
END;

IF t_green(3) THEN
        IF (((T < (114 - MinGreen[4])) AND (T > 59)) AND (MinOver3 OR (CurrentPhase3TimerAfter >= MinGreen[3])) AND
((GapOut3 OR (CurrentPhase3TimerAfter >= MaxGreen[3])) OR MaxOut3)) THEN
                IF (Call4 or Call10) THEN
                        sg_red(3);              /***(T > 59) ADDED TO AVERT PHASE 4 AFTER RELEASE WHEN ***/
                        stop(Phase3ClearTimer);                 /*** CYCLE TIME IS NOT IN PHASE BLOCK ***/
                        reset(Phase3ClearTimer);
                        start(Phase3ClearTimer);
                        NextRing1Phase := 4;
                        stop(CurrentPhase3TimerAfter);
                        Reset(CurrentPhase3TimerAfter);
                END;
        ELSE
                IF (((T < (14 - MinGreen[5])) OR (T > 65)) AND (MinOver3 OR (CurrentPhase3TimerAfter >=
MinGreen[3])) AND ((GapOut3 OR (CurrentPhase3TimerAfter >= MaxGreen[3])) OR MaxOut3)) THEN
                        IF (Call1 or Call5) THEN
                                sg_red(3);
                                stop(Phase3ClearTimer);
                                reset(Phase3ClearTimer);
                                start(Phase3ClearTimer);
                                NextRing1Phase := 1;
                                stop(CurrentPhase3TimerAfter);
                                Reset(CurrentPhase3TimerAfter);
                        END;
                ELSE
```

```
            IF ((MinOver3 OR (CurrentPhase3TimerAfter >= MinGreen[3])) AND ((GapOut3 OR
(CurrentPhase3TimerAfter >= MaxGreen[3])) OR MaxOut3)) THEN
                sg_red(3);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                start(Phase3ClearTimer);
                NextRing1Phase := 2;
                stop(CurrentPhase3TimerAfter);
                Reset(CurrentPhase3TimerAfter);
            END;
        END;
    END;
END;

IF t_green(4) THEN
    IF (Call1 or Call5) THEN
        IF (((T < (21 - MinGreen[1])) OR (T > 65)) AND MinOver4 AND (GapOut4 OR MaxOut4)) THEN
            sg_red(4);
            start(Phase4ClearTimer);
            NextRing1Phase := 1;
        END;
    ELSE
        IF (MinOver4 AND (GapOut4 OR MaxOut4)) THEN
            sg_red(4);
            start(Phase4ClearTimer);
            NextRing1Phase := 2;
        END;
    END;
END;

/********************************/
/**** RING #1 AMBER TIMERS ****/
/********************************/

IF (Phase1ClearTimer >= tAmber[1] + RedClear[1]) THEN
    IF NextRing1Phase = 2 THEN
        sg_green(2);        /*** Only Phase 2 is green here because Phase 5 could still be green. ***/
    END;
    stop(Phase1ClearTimer);
    reset(Phase1ClearTimer);
END;

IF (Phase2ClearTimer >= tAmber[2] + RedClear[2]) THEN
    IF NextRing1Phase = 3 THEN
        sg_green(3);
        IF (Call12) THEN
            sg_green(12);
            MinGreen[3] := 22;    /*** MAX IS 23 ***/
        ELSE
            MinGreen[3] := 8;
        END;
    END;

    IF NextRing1Phase = 4 THEN
        sg_green(4);
        IF (Call10) THEN
            sg_green(10);
            MinGreen[4] := 20;
        ELSE            /*** Maximum green (with semi-actuated coordinated phasing) is 20 ***/
            MinGreen[4] := 8;
        END;
    END;

    IF NextRing1Phase = 1 THEN
        sg_green(1);
        sg_green(5);
```

```
        END;
        stop(Phase2ClearTimer);
        reset(Phase2ClearTimer);
END;

IF (Phase3ClearTimer >= tAmber[3] + RedClear[3]) THEN
        IF NextRing1Phase = 4 THEN
                sg_green(4);
                IF (T <= 94) THEN                /*** So that the ped phase will not start if phase 4 starts late after ***/
                        IF (Call10) THEN         /*** the release from preemption.  Here, the ped phase will have ***/
                                sg_green(10); /*** min WALK time of 4 sec and full Pedestrian Clearance Interval ***/
                                MinGreen[4] := 20;/
                        ELSE                     /*** Maximum green (with semi-actuated coordinated phasing) is 20 ***/
                                MinGreen[4] := 8;
                        END;
                END;
        END;

        IF NextRing1Phase = 1 THEN
                sg_green(1);
                sg_green(5);
        END;

        IF NextRing1Phase = 2 THEN
                sg_green(2);             /*** Phases 2 and 6 are green because they start simultaneously after Phase 3. ***/
                sg_green(6);
                IF (T <= 36) THEN                /*** So that the ped phase will not start if phasea 2 & 6 start late after ***/
                        IF (Call11) THEN         /*** the release from preemption.  Here, the ped phase will have ***/
                                sg_green(11);/*** min WALK time of 4 sec and full Pedestrian Clearance Interval ***/
                        END;
                END;
        END;
        stop(Phase3ClearTimer);
        reset(Phase3ClearTimer);
END;

IF (Phase4ClearTimer >= tAmber[4] + RedClear[4]) THEN
        IF NextRing1Phase = 1 THEN
                sg_green(1);
                sg_green(5);
        END;

        IF NextRing1Phase = 2 THEN
                sg_green(2);
                sg_green(6);
                IF (Call11) THEN
                        sg_green(11);
                END;
        END;
        IF FirstAfterDwell = 1 THEN
                cycle := cycle +1;
        END;
        stop(Phase4ClearTimer);
        reset(Phase4ClearTimer);
END;

/* PEDESTRIAN GREEN PHASE END */

IF (t_green(10) >= PedGreen[2]) THEN                     /*** The ped greens for phases 3 and 4 are the same ***/
        sg_red(10);                                          /*** as for actuated.  The green time is 7 sec. ***/
        Call10 := 0;
        start(Ped10ClearTimer);
END;

IF (t_green(12) >= PedGreen[4]) THEN
        sg_red(12);
```

```
        Call12 := 0;
        start(Ped12ClearTimer);
END;

/*****************************/
/******* AMBER TIMERS ********/
/*****************************/

IF (Ped12ClearTimer >= PedClr[4]) THEN
        stop(Ped12ClearTimer);
        reset(Ped12ClearTimer);
END;

IF (Ped10ClearTimer >= PedClr[2]) THEN
        stop(Ped10ClearTimer);
        reset(Ped10ClearTimer);
END.

/*******************************************************************/
/** Ring 2 **********************************************************/
/*******************************************************************/

SUBROUTINE Ring2;

/********************************/
/*********** RING #2 ************/
/********************************/

IF t_green(5) THEN
        IF ((T = 14) OR (MinOver5 AND (GapOut5 OR MaxOut5))) THEN
        /*NEED =, NOT >= DUE TO PREEMPT RELEASE*/
                sg_red(5);
                start(Phase5ClearTimer);
                NextRing2Phase := 6;
        END;
END;

IF t_green(6) THEN
        IF (Call3 or Call12) THEN
                IF ((T >= 59) AND (T < (88 - MinGreen[3]))) THEN
                        sg_red(6);
                        start(Phase6ClearTimer);
                        NextRing1Phase := 3;
                END;
        ELSE
                IF (Call4 or Call10) THEN
                        IF ((T >= 59) AND (T < (114 - MinGreen[4]))) THEN
                                sg_red(6);
                                start(Phase6ClearTimer);
                                NextRing1Phase := 4;
                        END;
                ELSE
                        IF (Call1 or Call5) THEN
                                IF ((T >= 59) AND ((T < (14 - MinGreen[5])) OR (T > 65))) THEN
                                        sg_red(6);
                                        start(Phase6ClearTimer);
                                        NextRing1Phase := 1;
                                        NextRing2Phase := 5; /*** Maybe not necessary. ***/
                                END;
                        END;
                END;
        END;
END;

/********************************/
/**** RING #2 AMBER TIMERS ****/
```

```
/********************************/

IF (Phase5ClearTimer >= tAmber[5] + RedClear[5]) THEN
        IF NextRing2Phase = 6 THEN
                sg_green(6);
                IF (Call11) THEN
                        sg_green(11);
                END;
        END;
        stop(Phase5ClearTimer);
        reset(Phase5ClearTimer);

END;

IF (Phase6ClearTimer >= tAmber[6] + RedClear[6]) THEN
        IF NextRing2Phase = 3 THEN
                sg_green(3);
                IF (Call12) THEN
                        sg_green(12);
                        MinGreen[3] := 22;    /*** MAX IS 23 ***/
                ELSE
                        MinGreen[3] := 8;
                END;
        END;

        IF NextRing1Phase = 4 THEN
                sg_green(4);
                IF (Call10) THEN
                        sg_green(10);
                        MinGreen[4] := 20;
                ELSE                          /*** Maximum green (with semi-actuated coordinated phasing) is 20 ***/
                        MinGreen[4] := 8;
                END;
        END;

        IF NextRing2Phase = 5 THEN
                sg_green(1);
                sg_green(5);
        END;
        stop(Phase6ClearTimer);
        reset(Phase6ClearTimer);
END;

/* PEDESTRIAN GREEN PHASE END   */

IF (t_green(11)) THEN
        IF (T = 40) THEN              /*NEED =, NOT >= DUE TOI PREEMPT RELEASE*/
                sg_red(11);
                Call11 := 0;
                start(Ped11ClearTimer);
        END;
END;

/*****************************/
/******* AMBER TIMERS ********/
/*****************************/

IF (Ped11ClearTimer >= PedClr[3]) THEN
        stop(Ped11ClearTimer);
        reset(Ped11ClearTimer);
END.

/**************************************************************************/
/** Preemption ***********************************************************/
/**************************************************************************/
```

```
SUBROUTINE Preemption;

IF CurrentPhaseRing1=0 THEN

    /************** Check Current vehicle phase for Ring 1  ************/

    IF T_green(1) THEN
        CurrentPhaseRing1:=1;
    ELSE
        IF T_green(2) THEN
            CurrentPhaseRing1:=2;
        ELSE
            IF T_green(3)  THEN
                CurrentPhaseRing1:=3;
            ELSE
                IF T_green(4) THEN
                    CurrentPhaseRing1:=4;
                ELSE
                    CurrentPhaseRing1:=100;
                END;
            END;
        END;
    END;

    /************** Check Current vehicle phase for Ring 2  ************/

    IF T_green(5) THEN
        CurrentPhaseRing2:=5;
    ELSE
        IF T_green(6)  THEN
            CurrentPhaseRing2:=6;
        ELSE
            CurrentPhaseRing2:=100;
        END;
    END;

END;/**********END PUT HERE TO CHECK FOR PED PHASE EVERY SECOND**********/
/**********************************************************************/

/***********************************************************************************/
/**** The checks using B_CurrentPedPhaseRing* count only when the pedestrian clearance interval ***/
/**** overlaps with the track clearance phase (actual conflicting phases); this is what will be **********/
/**** counted as the pedestrian cutoff *****************************************************/
/***********************************************************************************/
/***********************************************************************************/

/************** Check Current pedestrian phase for Ring 1  *******/

/***    IF (((Ped9ClearTimer < SelPedClr[1]) AND Ped9ClearTimer > 0) or T_green(9)) THEN
        B_CurrentPedPhaseRing1:=9;
    ELSE ***/
        IF (((Ped10ClearTimer < SelPedClr[2]) AND Ped10ClearTimer > 0) or T_green(10)) THEN
            B_CurrentPedPhaseRing1:=10;
        ELSE
            IF (((Ped12ClearTimer < SelPedClr[4]) AND Ped12ClearTimer > 0) or T_green(12)) THEN
                B_CurrentPedPhaseRing1:=12;
            ELSE
                B_CurrentPedPhaseRing1:=100;
            END;
        END;
    /***END;***/

/************** Check Current pedestrian phase for Ring 2  *********/

IF (((Ped11ClearTimer < SelPedClr[3]) AND Ped11ClearTimer > 0) or T_green(11)) THEN
    B_CurrentPedPhaseRing2:=11;
```

```
ELSE
            B_CurrentPedPhaseRing2:=100;
END;

/**** Terminate Current Phase and Start Track Clearance Phase ****/

IF (TrackClearStart=0) THEN

            /************** Phase 1  ************************/
            IF ((CurrentPhaseRing1 = 1) AND (T_green(CurrentPhaseRing1)>= PreempMin[1])) THEN
                        sg_red(1);
                        stop(Phase1ClearTimer);
                        reset(Phase1ClearTimer);
                        stop(Phase2ClearTimer);
                        reset(Phase2ClearTimer);
                        stop(Phase4ClearTimer);
                        reset(Phase4ClearTimer);
                        stop(Phase5ClearTimer);
                        reset(Phase5ClearTimer);
                        stop(Phase6ClearTimer);
                        reset(Phase6ClearTimer);
                        stop(Phase3ClearTimer);
                        reset(Phase3ClearTimer);
                        start(CurrentClear1Timer);
/*****/      Trace(variable (CurrentClear1Timer));
                        Check := 1;
            END;

            IF ((CurrentClear1Timer >= tAmber[1] + RedClear[1]) AND (CurrentClear5Timer >= tAmber[5] + RedClear[5])) THEN
                        sg_green(3);
/*****/      Trace(variable (CurrentClear1Timer));
                        TrackClearStart:=1;
                        start(CurrentPhase3Timer);
                        stop(CurrentClear1Timer);
                        reset(CurrentClear1Timer);
            END;

            /************** Phase 5  ************************/
            IF ((CurrentPhaseRing2 = 5) AND (T_green(CurrentPhaseRing2)>= PreempMin[1])) THEN
                        sg_red(5);
                        stop(Phase1ClearTimer);
                        reset(Phase1ClearTimer);
                        stop(Phase2ClearTimer);
                        reset(Phase2ClearTimer);
                        stop(Phase4ClearTimer);
                        reset(Phase4ClearTimer);
                        stop(Phase5ClearTimer);
                        reset(Phase5ClearTimer);
                        stop(Phase6ClearTimer);
                        reset(Phase6ClearTimer);
                        stop(Phase3ClearTimer);
                        reset(Phase3ClearTimer);
                        start(CurrentClear5Timer);
/*****/      Trace(variable (CurrentClear5Timer));
                        Check := 5;
            END;

            IF ((CurrentClear5Timer >= tAmber[5] + RedClear[5]) AND (CurrentClear1Timer >= tAmber[1] + RedClear[1])) THEN
                        sg_green(3);
/*****/      Trace(variable (CurrentClear5Timer));
                        TrackClearStart:=1;
                        start(CurrentPhase3Timer);
                        stop(CurrentClear5Timer);
                        reset(CurrentClear5Timer);
            END;
```

```
        /************* Phase 2 ***********************/
        /*** IF ((CurrentPhaseRing1 = 2) AND (B_CurrentPedPhaseRing1 = 9) AND T_green(B_CurrentPedPhaseRing1))
THEN
                sg_red(9);
                start(Ped9ClearTimer);
                Check := 2;
        END; ***/ /***  This is not needed at the George Bush Intersection ***/

        IF ((CurrentPhaseRing1 = 2) AND (T_green(CurrentPhaseRing1) >= PreempMin[1]) AND
((T_green(CurrentPhaseRing2) >= PreempMin[1]) OR (CurrentPhaseRing2 = 100)) /*** AND (B_CurrentPedPhaseRing1 = 9) AND
(Ped9ClearTimer >= 0) ***/ ) THEN
                sg_red(2);
                stop(Phase1ClearTimer);
                reset(Phase1ClearTimer);
                stop(Phase2ClearTimer);
                reset(Phase2ClearTimer);
                stop(Phase4ClearTimer);
                reset(Phase4ClearTimer);
                stop(Phase5ClearTimer);
                reset(Phase5ClearTimer);
                stop(Phase6ClearTimer);
                reset(Phase6ClearTimer);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                start(CurrentClear2Timer);
/*****/  Trace(variable (CurrentClear2Timer));
                Check := 22;
                Trace(variable (Check));
        ELSE
                IF ((CurrentPhaseRing1 = 2) AND (T_green(CurrentPhaseRing1) >= PreempMin[1]) AND
(T_green(CurrentPhaseRing2) >= PreempMin[1])) THEN
                        sg_red(2);
                        stop(Phase2ClearTimer);
                        reset(Phase2ClearTimer);
                        start(CurrentClear2Timer);
                        Check := 22;
                        Trace(variable (Check));
                END;
        END;

        IF (CurrentClear2Timer = tAmber[2] + RedClear[2]) THEN
                sg_green(3);
/*****/  Trace(variable (CurrentClear2Timer));
                TrackClearStart:=1;
                start(CurrentPhase3Timer);
                stop(CurrentClear2Timer);
                /*** stop(Ped9ClearTimer); ***/
                /*** reset(Ped9ClearTimer); ***/
                reset(CurrentClear2Timer);
        END;

        /************* Phase 6 ***********************/
        IF ((CurrentPhaseRing2 = 6) AND (B_CurrentPedPhaseRing2 = 11) AND T_green(B_CurrentPedPhaseRing2)) THEN
                sg_red(11);
                start(Ped11ClearTimer);
                Check := 6;
        END;
        IF ((CurrentPhaseRing2 = 6) AND (T_green(CurrentPhaseRing2) >= PreempMin[1]) AND
((T_green(CurrentPhaseRing1) >= PreempMin[1]) OR (CurrentPhaseRing1 = 100)) AND (B_CurrentPedPhaseRing2 = 11) AND
(Ped11ClearTimer >= 0)) THEN
                sg_red(6);
                stop(Phase1ClearTimer);
                reset(Phase1ClearTimer);
                stop(Phase2ClearTimer);
                reset(Phase2ClearTimer);
                stop(Phase4ClearTimer);
```

```
                reset(Phase4ClearTimer);
                stop(Phase5ClearTimer);
                reset(Phase5ClearTimer);
                stop(Phase6ClearTimer);
                reset(Phase6ClearTimer);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                start(CurrentClear6Timer);
                Check := 66;
/*****/ Trace(variable (CurrentClear6Timer));
        ELSE
                IF ((CurrentPhaseRing2 = 6) AND (T_green(CurrentPhaseRing2) >= PreempMin[1]) AND
(T_green(CurrentPhaseRing1) >= PreempMin[1])) THEN
                        sg_red(6);
                        Start(CurrentClear6Timer);
                        Check := 66;
                END;
        END;

        IF (CurrentClear6Timer = tAmber[6] + RedClear[6]) THEN
                sg_green(3);
/*****/ Trace(variable (CurrentClear6Timer));
                IF (B_CurrentPedPhaseRing2 = 11) THEN
                        PreCutPhase11_SCJ3:=PreCutPhase11_SCJ3+1;
                        Trace(variable (PreCutPhase11_SCJ3));
                        sg_green(15);                                   /***Used to count ped cutoffs***/
                END;

