FIELD AND MODELING FRAMEWORK FOR EVALUATING TRUCK WEIGH STATION OPERATIONS

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FIELD AND MODELING EVALUATION OF A WEIGH STATION FACILITY

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ABSTRACT

Weigh-in-Motion (WIM) systems improve the capacity of weigh station operations significantly by screening trucks while traveling at high speeds and only requiring trucks within a threshold of a maximum permissible gross of axle weight to be weighed on more accurate static scales. Consequently, the operation of a weigh station is highly dependent on the accuracy of the screening WIM system. This thesis develops a procedure for relating axle accuracy to gross vehicle accuracy and develops a field and modeling framework for evaluating weigh station operations. The WIM scale operation at the Stephens City weigh station in Virginia is examined to demonstrate how the field and modeling framework can be applied to evaluate the operation of a weigh station. Specifically, the field evaluation evaluated the accuracy of the WIM technology in addition to the operations of the weigh station in terms of service time, system time, and delay incurred at the static scales. During the field evaluation of the Stephens City WIM load cell system, the WIM technology was found to estimate truck weights to within 6 and 7 percent of the static weights 95 percent of the time. The modeling framework provides a methodology that can be used to determine the effects of the truck demand, the WIM accuracy, the system threshold, and the WIM calibration on system performance. The number of vehicles sent to the static scale and bypass lanes as well as the amount of delay experienced were analyzed for various system characteristics. The proposed framework can be utilized to estimate vehicle delay at a weigh station.

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DEDICATIONS

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INTRODUCTION

1.1 PROBLEM OVERVIEW

The weights of trucks govern the design requirements for highway infrastructure such as roads and bridges. To enforce the weight limit requirements in different localities, weigh stations have been traditionally used to weigh vehicles and impose fines and/or penalties for exceeding weight limits. When queue lengths extended from the ramps into the mainline lanes on the highway, trucks would be turned away from weigh stations solely because there wasn't enough capacity. When trucks are turned away, enforcement levels are reduced and overweight vehicles would be able to continue traveling on the highway.

In the past twenty years, states have utilized Weigh-in-Motion (WIM) technology to reduce delay and increase enforcement of overweight vehicles. Weigh-in-Motion is defined by the American Society for Testing and Materials (ASTM) as the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces. Through WIM technology, trucks can be weighed dynamically and based on the estimated weight, the vehicle can be signaled to enter a static scale for a more accurate measurement.

Although WIM has improved weigh station operations, there are various types of WIM scales with various levels of accuracy. As accuracy decreases, the number of vehicles that must enter the static scale increases in order to ensure that all potential overweight vehicles are weighed on the static scale. Additionally, if the WIM underestimates a vehicle's weight, violating trucks could potentially go through the system without being stopped.

This thesis is based on a case study of a weigh station in Stephens City, Virginia. The relationship between WIM system accuracy and system operations will be analyzed beginning with a field evaluation of the accuracy and its impacts on operational characteristics, followed by a modeling evaluation of different scenarios using a sensitivity analysis.

1.2 THESIS OBJECTIVES

There are two major objectives to this thesis. First, is quantify the quality of weigh station operations as a function of the Weigh-in-Motion accuracy at the Stephens City Weigh Station. Second, is to develop a framework for the modeling of a weigh station operation. The framework is applied to the Stephens City Weigh Station. The model is used to analyze the current situation and to determine how differing WIM systems with various levels of accuracy would impact the operation of the weigh station.

1.3 RESEARCH APPROACH

The literature review consists of an analysis of various technical papers and other information sources in order to analyze the State-of-Practice technologies and emerging technologies. Topics investigated include the standards set by the American Society for Testing and Materials (ASTM), an overview of the major types of WIM systems, a comparison of the major types in terms of operational characteristics as well as accuracy, and calibration techniques. Then, emerging technologies will be discussed followed by design considerations and operational characteristics of WIM systems. The literature review serves the purpose of understanding the strengths and shortcomings of WIM technology.

The field evaluation at the Stephens City Weigh Station examines the operations of the WIM system using two video cameras set up to measure arrival rates and to monitor arrival rates and to establish a time stamp of trucks for determining a total system time for trucks sent to the static scale. One camera is positioned to concentrate on the diversion point between where trucks are forced to enter the static scale or to remain in the bypass lane. The second camera is positioned to concentrate on the merge point where the two lanes meet again after the static scale. Additionally, cameras were positioned to concentrate on the static scale to determine the service time required for each truck in the system. Data were also obtained using software obtained from International Road Dynamics (IRD), the manufacturer of the WIM system. The data list each truck, lane use, speed, weight, and other information. This data were also used to analyze trends for various times of day as well as days of the week. The static scale weight was manually recorded and compared to the WIM weight in order to determine the accuracy of the WIM scale. Establishing the accuracy and performance of the system provides a benchmark for further sensitivity analyses using analytical and simulation tools to quantify the impact on weigh station operation.

The modeling portion of the thesis is performed using the Integration simulation software package. Traffic volumes as well as the number of trucks sent to each lane and geometric characteristics are used as inputs in the model. The model is then fine tuned to best fit the travel time patterns and delay experienced in the field. After fine-tuning the model, several runs are performed in order to determine the possible effects on system performance that a more accurate WIM system would achieve. From the results, an organization would be able to determine which level of accuracy in a WIM system would be required to best fit the needs of their particular system.

The proposed methodology is applied to the Stephens City weigh station in the state of Virginia, which is located in the northern part of the state near milepost 304 on Interstate 81. Data collection took place on the northbound scale for three days and the southbound scale for one day. An additional day was used to determine service times in both directions for vehicles on the static scale.

1.4 THESIS CONTRIBUTIONS

Although research has been done in analyzing design characteristics of WIM systems as well as accuracy of WIM systems, there is a lack of information as to how the accuracy affects the operations at a weigh station. The goals of this thesis are to be able to quantify the impact of WIM system accuracy on weigh station operations through the analysis of travel time and delay characteristics as well as to determine the operational characteristics for various WIM system configurations and levels of accuracy.

1.5 THESIS LAYOUT

Following the introduction (Chapter One), Chapter Two will contain a literature review of research on existing and emerging WIM systems. Chapter Three of the thesis will be a paper on the field evaluation of WIM system accuracy and the impacts on weigh station operations. Next, Chapter Four will be a paper on the modeling evaluation of WIM system accuracy and the impacts on weigh station operations. Chapter Five will conclude the thesis with conclusions and recommendations for further research.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

Pavement and bridge structure design is based on the weights of the heavy vehicles traveling on a highway. Weigh stations have been in operation for many years for the purpose of ensuring that trucks do not exceed the legal weights of the localities that are being traveled through. Unfortunately, as the amount of trucks on highways increases, the queue lengths at the weigh stations also increase. When weigh station queues spill back on to the mainline travel lanes, the weigh stations are generally closed and violators can potentially go through the system. As a way of speeding up the process of weighing these heavy vehicles, WIM systems have been installed in many places to screen overweight vehicles (Laurita *et al*., 1994).

Weigh-in-Motion is defined by the ASTM as the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces (1994). Consequently, ASTM defines a WIM system as a set of sensors and supporting instruments which measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates tire loads, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information.

Weigh-in-Motion systems generally have four elements (Laurita *et al*., 1994). The roadway component includes detectors to check for vehicle presence as well as for vehicle speed, a WIM scale, and a height detector. The computer component consists of a desktop computer, a display, and a printer. The signalization component consists of a control assembly, directional signals, and variable message signs. Finally, the tracking component consists of a series of inductive loops.

