

# A MODELING FRAMEWORK AND CASE STUDY EVALUATION OF WEIGH STATION OPERATIONS

by:

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## ABSTRACT

The paper presents a methodology for evaluating weigh station operations. The methodology was used to evaluate operations at the Stephens City Weigh Station in Virginia for demonstration purposes. The model uses WIM screening accuracy, calibration, and demand as inputs with enforcement and delay measures as outputs. The methodology combines a Monte Carlo simulation for computing truck volume distribution between static scale and bypass lanes and the INTEGRATION microscopic simulation model for the evaluation of weigh station operations. The study demonstrated the adequacy of the Monte Carlo type of simulation for computing truck volume distribution between static scale and bypass lanes. Furthermore, the study demonstrated the efficiency of the INTEGRATION software for modeling of weigh station operations. By using the results of the model, decision-makers can determine enforcement and delay goals for the weigh-in-motion system being analyzed to develop a compromise between these two conflicting objectives.

**Key words:** Weigh-in-Motion (WIM), Weigh station operations, trucks.

## 1. INTRODUCTION

### 1.1 Background

The design of pavement and bridge structures requires accurate predictions of vehicle axle loads and vehicle classifications. Vehicle gross weight and axle weight restrictions have been imposed in order to ensure that vehicles do not exceed the design criteria of these roadway and bridge infrastructures. In order to ensure that truck weights are within allowable limits, numerous weigh stations have been constructed along major highways in the US. At these weigh stations, several technologies are available for screening trucks, including Weigh-in-Motion (WIM) technologies. These WIM systems, which allow for screening of trucks at high speeds, reduce delays that would otherwise have been incurred by trucks weighed on static scales. In a typical WIM system, trucks that are substantially less than the legal weight limit are allowed to bypass a static scale while trucks with weights that are exceeding the limit or within the margin error of a WIM system are required to be weighed more accurately on a static scale. Subsequently, the accuracy of these WIM technologies plays an important role in governing the number of trucks that enter the static scale. Consequently, the delay incurred at a weigh station is a function of the accuracy of the WIM system, the threshold of margin error, the truck arrival rate and distribution, and the weight distribution of these arrivals.

The American Society for Testing and Materials (ASTM) standards classify WIM systems into four types depending on the intended applications of the systems (ASTM, 1997). Type I and II, which have less accuracy, are designed for collecting data at high speeds on multi-lane roadways. Alternatively, Type III and IV are designed for weight enforcement at weigh stations and thus require a higher level of accuracy. Type III allow vehicles to travel at fairly high speeds (24 to 80 km/h) while Type IV are designed for low speeds (0 to 16 km/h).

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## 1.2 Paper Objectives

The objectives of this paper are two-fold. First, the paper develops a framework for evaluating the impact of truck screening accuracy on the traffic operations of a weigh station. Second, the paper applies the proposed framework to a case study and presents the findings of this case study.

## 1.3 Research Approach

The framework that is developed in this research effort involves two tasks. The first task establishes four truck volumes, namely the number of violator trucks that are sent to the static scale, the number of non-violator trucks that are sent to the static scale, the number of violator trucks that are diverted to the bypass lane, and the number of non-violator trucks that are diverted to the bypass lane. These volumes are estimated using a Monte Carlo simulation approach that requires five input parameters, namely the truck axle weight distribution, the level of WIM calibration, the WIM accuracy, the user defined axle and total weight threshold, and the truck arrival rate. The second task involves simulating the weigh station operations using the assigned four truck volumes. The simulation is conducted using the INTEGRATION microscopic traffic assignment and simulation model.

The validity of the proposed framework is demonstrated utilizing the Stephens City weigh station on I-81 as a case study application. Specifically, the truck axle weight distribution at the Stephens City weigh station for an entire week was collected. Furthermore, the calibration and accuracy of the WIM screening system was established by comparing total truck weights on the WIM and static scales. In addition, the number of violating and non-violating trucks that were sent to the static scale was recorded in the field as a means to validate the proposed methodology. Assuming, a normally distributed axle weight error, the distribution of the violating and non-violating trucks at the static scale were estimated using the proposed framework and compared to the field data in order to demonstrate the validity of the proposed framework. Subsequently, the case study utilized geometric, travel time, volume, and speed data to calibrate the INTEGRATION simulation model to the specific operation of the weigh station operation as well as to predict the weigh station operation for traffic scenarios that were not necessarily observed in the field. A total of 15 data sets at 15-minute intervals were utilized to calibrate the simulated weigh station operation to field conditions. Subsequently, a sensitivity analysis of WIM accuracy (5 levels), WIM thresholds (3 levels), and traffic demand (8 levels) were simulated using 10 random seeds resulting in a total of 1200 simulation scenarios. The average results across the 10 random number seeds was utilized for comparison purposes.

## 1.4 Paper Layout

The paper first describes the case study of the Stephens City weigh station including the site description, configuration, operations, and data collection. Next, the procedure used for model construction and calibration is discussed. Subsequently, the procedure used for system volume distribution is discussed. A sensitivity analysis is then performed with two different geometric layouts as well as degrees of accuracy, calibration, and demand followed by conclusions and recommendations for further research.

## 2. PROPOSED FRAMEWORK

As was mentioned earlier the proposed framework is composed of two tasks. The first task involves estimating the truck volume distribution between the static scale and bypass lanes. These volumes are further classified into violating and non-violating trucks depending on whether a truck exceeds the legal axle or gross weight limit. The second task utilizes the truck volume breakdown as input to a microscopic simulation model to compute the delay associated with the study scenario. This section describes the proposed framework prior to describing its application to the Stephens City case study.

The framework utilizes four vehicle classes that include: static scale violators, static scale non-violators, bypass violators, and bypass non-violators. Static scale violators are trucks that exceed either axle or gross weight limits and are instructed to enter the static scale. Static scale non-violators are vehicles that although they do not exceed either axle or gross

weight limits are erroneously diverted to the static scale by the WIM screening system. Bypass violators are vehicles that do violate state weight limits but are not directed to the static scale. These vehicles are the vehicles that are missed by the WIM screening system. Bypass non-violators are vehicles that do not exceed state weight limits that travel along the bypass lane and are not instructed to enter the static scale lane.

In an ideal world, the WIM screening system would be 100 percent accurate to ensure that only static scale violators and bypass non-violators travel through the weigh station. However, due to WIM scale inaccuracies and/or calibration deficiencies, some trucks that do not exceed weight limits are sent to the static scale and are thus classified as static scale non-violators. Additionally, some trucks that exceed weight limits are sent to the bypass lane and are thus classified as bypass violators.

From an enforcement perspective all violators should be sent to the static scale. Alternatively, from an operational perspective all non-violators should be sent to the bypass lane. Unfortunately, unless the WIM screening system is 100 percent accurate with perfect calibration, both enforcement and delay goals cannot be achieved. Therefore, a balance must be reached.

## **2.1 Estimating Truck Volume Distribution between Static and By-pass Lanes**

In order to accurately simulate a WIM facility, it is paramount that the truck volume assigned to the bypass and static scale lanes be estimated fairly precisely. The proposed methodology considers a normally distributed WIM axle weight error to compute the probability that a truck will be directed to either the static scale or bypass lane. Consequently, a first step in developing the framework is to investigate the validity of the normality assumption in the WIM error.

The proposed framework considers two levels of analyses in computing the distribution of trucks between the static and bypass lanes. In the first level, only gross vehicle weights are utilized to estimate truck volume distributions. Specifically, using the probability density function, the probability that a weight exceeds the threshold is computed for each truck. While this analysis is less accurate than the second analysis it is simpler to apply and does provide a benchmark for comparison purposes. Alternatively, the second level of analysis generates individual axle weights using a Monte Carlo type of simulation. The axle weights are then compared against axle thresholds to determine if a truck should be diverted to the bypass lane. The resulting difference in truck volume distribution between the two levels of analyses demonstrates the benefits of considering axle and gross truck weights versus only considering gross truck weights in distributing trucks between the static scale and bypass lanes.

### **2.1.1 Normality Distribution of WIM Error Function**

The WIM axle weight can be assumed to be a normally distributed random variable that is dependent on the accuracy of the WIM technology under consideration. In the case of a fully calibrated WIM system, the mean WIM axle weight is equal to the mean static scale weight (assumed to be the true weight). Alternatively, in the case of an uncalibrated WIM scale, the axle weight measurement is comprised of a systematic bias between the WIM and static scale axle weight in addition to a random error that is a function of the accuracy of the WIM technology, as illustrated in Figure 1. Figure 1 clearly illustrates the difference between the accuracy and calibration of a WIM scale. Specifically, the level of accuracy, as was mentioned earlier, is characterized by the width of the normal distribution whereas the offset between the WIM and static scale is a measure of the level of calibration of the WIM scale.

An analysis of the WIM gross weight accuracy was conducted as part of this study by comparing static scale and WIM gross truck weights. Specifically, a total of 491 northbound and 152 southbound static and WIM truck weights were compared. The distinction between directions was important in order to isolate the level of calibration for each of the WIM scales. While the mean WIM (northbound 34,129kg and southbound 33,762kg) and mean static scale (northbound 33,808kg and southbound 32,732kg) weights were not identical for both scales, a paired t-test assuming unequal variances between WIM and static scale measurements failed to reveal any statistical differences at the 90 percent confidence level. Consequently, it was concluded that both the northbound and southbound WIM scales were sufficiently calibrated.

In addition, the error density function was found to be consistent with a normal density function, as illustrated in Figure 2. Specifically, a Chi-squared goodness-of-fit test revealed no statistical difference between the error frequency and the normal distribution density function, at a 90 percent confidence level. Consequently, the assumption of a normally distributed WIM error function appears to be reasonable.

### 2.1.2 Probability Formulation

The proposed methodology employs a normal density function to estimate the probability that a truck gross weight will exceed the allowable weight limits. The inputs to the model include the truck gross weight distribution, the accuracy of the WIM system, any calibration bias in WIM weight measurements, and the user-defined weight threshold. This section demonstrates the application of the proposed methodology to the Stephens City weigh station trucks in an attempt to demonstrate the validity of the approach.

Specifically, using observed truck volume arrivals at the Stephens City weigh station, the normal error, and specified WIM thresholds the breakdown in truck volume between the static and bypass lanes was estimated. The estimated truck volume distribution was then compared to the field observed truck volume distribution in order to validate the proposed methodology. The truck volume and weight distribution were obtained from the WIM system software, which included a total of 33,712 trucks for the duration of the field evaluation, as demonstrated in Table 1. It is important to note that WIM weights were used in the analysis instead of static scale weights because static weights were only available for trucks that traveled in the static scale lane and not all trucks that arrived at the weigh station. The user specified weight threshold was set by the weigh station operators to be 0.96 for the entire field analysis. Comparing the WIM and static scale gross weights revealed a gross weight error function coefficient of variation (COV) of 5 percent and a minor systematic bias that was not statistically significant of 1270 kilograms (2800 pounds).

In applying the simple approach for estimating the truck volume distribution, the truck demand weight distribution was characterized, as summarized in Table 1. For each weight bin the bin mid-point was utilized as an estimate of the truck gross weight and used to compute the probability a truck exceeded the gross weight threshold. The frequency of trucks diverted to the static scale and the total number of trucks that would be diverted to the static scale was then computed, as demonstrated in Table 1.

Field observation of the weigh station operation revealed that a total of 2,316 of the 33,712 truck arrivals were diverted to the static scale (7 percent of total demand). Using the distribution of truck gross weights, the user specified weight threshold, and considering a normally distributed error function with a COV of 5 percent, the number of trucks that were estimated to be diverted to the static scales were computed to be 4,101 trucks (12 percent of the total demand), as demonstrated in Table 1. The relatively high error (77 percent error) between the estimated and observed flows clearly demonstrates that only considering gross truck weights is insufficient for the modeling of weigh station operations.

### 2.1.3 Monte Carlo Simulation

Step two was to establish a procedure that would consider both axle and gross weights in estimating the truck volume distribution between the static and bypass lanes. A truck distribution using a single day's worth of data on June 13, 2001 for a total of 6,147 trucks was utilized. The axle data were utilized using a Monte Carlo simulation to generate random axle weights that followed a desired axle accuracy. The procedure was repeated for every axle on every truck. If any of the axle or the gross weight laws exceeded the legal limits, the truck was sent in to the static scale. Since the procedure seemed reasonable compared to field conditions, it was used for various alternate scenarios. To be sure that the various random numbers generated didn't have a large effect on the trucks sent calculated to enter the static scale, 10 trials were run to see how closely the values correlated as shown in Figure 3. As shown, all 10 trials produced results of about 15% of the trucks sent to the static scale, which was within 1 percent of field observed conditions for the specific day. Therefore, it could be concluded that although the random numbers were changed, the percentage of trucks sent to the static scale remained relatively constant and was within 1 percent of field observations.

## 2.2 Evaluating Weigh Station Operations

Having computed the distribution of truck demand between bypass and static lanes, the framework utilizes the INTEGRATION simulation software (Van Aerde and Associates, 2002a and b) to evaluate the operations of the weigh station. The INTEGRATION model, which was developed over the past decade, has not only been validated against standard traffic flow theory (Rakha and Van Aerde, 1996; Rakha and Crowther, 2002), but has also been applied to real-life problems (Rakha *et al.*, 1998; Rakha *et al.*, 2000). This section provides a brief description of the INTEGRATION model in order to provide the reader with a basic understanding of the traffic-modeling component of the proposed framework.

The INTEGRATION model is a microscopic model that tracks individual vehicle movements at a deci-second level of resolution from the point it enters the network until it finally departs the network. Vehicle movement is captured by modeling car-following, lane-changing, and gap acceptance logic. Vehicle accelerations are constrained by the vehicle dynamics (Rakha and Ahn, 2002). The model estimates vehicle delay, stops, fuel consumption, and emissions on a second-by-second basis. Measures of Effectiveness (MOEs) can be estimated for a specific roadway section or for an entire trip. These MOEs can be further classified into five vehicle classes, as will be demonstrated later.

The execution of the INTEGRATION model requires a calibration of traffic demand and supply parameters. The calibration of traffic demand requires generating an Origin-Destination (O-D) demand while the calibration of traffic supply parameters entails selecting roadway car-following parameters that are reflective of weigh station operations.

## 3. CASE STUDY DESCRIPTION

### 3.1 Site Description

The Stephens City weigh station is located on Interstate 81 in Virginia, approximately 32 kilometers (20 miles) south of the West Virginia border. It is the first weigh station in the state for southbound traffic and the second weigh station for northbound traffic along Interstate 81. Both the Stevens City weigh station and Troutville weigh station, located approximately 240 kilometers (150 miles) south of the Stevens City weigh station on Interstate 81, use WIM screening technology off the mainline on ramps to increase enforcement and reduce delay at the weigh stations. Before the WIM systems were installed, trucks would enter the weigh station and once the queue spilled back onto the highway, bypass lights would be activated allowing the truck driver to bypass the weigh station. After the queue dissipated, trucks were allowed to enter the scale. There were two major problems with the older method. First, enforcement was difficult because many trucks were able to bypass the scales. Second, trucks running empty and below the legal limits were stopped and would experience unnecessary delay.

### 3.2 Site Configuration

The Stephens City weigh station included a scale house adjacent to the southbound lanes on Interstate 81 with static scales on both northbound and southbound lanes as well as a WIM scale screening system, as illustrated in Figure 4. The management of the weigh station operations was achieved visually and with the aid of a computer system. The Virginia Department of Motor Vehicles (DMV) managed the weigh station operations while the Virginia State Police enforced the state laws. Trucks were required to enter the station by leaving the highway through a deceleration lane. Subsequently, the truck driver was instructed, through the use of signs, to maintain a speed of 68 km/h (40 mph) and a minimum distance spacing of 30.5 meters (100 feet) from the preceding truck before traveling over the WIM scale. Trucks then traveled over the WIM scale in which axle configurations, axle weights, and gross vehicle weights were determined. A safety factor threshold was set by the weigh station operator for the screening of trucks. Generally, the threshold was set at 96 percent for the Stevens City weigh station. Consequently, a truck that weighed 96 percent or higher of the gross weight limit or the axle weight limit was notified through traffic signals to enter the static scale lane to be weighed on the static scale. Additionally, if the truck did not pass over the sensors completely, or other abnormalities were detected, the truck was directed to the static scale lane. Otherwise, the truck was allowed to use the bypass lane in order to bypass the scales (still maintaining a 68 km/h (40 mph) speed limit). An audio alert was sounded if a trucker took the bypass lane

when instructed to use the static scale lane and a red traffic signal was also activated in the bypass lane to stop the vehicle. In addition, the tracking system consisting of loop detectors informed the weigh station operator of any trucks that violated the weigh station procedures.