                TrackClearStart:=1;
                start(CurrentPhase3Timer);
                stop(CurrentClear6Timer);
                stop(Ped11ClearTimer);
                reset(CurrentClear6Timer);
                reset(Ped11ClearTimer);
        END;

        /************** Phase 4 ************************/
        IF ((CurrentPhaseRing1 = 4) AND (B_CurrentPedPhaseRing1 = 10) AND T_green(B_CurrentPedPhaseRing1)) THEN
                sg_red(10);
                start(Ped10ClearTimer);
/*****/ Trace(variable (CurrentClear4Timer));
                Check := 4;
        END;

        IF ((CurrentPhaseRing1 = 4) AND (T_green(CurrentPhaseRing1) >= PreempMin[1]) AND (B_CurrentPedPhaseRing1 =
10) AND (Ped10ClearTimer >= 0)) THEN
                sg_red(4);
                stop(Phase1ClearTimer);
                reset(Phase1ClearTimer);
                stop(Phase2ClearTimer);
                reset(Phase2ClearTimer);
                stop(Phase4ClearTimer);
                reset(Phase4ClearTimer);
                stop(Phase5ClearTimer);
                reset(Phase5ClearTimer);
                stop(Phase6ClearTimer);
                reset(Phase6ClearTimer);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                start(CurrentClear4Timer);
                Check := 44;
        ELSE
                IF ((CurrentPhaseRing1 = 4) AND (T_green(CurrentPhaseRing1) >= PreempMin[1])) THEN
                        sg_red(4);
                        start(CurrentClear4Timer);
                        Check := 44;
```

```
                        END;
                END;

                IF (CurrentClear4Timer = tAmber[4] + RedClear[4]) THEN
                        sg_green(3);
/*****/         Trace(variable (CurrentClear4Timer));
                        IF (B_CurrentPedPhaseRing1 = 10) THEN
                                PreCutPhase10_SCJ3:=PreCutPhase10_SCJ3+1;
                                Trace(variable (PreCutPhase10_SCJ3));
                                sg_green(14);                                   /***Used to count ped cutoffs***/
                        END;

                        TrackClearStart:=1;
                        start(CurrentPhase3Timer);
                        stop(CurrentClear4Timer);
                        stop(Ped10ClearTimer);
                        reset(CurrentClear4Timer);
                        reset(Ped10ClearTimer);
                END;

                /************** Phase 3 ***********************/
                IF ((CurrentPhaseRing1 = 3) AND (B_CurrentPedPhaseRing1 = 12) AND T_green(B_CurrentPedPhaseRing1)) THEN
                        IF (B_CurrentPedPhaseRing1 = 12) THEN
                                PreCutPhase12_SCJ3:=PreCutPhase12_SCJ3+1;
                                Trace(variable (PreCutPhase12_SCJ3));
                                sg_green(16);                                   /***Used to count ped cutoffs***/
                        END;

                        sg_red(12);
                        start(Ped12ClearTimer);
                        Check := 3;
                        Trace(variable (Check));
                END;

                IF ((CurrentPhaseRing1 = 3) AND (B_CurrentPedPhaseRing1 = 12) AND (Ped12ClearTimer >= 0)) THEN
                        start(CurrentPhase3Timer);
                        TrackClearStart:=1;
                        Check := 3;
                        Trace(variable (Check));
                ELSE
                        IF (CurrentPhaseRing1 = 3) THEN
                                sg_red(12);
                                start(CurrentPhase3Timer);
                                TrackClearStart:=1;
                                Check := 3;
                        END;
                END;

                /************** Phase red for Ring 1 ****************************/
                /******** T_stop is the time since the signal was green. ***************/

IF ((CurrentPhaseRing2 = 100) OR (CurrentPhaseRing2 = 5)) THEN
                IF ((CurrentPhaseRing1 = 100) AND (B_CurrentPedPhaseRing1 = 100) AND (B_CurrentPedPhaseRing2 = 100))  THEN
                        IF ((T_stop(1) >= 6) AND (T_stop(5) >= 6)) OR (T_stop(2) = 6) OR (T_stop(3) <= 6) OR (T_stop(4) = 6) OR
(T_stop(6) = 6) THEN
                                sg_green(3);
                                stop(Phase1ClearTimer);
                                reset(Phase1ClearTimer);
                                stop(Phase2ClearTimer);
                                reset(Phase2ClearTimer);
                                stop(Phase4ClearTimer);
                                reset(Phase4ClearTimer);
                                stop(Phase5ClearTimer);
                                reset(Phase5ClearTimer);
                                stop(Phase6ClearTimer);
                                reset(Phase6ClearTimer);
```

```
                        stop(Phase3ClearTimer);
/***/                   reset(Phase3ClearTimer);            /*** FOR PHASE 3 AFTER PREMPTION RELEASE ***/
                        TrackClearStart:=1;
                        start(CurrentPhase3Timer);
                        Check := 100;
                        Trace(variable (Check));
                END;
        END;
END;
        /************** Phase red for Ring 2 *****************************/
        /******** T_stop is the time since the signal was green. ***************/

IF ((CurrentPhaseRing1 = 100) OR (CurrentPhaseRing1 = 1))  THEN
        IF ((CurrentPhaseRing2 = 100)/* AND (B_CurrentPedPhaseRing2 = 100)*/) THEN
                IF ((T_stop(1) >= 6) AND (T_stop(5) >= 6)) OR (T_stop(2) = 6) OR (T_stop(3) <= 6) OR (T_stop(4) = 6) OR
(T_stop(6) = 6) THEN
                        sg_green(3);
                        stop(Phase1ClearTimer);
                        reset(Phase1ClearTimer);
                        stop(Phase2ClearTimer);
                        reset(Phase2ClearTimer);
                        stop(Phase4ClearTimer);
                        reset(Phase4ClearTimer);
                        stop(Phase5ClearTimer);
                        reset(Phase5ClearTimer);
                        stop(Phase6ClearTimer);
                        reset(Phase6ClearTimer);
                        stop(Phase3ClearTimer);
/***/                   reset(Phase3ClearTimer);            /*** FOR PHASE 3 AFTER PREMPTION RELEASE ***/
                        TrackClearStart:=1;
                        start(CurrentPhase3Timer);
                        Check := 100;
                        Trace(variable (Check));
                END;
        END;
END;
END;

/**** Start Dwell ******************************************************/
/***********************************************************************/

IF ((DwellPoint = 1) OR (CurrentPhase3Timer = TrackClrTime[1])) THEN

/***Enter this block when the track clearance phase ends or when the controller is already in dwell***/

/***    Call2 := presence(22) or occupancy(22) OR DwellRECALL[2];***/
        Call5 := presence(25) or occupancy(25) OR DwellRECALL[5];
        Call6 := presence(26) or occupancy(26) OR DwellRECALL[6];
        Call7 := presence(30) or occupancy(30) OR DwellRECALL[7];

/***    GapOut2 := headway(22) > Passage[2];***/
        GapOut5 := headway(25) > Passage[5];
        GapOut6 := headway(26) > Passage[6];
        GapOut7 := headway(30) > Passage[7];

/***    MinOver2 := t_green(2) >= MinDwellGreen[2];***/
        MinOver5 := t_green(5) >= MinDwellGreen[5];
        MinOver6 := t_green(6) >= MinDwellGreen[6];
        MinOver7 := t_green(7) >= MinDwellGreen[7];

/***    MaxOut2 := t_green(2) >= MaxDwellGreen[2];***/
        MaxOut5 := t_green(5) >= MaxDwellGreen[5];
        MaxOut6 := t_green(6) >= MaxDwellGreen[6];
        MaxOut7 := t_green(7) >= MaxDwellGreen[7];
```

```
        /*** CallPed9 := presence(23) or occupancy(23) or presence(24) or occupancy(24); ***/ /*** Not needed at this
intersection ; there is no NS ped phase on the West side of the intersection***/
        CallPed11 := presence(28) or occupancy(28);

                IF CallPed11 THEN
                        Call11 :=1;
                END;

        IF (StartDwell=0) THEN
                /************** End Track Clearance ************************/
                IF  (CurrentPhase3Timer = TrackClrTime[1]) THEN
                        sg_red(3);
                        start(ClearTrack);
        /*ClearTrack - timer for the yellow and red intervals for the track clearance phase*/
                                stop(CurrentPhase3Timer);
                        reset(CurrentPhase3Timer);
                        DwellPoint := 1;
                END;

/************* Start Dwell ********************************************/
/********************Start with Phase 4 Left Only**********************/
                IF (ClearTrack = tAmber[3] + RedClear[3]) THEN
                        sg_green(7);    /*Dwell begins with Phase 4 left, regardless of call; this is specified to be phase 7*/
                        stop(ClearTrack);
                        reset(ClearTrack);
                        StartDwell:=1;
                END;
        END;

        IF T_green(7) THEN              /*** Changed to go to phase 6 if no call for phase 5 ***/
                IF (MinOver7 AND (GapOut7 OR MaxOut7)) THEN
                        IF (Call5) THEN
                                NextDwell:=5;
                                sg_red(7);
                                start(Phase7ClearTimer);
                        ELSE
                                IF (Call6) THEN
                                        NextDwell:=6;
                                        sg_red(7);
                                        start(Phase7ClearTimer);
                                END;
                        END;
                END;
        END;

        IF T_green(5) THEN              /*** Changed to go to phase 7 if no call for phase 6 ***/
                IF (MinOver5 AND (GapOut5 OR MaxOut5)) THEN
                        IF (Call6) THEN
                                NextDwell:=26;
                                sg_red(5);
                                start(Phase5ClearTimer);
                        ELSE
                                IF (Call7) THEN
                                        NextDwell:=7;
                                        sg_red(5);
                                        start(Phase5ClearTimer);
                                END;
                        END;
                END;
        END;

        IF T_green(6) THEN              /*** Changed to go to phase 5 if no call for phase 7 ***/
                IF (MinOver6 AND (GapOut6 OR MaxOut6)) THEN
                        IF (Call7) THEN
                                NextDwell:=7;
                                sg_red(2);
```

```
                        sg_red(6);
                        start(Phase6ClearTimer);
                ELSE
                        IF (Call5) THEN
                                NextDwell:=5;
                                sg_red(2);
                                sg_red(6);
                                start(Phase6ClearTimer);
                        END;
                END;
        END;
END;

IF (t_green(11) = DwellPedGreen[2]) THEN
        sg_red(11);
        start(Ped11ClearTimer);
END;

IF (Ped11ClearTimer = PedClr[3]) THEN
        stop(Ped11ClearTimer);
        reset(Ped11ClearTimer);
END;

/*****************************/
/******* AMBER TIMERS ********/
/*****************************/

IF (Phase7ClearTimer = tAmber[7] + RedClear[7]) THEN
        IF (NextDwell = 5) THEN
                sg_green(5);
                sg_green(2);
                stop(Phase7ClearTimer);
                reset(Phase7ClearTimer);
        ELSE
                IF (NextDwell = 26) THEN
                        sg_green(2);
                        sg_green(6);
                        IF (Call11) THEN
                                sg_green(11);
                                MinGreen[6] := 14;
                                MinGreen[2] := 14;
                        ELSE
                                MinGreen[6] := 10;
                                MinGreen[2] := 10;
                        END;
                        stop(Phase7ClearTimer);
                        reset(Phase7ClearTimer);
                END;
        END;
END;

IF (Phase5ClearTimer = tAmber[5] + RedClear[5]) THEN
        IF (NextDwell = 26) THEN
                sg_green(2);
                sg_green(6);
                IF (Call11) THEN
                        sg_green(11);
                        MinGreen[6] := 14;
                        MinGreen[2] := 14;
                ELSE
                        MinGreen[6] := 10;
                        MinGreen[2] := 10;
                END;
                stop(Phase5ClearTimer);
                reset(Phase5ClearTimer);
        ELSE
```

```
                        IF (NextDwell = 7) THEN
                                sg_green(7);
                                stop(Phase5ClearTimer);
                                reset(Phase5ClearTimer);
                        END;
                END;
        END;

        IF (Phase6ClearTimer = tAmber[6] + RedClear[6]) THEN
                IF (NextDwell = 7) THEN
                        sg_green(7);
                        stop(Phase6ClearTimer);
                        reset(Phase6ClearTimer);
                ELSE
                        IF (NextDwell = 5) THEN
                                sg_green(5);
                                sg_green(2);
                                stop(Phase6ClearTimer);
                                reset(Phase6ClearTimer);
                        END;
                END;
        END;
END.

/*************************************************************************/
/** Release Preemption ***************************************************/
/*************************************************************************/

SUBROUTINE ReleasePreemption;

/** Check Current Phase at the end of Preemption *******************************/
IF (CurrentPhaseAfter1 = 0) THEN
        CurrentPhaseAfter1:=2;

        IF T_green(6) THEN
                CurrentPhaseAfter2:=6;
        ELSE
                IF T_green(2) THEN
                        CurrentPhaseAfter2:=2;
                ELSE
                        IF T_green(5) THEN
                                CurrentPhaseAfter2:=5;
                        ELSE
                                IF T_green(7) THEN
                                        CurrentPhaseAfter2:=7;
                                ELSE
                                        CurrentPhaseAfter2:=100;
                                END;
                        END;
                END;
        END;

END;

/** Terminate Current Phase ************************************************/
CallPed12 := presence(29) or occupancy(29);
        IF CallPed12 THEN  /*Pedestrian phase 12 runs with the track release phase*/
                Call12 :=1;
        END;

IF (EndPreemption=0) THEN

        /**** For the case that the Pedestrian phase is Green ********************/
        IF (Oneperform = 0) THEN
                Oneperform := 1;
                /*** IF (T_green(9)) THEN
```

```
            sg_red(9);
            start(Ped9ClearTimer);
            Ped9 := Ped9 + 1;
            Check := 9;
        END; ***/ /*** Not Needed at this Intersection ***/

        IF (T_green(11)) THEN
            sg_red(11);
            start(Ped11ClearTimer);
            Ped11 := Ped11 + 1;
            Check := 11;
        END;
    END;

    /************** Phase 2 ************************/
    IF ((CurrentPhaseAfter2 = 2) AND (T_green(CurrentPhaseAfter2)>= PreempMin[1]) AND ((T_red(11)) OR
(Ped11ClearTimer >= RetPedClr[3]))) THEN
        sg_red(2);
        sg_red(6);
/***Added to ensure proper transition from release of preemption back to "normal" mode***/
        stop(Phase1ClearTimer);
        reset(Phase1ClearTimer);
        stop(Phase2ClearTimer);
        reset(Phase2ClearTimer);
        stop(Phase4ClearTimer);
        reset(Phase4ClearTimer);
        stop(Phase5ClearTimer);
        reset(Phase5ClearTimer);
        stop(Phase6ClearTimer);
        reset(Phase6ClearTimer);
        stop(Phase3ClearTimer);
        reset(Phase3ClearTimer);
        stop(Phase7ClearTimer);
        reset(Phase7ClearTimer);
/**********************************************************************/
        start(CurrentClear2TimerAfter);
        Check := 26;
        Trace (variable (Check));
    END;
    IF (CurrentClear2TimerAfter = tAmber[2] + RedClear[2]) THEN
        sg_green(3);
        IF (Call12) THEN
            sg_green(12);
            MinGreen[3] := 22;/*** MAX IS 23 ***/
        ELSE
            MinGreen[3] := 10;
        END;
        EndPreemption:=1;
        start(CurrentPhase3TimerAfter);
        stop(CurrentClear2TimerAfter);
        reset(CurrentClear2TimerAfter);
    END;

    /************** Phase 5  ************************/
    IF ((CurrentPhaseAfter2 = 5) AND (T_green(CurrentPhaseAfter2) >= PreempMin[1]) /*** AND ((T_red(9)) OR
(Ped9ClearTimer >= RetPedClr[1])) ***/ ) THEN
        sg_red(2);
        sg_red(5);
/***Added to ensure proper transition from release of preemption back to "normal" mode***/
        stop(Phase1ClearTimer);
        reset(Phase1ClearTimer);
        stop(Phase2ClearTimer);
        reset(Phase2ClearTimer);
        stop(Phase4ClearTimer);
        reset(Phase4ClearTimer);
        stop(Phase5ClearTimer);
```

```
                reset(Phase5ClearTimer);
                stop(Phase6ClearTimer);
                reset(Phase6ClearTimer);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                stop(Phase7ClearTimer);
                reset(Phase7ClearTimer);
/************************************************************************/
                start(CurrentClear5TimerAfter);
                Check := 25;
                Trace (variable (Check));
        END;
        IF (CurrentClear5TimerAfter = tAmber[5] + RedClear[5]) THEN
                sg_green(3);
                IF (Call12) THEN
                        sg_green(12);
                        MinGreen[3] := 22;/*** MAX IS 23 ***/
                ELSE
                        MinGreen[3] := 8;
                END;
                EndPreemption:=1;
                start(CurrentPhase3TimerAfter);
                stop(CurrentClear5TimerAfter);
                reset(CurrentClear5TimerAfter);
        END;

        /************* Phase 6 ***********************/
        IF ((CurrentPhaseAfter2 = 6) AND (T_green(CurrentPhaseAfter2)>= PreempMin[1]) /*** AND ((T_red(9)) OR
(Ped9ClearTimer >= RetPedClr[1])) ***/ AND ((T_red(11)) OR (Ped11ClearTimer >= RetPedClr[3]))) THEN
                sg_red(2);
                sg_red(6);
/***Added to ensure proper transition from release of preemption back to "normal" mode***/
                stop(Phase1ClearTimer);
                reset(Phase1ClearTimer);
                stop(Phase2ClearTimer);
                reset(Phase2ClearTimer);
                stop(Phase4ClearTimer);
                reset(Phase4ClearTimer);
                stop(Phase5ClearTimer);
                reset(Phase5ClearTimer);
                stop(Phase6ClearTimer);
                reset(Phase6ClearTimer);
                stop(Phase3ClearTimer);
                reset(Phase3ClearTimer);
                stop(Phase7ClearTimer);
                reset(Phase7ClearTimer);
/*****************************************************************************/
                start(CurrentClear2TimerAfter);
                Check := 26;
                Trace (variable (Check));
        END;
        IF (CurrentClear2TimerAfter = tAmber[2] + RedClear[2]) THEN
                sg_green(3);
                IF (Call12) THEN
                        sg_green(12);
                        MinGreen[3] := 22;    /*** MAX IS 23 ***/
                ELSE
                        MinGreen[3] := 8;
                END;
                EndPreemption:=1;
                start(CurrentPhase3TimerAfter);
                stop(CurrentClear2TimerAfter);
                reset(CurrentClear2TimerAfter);
        END;

        /************* Phase 7 **********************/
```

```
    IF ((CurrentPhaseAfter2 = 7) AND (T_green(CurrentPhaseAfter2)>= PreempMin[1])) THEN
        sg_red(7);
/***Added to ensure proper transition from release of preemption back to "normal" mode***/
        stop(Phase1ClearTimer);
        reset(Phase1ClearTimer);
        stop(Phase2ClearTimer);
        reset(Phase2ClearTimer);
        stop(Phase4ClearTimer);
        reset(Phase4ClearTimer);
        stop(Phase5ClearTimer);
        reset(Phase5ClearTimer);
        stop(Phase6ClearTimer);
        reset(Phase6ClearTimer);
        stop(Phase3ClearTimer);
        reset(Phase3ClearTimer);
        stop(Phase7ClearTimer);
        reset(Phase7ClearTimer);
/**************************************************************************/
        start(CurrentClear7TimerAfter);
        Check := 7;
        Trace (variable (Check));
    END;
    IF (CurrentClear7TimerAfter = tAmber[7] + RedClear[7]) THEN
        sg_green(3);
        EndPreemption:=1;
        start(CurrentPhase3TimerAfter);
        stop(CurrentClear2TimerAfter);
        reset(CurrentClear2TimerAfter);
    END;


    /************** Phase red ************************/
    IF ((CurrentPhaseAfter2 = 100) AND ((Phase5ClearTimer >= tAmber[5] + RedClear[5]) or (Phase6ClearTimer >=
tAmber[6] + RedClear[6]) or (Phase7ClearTimer >= tAmber[7] + RedClear[7])) AND /*** ((T_red(9)) OR (Ped9ClearTimer >=
RetPedClr[1])) AND ***/ ((T_red(11)) OR (Ped11ClearTimer >= RetPedClr[3]))) THEN
        /*start(CurrentClear100TimerAfter);*/
        Check:=100;
        Trace (variable (Check));
        sg_green(3);
        IF (Call12) THEN
            sg_green(12);
            MinGreen[3] := 22;    /*** MAX IS 23 ***/
        ELSE
            MinGreen[3] := 8;
        END;
        EndPreemption:= 1;
        start(CurrentPhase3TimerAfter);
    END;

/**********NECESSARY FOR PED CUTOFF COUNTER TO WORK**********/
sg_red(13);
sg_red(14);
sg_red(15);
sg_red(16);
/**********NECESSARY FOR PED CUTOFF COUNTER TO WORK**********/

END.