2.2 STATE OF PRACTICE WIM TECHNOLOGIES

Weigh-in-Motion systems are classified in to four different types according to the ASTM specification E 1318-94 (ASTM 1994). Some of the existing technologies used in WIM scales are bending plates, piezoelectric sensors, and load cells. Recently, research has also been made in determining vehicle weight by pavement strain; however, this technology has not been widely utilized. In each of the systems, a site processor is used to sort and analyze the information obtained from the WIM sensors. Then, a communication device such as a modem is used to send the information to outside locations for further calculation and to assure that the system is operating properly. Operating software must also be used to interpret the signals from the WIM sensors and to be able to generate files that can be used and analyzed by monitoring agencies.

2.2.1 ASTM Classifications

ASTM classifies four types of WIM systems by speed range, type of application, and other desired characteristics. Table 2.1 illustrates the basic differences between each ASTM type (McCall *et al*., 1997). ASTM Type I and Type II WIM systems are used for traffic data collection and are used in up to four lanes of travel with speeds between 10 and 70 mph (16 and 113 km/h). ASTM Type III and IV WIM systems are used for weight enforcement in up to two lanes of travel with speeds between 15 and 50 mph (24 and 80 km/h) for Type III and speeds between 0 and 10 mph (0 to 16 km/h) for Type IV (McCall *et al*., 1997, and ASTM, 1997). Table 2.1 summarizes the major differences between each type of ASTM WIM system classifications.

Table 2.1: ASTM Weigh-in-Motion System Types

	CLASSIFICATION			
	Type I	Type II	Type III	Type IV
Speed Range	10-70 mph (16-113 km/h)	10-70 mph (16-113 km/h)	15-50 mph (24-80 km/h)	0-10 mph (0-16 km/h)
Application	traffic data collection	traffic data collection	Weight enforcement station	weight enforcement station
Number of Lanes	up to four	up to four	up to two	up to two
Bending Plate	X	X	X	X
Piezoelectric Sensor	X	X		
Load Cell	X	X	X	X
Wheel Load	X		X	X
Axle Load	X	X	X	X
Axle-Group Load	X	X	X	X
Gross Vehicle Weight	X	X	X	X
Speed	X	X	X	X
Center-to-Center Axle Spacing	X	X	X	X
Vehicle Class	X	X		
Site Identification Code	X	X	X	X
Lane and Direction of Travel	X	X	X	
Date and Time of Passage	X	X	X	X
Sequential Vehicle Record Number	X	X	X	X
Wheelbase	X	X		
Equivalent Single-Axle Load	X	X		
Violation Code	X	X	X	X

Source: FHWA "States' Successful Practices Weigh-in-Motion Handbook" and ASTM E 1318

2.2.2 Bending Plate System

A bending plate weigh-in-motion system is based on plates that contain strain gauges attached to it (McCall *et al*., 1997). These systems can be either portable or permanent, depending on the application. The dynamic load is calculated using the strain readings when a vehicle travels over the plates. Using calibration procedures and the measured dynamic load, the static load is determined. Depending on the intended usage, a bending plate system can be classified as ASTM Type I, II, III, or IV.

Bending plate systems can contain either one or two scales placed in the travel lanes perpendicular to the direction of travel. When two scales are used, a scale is used in each wheel path either side by side or spread out by 16 feet (5 meters). Additionally, two inductive loops are used upstream and downstream from the scales to determine the presence of a vehicle and to determine vehicle speeds. Similar to other WIM systems, data is analyzed by the site processor using the operating software and saved in an output format through a physical download on site or through a modem.

2.2.3 Piezoelectric System

A piezoelectric WIM system records the change in voltage induced as a vehicle passes over piezo sensors (McCall *et al*., 1997). This type of system is classified as an ASTM Type I or Type II depending on the number of sensors used and the intended information needed. A dynamic load is calculated from the readings through the sensors and from this information and calibration procedures, a static load is estimated.

When installing a piezoelectric system, sensors are placed in the pavement perpendicular to the travel lane (Ali *et al.,* 1994). The sensors span across the travel lane so that both tires ride across the surface. Inductive loops are also used to detect vehicles and to determine vehicle speeds and axle spacing. Again, this information can be analyzed from a site processor with operating software and can be saved in a manner so that the information can be downloaded on site or through a computer.

2.2.4 Load Cell System

In a load cell WIM system, a load cell is placed across the traffic lane (McCall *et al*., 1997). Each load cell has two scales that detect an axle and weigh both the right and left sides at the same time. Then, a sum is taken of the two scales in order to determine an axle weight. Depending on the design of the system, it can be classified as ASTM Type I, II, III, or IV. Generally, at least one inductive loop and one axle sensor is installed with the inductive loop upstream to determine when vehicles will be approaching the system. If a second loop is used, axle spacings will be used to determine vehicle speed. Again, the data is analyzed from the site processor and software and saved in a format available for download.

2.2.5 Comparison of WIM Technologies

Each of the three primary WIM systems has different costs, life spans, and accuracies. For example, Bushman and Pratt compared the three types of technologies with respect to accuracy, life span and cost, as summarized in Table 2.2. The study concluded that the piezoelectric systems are the least accurate at of the three technologies ±15% and also offer the lowest expected life span at 4 years. In general, the study concluded that as the accuracy of the system increases, the cost increases; however, the system also has a longer expected life span. The most accurate system analyzed was the single load cell system with 6 percent accuracy at a 95 percent confidence level and offers the longest life span. However, the single load cell system has an installation cost of more than double the bending plate system.

Table 2.2: Comparison of Common WIM Technologies

	Piezoelectric	**Bending Plate**	**Single Load Cell**
Accuracy (95% confidence)	± 15 %	± 10 %	± 6 %
Expected Life	4 Years	6 Years	12 Years
Initial Installation Cost	$9,000	$21,500	$48,700
Annual Life Cycle Cost	$4,750	$6,400	$8,300

2.2.6 Other WIM Technologies

Several other WIM technologies exist other than the common load cell, piezoelectric sensor, and bending plate systems. In a study done in Australia, vertical strain transducers were placed in 50-millimeter holes drilled into a dense fine sand subgrade (Marsh *et al.*, 1994). The holes along with axle detector tapes and a data collection system make up the system known as PAVWAY. The results showed that for a series of test runs, repeatable results for wheels on the same path could be obtained. The response at various speeds was also the same, and 12 months after installation showed accurate data as well. However, there exists a significant difference in response between summer and winter periods. The tests showed that a standard deviation of about 6% from the mean axle weight in 20 axle groups with random vehicles.

2.3 ACCURACY AND CALIBRATION OF WIM SYSTEMS

Accuracy in terms of weigh-in-motion refers to the closeness between a quantity measured or estimated by a WIM system and an accepted reference value (ASTM, 1997). It is important to decide the necessary accuracy needed before deciding the type of WIM to purchase. The ASTM gives accuracy limits for each type of WIM system as a standard to be set. Additionally, there have been many experimental studies to show the level of accuracy of the various WIM systems.

2.3.1 ASTM Accuracy Guidelines

The American Society for Testing and Materials (ASTM) establishes functional requirements for WIM system accuracy. Table 2.3 illustrates these functional performance requirements. As shown in the table, Types I, II, and III tolerances are given in terms of percentage of the original known value and for Type IV the tolerance is given in terms of the number of pounds over or under the actual weight.