### 3.3 Station Operations

The Virginia state law specifies the maximum weight limitations for various configurations of trucks. In general, a truck must not weigh more than 36,290 kilograms (80,000 lb) or 9,072 kilograms (20,000 lb) on any single axle. Tandem axles are allowed to carry 15,420 kilograms (34,000 lb) total on both axles. If a truck that is weighed on the static scale is found to exceed the legal limits, the truck is sent to the parking lot and must enter the scale house to pay the necessary overweight fine.

In the case of the Stevens City weigh station operation at the time of the study, northbound traffic drivers had to walk through a tunnel under the interstate in order to reach the scale house. If their truck load could not be reduced to the legal limits, in cases such as the hauling of large construction equipment, permits were obtained from the Virginia Department of Transportation (VDOT). Once at the static scale, the driver was instructed to enter the scale house (southbound traffic) or an information building (northbound traffic) in order to show the permit to the weigh station staff. Random inspections were also performed by the Virginia State Police in which a truck driver was instructed to pull over an inspection pit and the truck was then inspected to ensure that the truck was properly equipped. Once the truck was ready to leave the station, the driver pulled out of the parking lot and into the static scale lane to exit. The bypass lane and static scale lane then merged together and the truck entered the acceleration lane in order to enter onto Interstate 81.

### 3.4 Data Collection

Geometric data were obtained by measuring the length of the deceleration lane, the approach to the WIM scale, static scale lane, bypass lane, the merge area, and the acceleration lane back onto the freeway. In addition, arrival data were obtained from the WIM system using software developed by the supplier, International Road Dynamics. Accuracy and delay data were collected in the southbound direction on Monday, May 21, 2001 and also in the northbound direction on Wednesday, Friday, and Saturday on June 13, 15, and 16, 2001 respectively. Service time data were taken in both directions on Tuesday, May 22, 2001.

WIM accuracy was quantified by recording WIM gross weights for each truck that entered the static scale and comparing the WIM weights to the static scale gross weights. Individual axle weights were not recorded in order to disrupt the natural operation of the weigh station because the time required to perform such a task would not allow the weigh station to operate under a normal state, as the scale operator would be forced to wait a few seconds for the data to be recorded. The analytical procedure developed by Rakha *et al.* (2003) to estimate axle weight accuracies from gross vehicle accuracies was utilized to generate the WIM scale axle accuracy.

System time data were recorded by determining the time required by trucks to travel from the point where the bypass and static scale lanes diverged to the point where the two lanes merged. Video cameras were set on each of the points from inside the weigh station, and later the tapes were viewed while recording the company name or other distinguishing characteristics of the truck in order to determine the delay incurred by each truck. Service times at the static scale were obtained by videotaping the static scale and calculating the amount of time spent at the static scale. The service time was further classified for violating and non-violating trucks.

## 4. MODEL CONSTRUCTION AND CALIBRATION

This section describes how the input data to the INTEGRATION software were generated and how the INTEGRATION software was calibrated to field conditions.

## 4.1 Model Construction

The roadway geometric and truck demand data served as inputs to the INTEGRATION software. Figure 5 illustrates the link-node network structure that was utilized to model the weigh station operation. Specifically, the simulation model was coded to use node 1 as the origin node and node 2 as the destination node. Links 1, 9, and 10 were coded freeway links while link 2 was coded as the deceleration lane off of Interstate 81 leading into the WIM station and link 3 as the roadway leading up to the point where the trucks would be sent to the static scale or to the bypass lane. If the truck was sent to the bypass lane, link 4 was used; otherwise links 5 and 6 were utilized. Node 12 was coded as the location of the static scale by coding a bus stop that forced trucks to stop for a user-specified service time. Next, the vehicles merged back together on link 7 and used link 8 to accelerate back to freeway speeds.

Table 2 provides a summary of the link characteristics used in the simulation. A saturation flow rate of 1800 vehicles per hour was assumed for all links as well as a jam density of 125 vehicles per kilometer per lane for all links. However, a vehicle length equivalency factor of 4 was utilized in order to capture the longer length of trucks, which would result in a reduction in the jam density by a factor of 4. A free-speed of 105 km/h (65 mi/h) was used on links 2 and 8 to match the freeway speed limit, while the speed limit was set at 65 km/h (40 mi/h) on links 3, 4, and 7 to match the speed limit of the weigh station. Likewise, a speed-at-capacity was set at 80 percent of the free-speed (on links 2 and 8) and 50 percent of the WIM facility speed (on link numbers 3, 4, and 7) in order to account for the lower geometric design standards on the weigh station roadways (Rakha and Crowther, 2002). The free-speed, speed-at-capacity, and jam density for static scale links 5 and 6 were determined after comparing the simulation model to the known system times as will be discussed in calibration section.

In order to simulate the truck stopping at the static scale for trucks sent to links 5 and 6, a bus stop file was added to the master control file. Using the file, the simulation added a bus stop at the end of link 5 in which a non-violating truck (meaning that the truck did not exceed any weight limit) would experience a 10-second stop with a coefficient of variation of 0.00 and that a violating truck would experience a 45-second stop with a coefficient of variation of 0.42. The values for average service times and the coefficients of variation were obtained by observing field data.

## 4.2 Model Calibration

The system time data collected in the field were utilized to calibrate the model more accurately to field conditions. Specifically, 15 truck demand data for 15-minute intervals of field data over the three-day analysis period were used to calibrate the model. The 15 periods were selected to represent varying truck arrival rates in order to obtain a wide spectrum of scenarios. Link characteristics for the static scale lane were simulated until the simulated system time matched the field observed system times. Specifically, a free-speed of 11.5 km/h and a speed-at-capacity of 7.5 km/h along links 5 and 6 provided the best match between simulated and field data. Figure 6 illustrates the actual observed system time data along with the upper and lower bound 95 percent confidence limits together with the final simulation system times. The figure clearly demonstrates consistency between simulated and field observed conditions.

## 5. SENSITIVITY ANALYSIS

As was mentioned earlier, a statistical and a Monte Carlo simulation approach were utilized to generate the truck volume distribution at the weigh station, which in turn served as input to the INTEGRATION model. Subsequently, a sensitivity analysis of various factors was conducted as follows:

- Truck demand: included 100, 200, 300, 400, 500, 600, 700, and 800 veh/h (8 levels)
- WIM accuracy: WIM axle weight COVs of 0, 5, 10, 15, and 20 percent (5 levels)
- Calibration errors: calibration errors of -10, -5, 0, 5, and 10 percent of the mean weight (5 levels)
- Threshold values: threshold values of 0.90, 0.92, 0.94, 0.96, 0.98, and 1.00 (6 levels)

The entire sensitivity analysis was comprised of 1200 scenarios (8x5x5x6). The WIM accuracy of 5 percent was used to simulate a load cell system, while the 10 percent accuracy level was used to simulate a bending plate system, and the 15 percent accuracy level was used to simulate a piezoelectric system.

## 5.1 System Volume Distributions

The first sensitivity analysis examined the variation in truck volume distribution (static violators, static non-violators, bypass violators, and bypass non-violators) as a function of the WIM screening system accuracy, calibration, and the user-specified weight threshold factor. Given the multi-dimensional aspect of the problem, the results are displayed by first assuming a perfectly calibrated WIM scale and analyzing the effect of the WIM scale accuracy and weight threshold on the truck volume distribution. Subsequently, the threshold is fixed at 1.0 and the sensitivity of truck volume distribution as a function of the WIM scale accuracy and level of calibration is studied.

### 5.1.1 System Volume Distributions using Gross Weights

The first analysis of truck volume distribution involved studying only gross weight violations. Results of the sensitivity analysis of gross weights assuming a perfectly calibrated WIM scale (WIM and static scale means are identical) are illustrated in Figure 7. Figure 7 demonstrates that the number of violators that are diverted to the static scale increases as the accuracy of the WIM scale increases for a specific weight threshold. This increase in violators that are diverted to the static scale as the WIM scale accuracy increases is attributed to the higher probability of the WIM system to correctly screen a violating truck. Furthermore, as the accuracy of the WIM scale decreases the use of a lower threshold results in more violating trucks being diverted to the static scale. Consequently, enhancing enforcement can be achieved by either increasing the accuracy of the WIM screening system, by decreasing the weight threshold, or by a combination of both. In the case of a perfectly accurate WIM scale the use of a weight threshold will have no impact on the level of enforcement because all violators will be correctly screened regardless of the weight threshold.

In the lower-left graph (Figure 7), the variation in the number of violators that are missed by the WIM screening system (use the bypass lane) as a function of the WIM scale accuracy and weight threshold is illustrated. The figure demonstrates that as the accuracy of the WIM scale increases, the number of violating trucks that are missed is reduced. In addition, an increase in the weight threshold, unless the WIM scale is perfectly accurate, results in a lower enforcement rate. Alternatively, the use of a perfectly accurate WIM screening scale results in a 100 percent level of enforcement (no violating trucks using the bypass lane). It is also important to note that the sum of violators across the static scale and bypass lanes remain constant regardless of the WIM scale accuracy or the weight threshold.

The variation in number non-violators that are required to enter the static scale as a function of the WIM scale accuracy and weight threshold is illustrated in the upper-right graph of Figure 7. The figure demonstrates that a high percentage of the truck volume is erroneously screened as violators (approximately 25 percent of the demand for a threshold of 0.90). This high false alarm rate results in significant delays to the non-violating trucks that are sent to the static scales in addition to more significant delays to the violating trucks at the static scale. In addition, Figure 7 demonstrates that for a specific weight threshold as the accuracy of the WIM scale increases, the number of non-violators that are erroneously tagged as violators decreases. Additionally, as the threshold increases, less non-violators were sent to the static scale.

In the case of a weight threshold of 1.0, as the system accuracy decreases, the impact of the WIM scale level of calibration on the system's detection rate becomes marginal, as illustrated in Figure 8. If the system is under-calibrated (vehicle weights are under-estimated), fewer violators are sent to the static scale. On the contrary, when the system is over-calibrated (vehicle weights are over-estimated), more violators are sent to the static scale. For a perfectly accurate WIM scale, if the calibration is perfect or over-calibrated, all violators are sent to the static scale.

The variation in the number of missed violators as a function of the level of WIM scale calibration, as illustrated in the lower-left graph of Figure 8, displays reversed trends. Specifically, an under-calibrated WIM scale results in more violators being sent to the bypass lane, while an over-saturated WIM scale results in less vehicles being sent to the bypass lane.

The upper-right graph of Figure 8 illustrates how the number of non-violators sent to the static scale vary as a function of the level of WIM scale calibration. Specifically, as the over-calibrated WIM scale exceeds 10 percent, the accuracy of the scale no longer has an influence on the number of non-violators and the values converge to just over 20 percent. Finally, in the case of a perfectly accurate WIM scale, no non-violators are sent to the static scale when the scale is under-calibrated or perfectly calibrated.

In the lower-right graph of Figure 8, the number of non-violators sent to the bypass lane is demonstrated that as the calibration of the WIM scale shifts to the right (over-calibrated), fewer trucks are sent to the bypass lane. Alternatively, as the WIM scale is under-calibrated, or perfectly calibrated, a 100 percent accurate scale sends 99.1 percent of the vehicles to the bypass lane.

The analysis can be used to determine the effects that a new system would have given current weigh station operations. If calibration procedures are standardized and the scale can be checked often to make sure that it is calibrated correctly, a weigh station operator can determine the optimum threshold with a given accuracy to achieve an optimum enforcement rate and to reduce the percentage of trucks experiencing unnecessary delay. Figure 9 demonstrates the variation in missed violators and percentage of non-violators that experience unnecessary delays versus the user-specified weight threshold and WIM scale accuracy.

The data obtained in the sensitivity analysis are used to create charts that a decision maker can use for determining system characteristics necessary to meet enforcement and delay objectives. The top graph in Figure 9 can be used to determine the optimum threshold to achieve enforcement rate goals. For example, if the Department of Motor Vehicles (DMV) wanted to have an enforcement goal of capturing at least 95 percent of overweight trucks at the static scale, a scale accurate to a degree of  $\pm 5$  percent with a threshold of less than 0.94 would be required. The bottom graph can then be used to determine the corresponding percentage of non-violators that would be delayed at the static scale. If the scale with accuracy  $\pm 5$  percent were chosen with a threshold of 0.94, then 15 percent of non-violating trucks would experience unnecessary delays.

Alternatively, if the DMV wanted to reduce delays experienced by non-violating vehicles, a goal of only 5 percent of non-violators being stopped at the static scale might be chosen. The bottom graph suggests that a scale with accuracy  $\pm 5$  percent could be chosen with a threshold of 1.0. Then, using the top graph, it can be stated that with the proposed system, approximately 25 percent of violators would be missed.

### 5.1.2 System Volume Distributions using Individual Axle Weights

The second analysis of truck volume distributions involved analyzing both gross and axle weight violations using a Monte Carlo simulation approach. In order to ensure that the randomness in the approach did not play a large role in the sensitivity analysis, the percentage trucks sent to the static was plotted as a function of the trial number, as illustrated in Figure 3. The figure clearly illustrates a relatively stable behavior with approximately 15 percent of the truck volume being sent to the static scale.

The sensitivity analysis results for a perfectly calibrated WIM scale demonstrate that as a trend, a more accurate WIM scale results in more violators being sent to the static scale, as illustrated in the upper-left graph of Figure 10. However, as the weight threshold increases, fewer violators are sent to the static scale. With perfect accuracy, about 2.0 percent of all truck arrivals are sent to the static scale. In the lower-left graph of Figure 10, the number of bypass violators with respect to threshold demonstrates that as the system accuracy is reduced, more violators are missed. If the WIM scale is completely accurate, no violators are sent to the bypass lane.

The upper-right and lower-right graphs of Figure 10 show that a more accurate system results in more non-violators being sent to the bypass lane. As the weight threshold is decreased, the number of static and bypass non-violators begin to converge whereas with a higher threshold, the accuracy of the system plays a large role in determining the number of non-violators sent to the static scale and bypass lanes. If the scale is completely accurate, there are no non-violators sent to the static scale lane.

The upper-left and lower-left graphs of Figure 11 show the effect of calibration on the number of static violators given a threshold of 1.00. Generally, as calibration is shifted from left to right, more violators are sent to the static scale and less

to the bypass lane. It is interesting to note that if calibration is perfect given a 1.0 threshold, the accuracy of the system does not play a role in the number of violators sent to each scale (except when accuracy is perfect). The effects of calibration are also not as large as the accuracy of the scale is reduced.

The upper-right and lower-right graphs of Figure 11 indicate that as calibration is shifted from left to right, more non-violators are sent to the static scale and less use the bypass lane. At higher magnitudes of calibration errors, the number of non-violators sent to the static scale and bypass lane begin to converge. As expected, the number of non-violators sent to the bypass increases as the WIM scale accuracy increases.

Figure 12 illustrates the variation in percentage violators missed and the percent of non-violators delayed given perfect calibration considering both axle and gross truck weights. This figure can be compared to Figure 8 when only gross weights were considered. It is interesting to note that although trends are estimated well in a Monte Carlo simulation, the randomness can be shown at low volumes of vehicles such as the violators compared to a much smoother trend when higher volumes of vehicles are considered, such as the non-violators. When considering axle weights in addition to gross weights, fewer violators are missed when compared to the gross weight scenario. However, slightly more non-violators are delayed at the static scale when axle weights are considered. The difference indicates that it is very important to analyze an axle weight distribution because analyzing only gross weights does not give a good estimate of the classification of each truck.