/****************************/
/**** BEGIN MAIN SECTION ****/
/****************************/
Prese := presence(69) or occupancy(69) or presence(70) or occupancy(70) or presence(71) or occupancy(71) or presence(72) or
occupancy(72);

/*** The following two IF statements need to be read without any conditionals before them!!! ***/
```

```
IF (Simulationbegin = 0) THEN
          Simulationbegin := 1;
          set_sg_direct(17,off_red);          /***Signal begins in off mode; this is not the same as red***/
END;

IF (t_green(17) >= Warningtime) THEN
                    set_sg_direct(17,off_red);          /***The average green time given for 17 is the warning time***/
END;

IF presence(70) or presence(71) or occupancy(70) or occupancy(71) THEN
          IF (WT = 0) THEN                    /*** This block is only used once (when the train is detected at the crossing)***/
                    Warningtime := CurrentPreemptionTimer;
                    stop(CurrentPreemptionTimer);                    /*** Ends timing when train reaches center detector ***/
                    reset(CurrentPreemptionTimer);
                    stop(CurrentTrainDetTimer);
                    reset(CurrentTrainDetTimer);
                    Trace (variable (Warningtime));     /***This warning time is the actual warning time to the controller***/
                    WT := 1;
                    sg_green(17);                         /***Signal group 17 will be used to count the warning time***/
          END;
END;