Table 2.3: Comparison of WIM Technologies

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				Value □ lb (kg)	± lb (kg)
Wheel Load	± 25%		± 20%	5000 (2300)	250 (100)
Axle Load	± 20%	± 30%	± 15%	12,000 (5400)	500 (200)
Axle-Group Load	± 15%	± 20%	± 10%	25,000 (11,300)	1200 (500)
Gross-Vehicle Weight	± 10%	± 15%	± 6%	60,000 (27,200)	2500 (1100)
Speed	± 1 mph (2km/h)				
Axle-Spacing	± 0.5 ft (150mm)				

Source: ASTM Designation E 1318

Guidelines given by the ASTM do not only go into detail concerning accuracy guidelines for existing systems but also consider procedures for acceptance testing of new systems. For testing a Type I or Type II system, it is recommended that two vehicles loaded with a non-shifting load plus 51 additional vehicles that are selected from the traffic stream be utilized. The two test vehicles make multiple passes over the WIM sensors at a minimum speed, a maximum speed, and an intermediate speed. This allows for the evaluation of WIM systems over the full range of speeds and allows for making sure that reference values of tire-load measurement procedures give values that can be reproduced. The other vehicles are used to subject the system to various vehicle classes, just as it would be used in the travel stream. For a Type III system, the system must be able to detect a weight-limit or load-limit violation as well as control traffic control devices to direct overweight vehicles to a static scale and to allow other vehicles to proceed. Test loading allows variability and accuracy to be analyzed. All vehicles used for test loading must be weighed statically at certified scales at the location in which the acceptance test is performed. For a Type IV system, the acceptance test determines whether or not the system produces results consistent with the tolerance levels shown above. This should be tested using test vehicles at a static speed and up to 10 mph (16 km/h). The overall method for measuring accuracy is thus essentially the same.

2.3.2 Evaluating WIM Accuracy

Papagiannakis *et al*. (1996) have developed a procedure for evaluating the accuracy of WIM systems. Traditional procedure evaluates WIM accuracy with respect to static axle loads and static gross vehicle weights. However, in motion axle loads are much different from static axle loads. In the recommended procedure, the roadway roughness is measured as well as the average of the elevation of the two wheel paths for use in simulation. Then, a number of test trucks of at least five axles and with each truck at least five replicate runs should be made at the speed limit, the speed limit minus 20 km/h, the speed limit minus 10 km/h, and the speed limit plus 10 km/h. Next, the data should be analyzed and a coefficient of variation should be calculated. This value gives the error due to the machine. To find the error due to axle dynamics, the data for each test truck can then be put into VESYMF and PAREST software. The VESYMF simulation can be analyzed with another program known as HIST to calculate the probabilities of various

WIM measurements. This probability can be compared to a determined confidence level and based on whether or not the data qualifies, the WIM system can be termed accurate or not accurate based on the combination of the machine error and the error due to axle dynamics.

2.3.3 Inaccuracy of WIM Systems

In a study evaluating WIM systems in the province of Manitoba, Canada, it is shown that the results indicate large numbers of unreasonable data (Zhi et al 1999). Specifically, the results showed that WIM axle-spacing data were outside the 95 percent conformity values specified by the ASTM. The study also indicated that five to nine axle combination trucks yielded more accurate values than two and three axle vehicles. In the survey period, about 90 percent of truck weights were underestimated and the degree of underestimation was higher than 50 percent of the static weights. The study concluded that these errors occurred due to unstandardized calibration procedures and a drift in calibration over time. A further explanation was the fact that in an ideal situation, "the force is applied to a smooth and level road surface by perfectly round and dynamically balanced rolling wheels at constant speed in a vacuum". Obviously, this situation does not exist in real applications and thus error is induced. Additionally, axle spacing records were evaluated to determine whether or not the truck was classified correctly. The evaluation indicated that axle-spacing records were outside the 95 percent conformity range with a mean difference of 0.6 percent for inter-axle-spacing and 4.7 percent for axle unit spacing. The system classified over 95 percent of the vehicles accurately but significant errors were found in two specific truck classes. The percentage difference was defined in the study as the difference between the static weight and the WIM weight divided by the static weight. The study suggested that a standard calibration technique be established and that a relationship be determined between the monitoring period and the precision of WIM results.

2.3.4 Overcoming the Inaccuracies: WIM Calibration

In order to ensure that WIM systems give estimated weights that are as close as possible to the actual static weights, a calibration procedure is required. Factors such as pavement temperature, vehicle speed, and pavement conditions affect the estimated weight. ASTM recommends a procedure that includes acceptance testing and then a recalibration process for fine-tuning.

The errors incurred at a WIM facility are a combination of random errors and system errors. Factors such as loads, suspension, and tires make up random errors while factors such as vehicle type and axle location make up system errors. Statistical process control can be used to analyze the system errors through algorithms to correct the problems as well as in order to determine a factor to be used for calibration purposes. The procedure of statistical process control has been successful at minimizing error due to calibration drift of WIM facilities (Han *et al*., 1995).

2.3.5 ASTM Calibration Procedures

ASTM procedures recommend an eight-step process to calibrate WIM systems (ASTM). First, all WIM system settings should be adjusted to the vendor's recommendations or to a best estimate of proper setting based on previous experience. Second, vehicles that go through the system for calibration purposes must be forced into the static scales at the site or a nearby facility to obtain static weight data. With a radar gun or other means, speed data should be taken to measure the speed that the truck moves through the WIM sensors. Third, tire loads and axle spacing should be recorded at the static scales. Fourth, the difference should be calculated between the WIM system estimate and the reference value for the speeds, wheel loads, axle loads, axle group loads, gross vehicle weights, and axle spacing measurements. The differences should be expressed in percents and a mean value should be obtained for each set of measurements. Fifth, the calibration factors should be entered into the WIM system. Sixth, it should be determined whether or not the calibrated system can be expected to perform at the necessary tolerances. Seventh, if a large number of differences for the data occurs and does not meet the tolerances levels shown in the ASTM values for the specified system, the system will most likely not perform to a beneficial level. Eighth, precision and bias information should be noted although at this time, no procedure has been developed to determine what effect this data has on WIM system performance.

2.3.6 Caltrans Calibration Procedures

In the *States' Successful Practices Weigh-in-Motion Handbook*, the calibration procedures used by Caltrans are illustrated for a bending plate WIM system (McCall *et al*., 1997). The acceptance testing phase is done before the system becomes operable. This portion takes three stages including a system component operation check, the initial calibration process, and the 72-hour continuous operation check.

In the system component operation check, the roadway sensors and the on-site controller are observed using real-time reviewing capabilities. If there are inconsistencies in the tests, then there might be a problem with the system component. After the component check is completed, an initial calibration check is performed. Caltrans performs this test with only one vehicle although ASTM recommends a minimum of 13 test vehicles. First, the WIM weight, axle spacing, and overall vehicle length settings are adjusted using typical trucks in the traffic stream. Second, the test vehicle makes several runs in the WIM equipped lanes to check weights and axle spacing factors. The axle spacing factors predict speed, so it is important that this information be accurate. Third, the test truck drives over the WIM sensors in each lane at least three times at 5 mph (8 km/h) increments from 45 to 65 mph (72 to 105 km/h). The percentage error of the gross weight is calculated and plotted. The graphs can be used to adjust the WIM weight factors. After the factor is adjusted, the test truck makes two more runs to determine if the accuracy level meets Caltrans specifications. Finally, the 72-hour continuous operation check is performed. The data is analyzed through a thorough data review and once it is determined that the system is working on a continuous basis, the system is accepted and placed online.

In the fine-tuning and recalibration portion of the procedure, the parameters are adjusted when problems are encountered in a Quality Control procedure that are observed by conducting a real time review followed by a two level data review. Once the problems are discovered, methods for solving them can be found and then be tested for accuracy.