### 5.1.3 Gross versus Axle Weight Analysis

A comparison of the two analyses demonstrates that it is not appropriate to use gross weight distributions as a sole factor for estimating violators; instead an axle weight distribution is required. For example, the percentage of violators considering only gross weight violations results in approximately 0.9 percent violators while considering axle weights results in 2.0 percent violators (difference of over 50 percent). It should be noted that in general overall trends are very similar for both methodologies; however, the magnitude of the number of vehicles is much different between the two cases. The gross weight analysis is included to provide general trends in behavior. Furthermore, it is much easier in the field to collect data on gross weights as opposed to axle weights.

### 5.2 Expected Delay by Trucks

The delay experienced by trucks at the weigh station was estimated based on an O-D demand that was computed using a Monte Carlo simulation of truck distribution. Simulation was conducted for both the existing geometric alignment as well as a hypothetical mainline screening scenario. Table 3 and Table 4 summarize the delay in seconds by vehicle classification for the original scenario using a ramp sorting weigh-in-motion system. The results are also shown graphically in Figure 13 through Figure 20. It is important to note that the travel time of a non-violator along the static scale lane for a threshold of 1.00 on a perfectly accurate system is zero because no violating trucks are not be sent to the static scale.

As expected, when the weight threshold is increased, the average delay per truck decreases since fewer trucks are sent to the static scale. This difference is much more apparent at higher volumes. For example, at 100 vehicles per hour, a perfectly accurate scale results in a delay of 120 seconds per truck at a threshold of 1.00 and 141 seconds per truck at a threshold of 0.92 for a difference of only 21 seconds per truck. However, at 800 vehicles per hour, a perfectly accurate scale would result in a delay of 354 seconds per truck at a threshold of 1.00 and 487 seconds per truck at a threshold of 0.92 for a difference of 133 seconds per truck.

Additionally, as the accuracy of the WIM scale decreases more delay is incurred at the weigh station because more trucks are sent to the static scale versus the bypass lane. Specifically, at a demand of 100 veh/h, a perfectly accurate WIM scale results in an average travel time of 129 s/veh at a threshold of 0.96 whereas a  $\pm 20$  percent accurate scale results in an average travel time of 144 s/veh (difference of 15 seconds). Alternatively, a truck demand of 800 veh/h with a perfectly accurate WIM scale results in an average travel time of 385 s/veh at a threshold of 0.96 whereas a  $\pm 20$  percent accurate scale results in an average travel time of 485 s/veh (difference of 100 seconds). Similarly, differences in WIM accuracy result in travel time differences which are more significant at higher truck volumes.

The results presented can be utilized to evaluate the operation of a weigh station operation. For example, for a truck volume of 500 trucks per hour the choice between the use of a WIM screening scale with  $\pm 15$  percent accuracy versus a  $\pm 5$  percent accuracy can be evaluated. The results indicate that on average, 25 seconds per truck can be saved by choosing the more accurate scale. The planner can then determine whether or not the 25 second time savings can justify the added cost for a more accurate system.

Similar charts and graphs illustrating the variation in travel time for a hypothetical freeway screening system are provided in Table 5, Table 6, and Figure 21 through Figure 28. The results demonstrate that as a whole, using a mainline screening system results in reductions in travel times. Specifically, for 100 veh/h truck demand with a perfectly accurate WIM scale and a weight threshold of 1.0, the travel time is reduced from 120 seconds for the original case to 80 seconds with freeway screening case. Furthermore, for a truck demand of 800 veh/h, the average travel time is reduced from 354 seconds to 309 seconds for a difference of 45 seconds as a result of switching from a weigh station screening to a freeway screening system.

The trends for both sets of graphs are exactly the same; however, the mainline screening case has a lower magnitude of travel time compared to the original case. In a similar manner, a weigh station planner can use the mainline screening charts to compare results to the original ramp screening case. If the capital cost of the improved mainline system is less than the potential benefits in decreased delay by truck drivers, the project may in fact be worthwhile.

### 5.3 Calculating Total Delay for Alternatives

The design of a weigh station is not typically based on a typical peak hour; instead the design is based on a typical peak day. Consequently, this section describes how the daily delay can be computed using the procedures that were developed earlier. Specifically, the truck arrival distribution for 21 hours on Wednesday, June 13, 2001 on the northbound scale were analyzed. In order to compute the total delay, the data were aggregated into 15-minute intervals and given equivalent hourly volumes in order to use the tables described earlier in the paper. The hourly arrival rates were aggregated into different bins, as illustrated in Figure 29. The delay charts were used to produce the results in Table 7.

The table summarizes results for six alternative scenarios. The first three scenarios involve ramp screening while the latter three scenarios involve freeway screening (or mainline screening). For each scenario, a perfectly accurate scale with a threshold of 1.0 was evaluated along with a scale with  $\pm 5$  percent accuracy with a threshold of 0.96 and a scale with  $\pm 10$  percent accuracy and threshold of 0.92. All of the freeway screening cases resulted in fewer vehicle-hours of delay than the ramp screening cases. The delay ranges from 281 to 742 vehicle-hours of delay for the 21-hour period. Each alternative can be analyzed using a cost/benefit analysis in order to determine if a reduction in delay is worth the investment in an alternative screening system.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The paper presents a methodology for evaluating weigh station operations. The methodology combines a Monte Carlo type of approach for computing truck volume distribution between static scale and bypass lanes and the INTEGRATION microscopic simulation model for the evaluation of weigh station operations. The study demonstrated the adequacy of the Monte Carlo type of simulation for computing truck volume distribution between static scale and bypass lanes. Furthermore, the study demonstrated the efficiency of the INTEGRATION software for modeling of the operation of a weigh station.

The methodology can be applied to the modeling of weigh station operations to determine the effects that WIM screening accuracy, calibration, and demand has on system performance. In addition, the difference between a mainline screening facility and a traditional ramp screening system can be analyzed. The accuracy of the system is directly related to the level of enforcement and the amount of delay experienced by non-violators. It is the job of the decision-maker to determine enforcement and delay goals in order to develop a compromise between two conflicting objectives. A user-specified threshold for the screening of trucks also plays a large role in system performance. As the threshold is increased, less delay is incurred by trucks but violators are more apt to bypass the static scale.

It is recommended that further studies be conducted using a cost/benefit approach in order to compare alternative truck screening approaches. In addition, further studies are required in order to investigate the advantages of incorporating two WIM scales for screening purposes.

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**Table 1: WIM Volume Distribution Model**

<b>Threshold Factor</b>	0.96	
<b>Critical Gross Weight (1000 lb)</b>	76.8	
<b>Gross Weight COV</b>	0.05	
<b>Gross Weight Bias (1000 lb)</b>	0	
<b>Field Observed Static Volume</b>	2316	7%
<b>Estimated Static Scale Volume</b>	4101	12%
<b>Static Scale Volume Error</b>	77%	

Gross Weight (lb)	Gross Weight (kg)	Truck Frequency	Static Scale Probability	Static Scale Volume	Bypass Volume
0 to 5000	0 to 2270	0	0%	0	0
5001 to 10000	2271 to 4540	32	0%	0	32
10001 to 15000	4541 to 6810	375	0%	0	375
15001 to 20000	6811 to 9070	634	0%	0	634
20001 to 25000	9070 to 11340	446	0%	0	446
25001 to 30000	11341 to 13610	1196	0%	0	1196
30001 to 35000	13611 to 15880	2133	0%	0	2133
35001 to 40000	15881 to 18150	2524	0%	0	2524
40001 to 45000	18151 to 20420	2680	0%	0	2680
45001 to 50000	20421 to 22680	2812	0%	0	2812
50001 to 55000	22681 to 24950	2878	0%	0	2878
55001 to 60000	24951 to 27220	2636	0%	0	2636
60001 to 65000	27221 to 29490	2349	0%	0	2349
65001 to 70000	29491 to 31760	2758	1%	15	2743
70001 to 75000	31761 to 34020	5799	17%	999	4800
75001 to 80000	34021 to 36290	4164	67%	2802	1362
80001 to 85000	36291 to 38560	243	95%	232	11
85001 to 90000	38561 to 40830	14	100%	14	0
90001 to 95000	40831 to 43100	7	100%	7	0
95001 to 100000	43101 to 45360	4	100%	4	0
100001 to 105000	45361 to 47630	8	100%	8	0
105001 to 110000	47631 to 49900	4	100%	4	0
110001 to 115000	49901 to 52170	5	100%	5	0
115001 to 120000	52171 to 54440	2	100%	2	0
120001 to 125000	54441 to 56700	4	100%	4	0
125001 to 130000	56701 to 58970	2	100%	2	0
130001 to 135000	58971 to 61240	0	100%	0	0
135001 to 140000	61241 to 63510	0	100%	0	0
140001 to 145000	63511 to 65780	0	100%	0	0
145001 to 150000	65781 to 68040	1	100%	1	0
More than 150000	More than 68040	2	100%	2	0
<b>Totals</b>		<b>33712</b>		<b>4101</b>	<b>29611</b>

**Table 2: Link Characteristics**

<b>Link No.</b>	<b>Length (m)</b>	<b>Speed (km/h)</b>	<b>Saturation Flow (vph)</b>	<b>Speed at Capacity (km/h)</b>	<b>Jam Density (veh/km/lane)</b>
1	176	105	1800	70	125
2	574	65	1800	32.5	125
3	247	65	1800	32.5	125
4	199	11.5	1800	7.5	250
5	48	11.5	1800	7.5	250
6	334	65	1800	32.5	125
7	384	105	1800	70	125

**Table 3: Vehicle Travel Time by Classification (Original Case – Arrival Rate 100 to 400 veh/h)**

Volume 100

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	117.8	116.4	115.8
	Static, Non-Violator	207.6	209.6	0.0
	Static, Violator	254.2	247.5	235.7
	Average	140.8	128.7	120.4
5%	Bypass	117.8	117.5	116.2
	Static, Non-Violator	207.6	215.6	214.0
	Static, Violator	254.2	255.8	254.5
	Average	140.8	134.1	125.2
10%	Bypass	118.8	117.5	116.3
	Static, Non-Violator	207.8	211.5	210.1
	Static, Violator	248.4	256.1	245.2
	Average	143.9	137.1	128.5
15%	Bypass	117.3	117.6	117.5
	Static, Non-Violator	208.7	206.7	215.6
	Static, Violator	245.6	258.1	255.8
	Average	143.7	140.1	134.1
20%	Bypass	117.8	118.8	117.0
	Static, Non-Violator	208.1	207.8	210.6
	Static, Violator	251.8	248.4	253.6
	Average	147.7	143.9	136.9

Volume 200

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	129.1	126.5	123.4
	Static, Non-Violator	215.1	217.5	0.0
	Static, Violator	240.2	254.5	249.4
	Average	150.0	136.1	126.0
5%	Bypass	127.1	126.7	124.6
	Static, Non-Violator	213.0	210.8	223.2
	Static, Violator	238.2	243.5	252.7
	Average	146.5	137.4	129.1
10%	Bypass	128.9	126.4	126.5
	Static, Non-Violator	214.6	211.4	217.5
	Static, Violator	238.7	247.8	254.4
	Average	149.8	140.5	136.1
15%	Bypass	129.3	127.2	127.5
	Static, Non-Violator	214.8	213.7	212.8
	Static, Violator	240.3	241.6	257.8
	Average	153.5	145.0	140.1
20%	Bypass	129.4	128.9	128.1
	Static, Non-Violator	218.6	214.6	213.8
	Static, Violator	249.6	238.7	240.9
	Average	156.7	149.8	145.4

Volume 300

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	144.1	139.0	134.7
	Static, Non-Violator	224.3	230.2	0.0
	Static, Violator	269.8	269.7	259.7
	Average	163.8	148.5	138.0
5%	Bypass	143.0	138.5	136.1
	Static, Non-Violator	223.3	223.1	222.7
	Static, Violator	274.6	263.4	259.7
	Average	162.4	150.2	140.0
10%	Bypass	144.9	140.4	137.2
	Static, Non-Violator	227.1	224.1	219.6
	Static, Violator	273.1	257.7	274.5
	Average	165.6	154.2	144.5
15%	Bypass	145.5	142.4	138.6
	Static, Non-Violator	229.1	223.6	218.8
	Static, Violator	275.6	251.0	247.5
	Average	169.3	159.7	149.6
20%	Bypass	149.8	144.2	142.1
	Static, Non-Violator	226.7	229.6	229.5
	Static, Violator	263.1	284.0	268.6
	Average	174.0	166.4	159.8

Volume 400

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	165.5	150.6	145.6
	Static, Non-Violator	230.7	230.4	0.0
	Static, Violator	259.7	262.2	257.2
	Average	180.7	158.1	147.9
5%	Bypass	163.8	152.8	148.6
	Static, Non-Violator	232.2	234.1	225.9
	Static, Violator	269.4	267.3	268.2
	Average	179.6	162.9	152.6
10%	Bypass	166.0	156.3	152.4
	Static, Non-Violator	230.9	234.4	233.3
	Static, Violator	263.8	264.9	268.1
	Average	181.8	168.6	160.0
15%	Bypass	165.6	165.0	157.9
	Static, Non-Violator	235.6	232.5	233.2
	Static, Violator	268.8	254.1	255.4
	Average	184.8	178.9	168.4
20%	Bypass	175.3	166.2	163.7
	Static, Non-Violator	241.3	231.1	231.9
	Static, Violator	262.6	261.5	262.6
	Average	195.4	182.1	177.0

**Table 4: Vehicle Travel Time by Classification (Original Case – Arrival Rate 500 to 800 veh/h)**

**Volume 500**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	211.1	177.6	167.1
	Static, Non-Violator	264.5	248.6	0.0
	Static, Violator	300.5	285.1	279.4
	Average	224.2	184.9	169.8
5%	Bypass	210.7	183.5	170.2
	Static, Non-Violator	263.1	252.1	245.9
	Static, Violator	295.6	280.5	284.0
	Average	223.3	192.4	173.5
10%	Bypass	216.1	197.3	177.0
	Static, Non-Violator	266.5	253.8	248.8
	Static, Violator	298.3	287.3	290.9
	Average	228.8	206.8	183.4
15%	Bypass	231.6	205.1	185.2
	Static, Non-Violator	283.1	258.6	253.1
	Static, Violator	302.5	298.1	281.7
	Average	245.9	216.9	194.3
20%	Bypass	238.3	218.2	202.2
	Static, Non-Violator	283.4	265.6	257.4
	Static, Violator	309.7	289.7	295.2
	Average	252.5	229.6	212.7

**Volume 600**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	291.7	221.9	200.4
	Static, Non-Violator	331.8	281.8	0.0
	Static, Violator	352.1	309.6	301.8
	Average	301.1	227.7	202.5
5%	Bypass	290.5	240.5	208.9
	Static, Non-Violator	333.4	290.7	263.4
	Static, Violator	355.2	322.0	306.2
	Average	300.4	247.1	211.9
10%	Bypass	296.8	259.8	222.5
	Static, Non-Violator	338.3	304.1	281.7
	Static, Violator	360.9	340.5	309.3
	Average	307.0	267.2	228.1
15%	Bypass	317.7	273.3	247.2
	Static, Non-Violator	354.6	320.5	292.6
	Static, Violator	382.7	354.9	313.7
	Average	328.0	283.4	253.1
20%	Bypass	336.3	302.8	275.2
	Static, Non-Violator	366.7	344.8	318.8
	Static, Violator	385.5	371.7	348.5
	Average	345.8	313.3	283.9

**Volume 700**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	385.3	297.2	276.7
	Static, Non-Violator	432.5	368.4	0.0
	Static, Violator	476.5	397.3	383.3
	Average	397.0	304.1	279.2
5%	Bypass	389.4	321.4	284.3
	Static, Non-Violator	431.1	369.2	350.1
	Static, Violator	476.9	416.4	387.7
	Average	399.8	328.2	287.5
10%	Bypass	400.9	348.6	293.9
	Static, Non-Violator	438.5	387.3	362.8
	Static, Violator	482.7	443.7	377.2
	Average	410.7	355.8	299.7
15%	Bypass	402.8	367.8	339.5
	Static, Non-Violator	443.0	402.8	374.4
	Static, Violator	482.2	426.6	414.0
	Average	414.4	375.2	344.7
20%	Bypass	412.9	387.0	352.4
	Static, Non-Violator	444.3	422.8	400.4
	Static, Violator	480.3	463.7	420.3
	Average	422.8	396.0	361.5