IF Prese THEN
          IF (firsttimethru = 0) THEN                    /*** This must be read ONLY when train is 1st detected ***/
                    start(CurrentTrainDetTimer);                    /*** Starts timing when train is detected ***/
                    firsttimethru := 1;
          END;
          IF (Velocity(69)) THEN
                    Vel := Velocity(69)
          END;
          IF (Velocity(72)) THEN
                    Vel := Velocity(72)
          END;
/***/     Trace(variable (Vel));
          Sec_til_pre := (634 / Vel) - 36;                    /*** Seconds until preemption is to be started ***/
/***/     Trace (variable (Sec_til_pre));                    /*** 36 used becuase program rounds up for Sec_til_pre ***/
          IF (CurrentTrainDetTimer >= Sec_til_pre) THEN          /***Warning Time is 1 sec longer if Sec_til_pre ends***/
                    startpreemption := 1;                    /*** greater than .5; for less than .5, the WT is correct ***/
          END;
          IF (startpreemption = 1) THEN                    /*** Once preemption starts, it must remain until train leaves ***/
                    GOSUB Preemption;
                    IF (firsttimethru1 = 0) THEN               /*** This must be read ONLY the 1st time thru this block ***/
                              start(CurrentPreemptionTimer);
                              firsttimethru1 := 1;
                    END;
                    PreemptionOn:=1;
          END;
ELSE
          IF ((PreemptionOn=1) AND (EndPreemption=0)) THEN
                    GOSUB ReleasePreemption;
                    Trace (variable (PreemptionOn));
          ELSE
                    IF (EndPreemption = 0) OR (cycle = 3) THEN
                              GOSUB Compute_Conditionals;
                              GOSUB Ring1;
                              GOSUB Ring2;
                    ELSE
                              GOSUB CorrectionCompute_Conditionals;
                              GOSUB Ring1;
                              GOSUB Ring2;
                    END;
           END;
END.
```

APPENDIX B

POOLED T-TEST FOR AVERAGE VEHICLE DELAY

Table B1. Pooled *t*-Test for Entire Network with Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	5.44	2.86	4.15	29.42	29.75	-0.50	2.02	NO	Increase
Existing & 35-10	5.44	13.15	9.30	29.42	30.80	-1.43	2.02	NO	Increase
Existing & 50-5	5.44	1.10	3.27	29.42	26.12	5.78	2.02	YES	Decrease
Existing & 50-10	5.44	2.37	3.90	29.42	26.28	5.03	2.02	YES	Decrease
Existing & 65-5	5.44	0.84	3.14	29.42	26.01	6.10	2.02	YES	Decrease
Existing & 65-10	5.44	1.31	3.38	29.42	26.32	5.34	2.02	YES	Decrease
35-5 & 35-5	2.86	2.86	2.86	29.75	29.75	0.00	2.02	NO	Same
35-5 & 35-10	2.86	13.15	8.00	29.75	30.80	-1.18	2.02	NO	Increase
35-5 & 50-5	2.86	1.10	1.98	29.75	26.12	8.15	2.02	YES	Decrease
35-5 & 50-10	2.86	2.37	2.61	29.75	26.28	6.78	2.02	YES	Decrease
35-5 & 65-5	2.86	0.84	1.85	29.75	26.01	8.69	2.02	YES	Decrease
35-5 & 65-10	2.86	1.31	2.08	29.75	26.32	7.50	2.02	YES	Decrease
35-10 & 35-5	13.15	2.86	8.00	30.80	29.75	1.18	2.02	NO	Decrease
35-10 & 35-10	13.15	13.15	13.15	30.80	30.80	0.00	2.02	NO	Same
35-10 & 50-5	13.15	1.10	7.12	30.80	26.12	5.55	2.02	YES	Decrease
35-10 & 50-10	13.15	2.37	7.76	30.80	26.28	5.14	2.02	YES	Decrease
35-10 & 65-5	13.15	0.84	6.99	30.80	26.01	5.73	2.02	YES	Decrease
35-10 & 65-10	13.15	1.31	7.23	30.80	26.32	5.27	2.02	YES	Decrease
50-5 & 35-5	1.10	2.86	1.98	26.12	29.75	-8.15	2.02	YES	Increase
50-5 & 35-10	1.10	13.15	7.12	26.12	30.80	-5.55	2.02	YES	Increase
50-5 & 50-5	1.10	1.10	1.10	26.12	26.12	0.00	2.02	NO	Same
50-5 & 50-10	1.10	2.37	1.73	26.12	26.28	-0.38	2.02	NO	Increase
50-5 & 65-5	1.10	0.84	0.97	26.12	26.01	0.36	2.02	NO	Decrease
50-5 & 65-10	1.10	1.31	1.20	26.12	26.32	-0.57	2.02	NO	Increase

Table B1. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	2.37	2.86	2.61	26.28	29.75	-6.78	2.02	YES	Increase
50-10 & 35-10	2.37	13.15	7.76	26.28	30.80	-5.14	2.02	YES	Increase
50-10 & 50-5	2.37	1.10	1.73	26.28	26.12	0.38	2.02	NO	Decrease
50-10 & 50-10	2.37	2.37	2.37	26.28	26.28	0.00	2.02	NO	Same
50-10 & 65-5	2.37	0.84	1.60	26.28	26.01	0.68	2.02	NO	Decrease
50-10 & 65-10	2.37	1.31	1.84	26.28	26.32	-0.10	2.02	NO	Increase
65-5 & 35-5	0.84	2.86	1.85	26.01	29.75	-8.69	2.02	YES	Increase
65-5 & 35-10	0.84	13.15	6.99	26.01	30.80	-5.73	2.02	YES	Increase
65-5 & 50-5	0.84	1.10	0.97	26.01	26.12	-0.36	2.02	NO	Increase
65-5 & 50-10	0.84	2.37	1.60	26.01	26.28	-0.68	2.02	NO	Increase
65-5 & 65-5	0.84	0.84	0.84	26.01	26.01	0.00	2.02	NO	Same
65-5 & 65-10	0.84	1.31	1.07	26.01	26.32	-0.95	2.02	NO	Increase
65-10 & 35-5	1.31	2.86	2.08	26.32	29.75	-7.50	2.02	YES	Increase
65-10 & 35-10	1.31	13.15	7.23	26.32	30.80	-5.27	2.02	YES	Increase
65-10 & 50-5	1.31	1.10	1.20	26.32	26.12	0.57	2.02	NO	Decrease
65-10 & 50-10	1.31	2.37	1.84	26.32	26.28	0.10	2.02	NO	Decrease
65-10 & 65-5	1.31	0.84	1.07	26.32	26.01	0.95	2.02	NO	Decrease
65-10 & 65-10	1.31	1.31	1.31	26.32	26.32	0.00	2.02	NO	Same

Table B2. Pooled *t*-Test for Old Main Dr. with Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	9.03	5.46	7.24	23.49	24.17	-0.81	2.02	NO	Increase
Existing & 35-10	9.03	8.86	8.95	23.49	23.64	-0.17	2.02	NO	Increase
Existing & 50-5	9.03	3.40	6.22	23.49	20.81	3.40	2.02	YES	Decrease
Existing & 50-10	9.03	3.78	6.40	23.49	21.15	2.92	2.02	YES	Decrease
Existing & 65-5	9.03	2.17	5.60	23.49	21.60	2.52	2.02	YES	Decrease
Existing & 65-10	9.03	5.12	7.08	23.49	22.17	1.57	2.02	NO	Decrease
35-5 & 35-5	5.46	5.46	5.46	24.17	24.17	0.00	2.02	NO	Same
35-5 & 35-10	5.46	8.86	7.16	24.17	23.64	0.63	2.02	NO	Decrease
35-5 & 50-5	5.46	3.40	4.43	24.17	20.81	5.06	2.02	YES	Decrease
35-5 & 50-10	5.46	3.78	4.62	24.17	21.15	4.45	2.02	YES	Decrease
35-5 & 65-5	5.46	2.17	3.81	24.17	21.60	4.16	2.02	YES	Decrease
35-5 & 65-10	5.46	5.12	5.29	24.17	22.17	2.76	2.02	YES	Decrease
35-10 & 35-5	8.86	5.46	7.16	23.64	24.17	-0.63	2.02	NO	Increase
35-10 & 35-10	8.86	8.86	8.86	23.64	23.64	0.00	2.02	NO	Same
35-10 & 50-5	8.86	3.40	6.13	23.64	20.81	3.62	2.02	YES	Decrease
35-10 & 50-10	8.86	3.78	6.32	23.64	21.15	3.14	2.02	YES	Decrease
35-10 & 65-5	8.86	2.17	5.52	23.64	21.60	2.75	2.02	YES	Decrease
35-10 & 65-10	8.86	5.12	6.99	23.64	22.17	1.76	2.02	NO	Decrease
50-5 & 35-5	3.40	5.46	4.43	20.81	24.17	-5.06	2.02	YES	Increase
50-5 & 35-10	3.40	8.86	6.13	20.81	23.64	-3.62	2.02	YES	Increase
50-5 & 50-5	3.40	3.40	3.40	20.81	20.81	0.00	2.02	NO	Same
50-5 & 50-10	3.40	3.78	3.59	20.81	21.15	-0.57	2.02	NO	Increase
50-5 & 65-5	3.40	2.17	2.79	20.81	21.60	-1.51	2.02	NO	Increase
50-5 & 65-10	3.40	5.12	4.26	20.81	22.17	-2.09	2.02	YES	Increase

Table B2. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	3.78	5.46	4.62	21.15	24.17	-4.45	2.02	YES	Increase
50-10 & 35-10	3.78	8.86	6.32	21.15	23.64	-3.14	2.02	YES	Increase
50-10 & 50-5	3.78	3.40	3.59	21.15	20.81	0.57	2.02	NO	Decrease
50-10 & 50-10	3.78	3.78	3.78	21.15	21.15	0.00	2.02	NO	Same
50-10 & 65-5	3.78	2.17	2.97	21.15	21.60	-0.84	2.02	NO	Increase
50-10 & 65-10	3.78	5.12	4.45	21.15	22.17	-1.53	2.02	NO	Increase
65-5 & 35-5	2.17	5.46	3.81	21.60	24.17	-4.16	2.02	YES	Increase
65-5 & 35-10	2.17	8.86	5.52	21.60	23.64	-2.75	2.02	YES	Increase
65-5 & 50-5	2.17	3.40	2.79	21.60	20.81	1.51	2.02	NO	Decrease
65-5 & 50-10	2.17	3.78	2.97	21.60	21.15	0.84	2.02	NO	Decrease
65-5 & 65-5	2.17	2.17	2.17	21.60	21.60	0.00	2.02	NO	Same
65-5 & 65-10	2.17	5.12	3.65	21.60	22.17	-0.94	2.02	NO	Increase
65-10 & 35-5	5.12	5.46	5.29	22.17	24.17	-2.76	2.02	YES	Increase
65-10 & 35-10	5.12	8.86	6.99	22.17	23.64	-1.76	2.02	YES	Increase
65-10 & 50-5	5.12	3.40	4.26	22.17	20.81	2.09	2.02	YES	Decrease
65-10 & 50-10	5.12	3.78	4.45	22.17	21.15	1.53	2.02	NO	Decrease
65-10 & 65-5	5.12	2.17	3.65	22.17	21.60	0.94	2.02	NO	Decrease
65-10 & 65-10	5.12	5.12	5.12	22.17	22.17	0.00	2.02	NO	Same

Table B3. Pooled *t*-Test for Joe Routt Blvd. with Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	3.07	2.21	2.64	21.22	20.99	0.45	2.02	NO	Decrease
Existing & 35-10	3.07	8.89	5.98	21.22	21.82	-0.78	2.02	NO	Increase
Existing & 50-5	3.07	1.20	2.14	21.22	19.94	2.77	2.02	YES	Decrease
Existing & 50-10	3.07	3.09	3.08	21.22	19.54	3.02	2.02	YES	Decrease
Existing & 65-5	3.07	1.86	2.47	21.22	19.63	3.20	2.02	YES	Decrease
Existing & 65-10	3.07	2.94	3.01	21.22	19.63	2.89	2.02	YES	Decrease
35-5 & 35-5	2.21	2.21	2.21	20.99	20.99	0.00	2.02	NO	Same
35-5 & 35-10	2.21	8.89	5.55	20.99	21.82	-1.11	2.02	NO	Increase
35-5 & 50-5	2.21	1.20	1.70	20.99	19.94	2.54	2.02	YES	Decrease
35-5 & 50-10	2.21	3.09	2.65	20.99	19.54	2.81	2.02	YES	Decrease
35-5 & 65-5	2.21	1.86	2.03	20.99	19.63	3.01	2.02	YES	Decrease
35-5 & 65-10	2.21	2.94	2.58	20.99	19.63	2.68	2.02	YES	Decrease
35-10 & 35-5	8.89	2.21	5.55	21.82	20.99	1.11	2.02	NO	Decrease
35-10 & 35-10	8.89	8.89	8.89	21.82	21.82	0.00	2.02	NO	Same
35-10 & 50-5	8.89	1.20	5.04	21.82	19.94	2.65	2.02	YES	Decrease
35-10 & 50-10	8.89	3.09	5.99	21.82	19.54	2.94	2.02	YES	Decrease
35-10 & 65-5	8.89	1.86	5.37	21.82	19.63	2.99	2.02	YES	Decrease
35-10 & 65-10	8.89	2.94	5.91	21.82	19.63	2.85	2.02	YES	Decrease
50-5 & 35-5	1.20	2.21	1.70	19.94	20.99	-2.54	2.02	YES	Increase
50-5 & 35-10	1.20	8.89	5.04	19.94	21.82	-2.65	2.02	YES	Increase