2.3.7 Minnesota DOT Calibration Procedures

Weigh-in-Motion systems are re-calibrated in Minnesota through a computerized program that is based on data from the front axles of five-axle semis (McCall *et al.*, 1997). This process is used individually on each travel lane that the WIM system is installed. First, the system is calibrated through a test truck. Then, the system operates for a week and tests the data. Tests are done to find the peak values of loaded and unloaded trucks and if the peak gross vehicle weights occur at reasonable levels, the system is considered calibrated. If the percentage falls off of the desired level, the system is then re-calibrated through the automatic process. Also, if the front axle weights deviate from the reasonable levels with respect to the total gross vehicle weight, the system is recalibrated. The correction factor obtained in the software is multiplied by the sensor weight factor to determine a new sensor weight factor.

2.4 EMERGING WIM SYSTEM TECHNOLOGIES

New technologies involving WIM systems include new methods of estimating vehicle weights as well as the usage of Automatic Vehicle Identification (AVI) to minimize delay to trucks at WIM facilities. Newer forms of technology for estimating vehicle weights include a new technology developed by Omni Weight Corporation known as the OWC WIM system. The Automatic Vehicle Identification (AVI) system has already been used to a limited extent in some locations, but it is expected that most WIM systems will eventually move to this new technology.

2.4.1 Automatic Vehicle Identification Systems

In an AVI system, vehicles using the system carrying legal weights are able to bypass the weigh station (Barnett *et al.*, 1999). In this scenario, a WIM system is located upstream of a weigh station and the trucks are weighed with other vehicles at highway speeds. A transponder inside the truck is signaled by an antenna along the roadway that identifies the truck's information. If the truck is recognized by the computer database and is deemed to be under the weight limit, the truck is allowed to pass through. This information is sent to the transponder through a second antenna downstream of the first antenna. The responder through audio or visual alert tells the driver whether or not it is necessary to enter the weigh station. It is estimated that through this technology, the number of times that a truck enters or exits the roadway will be decreased and thus a reduction in accident rates should occur as well.

2.4.2 Mainline Screening WIM Systems

Another method used to minimize delay to truck drivers at weigh stations is the installation of mainline screening WIM systems. With mainline screening, trucks are monitored at freeway speeds and sent in to the Weigh Station only when there is a need to statically weigh the vehicle (International Road Dynamics, 2001). The truck would use the right-hand lane and using a combination of WIM sensors and AVI technology to determine whether the truck would need to bypass the static scale or to report to the static scale. Overhead signals or roadside signs notify the truck driver to let them know whether or not to bypass the static scale.

2.4.3 Omni Weight Corporation Safe Load System

The Omni Weight Corporation has developed a WIM scale known as the Safe Load System WIM Dynamic Scale Automated Truck Weigh Station (Omni Weight Corporation). The system is being installed on the Smart Road in Blacksburg, Virginia and being monitored by the Virginia Tech Transportation Institute. The Safe Load System was developed under ASTM guidelines as a Type III and IV WIM System. The system claims to save capital cost in installation by not requiring concrete slabs for the WIM sensors, provide weighing and classification software in one element, and provide a maintenance free rugged element without load bearing sensors.

2.5 WIM FACILITY DESIGN CONSIDERATIONS

Although the actual characteristics of different methods of weighing trucks in motion are different, the layout and the considerations that should be made are essentially the same. In all instances, cost will most likely be a key concern, but it is also important to analyze the location that is chosen for the WIM system. In cases where a long design life for pavements is established, the reliance on the WIM data will most likely be high. Additionally, the design speed is an important issue in designing the geometrics of a WIM facility.

2.5.1 WIM Considerations in New Jersey and Delaware

Weigh-in-Motion technology has been used successfully in New Jersey and Delaware for truck weight regulation (Laurita *et al.*, 1994). Both the New Jersey Department of Transportation and the Delaware Department of Transportation believe WIM systems are beneficial to screen and sort heavy vehicles to be weighed statically or to exit the system. In New Jersey, the stations are designed to weigh trucks at speeds up to 35 miles per hour and collecting data on vehicle speed, axle weights, and height. Only borderline trucks are designed to be weighed statically, thus increasing station capacity.

The design of WIM systems in New Jersey as well as most other locations share similar considerations such as initial capital cost, public opinion, land use, permit requirements, and maintenance costs. However, the location in which the stations are located also is an important factor. For example, it was determined that it was possible for truck drivers to avoid a station on Interstate 295 by using local roads. Police patrols were planned to monitor four alternate routes with portable piezoelectric sensors.

In Delaware, Greenman-Pedersen, Inc. developed a study to evaluate a medium to high speed WIM system for US Highway 13 and a proposed State Relief Route 1. The Delaware DOT has criteria that must be met including a single weigh station to be used for both highways, avoiding environmental impact, minimizing avoidance of the weigh station, avoiding the need to weigh all trucks statically, and minimizing the staffing requirements needed. Additionally, weigh stations are important for increasing pavement life because Delaware uses a 40-year design life as opposed to the standard 20-year design life used by other DOTs. Given the criteria, it was determined that a WIM system would best satisfy all of the above criteria.

2.5.2 Illinois WIM Facility Design Standards

Because of the rapid growth in the trucking industry, Illinois was faced with a problem of excessive delays at weigh stations with trucks backing up the ramp and onto the interstate (Coffinbargar, 1990). The design truck volume was for 5% of the average daily traffic, but recent figures show an actual truck volume of 25% to 40% of the average daily traffic. The WIM system is programmed to direct vehicles if it is within 10 percent of the legal limit or exceeds the limit, if the vehicle travels over the sensor at an improper speed, if the truck is not aligned correctly on the scale, or if a 100 foot (30.5 meter) spacing requirement is not met. The three basic design components of Illinois based facilities are the deceleration length, signal zone, and a deceleration and storage distance for the static scale. Figure 2-1 shows a typical Illinois WIM system layout.

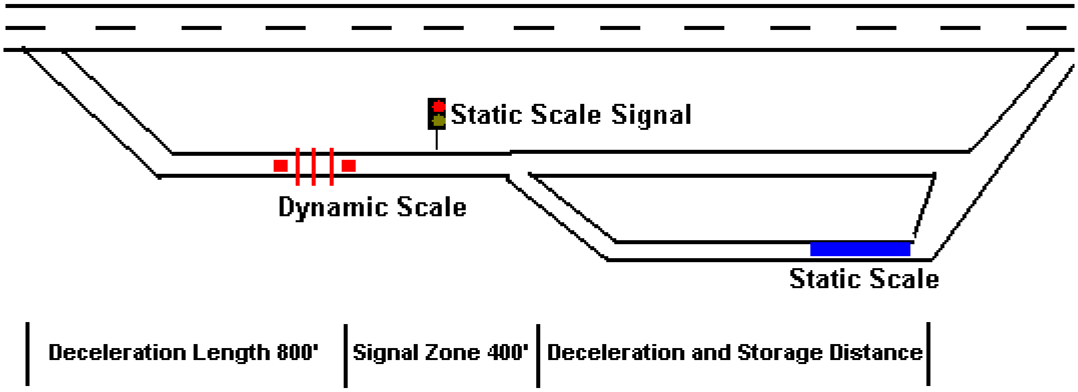


Figure 2-1: Typical Illinois WIM System Layout

Illinois typically uses a 30 mph (48.3 km/h) design speed for their WIM facilities. The length required to decelerate from 55 mph (88.5 km/h) to 30 mph (48.3 km/h) is 575 feet (175.3 meters) measured from the gore area of the station exit ramp. An additional 200 feet is recommended to allow for speed stabilization and to maintain the 100 feet (30.5 meters) of spacing required between vehicles. The signal zone is considered the distance between the WIM scale and the secondary signal. At the point where the truck is passing over the scale, 110 feet (33.5 meters) are passed until the signal is displayed and an additional 125 feet (38.1 meters) is needed for a 2.8 second viewing time. A secondary signal is displayed for 3.2 seconds in which the truck travels 165 feet (50.3 meters). Thus the total distance needed is 400 feet (121.9 meters). The two signals are used to ensure that for the length of time that the signal is displayed, multiple vehicles do not view the same signal. The storage length needed for the static scale is calculated through a series of equations that compute a storage length for all vehicles and 25% is taken to determine the storage length of a WIM facility.