**Volume 800**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	476.3	379.3	352.1
	Static, Non-Violator	521.4	440.1	0.0
	Static, Violator	569.7	476.5	457.4
	Average	487.4	385.2	354.2
5%	Bypass	475.5	413.9	359.9
	Static, Non-Violator	514.2	449.6	416.1
	Static, Violator	558.8	505.8	455.8
	Average	484.9	419.1	362.4
10%	Bypass	469.5	426.0	372.7
	Static, Non-Violator	509.5	469.4	447.8
	Static, Violator	549.6	517.7	457.5
	Average	479.5	433.5	378.8
15%	Bypass	497.6	459.8	411.8
	Static, Non-Violator	539.2	499.7	452.3
	Static, Violator	583.7	543.2	501.7
	Average	509.5	468.6	417.6
20%	Bypass	499.9	474.3	449.9
	Static, Non-Violator	541.7	517.7	495.1
	Static, Violator	571.2	553.0	537.2
	Average	512.9	485.2	459.1

**Table 5: Vehicle Travel Time by Classification (Mainline Screening Case – Arrival Rate 100 to 400 veh/h)**

**Volume 100**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	80.2	81.1	80.3
	Static, Non-Violator	204.9	207.3	0.0
	Static, Violator	252.0	244.6	234.4
	Average	111.4	97.3	86.2
5%	Bypass	80.2	80.5	81.1
	Static, Non-Violator	204.9	212.7	211.9
	Static, Violator	252.0	255.0	252.6
	Average	111.4	102.5	92.0
10%	Bypass	82.3	80.4	81.6
	Static, Non-Violator	206.1	208.2	207.3
	Static, Violator	245.9	255.8	242.1
	Average	116.7	106.5	96.9
15%	Bypass	81.3	80.5	80.5
	Static, Non-Violator	206.2	204.3	212.7
	Static, Violator	241.8	257.0	255.0
	Average	116.8	111.1	102.5
20%	Bypass	81.6	82.3	80.0
	Static, Non-Violator	205.9	206.1	207.8
	Static, Violator	250.7	245.9	253.0
	Average	122.2	116.7	106.8

**Volume 200**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	89.6	88.5	86.8
	Static, Non-Violator	210.6	212.5	0.0
	Static, Violator	237.0	251.1	243.4
	Average	118.8	101.4	89.9
5%	Bypass	88.2	89.3	87.4
	Static, Non-Violator	209.3	205.3	218.7
	Static, Violator	235.3	239.8	248.9
	Average	115.4	103.9	93.2
10%	Bypass	89.8	89.3	88.6
	Static, Non-Violator	210.2	206.6	212.3
	Static, Violator	235.6	242.5	251.1
	Average	119.0	108.6	101.5
15%	Bypass	88.7	88.9	88.5
	Static, Non-Violator	210.7	207.9	207.4
	Static, Violator	236.4	237.2	253.4
	Average	123.0	113.2	105.7
20%	Bypass	89.3	89.8	89.4
	Static, Non-Violator	214.8	210.2	208.4
	Static, Violator	245.1	235.6	237.7
	Average	127.4	119.0	113.3

**Volume 300**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	101.6	97.4	95.1
	Static, Non-Violator	218.6	224.0	0.0
	Static, Violator	264.2	262.1	250.8
	Average	129.8	110.1	99.2
5%	Bypass	101.0	97.8	95.6
	Static, Non-Violator	217.3	215.9	213.7
	Static, Violator	268.0	254.5	249.4
	Average	128.6	113.7	100.7
10%	Bypass	101.9	98.5	96.4
	Static, Non-Violator	221.4	217.1	211.0
	Static, Violator	267.0	248.9	266.1
	Average	131.4	117.7	106.3
15%	Bypass	103.1	102.1	97.5
	Static, Non-Violator	223.3	217.3	212.2
	Static, Violator	269.5	244.0	238.7
	Average	136.8	126.4	113.0
20%	Bypass	104.4	101.5	103.2
	Static, Non-Violator	220.5	223.2	223.2
	Static, Violator	255.1	276.4	261.2
	Average	140.5	132.5	127.1

**Volume 400**

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	122.9	105.9	103.1
	Static, Non-Violator	222.3	220.5	0.0
	Static, Violator	250.6	252.6	247.2
	Average	145.8	116.4	106.0
5%	Bypass	120.1	109.6	104.9
	Static, Non-Violator	223.8	224.8	213.8
	Static, Violator	259.7	258.1	255.8
	Average	143.6	123.7	110.1
10%	Bypass	121.7	110.5	107.5
	Static, Non-Violator	223.1	224.3	223.3
	Static, Violator	255.0	253.8	257.7
	Average	146.0	128.2	118.0
15%	Bypass	125.9	118.5	111.1
	Static, Non-Violator	227.5	223.6	224.0
	Static, Violator	258.5	246.2	247.1
	Average	153.4	139.9	126.6
20%	Bypass	129.7	122.0	120.1
	Static, Non-Violator	232.3	223.1	223.0
	Static, Violator	256.3	252.4	253.3
	Average	160.9	146.3	139.7

**Table 6: Vehicle Travel Time by Classification (Mainline Screening Case – Arrival Rate 500 to 800 veh/h)**

Volume 500

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	179.8	131.2	116.9
	Static, Non-Violator	239.5	233.7	0.0
	Static, Violator	270.3	267.1	264.0
	Average	194.2	141.2	120.4
5%	Bypass	183.1	136.4	122.8
	Static, Non-Violator	238.2	236.3	229.4
	Static, Violator	265.7	262.5	267.7
	Average	196.2	149.0	127.3
10%	Bypass	177.8	156.3	131.0
	Static, Non-Violator	239.1	235.2	233.9
	Static, Violator	267.1	266.6	273.3
	Average	192.9	169.2	139.8
15%	Bypass	196.4	178.6	144.4
	Static, Non-Violator	246.4	237.1	236.6
	Static, Violator	264.7	267.0	264.5
	Average	210.2	191.2	156.6
20%	Bypass	200.8	185.5	161.9
	Static, Non-Violator	246.6	236.9	237.6
	Static, Violator	267.6	261.6	270.8
	Average	215.1	197.8	176.1

Volume 600

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	277.3	183.5	149.9
	Static, Non-Violator	259.6	250.1	0.0
	Static, Violator	274.6	276.0	277.6
	Average	273.6	189.8	152.4
5%	Bypass	268.2	213.1	165.8
	Static, Non-Violator	259.2	256.5	240.1
	Static, Violator	275.4	281.6	282.7
	Average	266.5	218.7	169.6
10%	Bypass	276.5	233.5	185.7
	Static, Non-Violator	267.4	256.5	250.9
	Static, Violator	282.1	287.5	276.9
	Average	274.6	237.6	191.9
15%	Bypass	301.4	253.2	220.6
	Static, Non-Violator	268.0	259.9	253.8
	Static, Violator	290.8	286.6	273.1
	Average	293.0	255.1	225.0
20%	Bypass	312.9	277.9	252.1
	Static, Non-Violator	267.6	270.9	258.9
	Static, Violator	281.2	289.9	280.5
	Average	299.7	276.6	253.8

Volume 700

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	371.4	263.5	230.3
	Static, Non-Violator	331.6	319.5	0.0
	Static, Violator	362.7	347.6	347.5
	Average	363.1	269.1	232.9
5%	Bypass	374.4	298.1	244.3
	Static, Non-Violator	328.4	319.7	316.1
	Static, Violator	362.1	362.8	354.0
	Average	364.8	301.6	247.7
10%	Bypass	384.3	327.2	264.7
	Static, Non-Violator	332.4	317.9	321.3
	Static, Violator	365.3	364.9	337.3
	Average	372.8	326.8	269.6
15%	Bypass	404.9	360.8	315.6
	Static, Non-Violator	331.1	318.6	314.7
	Static, Violator	359.4	342.8	351.4
	Average	385.9	352.8	316.1
20%	Bypass	421.9	390.2	344.6
	Static, Non-Violator	322.0	321.5	324.2
	Static, Violator	346.3	356.9	343.5
	Average	392.7	374.7	341.2

Volume 800

Accuracy	Classification	Threshold		
		0.92	0.96	1.00
0%	Bypass	469.3	350.8	306.9
	Static, Non-Violator	408.9	391.3	0.0
	Static, Violator	452.8	427.0	418.1
	Average	456.7	355.0	309.2
5%	Bypass	474.8	387.5	320.9
	Static, Non-Violator	406.1	387.7	382.2
	Static, Violator	447.2	439.8	422.5
	Average	460.4	388.5	323.6
10%	Bypass	481.6	412.3	349.0
	Static, Non-Violator	402.6	394.5	402.2
	Static, Violator	441.4	440.9	415.0
	Average	463.9	410.5	353.4
15%	Bypass	501.8	456.6	394.5
	Static, Non-Violator	405.6	402.8	390.5
	Static, Violator	445.3	443.5	439.5
	Average	477.1	446.7	394.7
20%	Bypass	513.2	485.7	443.1
	Static, Non-Violator	399.3	406.5	405.5
	Static, Violator	425.2	442.3	441.1
	Average	479.7	467.7	436.8

Table 7: Total Delay for Five Alternatives

Demand Level	Frequency	Average Delay in 15 minute interval (sec/veh)					
		Case A	Case B	Case C	Case D	Case E	Case F
100	4	61	75	85	27	44	58
200	19	67	78	91	31	45	60
300	42	79	91	103	40	55	72
400	17	89	104	121	47	65	87
500	2	111	133	170	61	82	134
<b>Total Delay for 21 hour day (veh-hr)</b>		553	643	742	281	390	523