50-5 & 50-5	1.20	1.20	1.20	19.94	19.94	0.00	2.02	NO	Same
50-5 & 50-10	1.20	3.09	2.14	19.94	19.54	0.85	2.02	NO	Decrease
50-5 & 65-5	1.20	1.86	1.53	19.94	19.63	0.79	2.02	NO	Decrease
50-5 & 65-10	1.20	2.94	2.07	19.94	19.63	0.68	2.02	NO	Decrease

Table B3. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
50-10 & 35-5	3.09	2.21	2.65	19.54	20.99	-2.81	2.02	YES	Increase
50-10 & 35-10	3.09	8.89	5.99	19.54	21.82	-2.94	2.02	YES	Increase
50-10 & 50-5	3.09	1.20	2.14	19.54	19.94	-0.85	2.02	NO	Increase
50-10 & 50-10	3.09	3.09	3.09	19.54	19.54	0.00	2.02	NO	Same
50-10 & 65-5	3.09	1.86	2.47	19.54	19.63	-0.18	2.02	NO	Increase
50-10 & 65-10	3.09	2.94	3.02	19.54	19.63	-0.16	2.02	NO	Increase
65-5 & 35-5	1.86	2.21	2.03	19.63	20.99	-3.01	2.02	YES	Increase
65-5 & 35-10	1.86	8.89	5.37	19.63	21.82	-2.99	2.02	YES	Increase
65-5 & 50-5	1.86	1.20	1.53	19.63	19.94	-0.79	2.02	YES	Increase
65-5 & 50-10	1.86	3.09	2.47	19.63	19.54	0.18	2.02	NO	Decrease
65-5 & 65-5	1.86	1.86	1.86	19.63	19.63	0.00	2.02	NO	Same
65-5 & 65-10	1.86	2.94	2.40	19.63	19.63	0.00	2.02	NO	Decrease
65-10 & 35-5	2.94	2.21	2.58	19.63	20.99	-2.68	2.02	YES	Increase
65-10 & 35-10	2.94	8.89	5.91	19.63	21.82	-2.85	2.02	YES	Increase
65-10 & 50-5	2.94	1.20	2.07	19.63	19.94	-0.68	2.02	NO	Increase
65-10 & 50-10	2.94	3.09	3.02	19.63	19.54	0.16	2.02	NO	Decrease
65-10 & 65-5	2.94	1.86	2.40	19.63	19.63	0.00	2.02	NO	Increase
65-10 & 65-10	2.94	2.94	2.94	19.63	19.63	0.00	2.02	NO	Same

Table B4. Pooled *t*-Test for George Bush Dr. with Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	16.29	6.01	11.15	37.75	38.17	-0.40	2.02	NO	Increase
Existing & 35-10	16.29	27.71	22.00	37.75	40.33	-1.74	2.02	NO	Increase
Existing & 50-5	16.29	3.74	10.01	37.75	32.98	4.76	2.02	YES	Decrease
Existing & 50-10	16.29	4.30	10.29	37.75	33.27	4.41	2.02	YES	Decrease
Existing & 65-5	16.29	3.81	10.05	37.75	32.29	5.44	2.02	YES	Decrease
Existing & 65-10	16.29	5.83	11.06	37.75	32.58	4.91	2.02	YES	Decrease
35-5 & 35-5	6.01	6.01	6.01	38.17	38.17	0.00	2.02	NO	Same
35-5 & 35-10	6.01	27.71	16.86	38.17	40.33	-1.67	2.02	NO	Increase
35-5 & 50-5	6.01	3.74	4.88	38.17	32.98	7.43	2.02	YES	Decrease
35-5 & 50-10	6.01	4.30	5.16	38.17	33.27	6.82	2.02	YES	Decrease
35-5 & 65-5	6.01	3.81	4.91	38.17	32.29	8.38	2.02	YES	Decrease
35-5 & 65-10	6.01	5.83	5.92	38.17	32.58	7.26	2.02	YES	Decrease
35-10 & 35-5	27.71	6.01	16.86	40.33	38.17	1.67	2.02	NO	Decrease
35-10 & 35-10	27.71	27.71	27.71	40.33	40.33	0.00	2.02	NO	Same
35-10 & 50-5	27.71	3.74	15.72	40.33	32.98	5.86	2.02	YES	Decrease
35-10 & 50-10	27.71	4.30	16.01	40.33	33.27	5.58	2.02	YES	Decrease
35-10 & 65-5	27.71	3.81	15.76	40.33	32.29	6.40	2.02	YES	Decrease
35-10 & 65-10	27.71	5.83	16.77	40.33	32.58	5.99	2.02	YES	Decrease
50-5 & 35-5	3.74	6.01	4.88	32.98	38.17	-7.43	2.02	YES	Increase
50-5 & 35-10	3.74	27.71	15.72	32.98	40.33	-5.86	2.02	YES	Increase
50-5 & 50-5	3.74	3.74	3.74	32.98	32.98	0.00	2.02	NO	Same
50-5 & 50-10	3.74	4.30	4.02	32.98	33.27	-0.46	2.02	NO	Increase
50-5 & 65-5	3.74	3.81	3.78	32.98	32.29	1.12	2.02	NO	Decrease
50-5 & 65-10	3.74	5.83	4.78	32.98	32.58	0.58	2.02	NO	Decrease

Table B4. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
50-10 & 35-5	4.30	6.01	5.16	33.27	38.17	-6.82	2.02	YES	Increase
50-10 & 35-10	4.30	27.71	16.01	33.27	40.33	-5.58	2.02	YES	Increase
50-10 & 50-5	4.30	3.74	4.02	33.27	32.98	0.46	2.02	NO	Decrease
50-10 & 50-10	4.30	4.30	4.30	33.27	33.27	0.00	2.02	NO	Same
50-10 & 65-5	4.30	3.81	4.06	33.27	32.29	1.54	2.02	NO	Decrease
50-10 & 65-10	4.30	5.83	5.06	33.27	32.58	0.97	2.02	NO	Decrease
65-5 & 35-5	3.81	6.01	4.91	32.29	38.17	-8.38	2.02	YES	Increase
65-5 & 35-10	3.81	27.71	15.76	32.29	40.33	-6.40	2.02	YES	Increase
65-5 & 50-5	3.81	3.74	3.78	32.29	32.98	-1.12	2.02	NO	Increase
65-5 & 50-10	3.81	4.30	4.06	32.29	33.27	-1.54	2.02	NO	Increase
65-5 & 65-5	3.81	3.81	3.81	32.29	32.29	0.00	2.02	NO	Same
65-5 & 65-10	3.81	5.83	4.82	32.29	32.58	-0.41	2.02	NO	Increase
65-10 & 35-5	5.83	6.01	5.92	32.58	38.17	-7.26	2.02	YES	Increase
65-10 & 35-10	5.83	27.71	16.77	32.58	40.33	-5.99	2.02	YES	Increase
65-10 & 50-5	5.83	3.74	4.78	32.58	32.98	-0.58	2.02	NO	Increase
65-10 & 50-10	5.83	4.30	5.06	32.58	33.27	-0.97	2.02	NO	Increase
65-10 & 65-5	5.83	3.81	4.82	32.58	32.29	0.41	2.02	NO	Decrease
65-10 & 65-10	5.83	5.83	5.83	32.58	32.58	0.00	2.02	NO	Same

Table B5. Pooled *t*-Test for Entire Network with Short Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	2.71	2.01	2.36	26.76	26.45	0.65	2.02	NO	Decrease
Existing & 35-10	2.71	4.22	3.47	26.76	27.99	-2.09	2.02	YES	Increase
Existing & 50-5	2.71	1.31	2.01	26.76	25.40	3.04	2.02	YES	Decrease
Existing & 50-10	2.71	0.66	1.69	26.76	25.32	3.52	2.02	YES	Decrease
Existing & 65-5	2.71	1.68	2.19	26.76	25.08	3.59	2.02	YES	Decrease
Existing & 65-10	2.71	1.21	1.96	26.76	25.59	2.65	2.02	YES	Decrease
35-5 & 35-5	2.01	2.01	2.01	26.45	26.45	0.00	2.02	NO	Same
35-5 & 35-10	2.01	4.22	3.12	26.45	27.99	-2.77	2.02	YES	Increase
35-5 & 50-5	2.01	1.31	1.66	26.45	25.40	2.57	2.02	YES	Decrease
35-5 & 50-10	2.01	0.66	1.34	26.45	25.32	3.09	2.02	YES	Decrease
35-5 & 65-5	2.01	1.68	1.85	26.45	25.08	3.18	2.02	YES	Decrease
35-5 & 65-10	2.01	1.21	1.61	26.45	25.59	2.14	2.02	YES	Decrease
35-10 & 35-5	4.22	2.01	3.12	27.99	26.45	2.77	2.02	YES	Decrease
35-10 & 35-10	4.22	4.22	4.22	27.99	27.99	0.00	2.02	NO	Same
35-10 & 50-5	4.22	1.31	2.77	27.99	25.40	4.93	2.02	YES	Decrease
35-10 & 50-10	4.22	0.66	2.44	27.99	25.32	5.41	2.02	YES	Decrease
35-10 & 65-5	4.22	1.68	2.95	27.99	25.08	5.36	2.02	YES	Decrease
35-10 & 65-10	4.22	1.21	2.71	27.99	25.59	4.61	2.02	YES	Decrease
50-5 & 35-5	1.31	2.01	1.66	25.40	26.45	-2.57	2.02	YES	Increase
50-5 & 35-10	1.31	4.22	2.77	25.40	27.99	-4.93	2.02	YES	Increase
50-5 & 50-5	1.31	1.31	1.31	25.40	25.40	0.00	2.02	NO	Same
50-5 & 50-10	1.31	0.66	0.99	25.40	25.32	0.26	2.02	NO	Decrease
50-5 & 65-5	1.31	1.68	1.49	25.40	25.08	0.82	2.02	NO	Decrease
50-5 & 65-10	1.31	1.21	1.26	25.40	25.59	-0.53	2.02	NO	Increase

Table B5. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
50-10 & 35-5	0.66	2.01	1.34	25.32	26.45	-3.09	2.02	YES	Increase
50-10 & 35-10	0.66	4.22	2.44	25.32	27.99	-5.41	2.02	YES	Increase
50-10 & 50-5	0.66	1.31	0.99	25.32	25.40	-0.26	2.02	NO	Increase
50-10 & 50-10	0.66	0.66	0.66	25.32	25.32	0.00	2.02	NO	Same
50-10 & 65-5	0.66	1.68	1.17	25.32	25.08	0.69	2.02	NO	Decrease
50-10 & 65-10	0.66	1.21	0.93	25.32	25.59	-0.89	2.02	NO	Increase
65-5 & 35-5	1.68	2.01	1.85	25.08	26.45	-3.18	2.02	YES	Increase
65-5 & 35-10	1.68	4.22	2.95	25.08	27.99	-5.36	2.02	YES	Increase
65-5 & 50-5	1.68	1.31	1.49	25.08	25.40	-0.82	2.02	NO	Increase
65-5 & 50-10	1.68	0.66	1.17	25.08	25.32	-0.69	2.02	NO	Increase
65-5 & 65-5	1.68	1.68	1.68	25.08	25.08	0.00	2.02	NO	Same
65-5 & 65-10	1.68	1.21	1.44	25.08	25.59	-1.34	2.02	NO	Increase
65-10 & 35-5	1.21	2.01	1.61	25.59	26.45	-2.14	2.02	YES	Increase
65-10 & 35-10	1.21	4.22	2.71	25.59	27.99	-4.61	2.02	YES	Increase
65-10 & 50-5	1.21	1.31	1.26	25.59	25.40	0.53	2.02	NO	Decrease
65-10 & 50-10	1.21	0.66	0.93	25.59	25.32	0.89	2.02	NO	Decrease
65-10 & 65-5	1.21	1.68	1.44	25.59	25.08	1.34	2.02	NO	Decrease
65-10 & 65-10	1.21	1.21	1.21	25.59	25.59	0.00	2.02	NO	Same

Table B6. Pooled *t*-Test for Old Main Dr. with Short Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
Existing & 35-5	7.28	1.94	4.61	21.47	21.64	-0.26	2.02	NO	Increase
Existing & 35-10	7.28	4.96	6.12	21.47	22.42	-1.22	2.02	NO	Increase
Existing & 50-5	7.28	1.98	4.63	21.47	19.89	2.32	2.02	YES	Decrease
Existing & 50-10	7.28	2.41	4.85	21.47	20.05	2.04	2.02	YES	Decrease
Existing & 65-5	7.28	2.54	4.91	21.47	20.64	1.19	2.02	NO	Decrease
Existing & 65-10	7.28	4.73	6.01	21.47	21.37	0.12	2.02	NO	Decrease
35-5 & 35-5	1.94	1.94	1.94	21.64	21.64	0.00	2.02	NO	Same
35-5 & 35-10	1.94	4.96	3.45	21.64	22.42	-1.33	2.02	NO	Increase
35-5 & 50-5	1.94	1.98	1.96	21.64	19.89	3.97	2.02	YES	Decrease
35-5 & 50-10	1.94	2.41	2.17	21.64	20.05	3.42	2.02	YES	Decrease
35-5 & 65-5	1.94	2.54	2.24	21.64	20.64	2.13	2.02	YES	Decrease
35-5 & 65-10	1.94	4.73	3.33	21.64	21.37	0.47	2.02	NO	Decrease
35-10 & 35-5	4.96	1.94	3.45	22.42	21.64	1.33	2.02	NO	Decrease
35-10 & 35-10	4.96	4.96	4.96	22.42	22.42	0.00	2.02	NO	Same
35-10 & 50-5	4.96	1.98	3.47	22.42	19.89	4.30	2.02	YES	Decrease
35-10 & 50-10	4.96	2.41	3.69	22.42	20.05	3.91	2.02	YES	Decrease
35-10 & 65-5	4.96	2.54	3.75	22.42	20.64	2.92	2.02	YES	Decrease
35-10 & 65-10	4.96	4.73	4.84	22.42	21.37	1.51	2.02	NO	Decrease
50-5 & 35-5	1.98	1.94	1.96	19.89	21.64	-3.97	2.02	YES	Increase
50-5 & 35-10	1.98	4.96	3.47	19.89	22.42	-4.30	2.02	YES	Increase
50-5 & 50-5	1.98	1.98	1.98	19.89	19.89	0.00	2.02	NO	Same
50-5 & 50-10	1.98	2.41	2.19	19.89	20.05	-0.34	2.02	NO	Increase
50-5 & 65-5	1.98	2.54	2.26	19.89	20.64	-1.57	2.02	NO	Increase
50-5 & 65-10	1.98	4.73	3.35	19.89	21.37	-2.57	2.02	YES	Increase

Table B6. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	2.41	1.94	2.17	20.05	21.64	-3.42	2.02	YES	Increase
50-10 & 35-10	2.41	4.96	3.69	20.05	22.42	-3.91	2.02	YES	Increase
50-10 & 50-5	2.41	1.98	2.19	20.05	19.89	0.34	2.02	NO	Decrease
50-10 & 50-10	2.41	2.41	2.41	20.05	20.05	0.00	2.02	NO	Same
50-10 & 65-5	2.41	2.54	2.47	20.05	20.64	-1.18	2.02	NO	Increase
50-10 & 65-10	2.41	4.73	3.57	20.05	21.37	-2.22	2.02	YES	Increase