2.6 WEIGH STATION OPERATIONS

Similar to any transportation facility, a weigh station has characteristics such as capacity and delay that show how efficient the station operates. Long vehicle queues can cause excessive delay to the facility and at times to the adjoining highway that the weigh station is monitoring. Additionally, where traffic must enter and exit a roadway, accident rates also increase. Weigh-in-Motion has the potential to increase weigh station capacity and thus can reduce queue length and system time.

2.6.1 Truck Delay at Weigh Stations

Only a few studies have evaluated the operation of a weigh station. The first of these studies was a field evaluation of the Williamsville weigh station in Springfield, Illinois (Benekohal *et al*., 1999). The study attempted to measure the delay and traffic conflicts experienced by trucks at the weigh station. The goal of the study was to quantify the delay at the weigh station in order to evaluate the effectiveness of AVI in a WIM system environment as well as to examine potential benefits of Intelligent Transportation System (ITS) technologies. In the study, delay was determined to be the difference between the ideal travel time and the observed travel time. If the delay was small, it was determined that the truck bypassed the weigh station because it was closed. Longer delays indicated that the truck was weighed at the station. The study computed an average delay of 4.95 minutes per truck that ranged from 3.56 to 6.59 minutes per truck for the various recording intervals. The maximum delay for the recording intervals ranged from 8.69 to 137.62 minutes per truck. It was found that 30 percent of the trucks were not weighed simply because queues were too long and thus were allowed to bypass the static scales in order to prevent queue spillbacks. The study also demonstrated that in many instances trucks with legal weights experienced unnecessary delays at the weigh station because they were requested to enter the static scales. Based on the conclusions of the study, the Illinois Department of Transportation considered the addition of an AVI system to the existing WIM system. The study concluded that should the weigh station integrate AVI and WIM, there would be a reduction of delays and an increase in productivity.

2.6.2 Capacity Enhancement at Weigh Stations

There is two approaches that weigh stations can increase capacity using a WIM system: mainline electronic screening and physical expansion (Kamyab, 1998). In mainline electronic screening, trucks with an AVI system are able to send information to a controller that identifies the truck and the WIM weight measurement to determine whether or not the truck needs to be stopped for further screening. A simulation was done using a microscopic, stochastic model for a before and after scenario. The second method for increasing capacity is physical expansion. With physical expansion, a ramp WIM system and bypass lane is added to allow vehicles that do not exceed the weight requirement to continue through the system without stopping. A simulation was also performed with a before and after scenario to calculate the effectiveness. Through the simulation results, it is shown that travel times will decrease as well as the number of trucks with an unauthorized bypass (not able to be weighed due to excessive queues). Physical expansion would solve the problems in a shorter amount of time, but electronic screening has the potential to permanently eliminate inefficiencies of WIM stations.

2.6.3 Accident Reduction Effects of WIM Stations with AVI Technology

In the past, truck weight enforcement has always been performed by forcing vehicles to enter and exit the highway to travel through a weigh station. The chance of accidents increases around weigh stations due to disruption of the traffic stream as well as general truck characteristics such as the need for longer deceleration distances and larger turning radii (Barnett *et al.*, 1999). A control zone was taken to include a section of roadway 3500 feet (1067 meters) before the weigh station and an influence zone was taken to include 2500 feet (762 meters) before and after the weigh station. Eight weigh stations were analyzed and the data showed that there were 38% fewer accidents in the control zones than in the influence zones. Thus, technologies using a WIM-AVI system could reduce accident levels by a maximum of 38% given the field data, should every vehicle be equipped with an AVI transponder.

2.6.4 Enforcement Measures of Effectiveness

Although it is important to consider delay and capacity at weigh stations, it is also important to look into the most important characteristic of all, enforcement. In a study by Hanscom and Goelzer (1998), measures of effectiveness of truck weight enforcement were evaluated. Traditionally, Hanscom and Goelzer point out that enforcement is merely gauged by the number of trucks weighed, the number of violators, and the amount of fines. They believe rather that "a true measure of the effectiveness of truck weight enforcement programs must indicate what, if any, real effect (i.e., improved weight law compliance, extended pavement life) is actually achieved. The measures of effectiveness were ranked based on the practicality, reliability, ability to be randomly sampled, absence of bias, compatibility with existing data collection methods, sensitivity to infrastructure damage, and use in future technology.

Based on the criteria for a measure of effectiveness, there were five main measures established that demonstrate enforcement efforts. First, the severity of the overweight violation must be considered. This could be taken to be the gross vehicle weight, axle weights, or bridge formula weights. Second, the proportion of overweight trucks in the sample should be calculated. Third, Equivalent Single Axle Loads (ESALs) should be determined as a direct measure of the effects that the vehicle has on pavement wear.

Fourth, excess ESALs should be calculated as “the sum of the total ESALs attributable to the illegal portion of the individual single or tandem axle group.” Fifth, bridge formula violations should be determined. This data serves as a more accurate way to compare enforcement measures of weigh station facilities.

2.7 SUMMARY

From the literature review, three types of WIM systems are commonly used: bending plate, piezoelectric, and load cell. The three types provide varying levels of accuracy and a different cost associated with each. Studies have shown that accuracy and calibration measures at current WIM systems are less than desirable. Additionally, a large amount of delay occurs at weigh stations, even when WIM technologies are used.

The research that has been performed has examined the accuracy and calibration problems at weigh station and additionally, the problems concerning delay are addressed. However, there is a lack of research in terms of the potential links between accuracy, calibration, and delay. One of the goals of this thesis is to examine the links between the three elements.

CHAPTER THREE:
A CASE STUDY FIELD EVALUATION OF THE ACCURACY AND OPERATION OF A TRUCK WEIGH STATION

3.1 INTRODUCTION

Chapter three describes the Stephens City weigh station configuration, operational procedures, and evaluation of data. Initially, a characterization of the truck traffic is discussed followed by an analysis of the system's accuracy. Next, an analysis of the system operations is presented followed by conclusions and recommendations for further research.

3.2 RESEARCH APPROACH

The proposed approach involved setting up two video cameras focused at the entrance and exit ramps of the static scale lane with both cameras set up in the scale house. The entrance ramp camera served two purposes. First, it measured the arrival rate at the static scale. Second, it established the time stamp of arriving trucks at the static scale, which together with the time stamp at the exit of the static scale lane was utilized to compute the total time spent in the system. In order to use this methodology at both low and high volume locations, it was important to zoom out as much as possible on the entrance camera. This ensured that entrance time as well as queuing time were considered in the system time.

The proposed methodology attempted to relate the operation of the weigh station with the accuracy of the WIM system by recording static scale and WIM weights. Comparing the static and WIM weights provided the accuracy of the WIM system. Establishing the accuracy and performance of the system provided a benchmark for further sensitivity analyses to be conducted using analytical and simulation tools that could quantify the impact of the WIM system accuracy on the weigh station operation.

The proposed methodology was applied to the Stephens City weigh station in the state of Virginia, which is located in the northern part of the state near milepost 304 on Interstate 81. Specifically, data were collected for the northbound and southbound directions, which included three days worth of data for the northbound scale and a single day's worth of data for the southbound scale. Unfortunately, it was not possible to collect further data for the southbound direction because the weigh station was under construction during the remainder of the study.