Case A: Ramp Screening with  $\pm 0\%$  accuracy, 1.0 threshold

Case B: Ramp Screening with  $\pm 5\%$  accuracy, 0.96 threshold

Case C: Ramp Screening with  $\pm 10\%$  accuracy, 0.92 threshold

Case D: Freeway Screening with  $\pm 0\%$  accuracy, 1.0 threshold

Case E: Freeway Screening with  $\pm 5\%$  accuracy, 0.96 threshold

Case F: Freeway Screening with  $\pm 10\%$  accuracy, 0.92 threshold

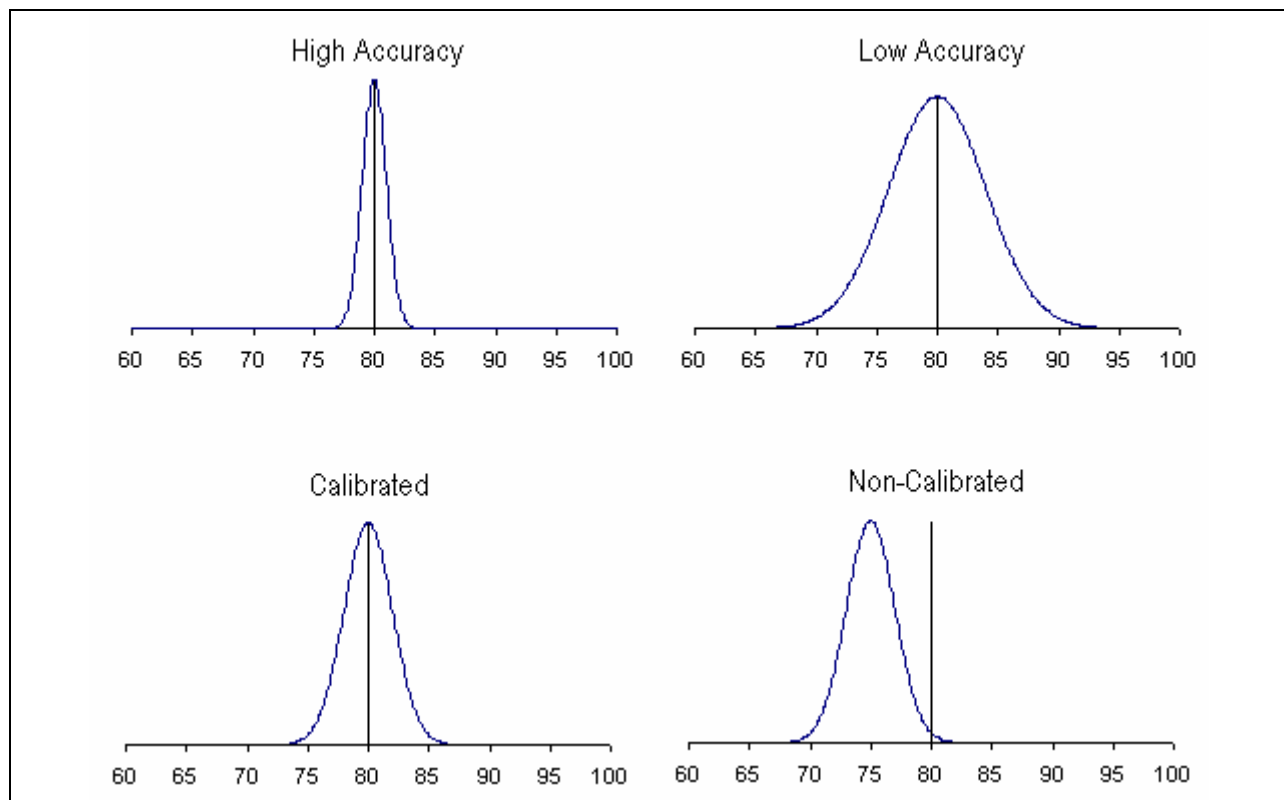


Figure 1: WIM Accuracy vs. Calibration

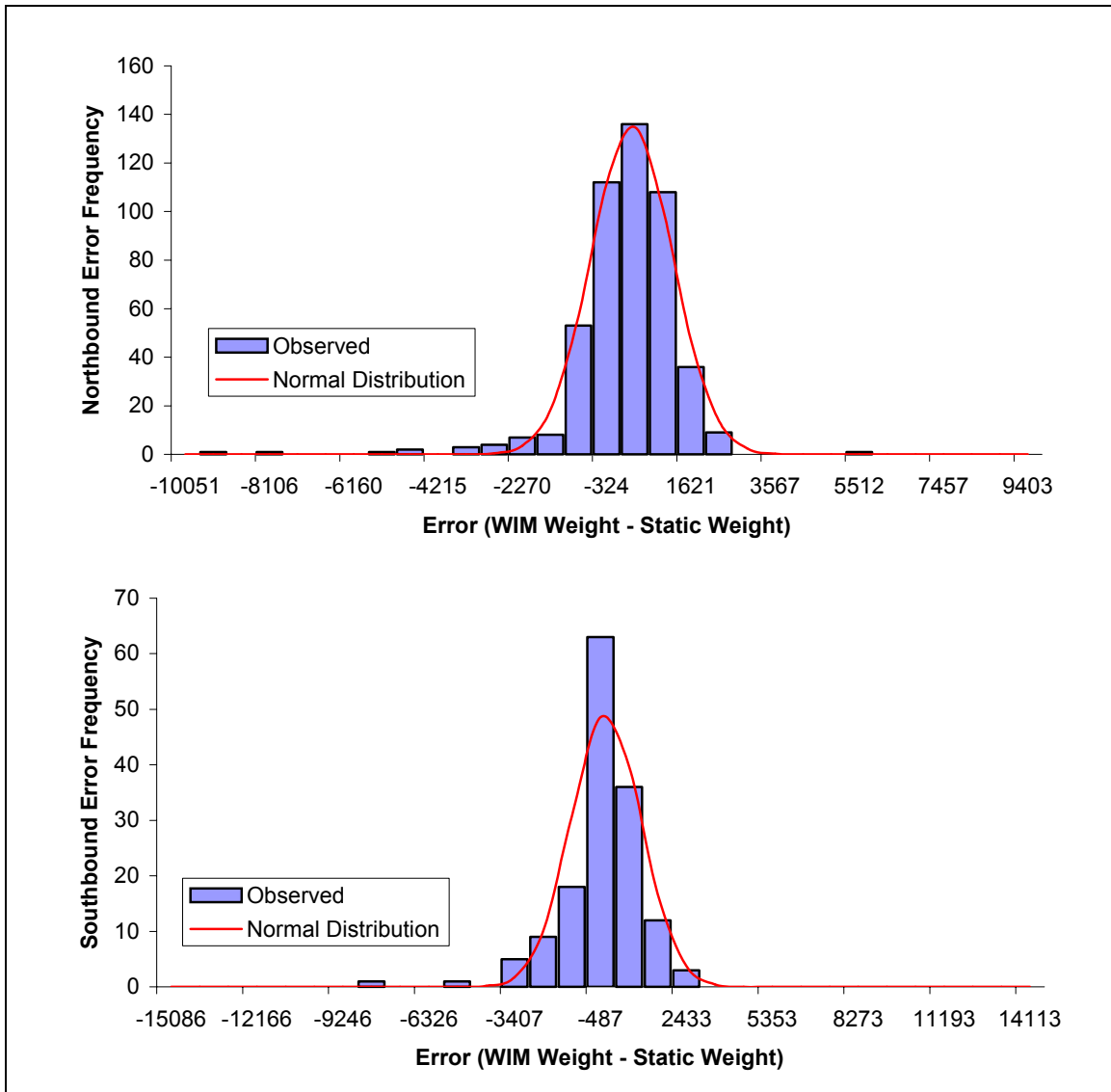


Figure 2: Error Distribution for Northbound and Southbound WIM Scales

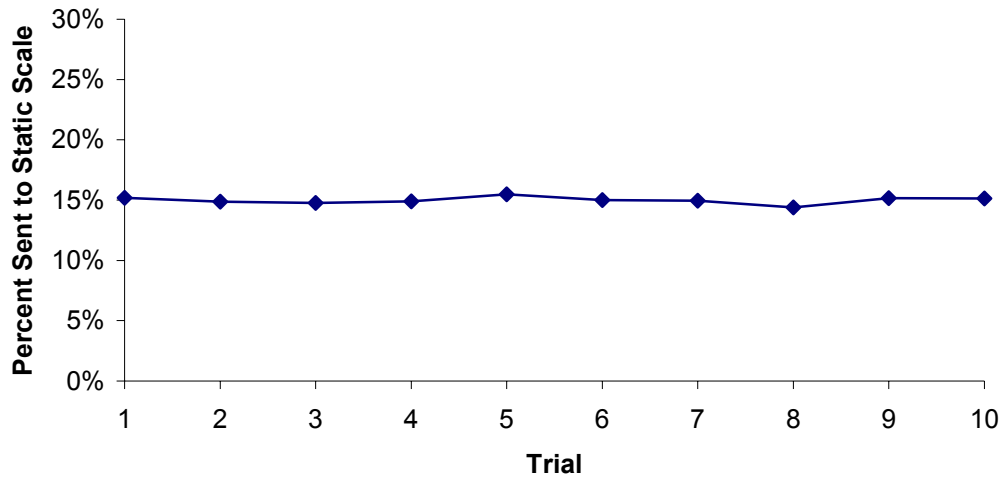


Figure 3: Monte Carlo Simulation Results for 10 Trials

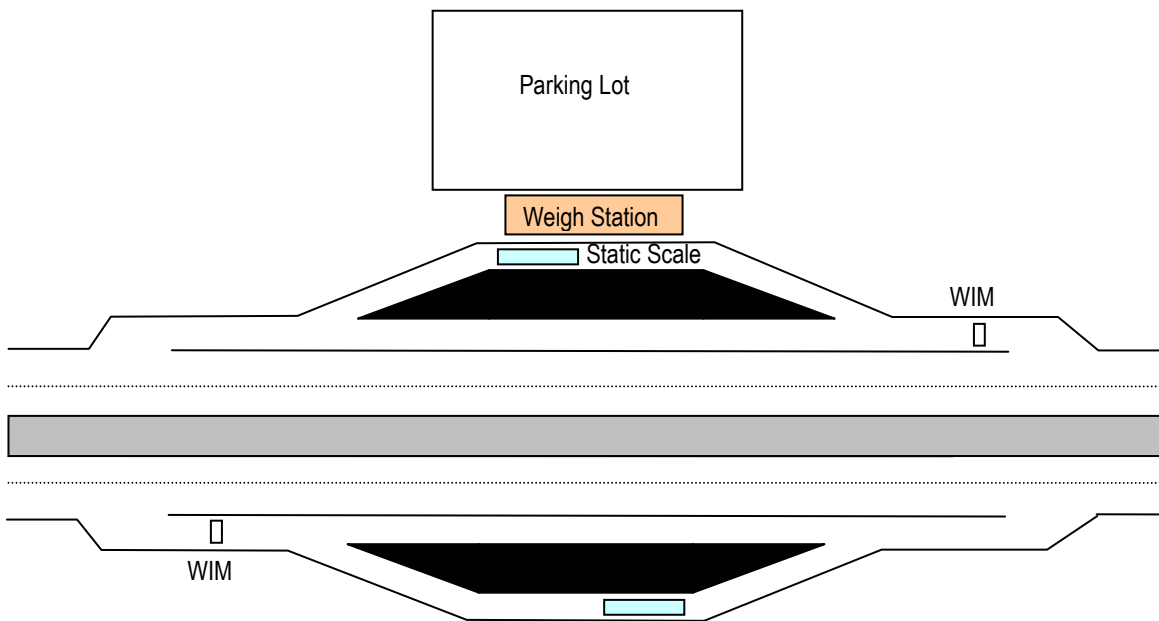


Figure 4: Stephens City Weigh Station Layout

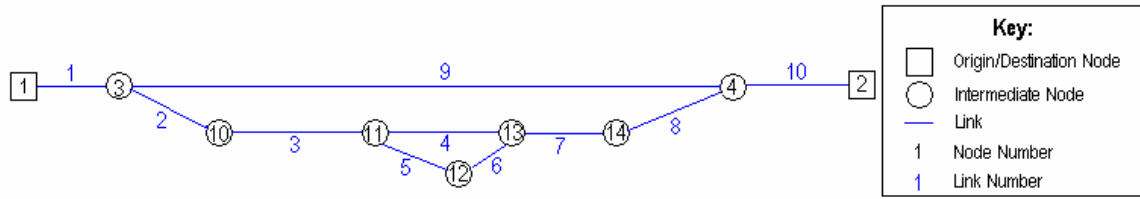


Figure 5: Link-Node Diagram

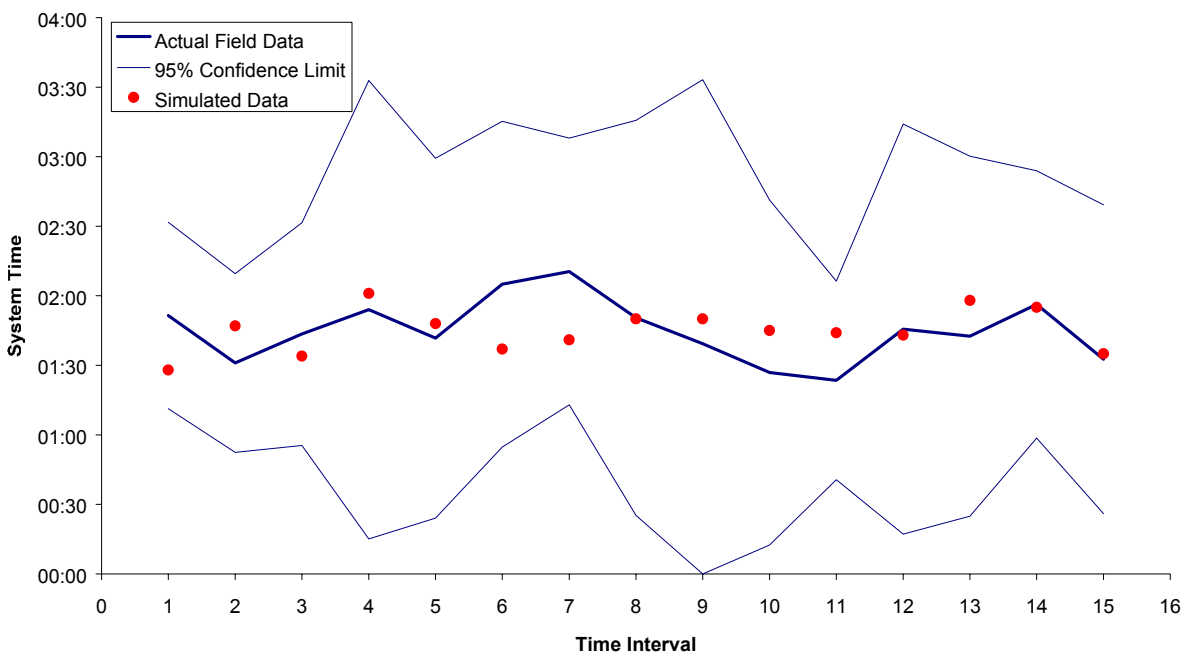


Figure 6: Average Simulated and Actual System Time

For Perfect Calibration

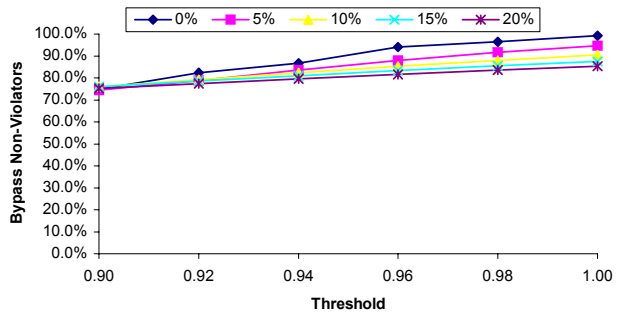
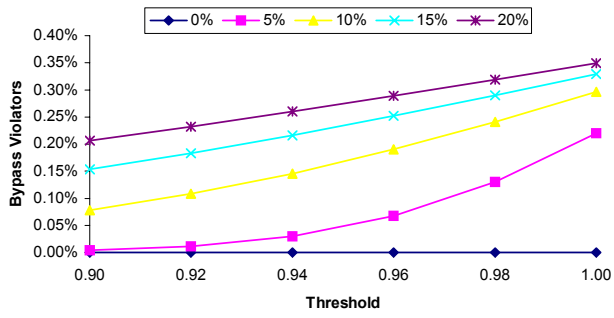
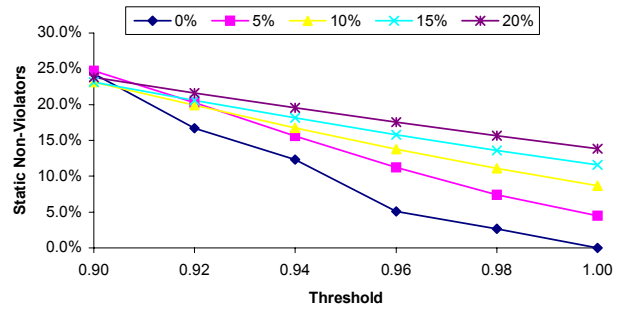
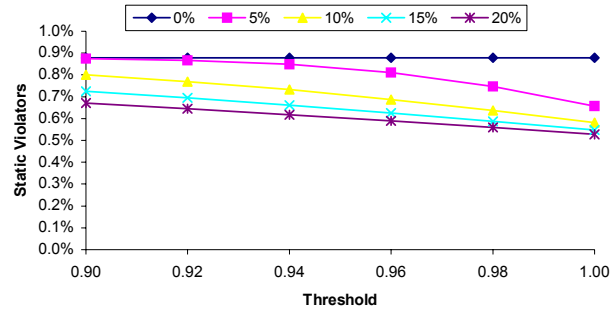


Figure 7: Number of Vehicles vs. Threshold given Accuracy

For 1.00 Threshold

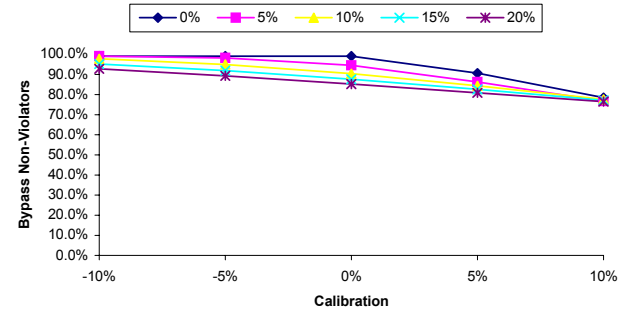
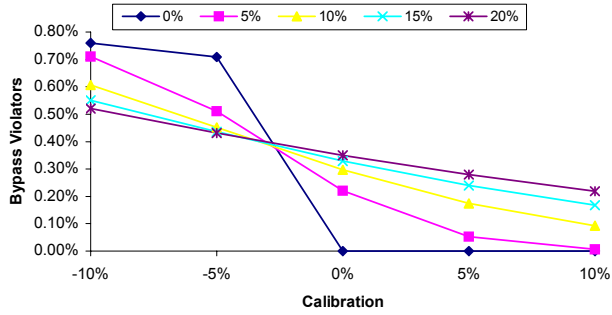
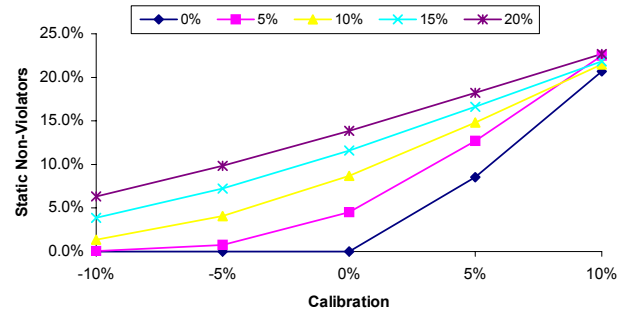
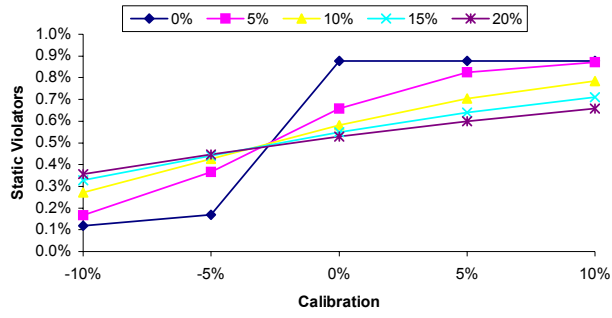
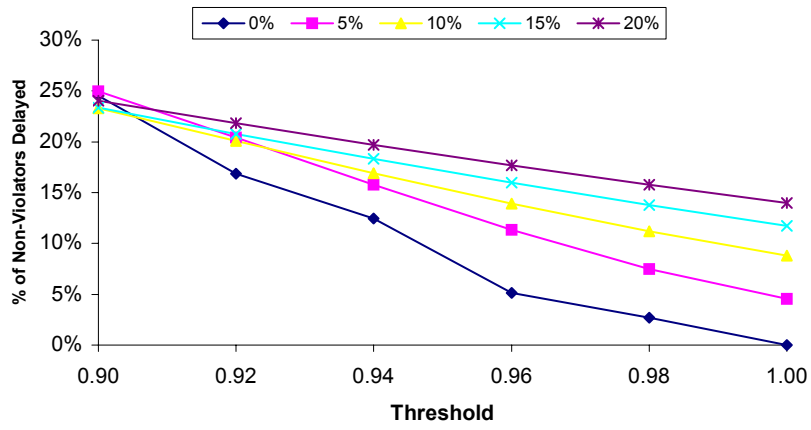
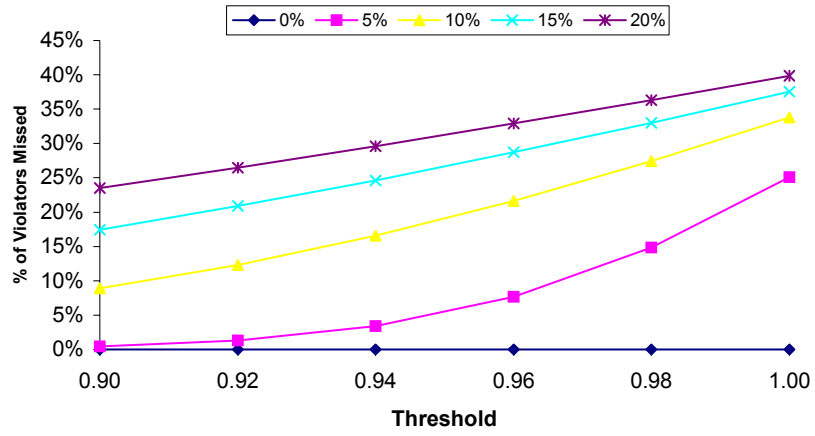