65-5 & 35-5	2.54	1.94	2.24	20.64	21.64	-2.13	2.02	YES	Increase
65-5 & 35-10	2.54	4.96	3.75	20.64	22.42	-2.92	2.02	YES	Increase
65-5 & 50-5	2.54	1.98	2.26	20.64	19.89	1.57	2.02	NO	Decrease
65-5 & 50-10	2.54	2.41	2.47	20.64	20.05	1.18	2.02	NO	Decrease
65-5 & 65-5	2.54	2.54	2.54	20.64	20.64	0.00	2.02	NO	Same
65-5 & 65-10	2.54	4.73	3.63	20.64	21.37	-1.23	2.02	NO	Increase
65-10 & 35-5	4.73	1.94	3.33	21.37	21.64	-0.47	2.02	NO	Increase
65-10 & 35-10	4.73	4.96	4.84	21.37	22.42	-1.51	2.02	NO	Increase
65-10 & 50-5	4.73	1.98	3.35	21.37	19.89	2.57	2.02	YES	Decrease
65-10 & 50-10	4.73	2.41	3.57	21.37	20.05	2.22	2.02	YES	Decrease
65-10 & 65-5	4.73	2.54	3.63	21.37	20.64	1.23	2.02	NO	Decrease
65-10 & 65-10	4.73	4.73	4.73	21.37	21.37	0.00	2.02	NO	Same

Table B7. Pooled *t*-Test for Joe Routt Blvd. with Short Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
Existing & 35-5	2.66	2.74	2.70	20.58	20.53	0.10	2.02	NO	Decrease
Existing & 35-10	2.66	4.64	3.65	20.58	20.86	-0.47	2.02	NO	Increase
Existing & 50-5	2.66	1.34	2.00	20.58	19.56	2.28	2.02	YES	Decrease
Existing & 50-10	2.66	2.48	2.57	20.58	19.20	2.72	2.02	YES	Decrease
Existing & 65-5	2.66	2.69	2.67	20.58	19.28	2.53	2.02	YES	Decrease
Existing & 65-10	2.66	3.14	2.90	20.58	19.94	1.20	2.02	NO	Decrease
35-5 & 35-5	2.74	2.74	2.74	20.53	20.53	0.00	2.02	NO	Same
35-5 & 35-10	2.74	4.64	3.69	20.53	20.86	-0.55	2.02	NO	Increase
35-5 & 50-5	2.74	1.34	2.04	20.53	19.56	2.14	2.02	YES	Decrease
35-5 & 50-10	2.74	2.48	2.61	20.53	19.20	2.60	2.02	YES	Decrease
35-5 & 65-5	2.74	2.69	2.71	20.53	19.28	2.40	2.02	YES	Decrease
35-5 & 65-10	2.74	3.14	2.94	20.53	19.94	1.09	2.02	NO	Decrease
35-10 & 35-5	4.64	2.74	3.69	20.86	20.53	0.55	2.02	NO	Decrease
35-10 & 35-10	4.64	4.64	4.64	20.86	20.86	0.00	2.02	NO	Same
35-10 & 50-5	4.64	1.34	2.99	20.86	19.56	2.38	2.02	YES	Decrease
35-10 & 50-10	4.64	2.48	3.56	20.86	19.20	2.78	2.02	YES	Decrease
35-10 & 65-5	4.64	2.69	3.67	20.86	19.28	2.62	2.02	YES	Decrease
35-10 & 65-10	4.64	3.14	3.89	20.86	19.94	1.48	2.02	NO	Decrease
50-5 & 35-5	1.34	2.74	2.04	19.56	20.53	-2.14	2.02	YES	Increase
50-5 & 35-10	1.34	4.64	2.99	19.56	20.86	-2.38	2.02	YES	Increase
50-5 & 50-5	1.34	1.34	1.34	19.56	19.56	0.00	2.02	NO	Same
50-5 & 50-10	1.34	2.48	1.91	19.56	19.20	0.83	2.02	NO	Decrease
50-5 & 65-5	1.34	2.69	2.01	19.56	19.28	0.64	2.02	NO	Decrease
50-5 & 65-10	1.34	3.14	2.24	19.56	19.94	-0.79	2.02	NO	Increase

Table B7. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	2.48	2.74	2.61	19.20	20.53	-2.60	2.02	YES	Increase
50-10 & 35-10	2.48	4.64	3.56	19.20	20.86	-2.78	2.02	YES	Increase
50-10 & 50-5	2.48	1.34	1.91	19.20	19.56	-0.83	2.02	NO	Increase
50-10 & 50-10	2.48	2.48	2.48	19.20	19.20	0.00	2.02	NO	Same
50-10 & 65-5	2.48	2.69	2.59	19.20	19.28	-0.14	2.02	NO	Increase
50-10 & 65-10	2.48	3.14	2.81	19.20	19.94	-1.39	2.02	NO	Increase
65-5 & 35-5	2.69	2.74	2.71	19.28	20.53	-2.40	2.02	YES	Increase
65-5 & 35-10	2.69	4.64	3.67	19.28	20.86	-2.62	2.02	YES	Increase
65-5 & 50-5	2.69	1.34	2.01	19.28	19.56	-0.64	2.02	NO	Increase
65-5 & 50-10	2.69	2.48	2.59	19.28	19.20	0.14	2.02	NO	Decrease
65-5 & 65-5	2.69	2.69	2.69	19.28	19.28	0.00	2.02	NO	Same
65-5 & 65-10	2.69	3.14	2.92	19.28	19.94	-1.23	2.02	NO	Increase
65-10 & 35-5	3.14	2.74	2.94	19.94	20.53	-1.09	2.02	NO	Increase
65-10 & 35-10	3.14	4.64	3.89	19.94	20.86	-1.48	2.02	NO	Increase
65-10 & 50-5	3.14	1.34	2.24	19.94	19.56	0.79	2.02	NO	Decrease
65-10 & 50-10	3.14	2.48	2.81	19.94	19.20	1.39	2.02	NO	Decrease
65-10 & 65-5	3.14	2.69	2.92	19.94	19.28	1.23	2.02	NO	Decrease
65-10 & 65-10	3.14	3.14	3.14	19.94	19.94	0.00	2.02	NO	Same

Table B8. Pooled *t*-Test for George Bush Dr. with Short Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	7.44	7.08	7.26	33.59	32.79	0.94	2.02	NO	Decrease
Existing & 35-10	7.44	10.53	8.98	33.59	35.49	-2.00	2.02	NO	Increase
Existing & 50-5	7.44	4.82	6.13	33.59	32.16	1.82	2.02	NO	Decrease
Existing & 50-10	7.44	2.29	4.87	33.59	32.07	2.18	2.02	YES	Decrease
Existing & 65-5	7.44	5.64	6.54	33.59	31.13	3.05	2.02	YES	Decrease
Existing & 65-10	7.44	3.80	5.62	33.59	31.43	2.88	2.02	YES	Decrease
35-5 & 35-5	7.08	7.08	7.08	32.79	32.79	0.00	2.02	NO	Same
35-5 & 35-10	7.08	10.53	8.80	32.79	35.49	-2.87	2.02	YES	Increase
35-5 & 50-5	7.08	4.82	5.95	32.79	32.16	0.82	2.02	NO	Decrease
35-5 & 50-10	7.08	2.29	4.69	32.79	32.07	1.05	2.02	NO	Decrease
35-5 & 65-5	7.08	5.64	6.36	32.79	31.13	2.09	2.02	YES	Decrease
35-5 & 65-10	7.08	3.80	5.44	32.79	31.43	1.85	2.02	NO	Decrease
35-10 & 35-5	10.53	7.08	8.80	35.49	32.79	2.87	2.02	YES	Decrease
35-10 & 35-10	10.53	10.53	10.53	35.49	35.49	0.00	2.02	NO	Same
35-10 & 50-5	10.53	4.82	7.67	35.49	32.16	3.80	2.02	YES	Decrease
35-10 & 50-10	10.53	2.29	6.41	35.49	32.07	4.27	2.02	YES	Decrease
35-10 & 65-5	10.53	5.64	8.08	35.49	31.13	4.85	2.02	YES	Decrease
35-10 & 65-10	10.53	3.80	7.16	35.49	31.43	4.79	2.02	YES	Decrease
50-5 & 35-5	4.82	7.08	5.95	32.16	32.79	-0.82	2.02	NO	Increase
50-5 & 35-10	4.82	10.53	7.67	32.16	35.49	-3.80	2.02	YES	Increase
50-5 & 50-5	4.82	4.82	4.82	32.16	32.16	0.00	2.02	NO	Same
50-5 & 50-10	4.82	2.29	3.56	32.16	32.07	0.15	2.02	NO	Decrease
50-5 & 65-5	4.82	5.64	5.23	32.16	31.13	1.43	2.02	NO	Decrease
50-5 & 65-10	4.82	3.80	4.31	32.16	31.43	1.11	2.02	NO	Decrease

Table B8. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
50-10 & 35-5	2.29	7.08	4.69	32.07	32.79	-1.05	2.02	NO	Increase
50-10 & 35-10	2.29	10.53	6.41	32.07	35.49	-4.27	2.02	YES	Increase
50-10 & 50-5	2.29	4.82	3.56	32.07	32.16	-0.15	2.02	NO	Increase
50-10 & 50-10	2.29	2.29	2.29	32.07	32.07	0.00	2.02	NO	Same
50-10 & 65-5	2.29	5.64	3.97	32.07	31.13	1.50	2.02	NO	Decrease
50-10 & 65-10	2.29	3.80	3.05	32.07	31.43	1.16	2.02	NO	Decrease
65-5 & 35-5	5.64	7.08	6.36	31.13	32.79	-2.09	2.02	YES	Increase
65-5 & 35-10	5.64	10.53	8.08	31.13	35.49	-4.85	2.02	YES	Increase
65-5 & 50-5	5.64	4.82	5.23	31.13	32.16	-1.43	2.02	NO	Increase
65-5 & 50-10	5.64	2.29	3.97	31.13	32.07	-1.50	2.02	NO	Increase
65-5 & 65-5	5.64	5.64	5.64	31.13	31.13	0.00	2.02	NO	Same
65-5 & 65-10	5.64	3.80	4.72	31.13	31.43	-0.45	2.02	NO	Increase
65-10 & 35-5	3.80	7.08	5.44	31.43	32.79	-1.85	2.02	NO	Increase
65-10 & 35-10	3.80	10.53	7.16	31.43	35.49	-4.79	2.02	YES	Increase
65-10 & 50-5	3.80	4.82	4.31	31.43	32.16	-1.11	2.02	NO	Increase
65-10 & 50-10	3.80	2.29	3.05	31.43	32.07	-1.16	2.02	NO	Increase
65-10 & 65-5	3.80	5.64	4.72	31.43	31.13	0.45	2.02	NO	Decrease
65-10 & 65-10	3.80	3.80	3.80	31.43	31.43	0.00	2.02	NO	Same

Table B9. Pooled *t*-Test for Entire Network with Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
Existing & 35-5	6.17	5.77	5.97	31.72	32.90	-1.53	2.02	NO	Increase
Existing & 35-10	6.17	25.07	15.62	31.72	34.14	-1.94	2.02	NO	Increase
Existing & 50-5	6.17	2.03	4.10	31.72	28.95	4.33	2.02	YES	Decrease
Existing & 50-10	6.17	4.31	5.24	31.72	28.96	3.82	2.02	YES	Decrease
Existing & 65-5	6.17	2.03	4.10	31.72	27.20	7.06	2.02	YES	Decrease
Existing & 65-10	6.17	1.56	3.86	31.72	27.19	7.28	2.02	YES	Decrease
35-5 & 35-5	5.77	5.77	5.77	32.90	32.90	0.00	2.02	NO	Same
35-5 & 35-10	5.77	25.07	15.42	32.90	34.14	-1.00	2.02	NO	Increase
35-5 & 50-5	5.77	2.03	3.90	32.90	28.95	6.33	2.02	YES	Decrease
35-5 & 50-10	5.77	4.31	5.04	32.90	28.96	5.56	2.02	YES	Decrease
35-5 & 65-5	5.77	2.03	3.90	32.90	27.20	9.13	2.02	YES	Decrease
35-5 & 65-10	5.77	1.56	3.66	32.90	27.19	9.43	2.02	YES	Decrease
35-10 & 35-5	25.07	5.77	15.42	34.14	32.90	1.00	2.02	NO	Decrease
35-10 & 35-10	25.07	25.07	25.07	34.14	34.14	0.00	2.02	NO	Same
35-10 & 50-5	25.07	2.03	13.55	34.14	28.95	4.46	2.02	YES	Decrease
35-10 & 50-10	25.07	4.31	14.69	34.14	28.96	4.28	2.02	YES	Decrease
35-10 & 65-5	25.07	2.03	13.55	34.14	27.20	5.97	2.02	YES	Decrease
35-10 & 65-10	25.07	1.56	13.31	34.14	27.19	6.02	2.02	YES	Decrease
50-5 & 35-5	2.03	5.77	3.90	28.95	32.90	-6.33	2.02	YES	Increase
50-5 & 35-10	2.03	25.07	13.55	28.95	34.14	-4.46	2.02	YES	Increase
50-5 & 50-5	2.03	2.03	2.03	28.95	28.95	0.00	2.02	NO	Same
50-5 & 50-10	2.03	4.31	3.17	28.95	28.96	-0.01	2.02	NO	Increase
50-5 & 65-5	2.03	2.03	2.03	28.95	27.20	3.88	2.02	YES	Decrease
50-5 & 65-10	2.03	1.56	1.79	28.95	27.19	4.15	2.02	YES	Decrease

Table B9. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
50-10 & 35-5	4.31	5.77	5.04	28.96	32.90	-5.56	2.02	YES	Increase
50-10 & 35-10	4.31	25.07	14.69	28.96	34.14	-4.28	2.02	YES	Increase
50-10 & 50-5	4.31	2.03	3.17	28.96	28.95	0.01	2.02	NO	Decrease
50-10 & 50-10	4.31	4.31	4.31	28.96	28.96	0.00	2.02	NO	Same
50-10 & 65-5	4.31	2.03	3.17	28.96	27.20	3.12	2.02	YES	Decrease
50-10 & 65-10	4.31	1.56	2.93	28.96	27.19	3.26	2.02	YES	Decrease
65-5 & 35-5	2.03	5.77	3.90	27.20	32.90	-9.13	2.02	YES	Increase
65-5 & 35-10	2.03	25.07	13.55	27.20	34.14	-5.97	2.02	YES	Increase
65-5 & 50-5	2.03	2.03	2.03	27.20	28.95	-3.88	2.02	YES	Increase
65-5 & 50-10	2.03	4.31	3.17	27.20	28.96	-3.12	2.02	YES	Increase
65-5 & 65-5	2.03	2.03	2.03	27.20	27.20	0.00	2.02	NO	Same
65-5 & 65-10	2.03	1.56	1.79	27.20	27.19	0.01	2.02	NO	Decrease
65-10 & 35-5	1.56	5.77	3.66	27.19	32.90	-9.43	2.02	YES	Increase
65-10 & 35-10	1.56	25.07	13.31	27.19	34.14	-6.02	2.02	YES	Increase
65-10 & 50-5	1.56	2.03	1.79	27.19	28.95	-4.15	2.02	YES	Increase
65-10 & 50-10	1.56	4.31	2.93	27.19	28.96	-3.26	2.02	YES	Increase
65-10 & 65-5	1.56	2.03	1.79	27.19	27.20	-0.01	2.02	NO	Increase