3.3 CASE STUDY DESCRIPTION

3.3.1 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 the 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 signaling 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.

3.3.2 Site Configuration

The Stephens City weigh station includes 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 to screen truck weights, as illustrated in Figure 3-1. The management of the weigh station operations is achieved by observing trucks from the tower and with the aid of computer systems. The Virginia Department of Motor Vehicles (DMV) manages the weigh station operations while the Virginia State Police enforces the state laws. Trucks must enter the station by leaving the highway through a deceleration lane. The truck driver is instructed through the use of signs to maintain a speed of 68 km/h (40 mph) and also a distance spacing of 30.5 meters (100 feet) from the preceding truck before traveling over the WIM scale. The truck then passes over the WIM scale in which axle configurations, axle weights, and gross vehicle weights are determined. A safety factor is set by the weigh station operator for the diversion of trucks to the static scales when the threshold is exceeded. Generally, this was set to be 96 percent for the Stevens City weigh station, thus if a truck screened 96 percent or higher of the gross weight limit or the axle weight limit, the truck driver 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 sorted 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 is sounded if a trucker takes the bypass lane instead of the static scale lane and a red traffic signal is also activated in the bypass lane to stop the vehicle. A tracking system consisting of loop detectors tells the weigh station operator, which trucks enter the bypass lane and which enter the static scale lane.

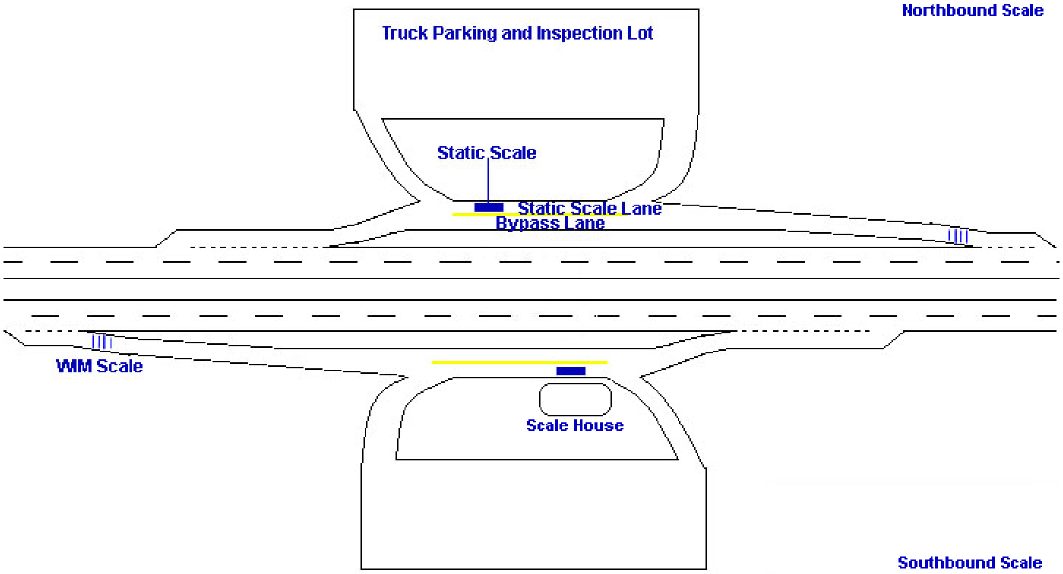


Figure 3-1: Stephens City Weigh Station Layout

3.3.3 Station Operations

Several scenarios exist for trucks that are forced to enter the static scales. Virginia state law states 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 9,070 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. For northbound traffic, the driver must walk through a tunnel under the interstate in order to reach the scale house. If a load cannot be reduced to legal limits in cases such as the hauling of large construction equipment, permits may be obtained from the Virginia Department of Transportation (VDOT). Once at the static scale, the driver is 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 are also performed by the Virginia State Police in which a truck driver is instructed to pull over an inspection pit and the truck is then inspected to ensure that the truck is properly equipped. Once the truck is ready to leave the station, the driver pulls out of the parking lot and into the static scale lane to exit. The bypass lane and static scale lane then merge together and the truck enters the acceleration lane in order to enter onto Interstate 81.

3.3.4 Data Collection

Data were gathered from the northbound and southbound scales in order to provide a basis for further comparison. Arrival data were obtained from the WIM system using software developed by the supplier, International Road Dynamics (IRD). 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.

Accuracy data were taken 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 ensure that the delay data not be influenced by the study. The time needed to perform the 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. There is no report available that the static scale can generate to produce weight by axle records. Both scales were evaluated to observe general trends between the accuracies of the gross weights of the two different scales. However, all other data included violators who were violating in any way, whether it was by gross weight or axle weight. System time data were recorded by determining the time required by trucks to travel from the point where the bypass and static scale lanes diverge to the point where the two lanes merge back together. Video cameras inside the weigh station were directed at the merge and diverge points, and later the tapes were viewed to compute the time the truck spent in the system by matching trucks at the entry and exit points. It was also determined whether or not the truck was coming from or going into the parking lot for further evaluation. In addition, service time data were obtained by videotaping the static scale operation and measuring the service time of both violating and non-violating trucks.

3.4 TRAFFIC CHARACTERIZATION

The operations of a weigh station is dependent on a number of factors that include the arrival demand, the weight distribution of trucks, the service time for violating and non-violating trucks, the geometric configuration of the weigh station, the accuracy of the WIM system, and the operator defined threshold for diverting trucks to the static scales. This section focuses on characterizing the truck traffic arriving at the weigh station. Subsequent sections characterize other aspects of the operations of the weigh station.

3.4.1 Demand and Weight Distribution Methodology

In order to understand how operations are affected by the accuracy of the system, it is important to understand the traffic that goes through the system. The truck demand, truck weights, and percentage of trucks sent into the static scale can vary by day and also by hour. This section focuses on general trends that can be observed using the data from the International Road Dynamics (IRD) software. The analysis was performed using the week from Saturday, June 9, 2001 to Sunday, June 15, 2001. No holidays fall between June 9 and June 15; therefore, the week was assumed to be fairly representative of a standard week at the weigh station. The IRD computer collected data from 12:15AM to 7:15PM every day in this period but did not collect data after 7:15PM due to an unknown error in the system.

3.4.2 Truck Demand Variation

Figure 3-2 shows the traffic volumes for all vehicles traveling through the weigh station in a 19-hour period between 12:15AM and 7:15PM. Also shown are the number of vehicles that bypassed the static scale and the number of vehicles that were sent to the static scale. In the time period analyzed, the midweek including Tuesday, Wednesday, and Thursday incurred the highest truck volume arrivals. Although the data represent only 19 hours, it is believed that daily trends would be similar. Saturday was a very slow day with just over 2000 vehicles, and perhaps this can be explained by the fact that truck drivers may try to be home for weekends arriving on Fridays (Friday was the second lightest traffic day) and then traveling on Sundays.