Figure 8: Number of Vehicles vs. Calibration given Accuracy

**For Perfect Calibration**



**Figure 9: Percent of Violators Missed and Percent of Non-Violators Delayed**

For Perfect Calibration

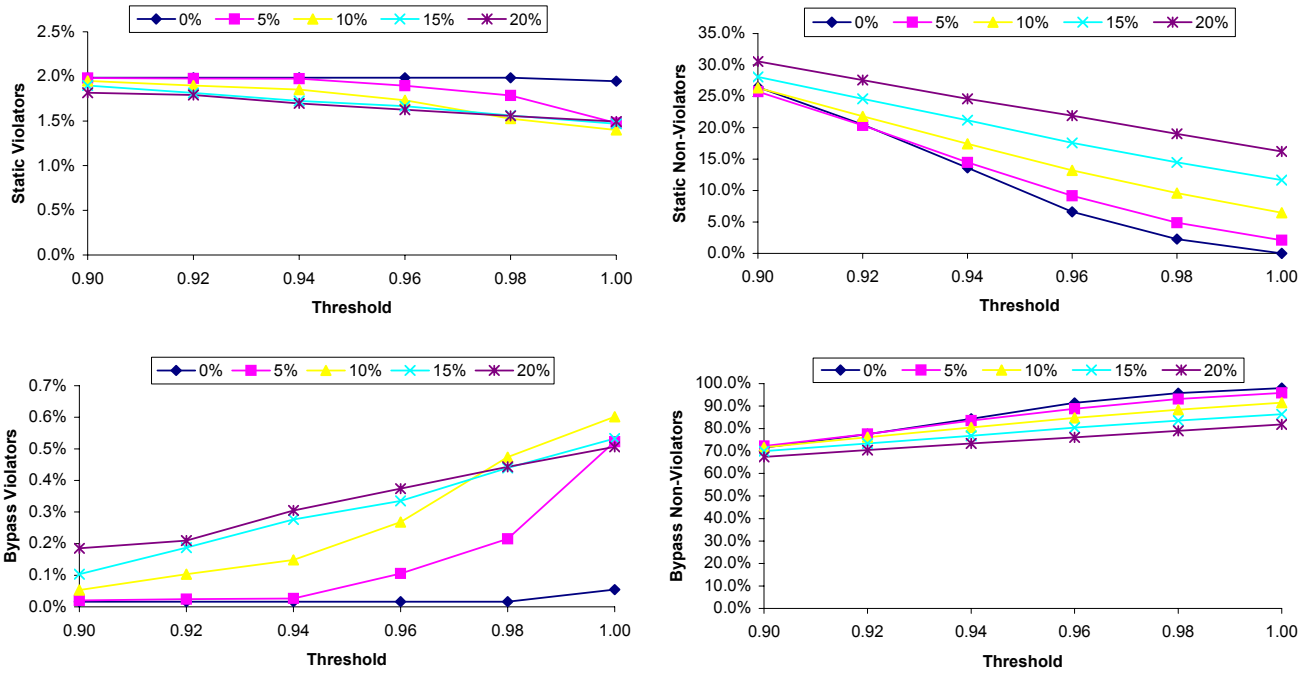


Figure 10: Number of Vehicles vs. Threshold given Accuracy

For 1.00 Threshold

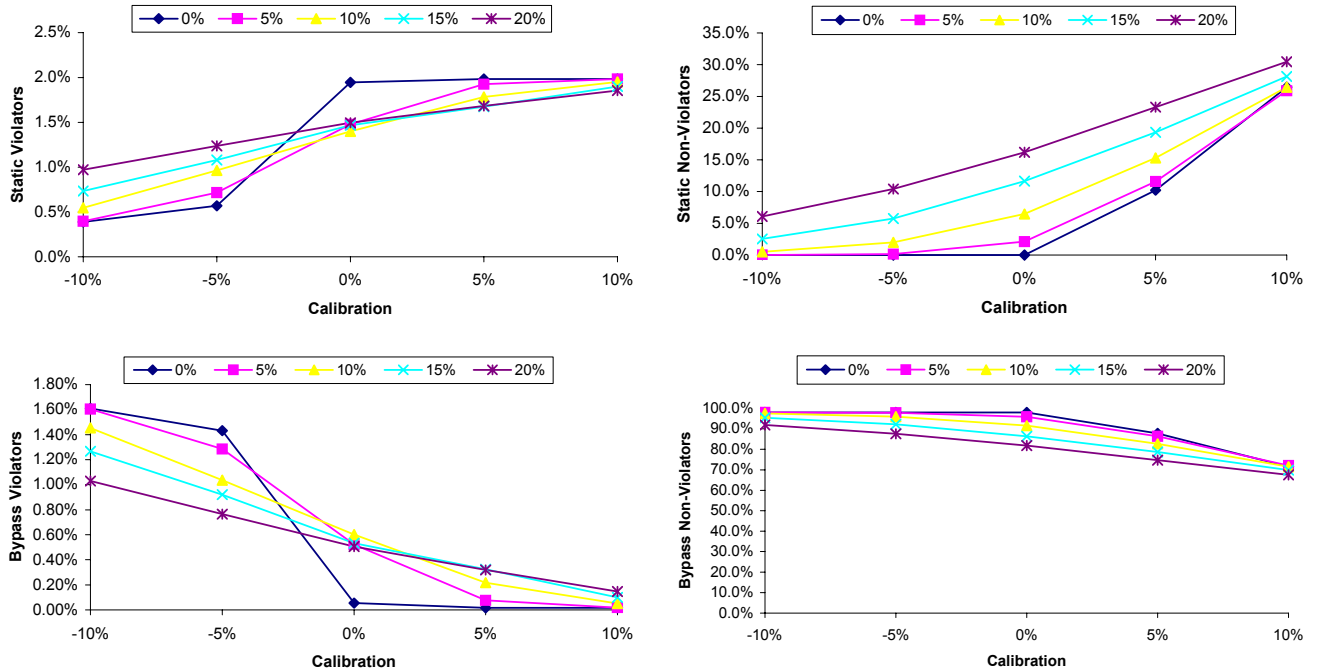


Figure 11: Number of Vehicles vs. Calibration given Accuracy

For Perfect Calibration

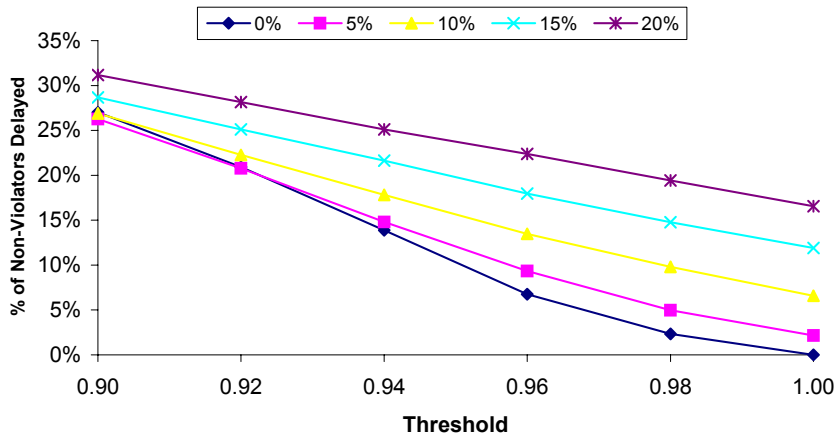
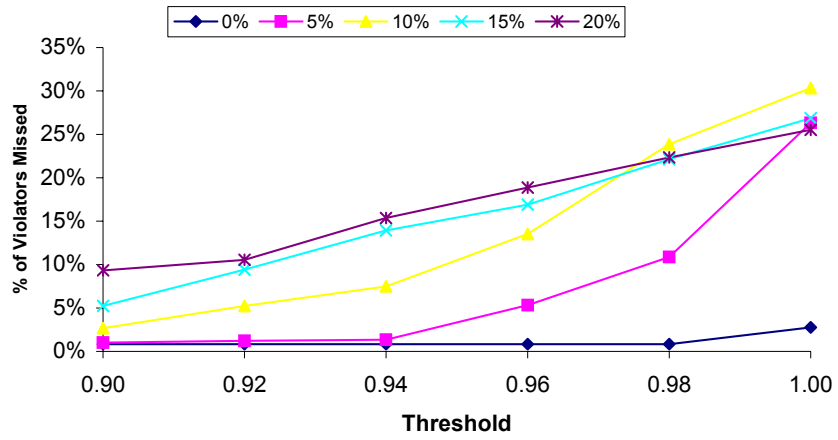


Figure 12: Percent of Violators Missed and Percent of Non-Violators Delayed

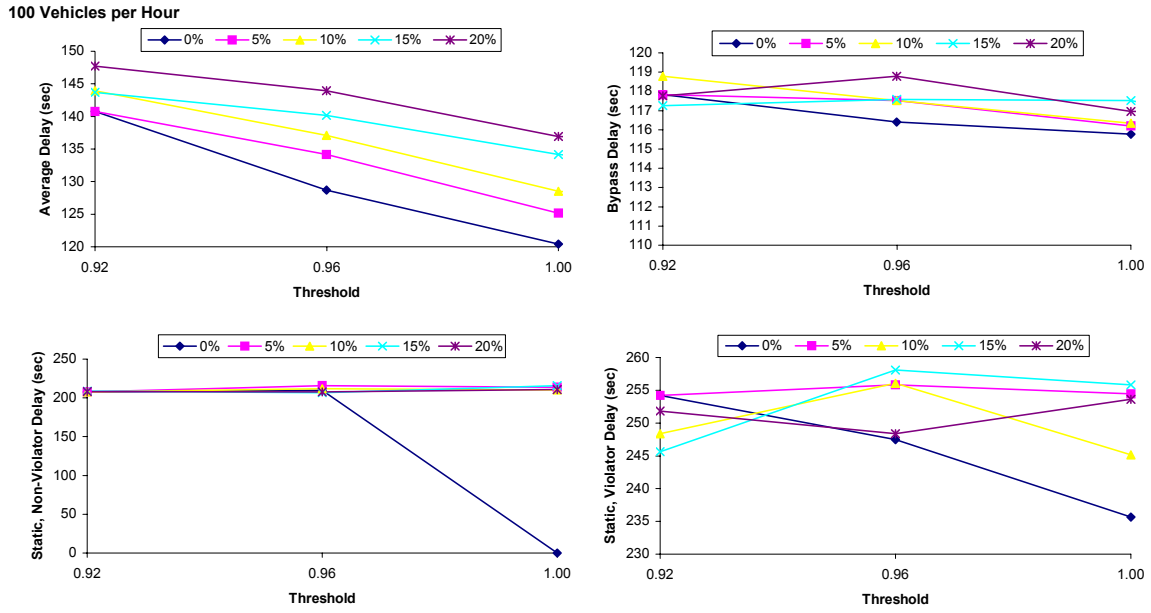


Figure 13: Vehicle Travel Time with Demand of 100 veh/h (Original Case)

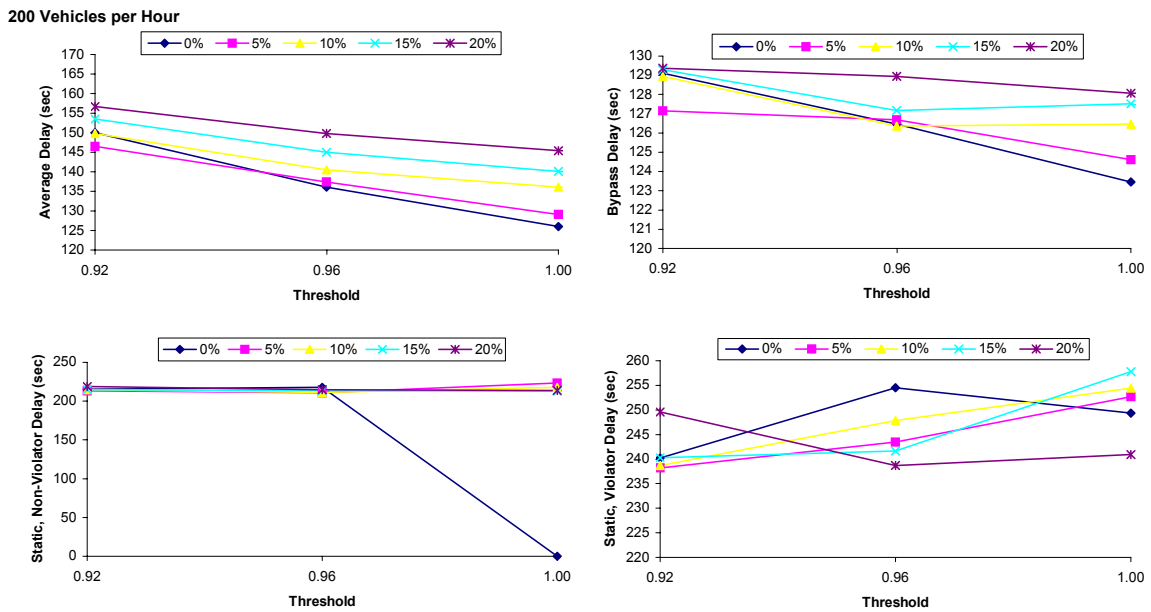


Figure 14: Vehicle Travel Time with Demand of 200 veh/h (Original Case)

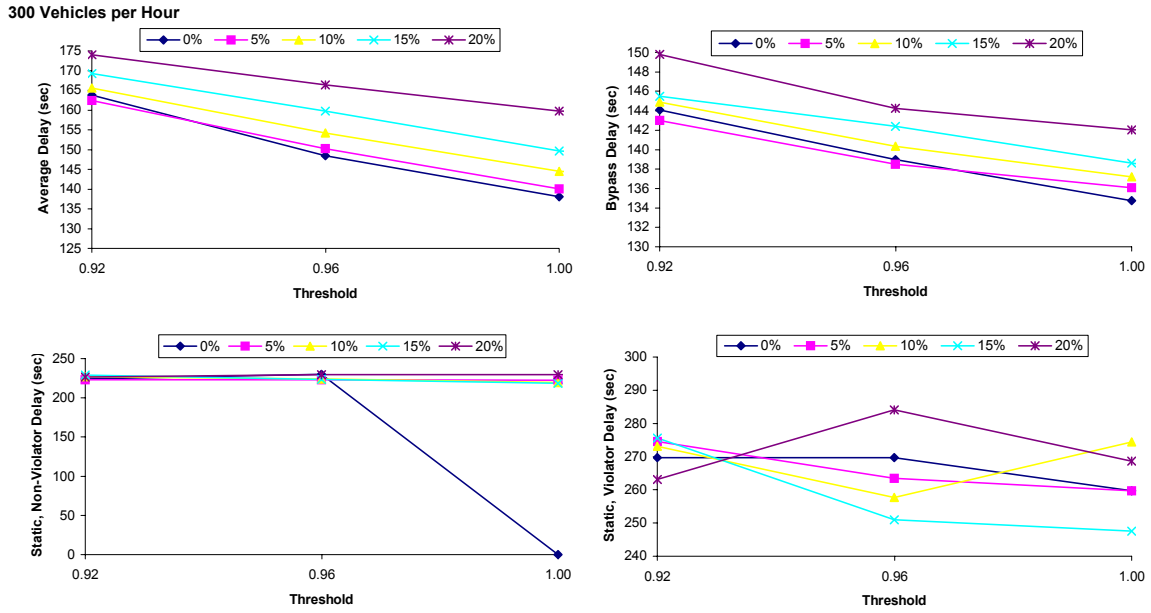


Figure 15: Vehicle Travel Time with Demand of 300 veh/h (Original Case)