65-10 & 65-10	1.56	1.56	1.56	27.19	27.19	0.00	2.02	NO	Same

Table B10. Pooled *t*-Test for Old Main Dr. with Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	14.01	10.26	12.13	24.33	27.27	-2.67	2.02	YES	Increase
Existing & 35-10	14.01	32.22	23.12	24.33	26.99	-1.75	2.02	NO	Increase
Existing & 50-5	14.01	2.46	8.24	24.33	22.41	2.12	2.02	YES	Decrease
Existing & 50-10	14.01	6.69	10.35	24.33	23.11	1.20	2.02	NO	Decrease
Existing & 65-5	14.01	7.33	10.67	24.33	23.19	1.10	2.02	NO	Decrease
Existing & 65-10	14.01	4.87	9.44	24.33	22.92	1.45	2.02	NO	Decrease
35-5 & 35-5	10.26	10.26	10.26	27.27	27.27	0.00	2.02	NO	Same
35-5 & 35-10	10.26	32.22	21.24	27.27	26.99	0.19	2.02	NO	Decrease
35-5 & 50-5	10.26	2.46	6.36	27.27	22.41	6.09	2.02	YES	Decrease
35-5 & 50-10	10.26	6.69	8.48	27.27	23.11	4.52	2.02	YES	Decrease
35-5 & 65-5	10.26	7.33	8.80	27.27	23.19	4.35	2.02	YES	Decrease
35-5 & 65-10	10.26	4.87	7.56	27.27	22.92	5.00	2.02	YES	Decrease
35-10 & 35-5	32.22	10.26	21.24	26.99	27.27	-0.19	2.02	NO	Increase
35-10 & 35-10	32.22	32.22	32.22	26.99	26.99	0.00	2.02	NO	Same
35-10 & 50-5	32.22	2.46	17.34	26.99	22.41	3.48	2.02	YES	Decrease
35-10 & 50-10	32.22	6.69	19.46	26.99	23.11	2.78	2.02	YES	Decrease
35-10 & 65-5	32.22	7.33	19.78	26.99	23.19	2.70	2.02	YES	Decrease
35-10 & 65-10	32.22	4.87	18.55	26.99	22.92	2.99	2.02	YES	Decrease
50-5 & 35-5	2.46	10.26	6.36	22.41	27.27	-6.09	2.02	YES	Increase
50-5 & 35-10	2.46	32.22	17.34	22.41	26.99	-3.48	2.02	YES	Increase
50-5 & 50-5	2.46	2.46	2.46	22.41	22.41	0.00	2.02	NO	Same
50-5 & 50-10	2.46	6.69	4.58	22.41	23.11	-1.03	2.02	NO	Increase
50-5 & 65-5	2.46	7.33	4.90	22.41	23.19	-1.11	2.02	NO	Increase
50-5 & 65-10	2.46	4.87	3.67	22.41	22.92	-0.84	2.02	NO	Increase

Table B10. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	6.69	10.26	8.48	23.11	27.27	-4.52	2.02	YES	Increase
50-10 & 35-10	6.69	32.22	19.46	23.11	26.99	-2.78	2.02	YES	Increase
50-10 & 50-5	6.69	2.46	4.58	23.11	22.41	1.03	2.02	NO	Decrease
50-10 & 50-10	6.69	6.69	6.69	23.11	23.11	0.00	2.02	NO	Same
50-10 & 65-5	6.69	7.33	7.01	23.11	23.19	-0.10	2.02	NO	Increase
50-10 & 65-10	6.69	4.87	5.78	23.11	22.92	0.24	2.02	NO	Decrease
65-5 & 35-5	7.33	10.26	8.80	23.19	27.27	-4.35	2.02	YES	Increase
65-5 & 35-10	7.33	32.22	19.78	23.19	26.99	-2.70	2.02	YES	Increase
65-5 & 50-5	7.33	2.46	4.90	23.19	22.41	1.11	2.02	NO	Decrease
65-5 & 50-10	7.33	6.69	7.01	23.19	23.11	0.10	2.02	NO	Decrease
65-5 & 65-5	7.33	7.33	7.33	23.19	23.19	0.00	2.02	NO	Same
65-5 & 65-10	7.33	4.87	6.10	23.19	22.92	0.34	2.02	NO	Decrease
65-10 & 35-5	4.87	10.26	7.56	22.92	27.27	-5.00	2.02	YES	Increase
65-10 & 35-10	4.87	32.22	18.55	22.92	26.99	-2.99	2.02	YES	Increase
65-10 & 50-5	4.87	2.46	3.67	22.92	22.41	0.84	2.02	NO	Decrease
65-10 & 50-10	4.87	6.69	5.78	22.92	23.11	-0.24	2.02	NO	Increase
65-10 & 65-5	4.87	7.33	6.10	22.92	23.19	-0.34	2.02	NO	Increase
65-10 & 65-10	4.87	4.87	4.87	22.92	22.92	0.00	2.02	NO	Same

Table B11. Pooled *t*-Test for Joe Routt Blvd. with Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
Existing & 35-5	4.04	5.07	4.56	21.89	22.17	-0.41	2.02	NO	Increase
Existing & 35-10	4.04	23.51	13.78	21.89	23.23	-1.14	2.02	NO	Increase
Existing & 50-5	4.04	2.86	3.45	21.89	20.15	2.97	2.02	YES	Decrease
Existing & 50-10	4.04	6.48	5.26	21.89	20.55	1.85	2.02	NO	Decrease
Existing & 65-5	4.04	3.65	3.85	21.89	19.39	4.03	2.02	YES	Decrease
Existing & 65-10	4.04	1.65	2.85	21.89	19.58	4.34	2.02	YES	Decrease
35-5 & 35-5	5.07	5.07	5.07	22.17	22.17	0.00	2.02	NO	Same
35-5 & 35-10	5.07	23.51	14.29	22.17	23.23	-0.89	2.02	NO	Increase
35-5 & 50-5	5.07	2.86	3.96	22.17	20.15	3.21	2.02	YES	Decrease
35-5 & 50-10	5.07	6.48	5.77	22.17	20.55	2.13	2.02	YES	Decrease
35-5 & 65-5	5.07	3.65	4.36	22.17	19.39	4.21	2.02	YES	Decrease
35-5 & 65-10	5.07	1.65	3.36	22.17	19.58	4.47	2.02	YES	Decrease
35-10 & 35-5	23.51	5.07	14.29	23.23	22.17	0.89	2.02	NO	Decrease
35-10 & 35-10	23.51	23.51	23.51	23.23	23.23	0.00	2.02	NO	Same
35-10 & 50-5	23.51	2.86	13.18	23.23	20.15	2.68	2.02	YES	Decrease
35-10 & 50-10	23.51	6.48	14.99	23.23	20.55	2.19	2.02	YES	Decrease
35-10 & 65-5	23.51	3.65	13.58	23.23	19.39	3.30	2.02	YES	Decrease
35-10 & 65-10	23.51	1.65	12.58	23.23	19.58	3.26	2.02	YES	Decrease
50-5 & 35-5	2.86	5.07	3.96	20.15	22.17	-3.21	2.02	YES	Increase
50-5 & 35-10	2.86	23.51	13.18	20.15	23.23	-2.68	2.02	YES	Increase
50-5 & 50-5	2.86	2.86	2.86	20.15	20.15	0.00	2.02	NO	Same
50-5 & 50-10	2.86	6.48	4.67	20.15	20.55	-0.59	2.02	NO	Increase
50-5 & 65-5	2.86	3.65	3.26	20.15	19.39	1.33	2.02	NO	Decrease
50-5 & 65-10	2.86	1.65	2.26	20.15	19.58	1.21	2.02	NO	Decrease

Table B11. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	6.48	5.07	5.77	20.55	22.17	-2.13	2.02	YES	Increase
50-10 & 35-10	6.48	23.51	14.99	20.55	23.23	-2.19	2.02	YES	Increase
50-10 & 50-5	6.48	2.86	4.67	20.55	20.15	0.59	2.02	NO	Decrease
50-10 & 50-10	6.48	6.48	6.48	20.55	20.55	0.00	2.02	NO	Same
50-10 & 65-5	6.48	3.65	5.06	20.55	19.39	1.63	2.02	NO	Decrease
50-10 & 65-10	6.48	1.65	4.06	20.55	19.58	1.53	2.02	NO	Decrease
65-5 & 35-5	3.65	5.07	4.36	19.39	22.17	-4.21	2.02	YES	Increase
65-5 & 35-10	3.65	23.51	13.58	19.39	23.23	-3.30	2.02	YES	Increase
65-5 & 50-5	3.65	2.86	3.26	19.39	20.15	-1.33	2.02	NO	Increase
65-5 & 50-10	3.65	6.48	5.06	19.39	20.55	-1.63	2.02	NO	Increase
65-5 & 65-5	3.65	3.65	3.65	19.39	19.39	0.00	2.02	NO	Same
65-5 & 65-10	3.65	1.65	2.65	19.39	19.58	-0.36	2.02	NO	Increase
65-10 & 35-5	1.65	5.07	3.36	19.58	22.17	-4.47	2.02	YES	Increase
65-10 & 35-10	1.65	23.51	12.58	19.58	23.23	-3.26	2.02	YES	Increase
65-10 & 50-5	1.65	2.86	2.26	19.58	20.15	-1.21	2.02	NO	Increase
65-10 & 50-10	1.65	6.48	4.06	19.58	20.55	-1.53	2.02	NO	Increase
65-10 & 65-5	1.65	3.65	2.65	19.58	19.39	0.36	2.02	NO	Decrease
65-10 & 65-10	1.65	1.65	1.65	19.58	19.58	0.00	2.02	NO	Same

Table B12. Pooled *t*-Test for George Bush Dr. with Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**
Existing & 35-5	18.61	15.09	16.85	41.91	42.44	-0.41	2.02	NO	Increase
Existing & 35-10	18.61	36.28	27.44	41.91	44.79	-1.74	2.02	NO	Increase
Existing & 50-5	18.61	7.68	13.15	41.91	37.98	3.43	2.02	YES	Decrease
Existing & 50-10	18.61	10.75	14.68	41.91	37.37	3.75	2.02	YES	Decrease
Existing & 65-5	18.61	4.88	11.75	41.91	34.02	7.27	2.02	YES	Decrease
Existing & 65-10	18.61	8.84	13.73	41.91	34.08	6.68	2.02	YES	Decrease
35-5 & 35-5	15.09	15.09	15.09	42.44	42.44	0.00	2.02	NO	Same
35-5 & 35-10	15.09	36.28	25.68	42.44	44.79	-1.46	2.02	NO	Increase
35-5 & 50-5	15.09	7.68	11.38	42.44	37.98	4.19	2.02	YES	Decrease
35-5 & 50-10	15.09	10.75	12.92	42.44	37.37	4.47	2.02	YES	Decrease
35-5 & 65-5	15.09	4.88	9.98	42.44	34.02	8.43	2.02	YES	Decrease
35-5 & 65-10	15.09	8.84	11.96	42.44	34.08	7.65	2.02	YES	Decrease
35-10 & 35-5	36.28	15.09	25.68	44.79	42.44	1.46	2.02	NO	Decrease
35-10 & 35-10	36.28	36.28	36.28	44.79	44.79	0.00	2.02	NO	Same
35-10 & 50-5	36.28	7.68	21.98	44.79	37.98	4.59	2.02	YES	Decrease
35-10 & 50-10	36.28	10.75	23.52	44.79	37.37	4.84	2.02	YES	Decrease
35-10 & 65-5	36.28	4.88	20.58	44.79	34.02	7.50	2.02	YES	Decrease
35-10 & 65-10	36.28	8.84	22.56	44.79	34.08	7.13	2.02	YES	Decrease
50-5 & 35-5	7.68	15.09	11.38	37.98	42.44	-4.19	2.02	YES	Increase
50-5 & 35-10	7.68	36.28	21.98	37.98	44.79	-4.59	2.02	YES	Increase
50-5 & 50-5	7.68	7.68	7.68	37.98	37.98	0.00	2.02	NO	Same
50-5 & 50-10	7.68	10.75	9.22	37.98	37.37	0.63	2.02	NO	Decrease
50-5 & 65-5	7.68	4.88	6.28	37.98	34.02	4.99	2.02	YES	Decrease
50-5 & 65-10	7.68	8.84	8.26	37.98	34.08	4.29	2.02	YES	Decrease

Table B12. Continued

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?
50-10 & 35-5	10.75	15.09	12.92	37.37	42.44	-4.47	2.02	YES	Increase
50-10 & 35-10	10.75	36.28	23.52	37.37	44.79	-4.84	2.02	YES	Increase
50-10 & 50-5	10.75	7.68	9.22	37.37	37.98	-0.63	2.02	NO	Increase
50-10 & 50-10	10.75	10.75	10.75	37.37	37.37	0.00	2.02	NO	Same
50-10 & 65-5	10.75	4.88	7.82	37.37	34.02	3.78	2.02	YES	Decrease
50-10 & 65-10	10.75	8.84	9.80	37.37	34.08	3.32	2.02	YES	Decrease
65-5 & 35-5	4.88	15.09	9.98	34.02	42.44	-8.43	2.02	YES	Increase
65-5 & 35-10	4.88	36.28	20.58	34.02	44.79	-7.50	2.02	YES	Increase
65-5 & 50-5	4.88	7.68	6.28	34.02	37.98	-4.99	2.02	YES	Increase
65-5 & 50-10	4.88	10.75	7.82	34.02	37.37	-3.78	2.02	YES	Increase
65-5 & 65-5	4.88	4.88	4.88	34.02	34.02	0.00	2.02	NO	Same
65-5 & 65-10	4.88	8.84	6.86	34.02	34.08	-0.06	2.02	NO	Increase
65-10 & 35-5	8.84	15.09	11.96	34.08	42.44	-7.65	2.02	YES	Increase
65-10 & 35-10	8.84	36.28	22.56	34.08	44.79	-7.13	2.02	YES	Increase
65-10 & 50-5	8.84	7.68	8.26	34.08	37.98	-4.29	2.02	YES	Increase
65-10 & 50-10	8.84	10.75	9.80	34.08	37.37	-3.32	2.02	YES	Increase
65-10 & 65-5	8.84	4.88	6.86	34.08	34.02	0.06	2.02	NO	Decrease
65-10 & 65-10	8.84	8.84	8.84	34.08	34.08	0.00	2.02	NO	Same

Table B13. Pooled *t*-Test for Entire Network with Short vs. Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	2.71	5.44	4.08	26.76	29.42	-4.17	2.02	YES	Increase
35-5	2.01	2.86	2.44	26.45	29.75	-6.68	2.02	YES	Increase
35-10	4.22	13.15	8.68	27.99	30.80	-3.02	2.02	YES	Increase
50-5	1.31	1.10	1.21	25.40	26.12	-2.07	2.02	YES	Increase
50-10	0.66	2.37	1.51	25.32	26.28	-2.47	2.02	YES	Increase
65-5	1.68	0.84	1.26	25.08	26.01	-2.61	2.02	YES	Increase