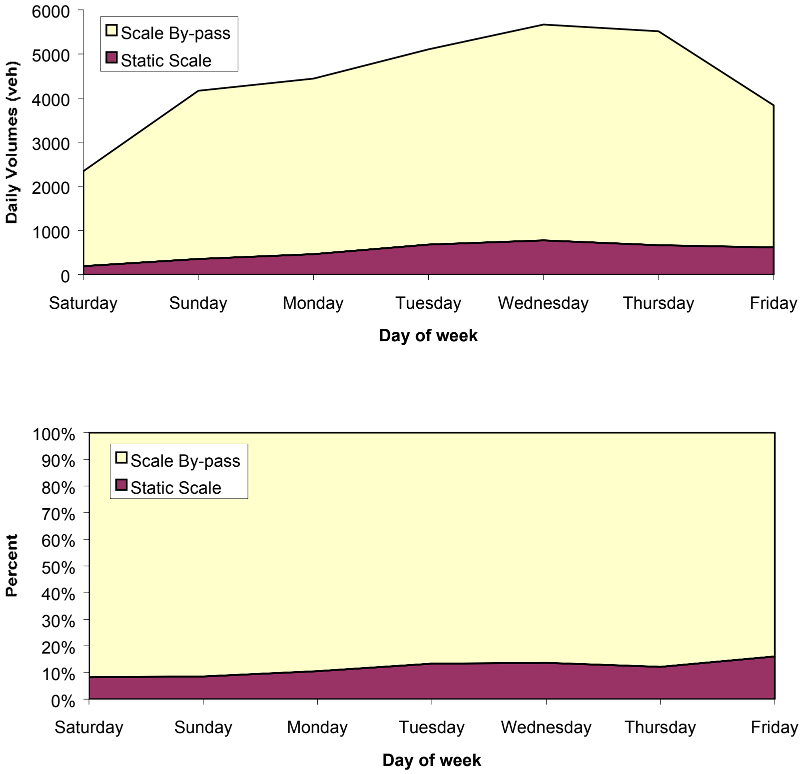
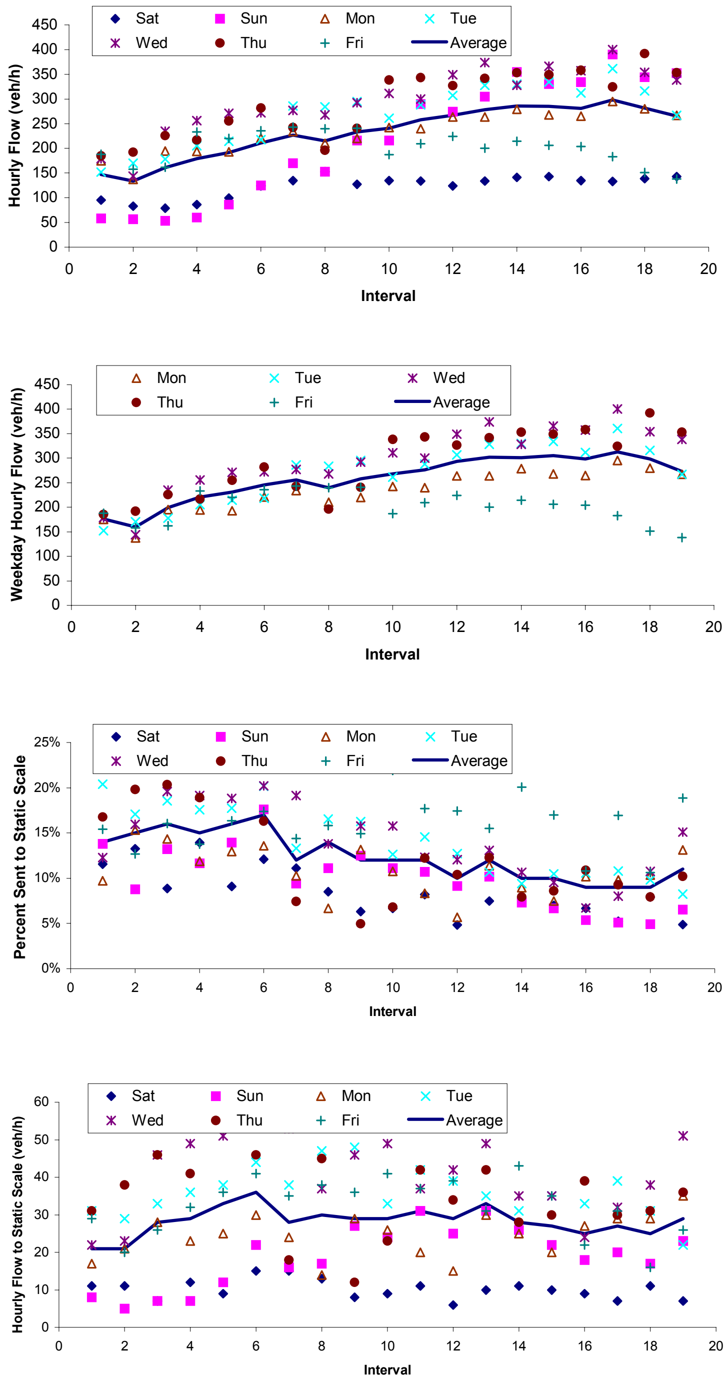


Figure 3-2: Northbound Scale Traffic Volumes (12:15PM to 7:15PM) and Percentage Sent to Static Scale

It was also important to know overall trends for each hour during the time period and this is illustrated in Figure 3-3. In the chart, "Hour 1" equates to the time period from 12:15AM to 1:15AM and "Hour 19" equates to 6:15PM to 7:15PM. The peak time period for most days appeared to be 4:15 to 5:15PM for Sunday, Monday, Tuesday, and Wednesday. The peak for Thursday came an hour later, between 5:15PM and 6:15PM. Friday and Saturday were fairly light in the same time period where the peak volumes occurred on other days. Sunday started out very light and moved up rapidly which enhanced the thought that truck drivers are home for the weekend and leave Sunday afternoon to start driving again. By looking at the weekday averages as opposed to the overall averages, it can be concluded that the weekday averages were higher but the overall trend throughout the day was similar.



Interval	Start Time	End Time
1	12:15 AM	1:15 AM
2	1:15 AM	2:15 AM
3	2:15 AM	3:15 AM
4	3:15 AM	4:15 AM
5	4:15 AM	5:15 AM
6	5:15 AM	6:15 AM
7	6:15 AM	7:15 AM
8	7:15 AM	8:15 AM
9	8:15 AM	9:15 AM
10	9:15 AM	10:15 AM
11	10:15 AM	11:15 AM
12	11:15 AM	12:15 PM
13	12:15 PM	1:15 PM
14	1:15 PM	2:15 PM
15	2:15 PM	3:15 PM
16	3:15 PM	4:15 PM
17	4:15 PM	5:15 PM
18	5:15 PM	6:15 PM
19	6:15 PM	7:15 PM

Figure 3-3: Northbound Scale Volume (All Days and Weekdays), Static Scale Volume, and Percent Sent to Static Scale by Hour

3.4.3 Truck Weight Distribution

Another important element needed to understand the operations of the station was to determine average truck weights for each hour and day of the week to determine if there was a period of time that trucks generally ran with heavier or lighter loads than other times. Figure 3-4 shows the average gross weights for each time interval and day of week. Monday consistently appeared to involve lower average gross weight for each time interval whereas Sunday generally had the highest averages. However, the difference between the high and low values only represented about an 8% difference; thus the difference was not very significant. Figure 3-4 also shows that trucks tend to run at fairly steady weights hour by hour; however, there was a high variability in the midday but more uniform in the early and late hours.