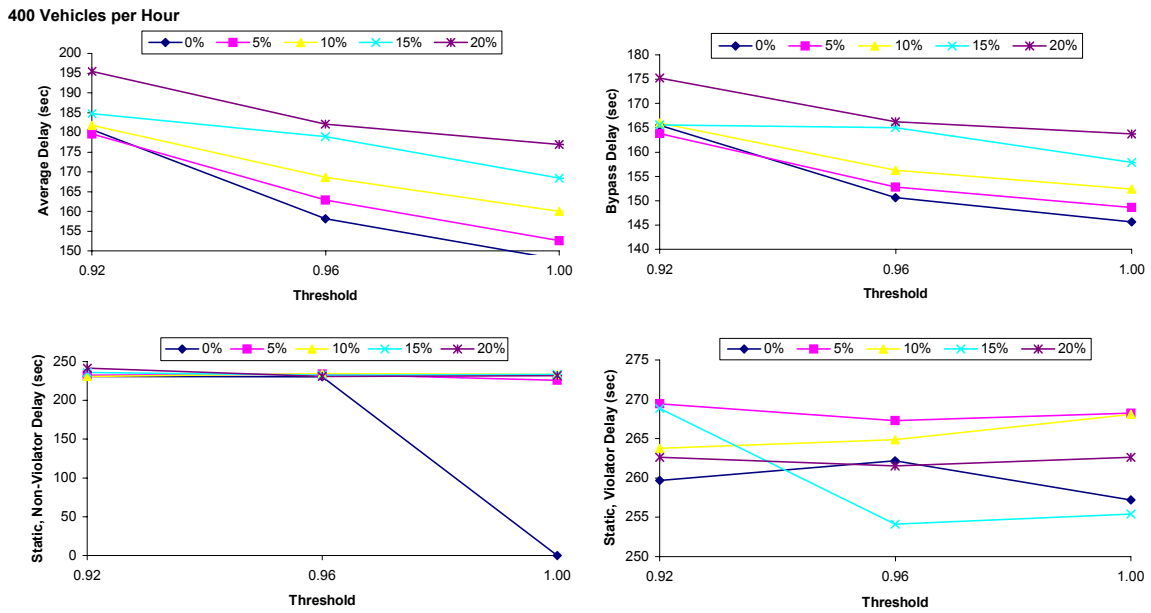


Figure 16: Vehicle Travel Time with Demand of 400 veh/h (Original Case)

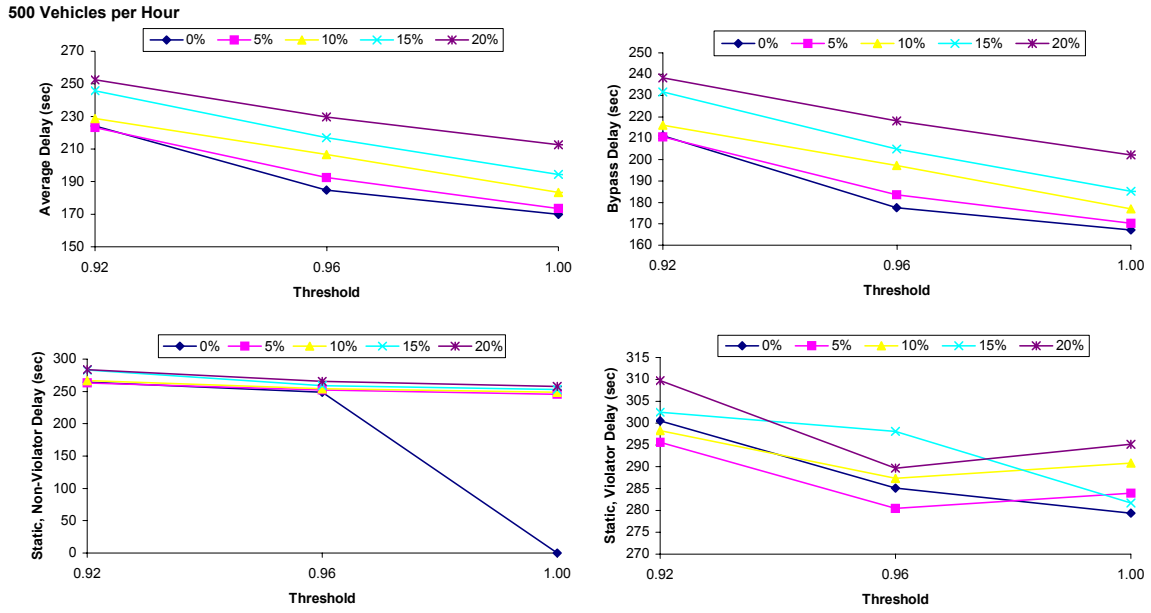


Figure 17: Vehicle Travel Time with Demand of 500 veh/h (Original Case)

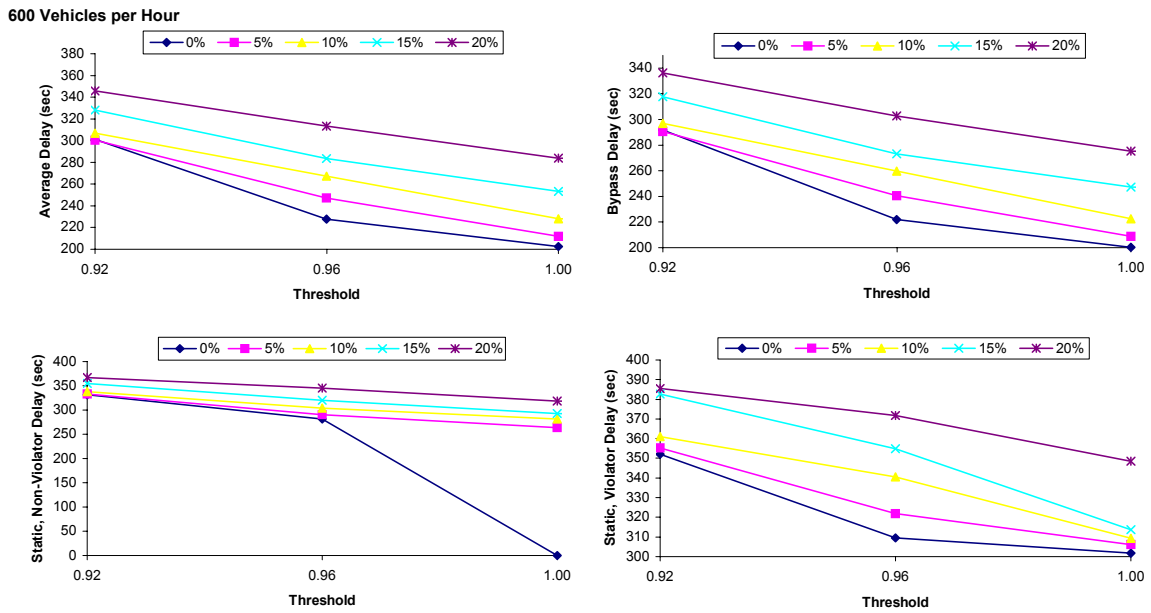


Figure 18: Vehicle Travel Time with Demand of 600 veh/h (Original Case)

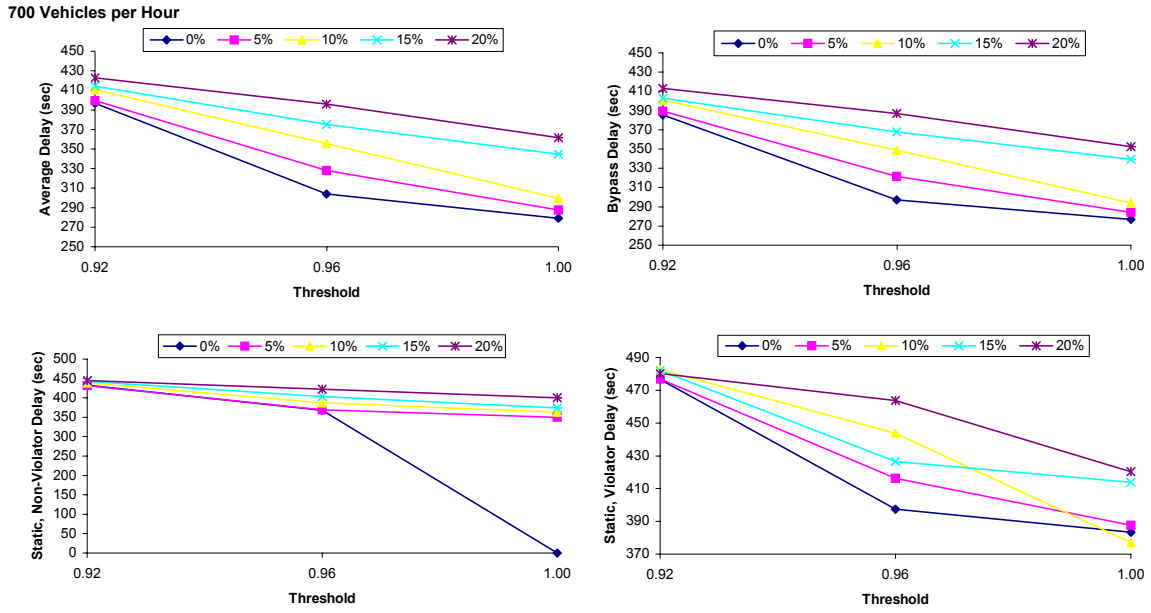


Figure 19: Vehicle Travel Time with Demand of 700 veh/h (Original Case)

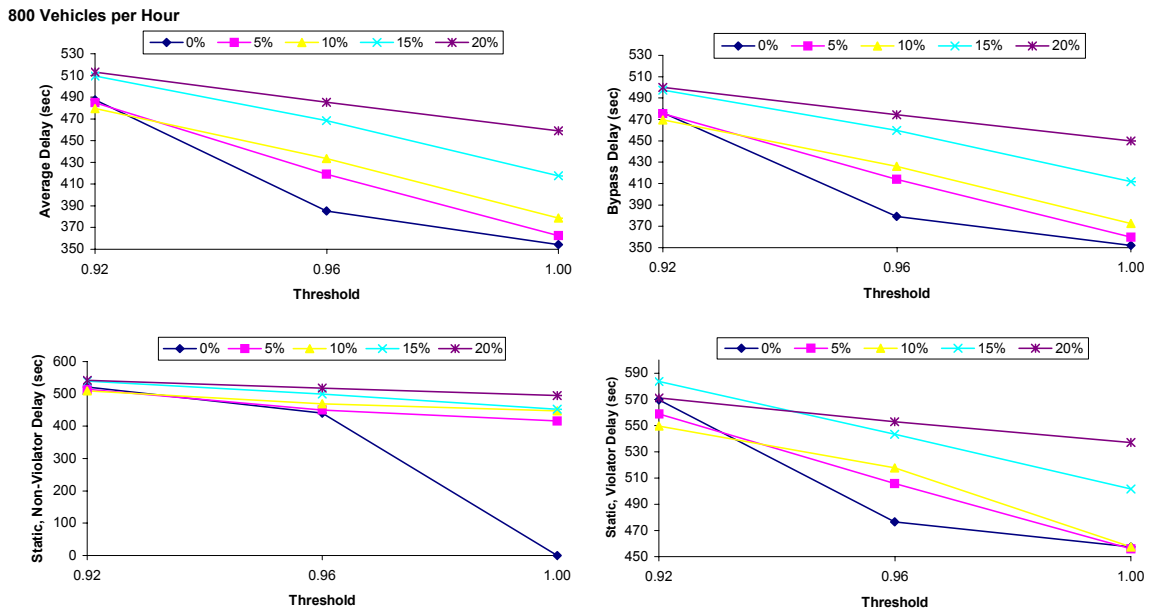


Figure 20: Vehicle Travel Time with Demand of 800 veh/h (Original Case)

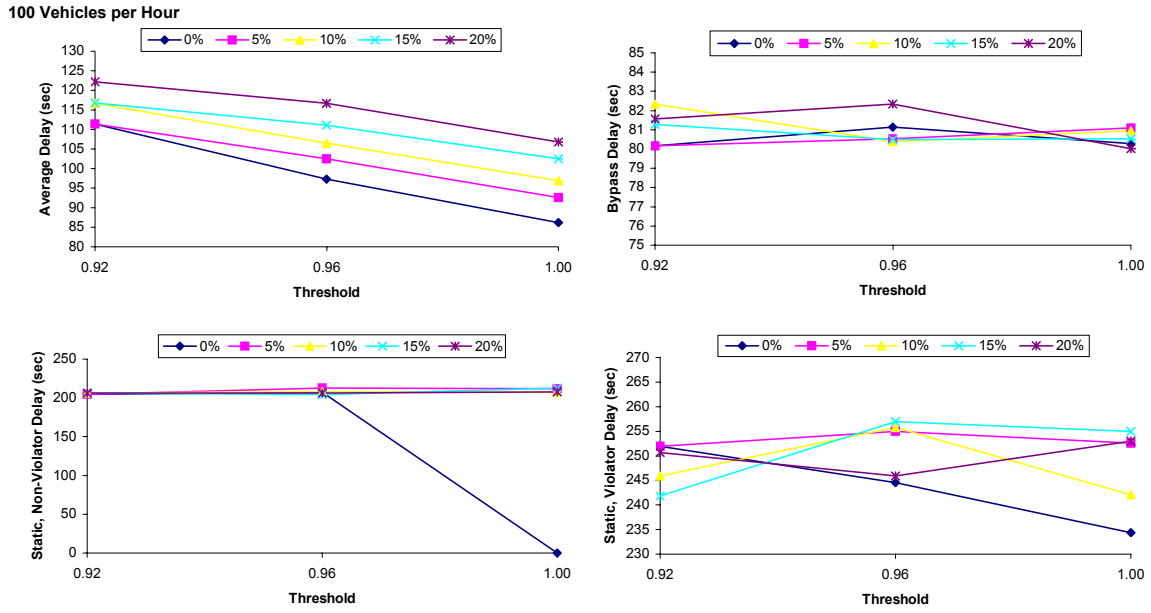


Figure 21: Vehicle Travel Time with Demand of 100 veh/h (Mainline Screening Case)

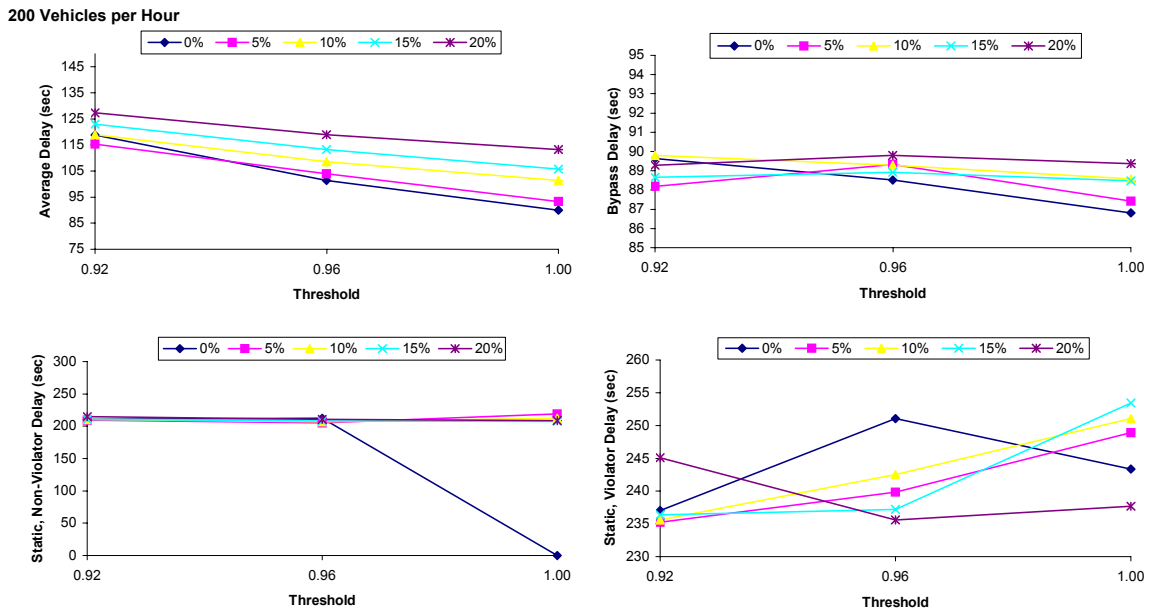


Figure 22: Vehicle Travel Time with Demand of 200 veh/h (Mainline Screening Case)