65-10	1.21	1.31	1.26	25.59	26.32	-2.06	2.02	YES	Increase

[1]: Change in Delay from Short to Average Train Length

Table B14. Pooled *t*-Test for Old Main Dr. with Short vs. Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	7.28	9.03	8.15	21.47	23.49	-2.23	2.02	YES	Increase
35-5	1.94	5.46	3.70	21.64	24.17	-4.16	2.02	YES	Increase
35-10	4.96	8.86	6.91	22.42	23.64	-1.47	2.02	NO	Increase
50-5	1.98	3.40	2.69	19.89	20.81	-1.77	2.02	NO	Increase
50-10	2.41	3.78	3.09	20.05	21.15	-1.98	2.02	NO	Increase
65-5	2.54	2.17	2.35	20.64	21.60	-2.00	2.02	NO	Increase
65-10	4.73	5.12	4.93	21.37	22.17	-1.13	2.02	NO	Increase

[1]: Change in Delay from Short to Average Train Length

Table B15. Pooled *t*-Test for Joe Routt Blvd. with Short vs. Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?[1]
Existing	2.66	3.07	2.87	20.58	21.22	-1.18	2.02	NO	Increase
35-5	2.74	2.21	2.47	20.53	20.99	-0.92	2.02	NO	Increase
35-10	4.64	8.89	6.76	20.86	21.82	-1.16	2.02	NO	Increase
50-5	1.34	1.20	1.27	19.56	19.94	-1.05	2.02	NO	Increase
50-10	2.48	3.09	2.78	19.20	19.54	-0.64	2.02	NO	Increase
65-5	2.69	1.86	2.27	19.28	19.63	-0.74	2.02	NO	Increase
65-10	3.14	2.94	3.04	19.94	19.63	0.56	2.02	NO	Decrease

[1]: Change in Delay from Short to Average Train Length

Table B16. Pooled *t*-Test for George Bush Dr. with Short vs. Average Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?[1]
Existing	7.44	16.29	11.86	33.59	37.75	-3.81	2.02	YES	Increase
35-5	7.08	6.01	6.55	32.79	38.17	-6.64	2.02	YES	Increase
35-10	10.53	27.71	19.12	35.49	40.33	-3.50	2.02	YES	Increase
50-5	4.82	3.74	4.28	32.16	32.98	-1.25	2.02	NO	Increase
50-10	2.29	4.30	3.30	32.07	33.27	-2.09	2.02	YES	Increase
65-5	5.64	3.81	4.73	31.13	32.29	-1.70	2.02	NO	Increase
65-10	3.80	5.83	4.81	31.43	32.58	-1.65	2.02	NO	Increase

[1]: Change in Delay from Short to Average Train Length

Table B17. Pooled *t*-Test for Entire Network with Average vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?[1]**
Existing	5.44	6.17	5.80	29.42	31.72	-3.01	2.02	YES	Increase
35-5	2.86	5.77	4.31	29.75	32.90	-4.81	2.02	YES	Increase
35-10	13.15	25.07	19.11	30.80	34.14	-2.42	2.02	YES	Increase
50-5	1.10	2.03	1.57	26.12	28.95	-7.15	2.02	YES	Increase
50-10	2.37	4.31	3.34	26.28	28.96	-4.63	2.02	YES	Increase
65-5	0.84	2.03	1.43	26.01	27.20	-3.15	2.02	YES	Increase
65-10	1.31	1.56	1.43	26.32	27.19	-2.31	2.02	YES	Increase

[1]: Change in Delay from Short to Average Train Length

Table B18. Pooled *t*-Test for Old Main Dr. with Average vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?[1]**
Existing	9.03	14.01	11.52	23.49	24.33	-0.79	2.02	NO	Increase
35-5	5.46	10.26	7.86	24.17	27.27	-3.50	2.02	YES	Increase
35-10	8.86	32.22	20.54	23.64	26.99	-2.34	2.02	YES	Increase
50-5	3.40	2.46	2.93	20.81	22.41	-2.97	2.02	YES	Increase
50-10	3.78	6.69	5.23	21.15	23.11	-2.71	2.02	YES	Increase
65-5	2.17	7.33	4.75	21.60	23.19	-2.30	2.02	YES	Increase
65-10	5.12	4.87	5.00	22.17	22.92	-1.07	2.02	NO	Increase

[1]: Change in Delay from Short to Average Train Length

Table B19. Pooled *t*-Test for Joe Routt Blvd. with Average vs. LongTrain Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	3.07	4.04	3.56	21.22	21.89	-1.14	2.02	NO	Increase
35-5	2.21	5.07	3.64	20.99	22.17	-1.96	2.02	NO	Increase
35-10	8.89	23.51	16.20	21.82	23.23	-1.11	2.02	NO	Increase
50-5	1.20	2.86	2.03	19.94	20.15	-0.48	2.02	NO	Increase
50-10	3.09	6.48	4.78	19.54	20.55	-1.46	2.02	NO	Increase
65-5	1.86	3.65	2.75	19.63	19.39	0.45	2.02	NO	Decrease
65-10	2.94	1.65	2.30	19.63	19.58	0.11	2.02	NO	Decrease

[1]: Change in Delay from Short to Average Train Length

Table B20. Pooled *t*-Test for George Bush Dr. with Average vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	16.29	18.61	17.45	37.75	41.91	-3.15	2.02	YES	Increase
35-5	6.01	15.09	10.55	38.17	42.44	-4.16	2.02	YES	Increase
35-10	27.71	36.28	31.99	40.33	44.79	-2.49	2.02	YES	Increase
50-5	3.74	7.68	5.71	32.98	37.98	-6.61	2.02	YES	Increase
50-10	4.30	10.75	7.53	33.27	37.37	-4.72	2.02	YES	Increase
65-5	3.81	4.88	4.35	32.29	34.02	-2.62	2.02	YES	Increase
65-10	5.83	8.84	7.33	32.58	34.08	-1.75	2.02	NO	Increase

[1]: Change in Delay from Short to Average Train Length

Table B21. Pooled *t*-Test for Entire Network with Short vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?[1]
Existing	2.71	6.17	4.44	26.76	31.72	-7.44	2.02	YES	Increase
35-5	2.01	5.77	3.89	26.45	32.90	-	2.02	YES	Increase
35-10	4.22	25.07	14.65	27.99	34.14	-5.08	2.02	YES	Increase
50-5	1.31	2.03	1.67	25.40	28.95	-8.68	2.02	YES	Increase
50-10	0.66	4.31	2.49	25.32	28.96	-7.30	2.02	YES	Increase
65-5	1.68	2.03	1.85	25.08	27.20	-4.92	2.02	YES	Increase
65-10	1.21	1.56	1.38	25.59	27.19	-4.31	2.02	YES	Increase

[1]: Change in Delay from Short to Average Train Length

Table B22. Pooled *t*-Test for Old Main Dr. with Short vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	Test Stat	Reject H_0?	Delay?[1]
Existing	7.28	14.01	10.65	21.47	24.33	-2.78	2.02	YES	Increase
35-5	1.94	10.26	6.10	21.64	27.27	-7.21	2.02	YES	Increase
35-10	4.96	32.22	18.59	22.42	26.99	-3.35	2.02	YES	Increase
50-5	1.98	2.46	2.22	19.89	22.41	-5.36	2.02	YES	Increase
50-10	2.41	6.69	4.55	20.05	23.11	-4.54	2.02	YES	Increase
65-5	2.54	7.33	4.94	20.64	23.19	-3.64	2.02	YES	Increase
65-10	4.73	4.87	4.80	21.37	22.92	-2.24	2.02	YES	Increase

[1]: Change in Delay from Short to Average Train Length

Table B23. Pooled *t*-Test for Joe Routt Blvd. with Short vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	2.66	4.04	3.35	20.58	21.89	-2.27	2.02	YES	Increase
35-5	2.74	5.07	3.90	20.53	22.17	-2.63	2.02	YES	Increase
35-10	4.64	23.51	14.08	20.86	23.23	-2.00	2.02	YES	Increase
50-5	1.34	2.86	2.10	19.56	20.15	-1.28	2.02	NO	Increase
50-10	2.48	6.48	4.48	19.20	20.55	-2.02	2.02	NO	Increase
65-5	2.69	3.65	3.17	19.28	19.39	-0.21	2.02	NO	Increase
65-10	3.14	1.65	2.40	19.94	19.58	0.74	2.02	NO	Decrease

[1]: Change in Delay from Short to Average Train Length

Table B24. Pooled *t*-Test for George Bush Dr. with Short vs. Long Train Length

Comparison	S_1^2	S_2^2	S_p^2	$\overline{X}_1$	$\overline{X}_2$	T_0	**Test Stat**	**Reject H_0?**	**Delay?**[1]
Existing	7.44	18.61	13.03	33.59	41.91	-7.28	2.02	YES	Increase
35-5	7.08	15.09	11.08	32.79	42.44	-9.16	2.02	YES	Increase
35-10	10.53	36.28	23.40	35.49	44.79	-6.08	2.02	YES	Increase
50-5	4.82	7.68	6.25	32.16	37.98	-7.35	2.02	YES	Increase
50-10	2.29	10.75	6.52	32.07	37.37	-6.55	2.02	YES	Increase
65-5	5.64	4.88	5.26	31.13	34.02	-4.00	2.02	YES	Increase
65-10	3.80	8.84	6.32	31.43	34.08	-3.33	2.02	YES	Increase

[1]: Change in Delay from Short to Average Train Length

APPENDIX C

95% CONFIDENCE INTERVAL DELAY COMPARISONS

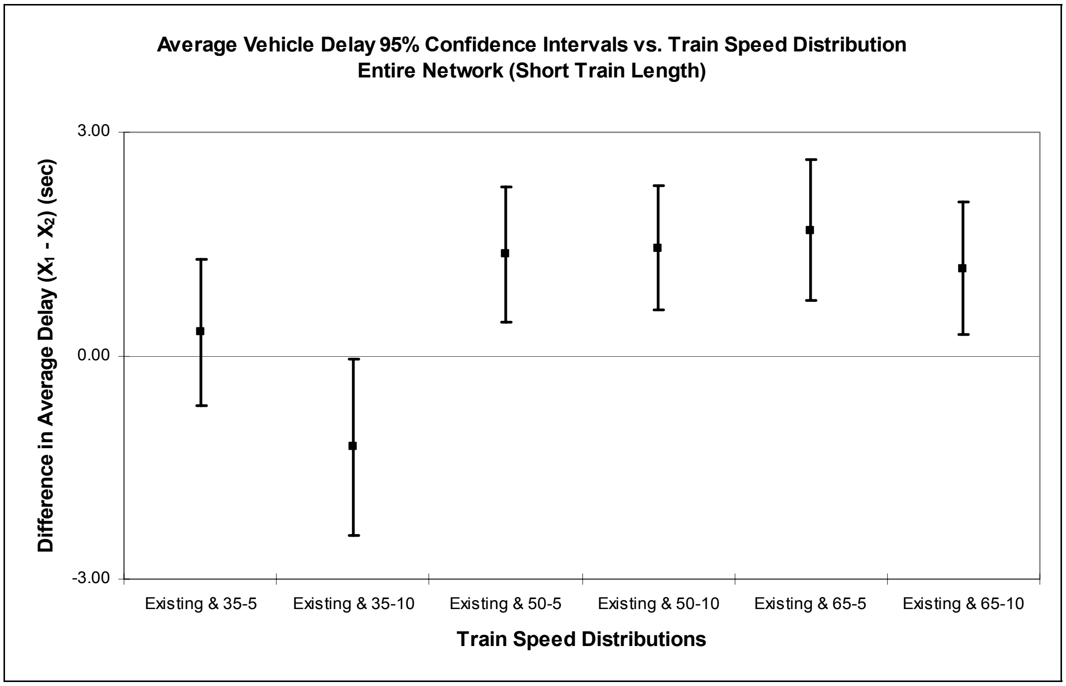

Figure C1. 95% Confidence Intervals on $\mu_1 - \mu_2$ (Entire Network, Short Train Length)

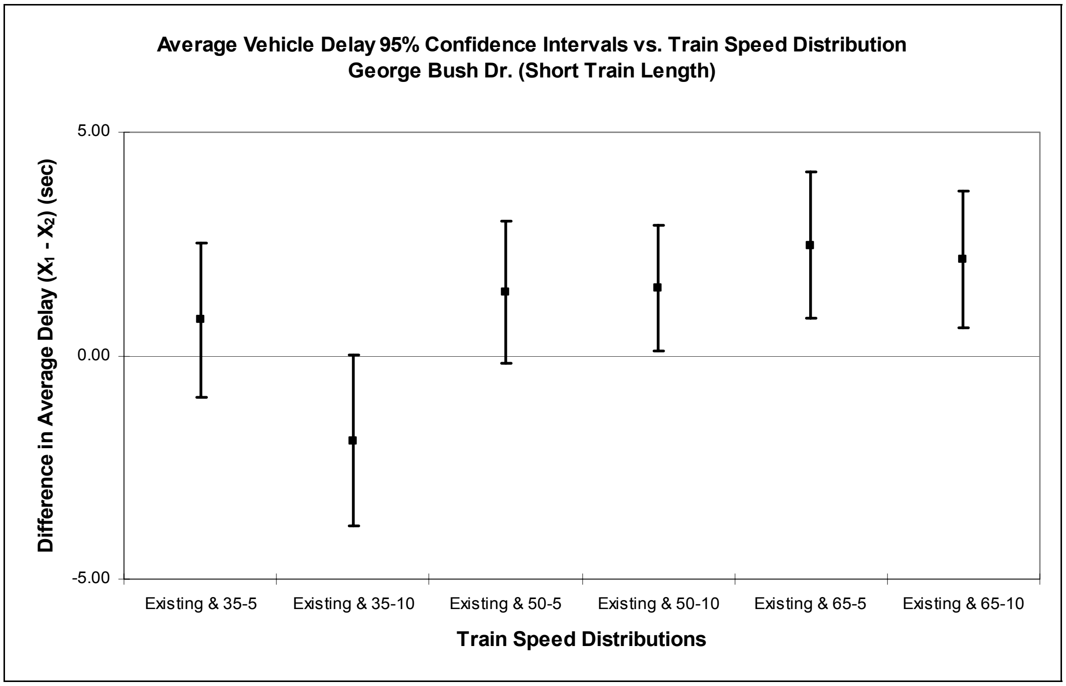

Figure C2. 95% Confidence Intervals on $\mu_1 - \mu_2$ (George Bush Dr., Short Train Length)

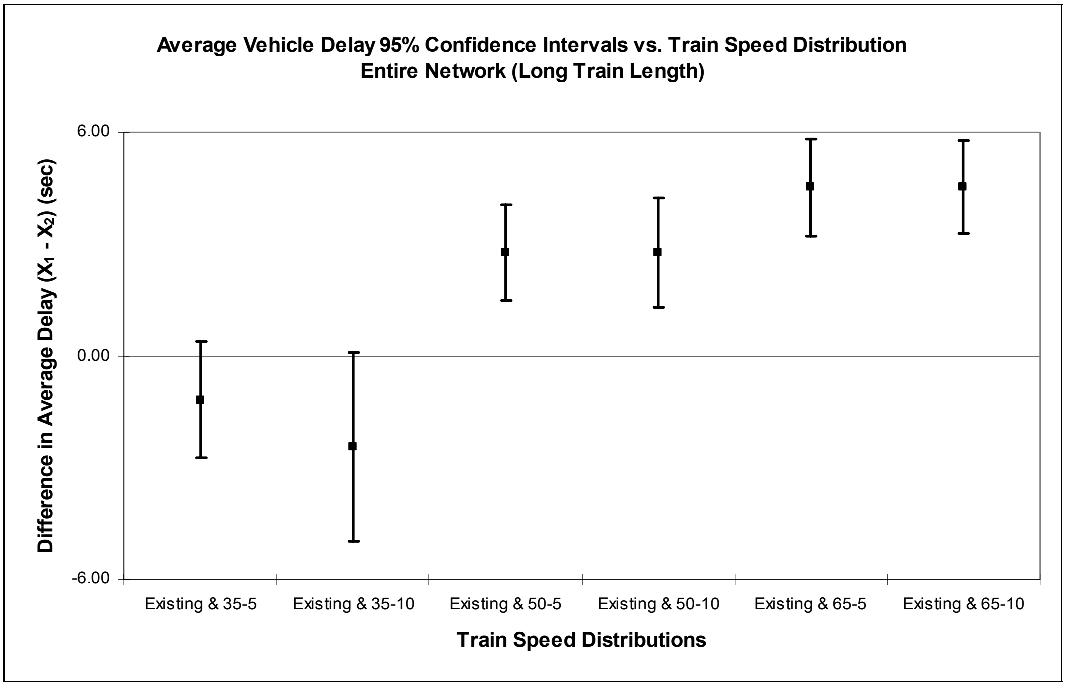

Figure C3. 95% Confidence Intervals on $\mu_1 - \mu_2$ (Entire Network, Long Train Length)

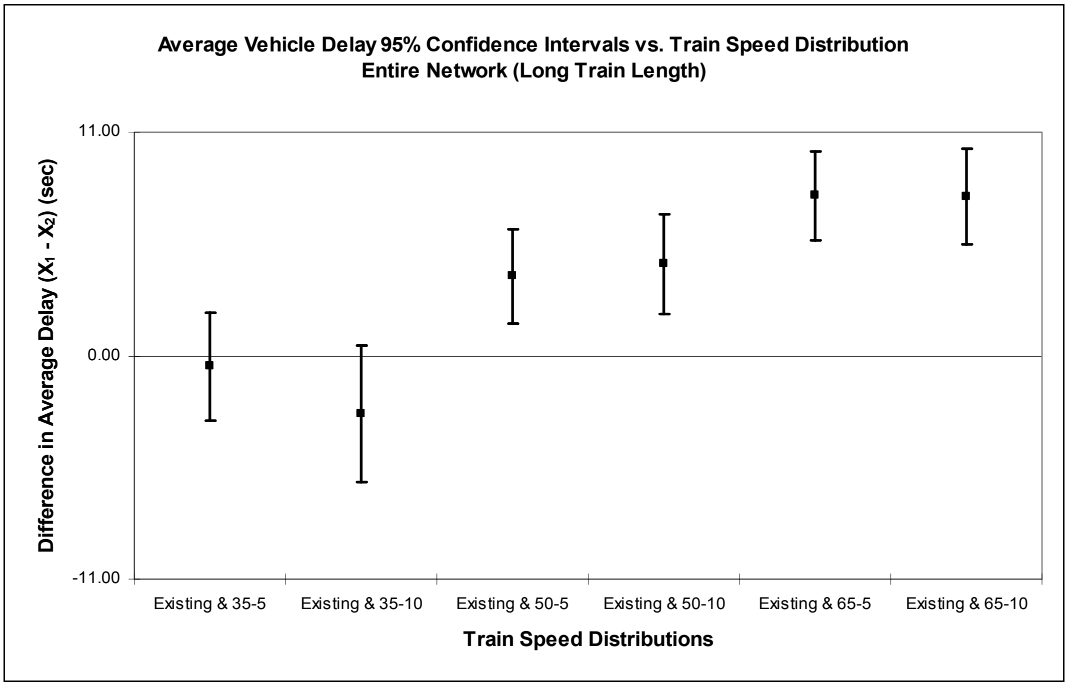

Figure C4. 95% Confidence Intervals on $\mu_1 - \mu_2$ (George Bush Dr., Long Train Length)

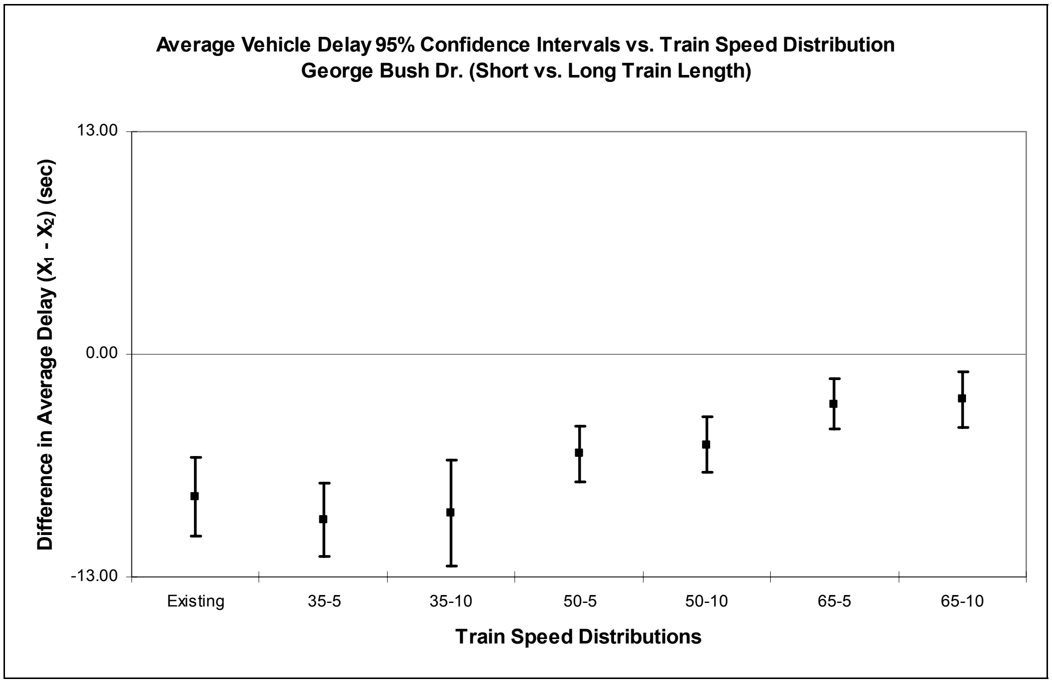

Figure C5. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions
(George Bush Dr., Short vs. Long Train Length)

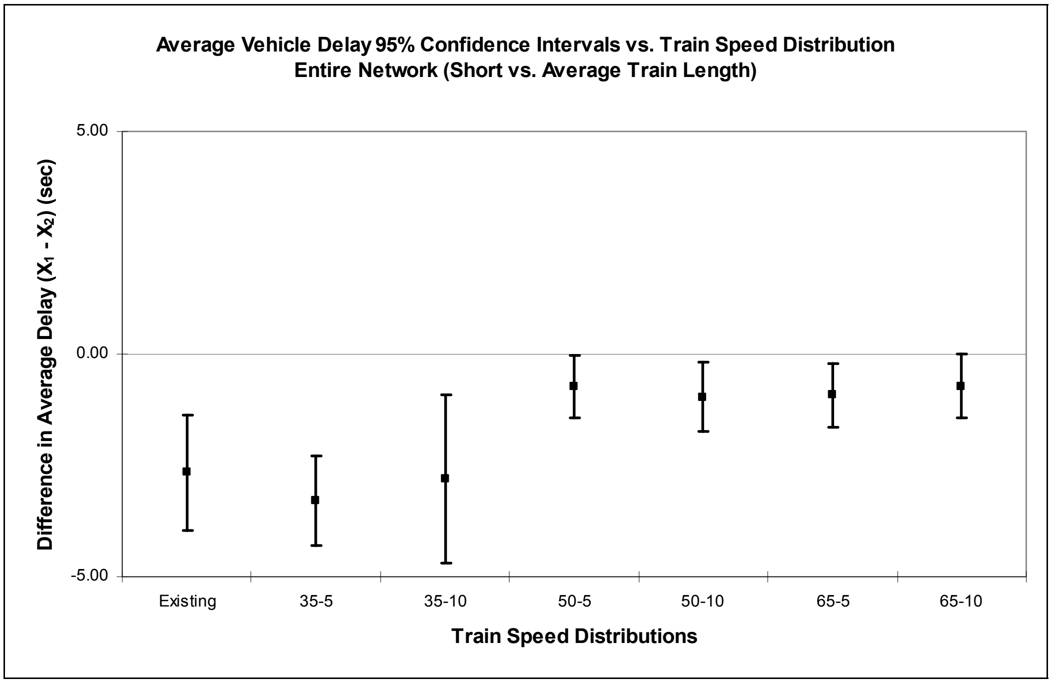

Figure C6. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions
(Entire Network, Short vs. Average Train Length)

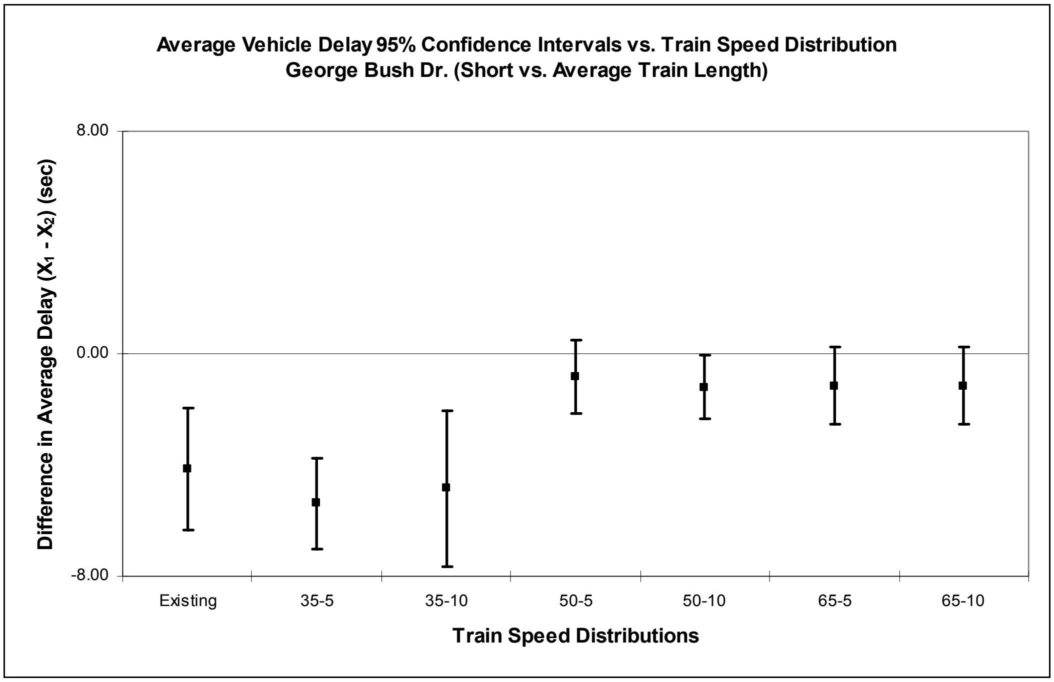

Figure C7. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions
(George Bush Dr., Short vs. Average Train Length)

Figure C8. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions (Entire Network, Average vs. Long Train Length)

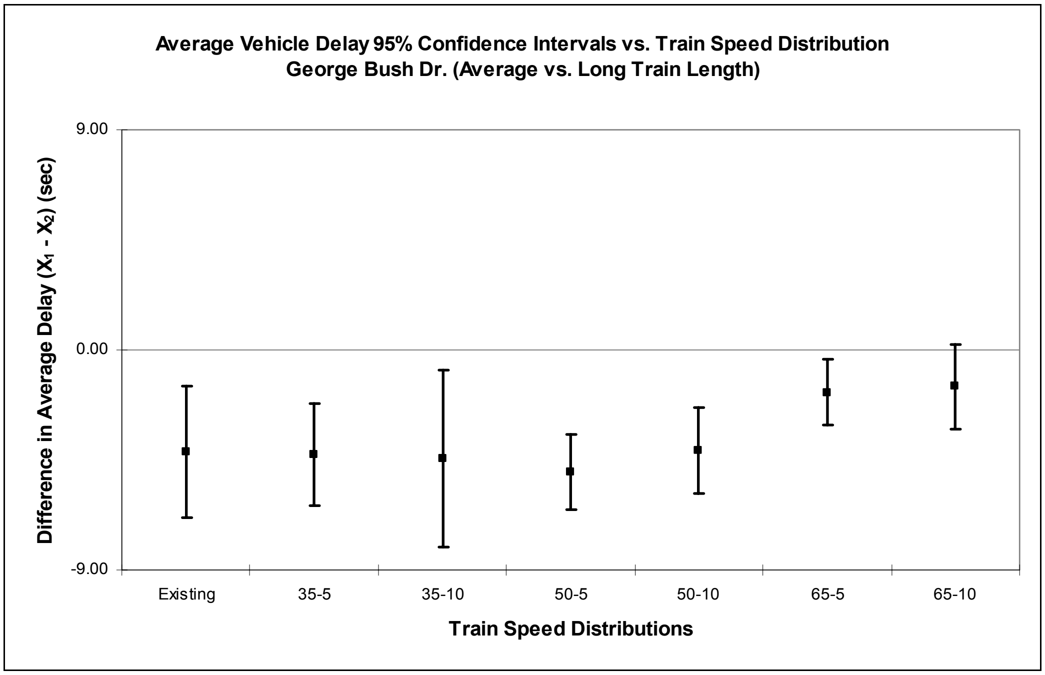

Figure C9. 95% Confidence Intervals on $\mu_1 - \mu_2$ for All Distributions (George Bush Dr., Average vs. Long Train Length)

APPENDIX D

PEDESTRIAN CUTOFF DATA

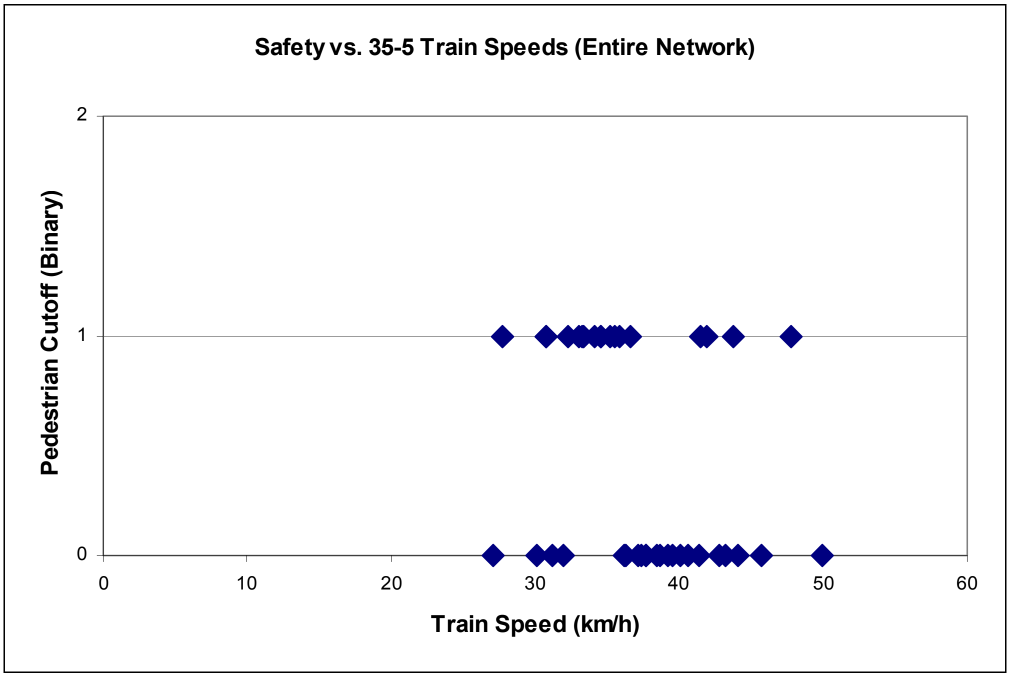

Figure D1. Pedestrian Cutoffs vs. Train Speed for the 35-5 Train Speed Distribution

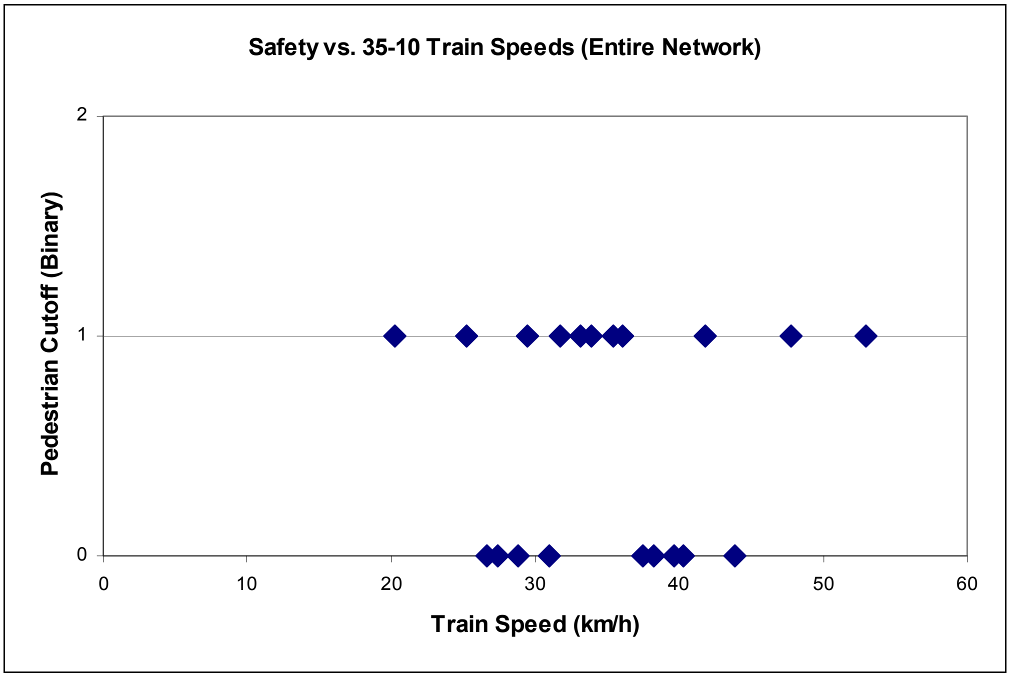

Figure D2. Pedestrian Cutoffs vs. Train Speed for the 35-10 Train Speed Distribution

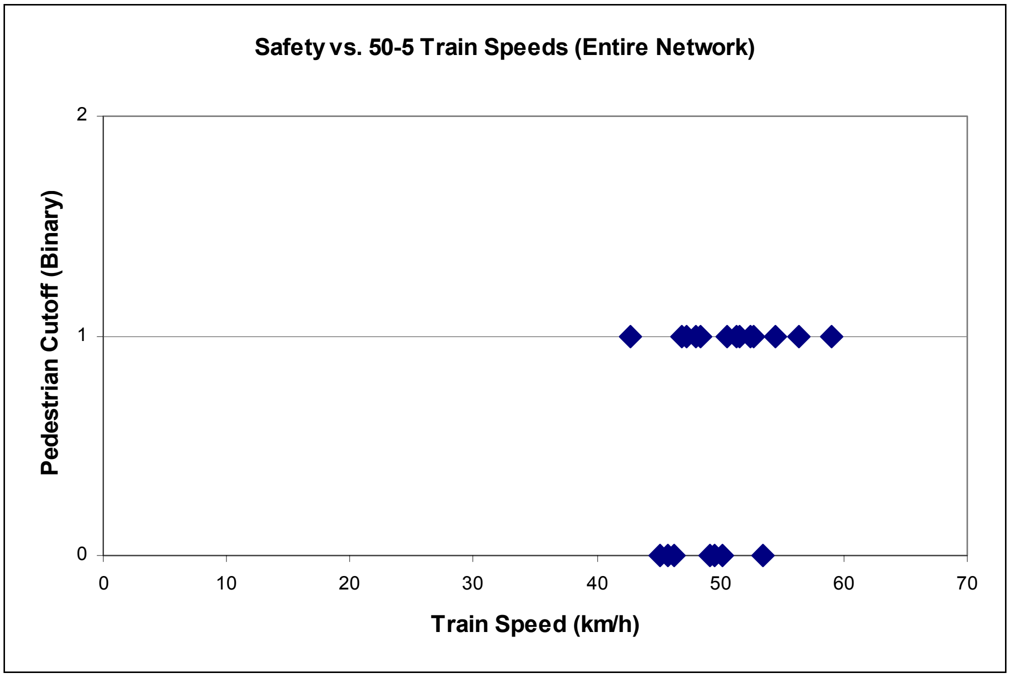

Figure D3. Pedestrian Cutoffs vs. Train Speed for the 50-5 Train Speed Distribution

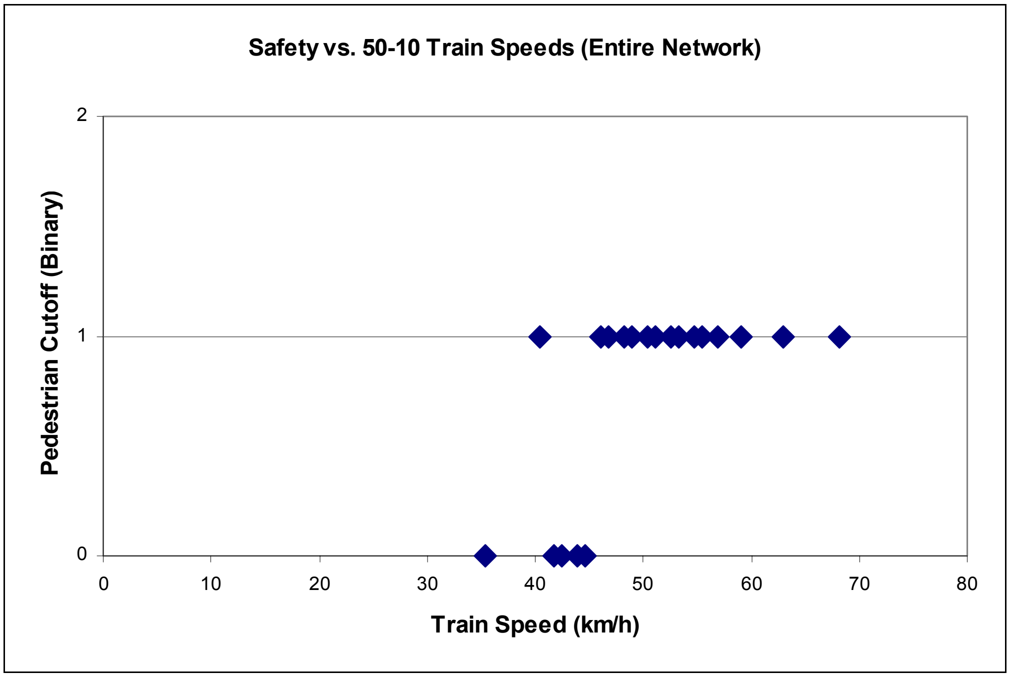

Figure D4. Pedestrian Cutoffs vs. Train Speed for the 50-10 Train Speed Distribution

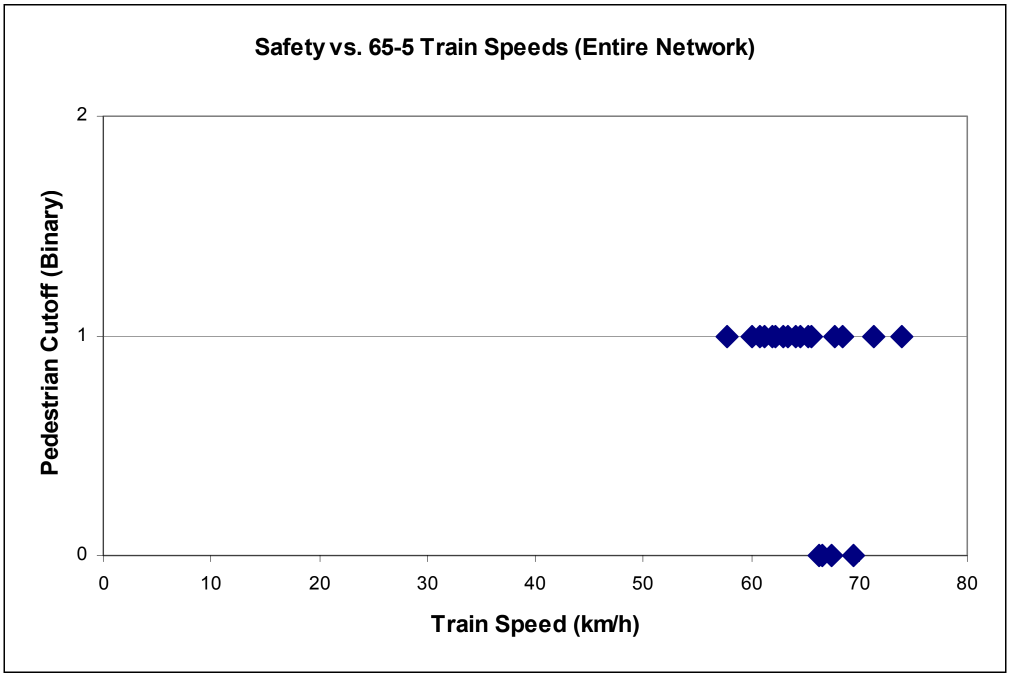

Figure D5. Pedestrian Cutoffs vs. Train Speed for the 65-5 Train Speed Distribution

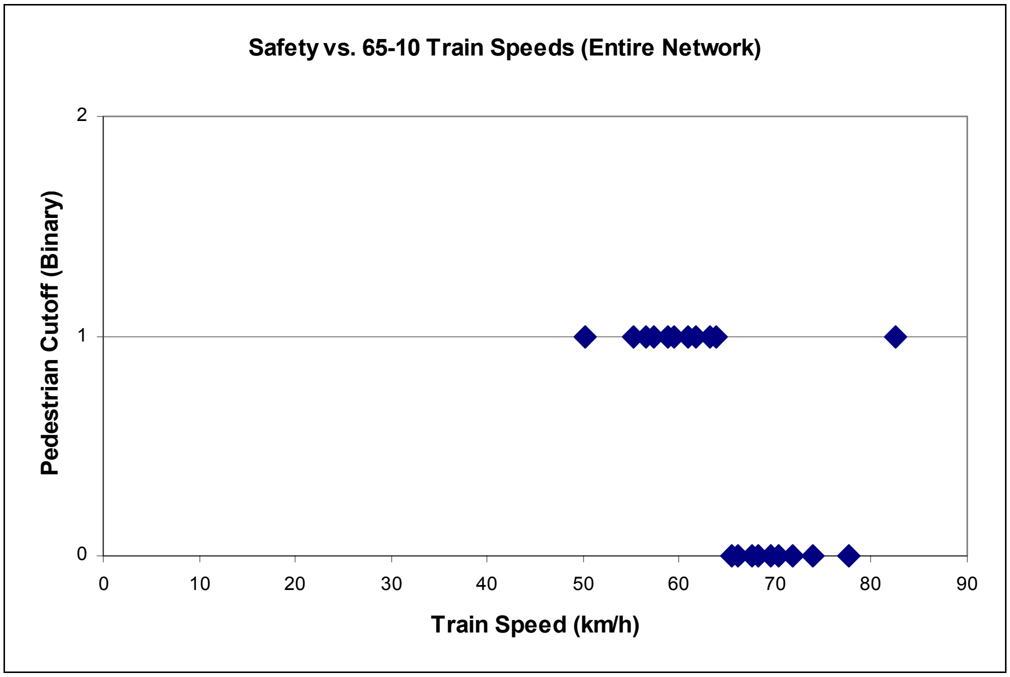

Figure D6. Pedestrian Cutoffs vs. Train Speed for the 65-10 Train Speed Distribution

APPENDIX E

EMISSIONS PLOTS

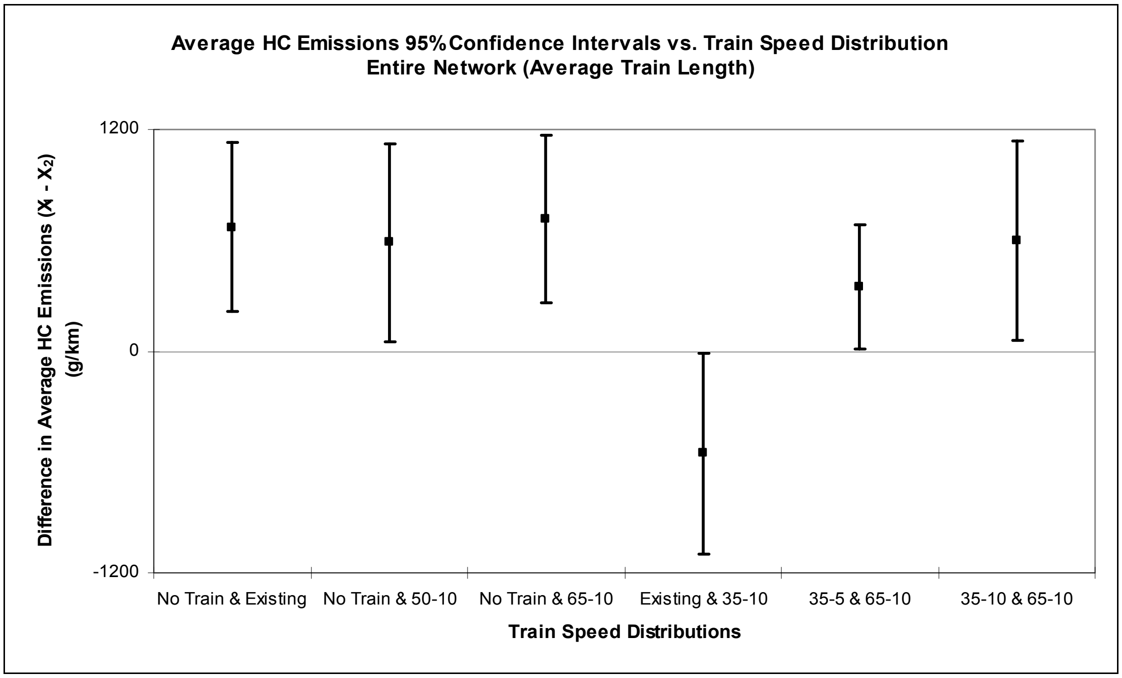

Figure E1. 95% Confidence Intervals on $\mu_1 - \mu_2$ for HC Emissions

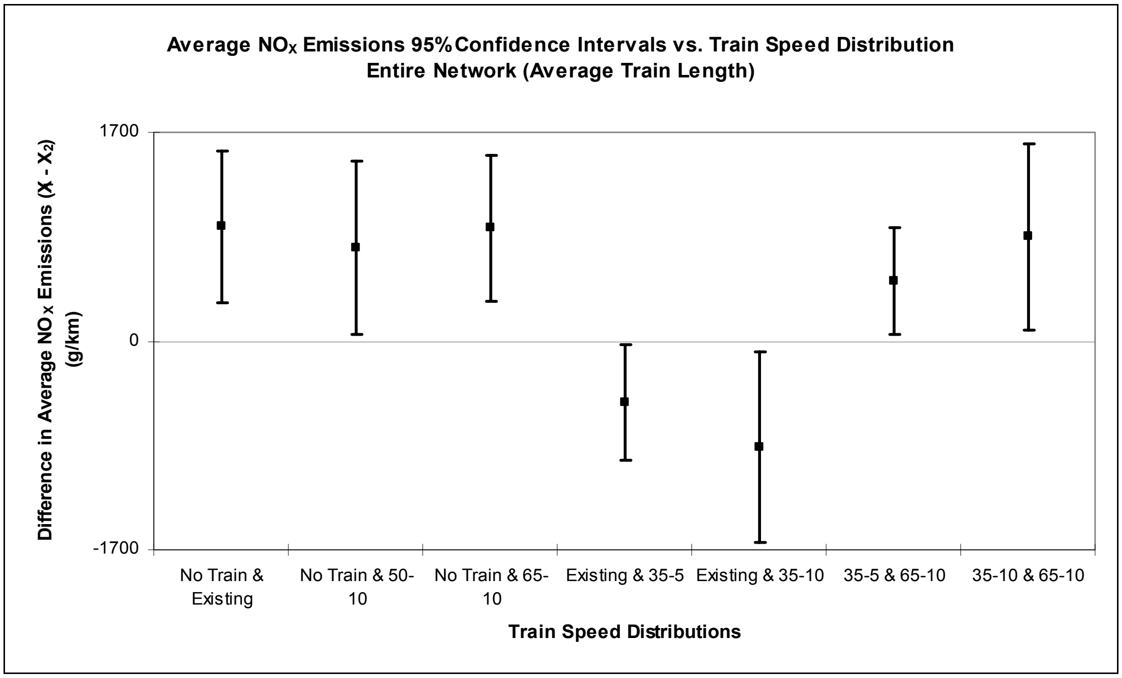

Figure E2. 95% Confidence Intervals on $\mu_1 - \mu_2$ for NO_X Emissions

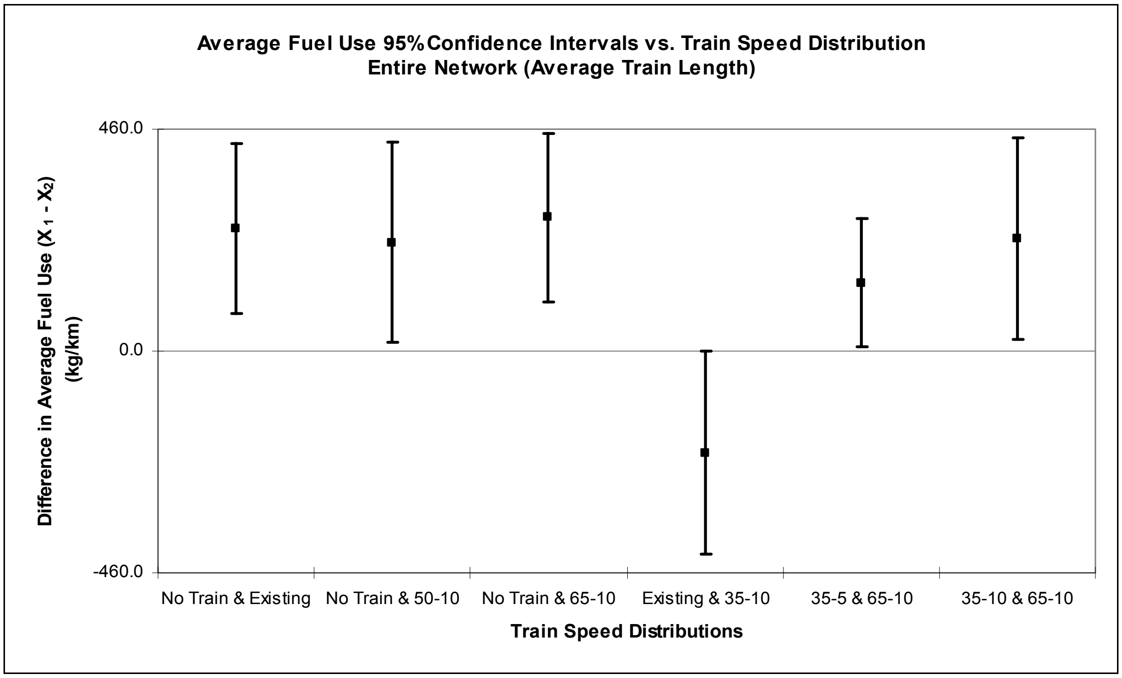

Figure E3. 95% Confidence Intervals on $\mu_1 - \mu_2$ for Fuel Use

VITA

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