300 Vehicles per Hour

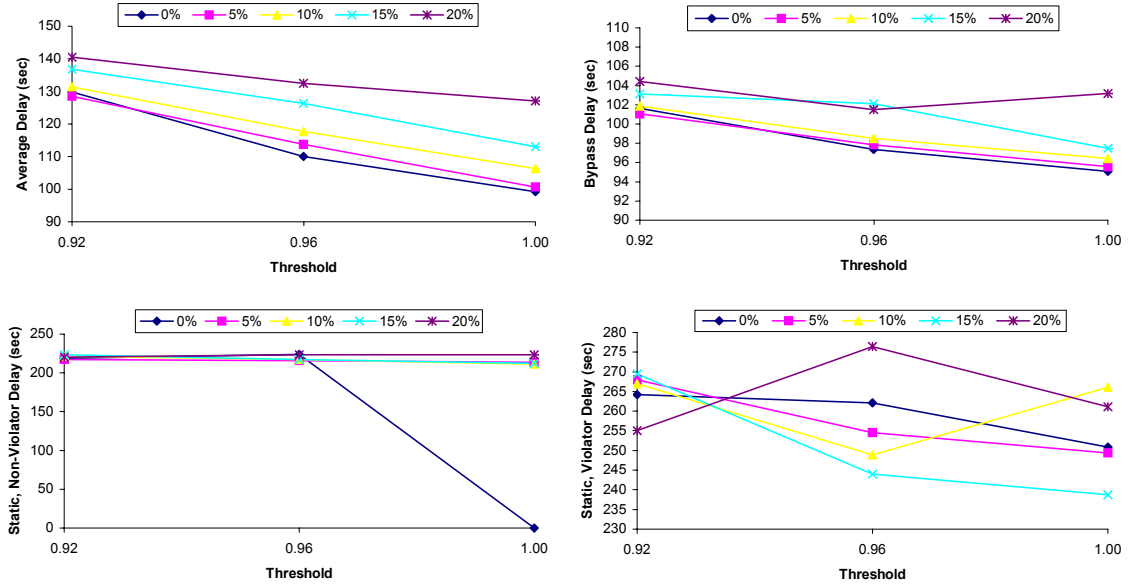


Figure 23: Vehicle Travel Time with Demand of 300 veh/h (Mainline Screening Case)

400 Vehicles per Hour

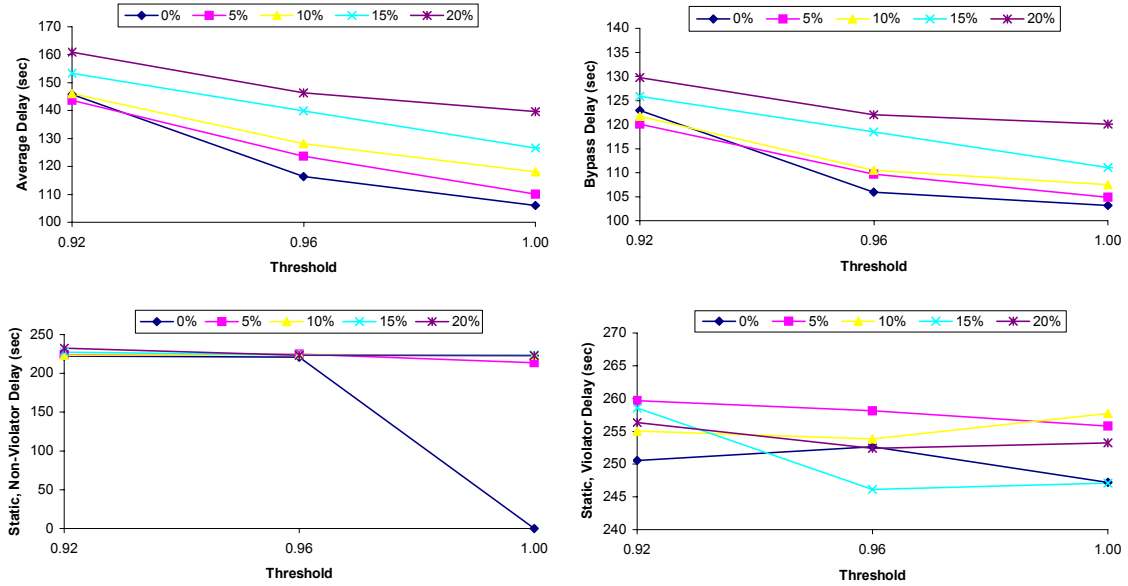


Figure 24: Vehicle Travel Time with Demand of 400 veh/h (Mainline Screening Case)

500 Vehicles per Hour

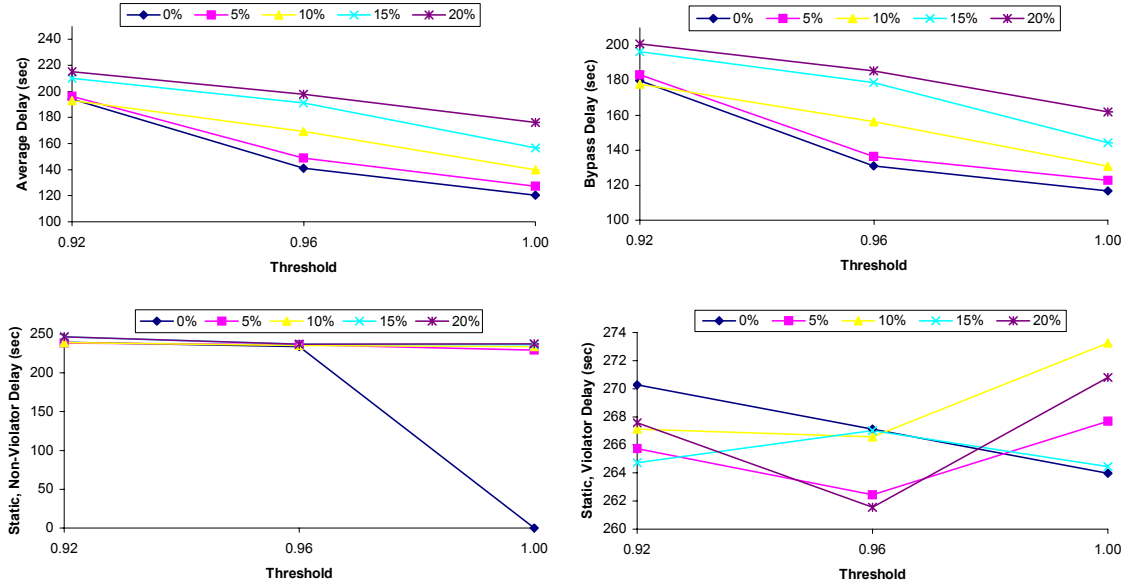


Figure 25: Vehicle Travel Time with Demand of 500 veh/h (Mainline Screening Case)

600 Vehicles per Hour

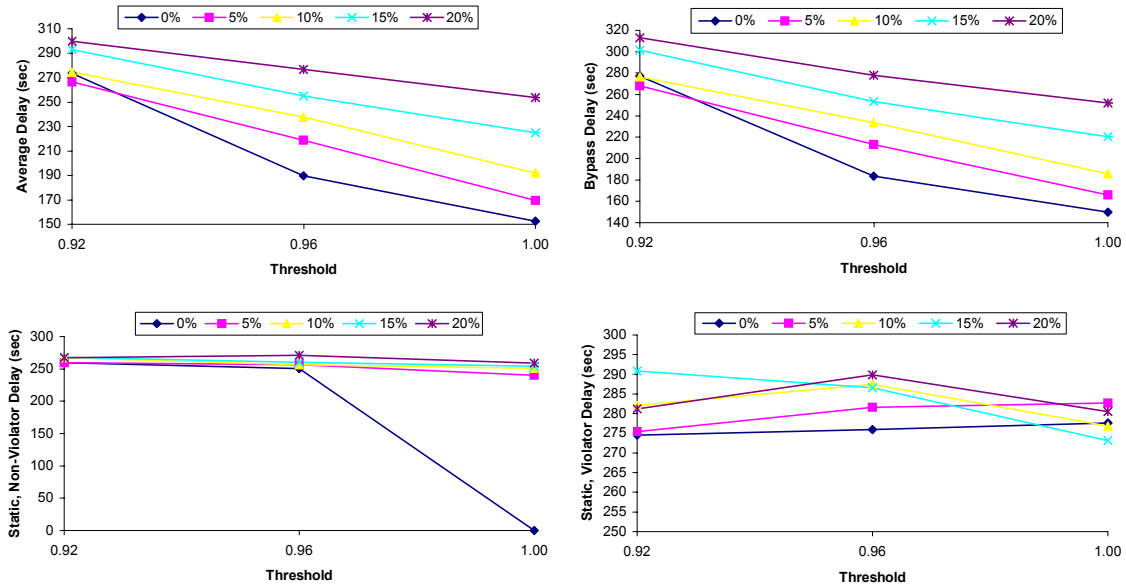


Figure 26: Vehicle Travel Time with Demand of 600 veh/h (Mainline Screening Case)

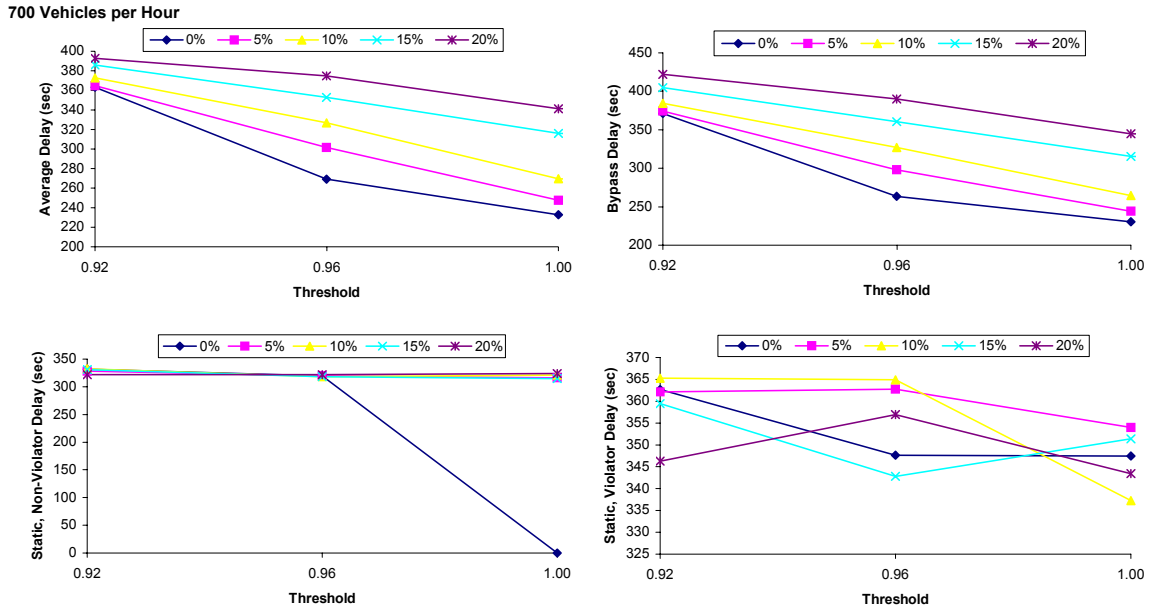


Figure 27: Vehicle Travel Time with Demand of 700 veh/h (Mainline Screening Case)

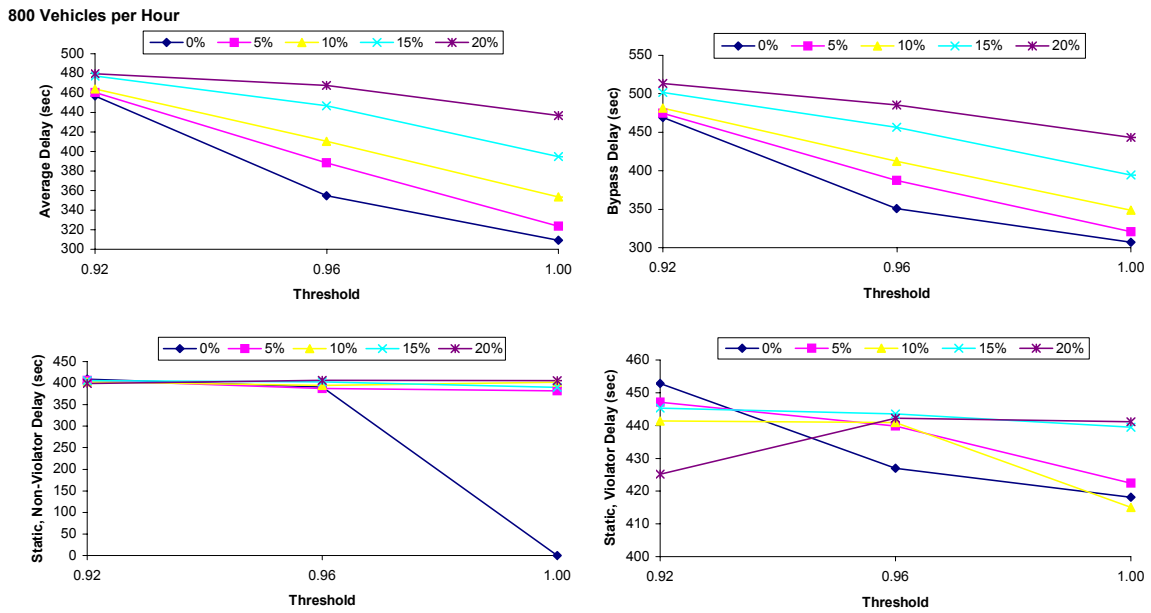


Figure 28: Vehicle Travel Time with Demand of 800 veh/h (Mainline Screening Case)

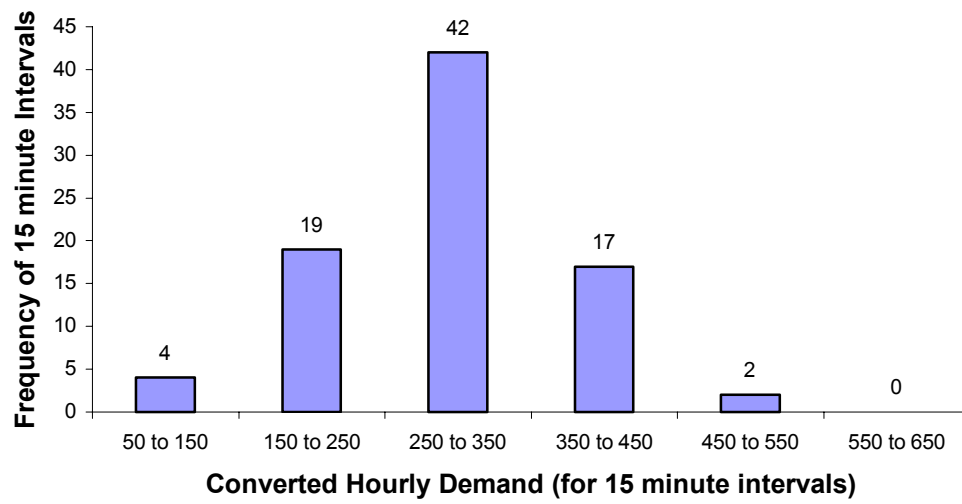


Figure 29: Frequency Distribution of Demand Levels