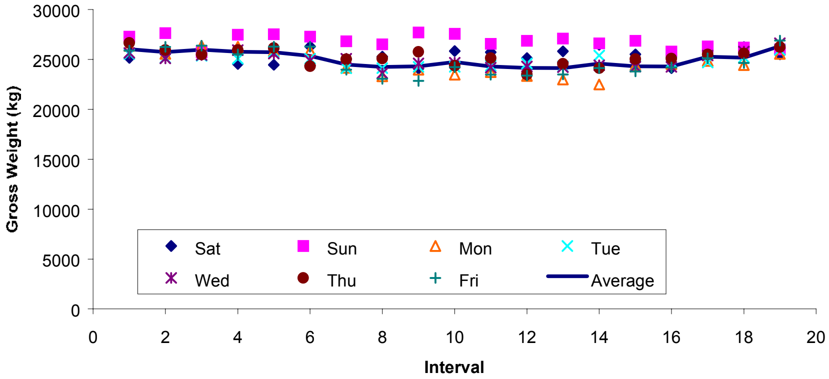


Figure 3-4: Average Hourly Northbound Truck Weight by Day and Recording Interval

3.4.4 Static Scale and Bypass Lane Distribution

To understand the operations of the static scale as opposed to the bypass lanes, it is important to show the percentages of vehicles sent into the static scale by day of week and hour of day. Figure 3-2 shows the percentage of trucks that were sent to the static scale for each day in the observation period. An average of 12% were sent to the static scale with a range from about 8% on Saturday to 16% on Friday. From Figure 3-2, it can be shown that as a general trend, a higher percentage of trucks were sent to the scale during the early morning hours and in the late afternoon. The fewest percentage were sent to the scale during the midday. The data show that the average weight and the percentage of vehicles sent to the static scale do not seem to correlate.

3.5 WIM ACCURACY ANALYSIS

The accuracy of the WIM scale was quantified by comparing gross truck weights for identical vehicles from the WIM system to static scale gross vehicle weights. Because it was not possible to obtain individual axle weights from the static scale the analysis only involved gross truck weights, however a procedure was developed to relate the axle weight accuracy to the gross truck weight accuracy, as will be described in the following sections.

3.5.1 WIM Weight Error Density Distribution

Prior to describing how the axle weight accuracy can be related to the gross vehicle weight accuracy, the probability density function of the WIM weight error is analyzed in this section. The WIM axle weight can be assumed to be a 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 true weight). Alternatively, an uncalibrated WIM 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.

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 and 95 percent confidence levels. 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 3-5. 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.

Finally, it should be noted that the data that were gathered indicated that the gross truck weight accuracy was estimated to be within 6 and 7 percent of the static scale weight 95 percent of the time for the northbound and southbound WIM scales, respectively. These results are on the borderline of the ASTM WIM specifications for Type III WIM technology (ASTM, 1997). Specifically, the ASTM standards indicate that Type III WIM functional performance requirements are ±6% with a 95% probability of conformity.

3.5.2 Monte Carlo Simulations

Prior to developing the relationship between axle and gross weight accuracy, a brief overview of a Monte Carlo type of simulation is presented. Monte Carlo methods are used to solve models, which cannot be solved using standard numerical techniques. Instead, an analogous statistical model is constructed for the desired problem. Specifically, an experiment is set up to duplicate the features of the problem under study.

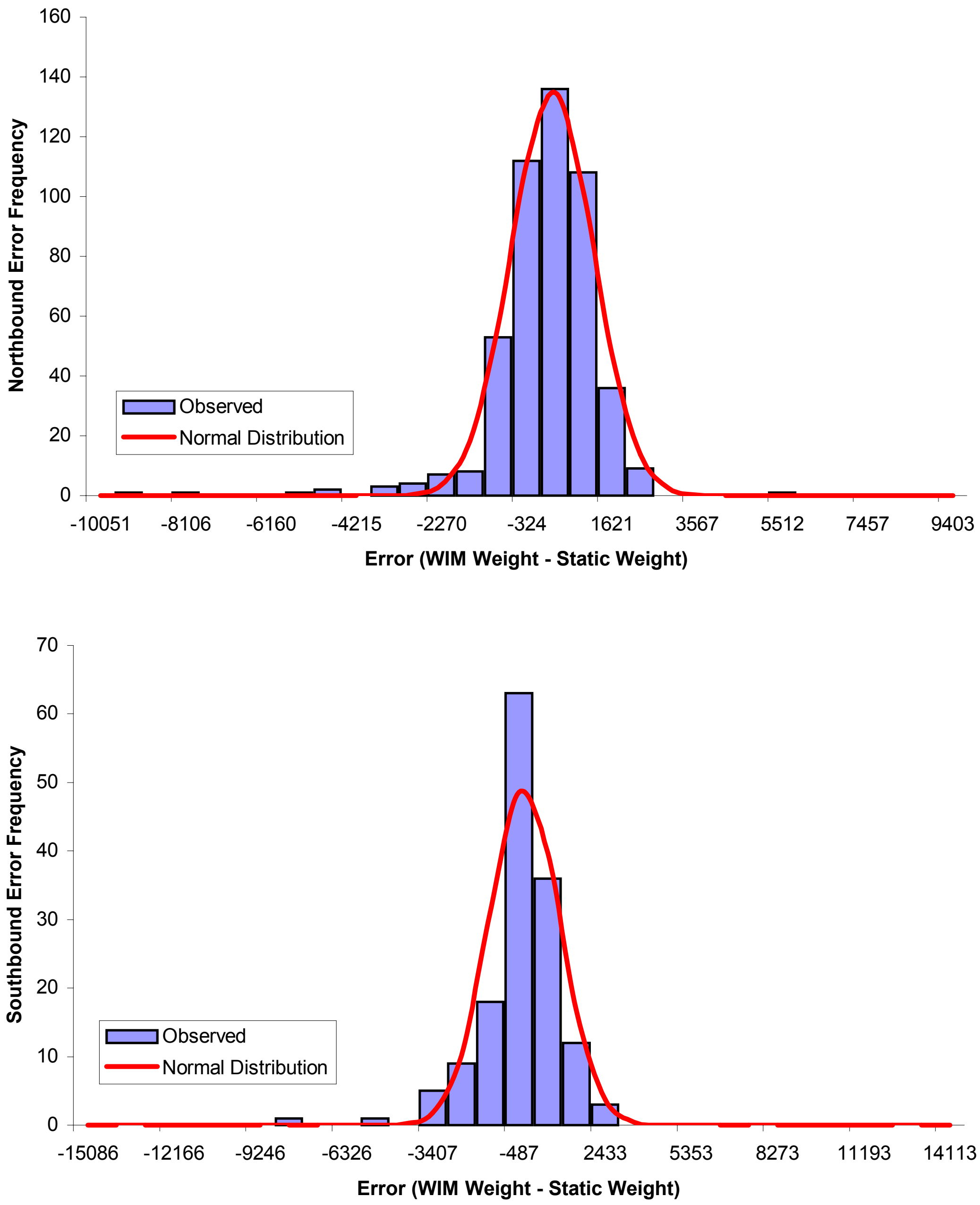


Figure 3-5: Northbound and Southbound Scale Errors

This calculation process is entirely numerical and is carried out by supplying random numbers into the system and obtaining numerical answers. Drew (1968) mentions "the idea of using random numbers was introduced by Tippett (1960), who generated 10,400 random numbers by taking the terminal digits of entries in a census table. The RAND Corporation used an electronic roulette wheel to prepare the million-digit book of random number tables (hence the name *Monte Carlo*)."

A wide variety of natural phenomena have been used to produce randomness, although some controversy exists about the validity of such procedures. However, Drew mentions that "for practical purposes, these arguments are irrelevant; one is forced to accept any phenomenon as random whose behavior is not predictable by any obvious deterministic laws and whose numbers satisfy several standard tests of randomness to ensure, for example, that each decimal digit occurs with equal frequency without any serial correlation."

A Monte Carlo method is often reserved for a procedure in which the process sampled has been modified to increase precision, whereas the term simulation is used when the process sampled is a close model of the real system. The use of Monte Carlo simulation involves generating uniformly distributed random numbers that range from 0.0 to 1.0. Subsequently, an analytic inversion of the probability cumulative distribution function is required to calculate the value of the variable that follows the desired probability density function, as illustrated in Figure 3-6. The success of this method depends on being able to integrate the density function and being able to take the inverse of the integrated function.

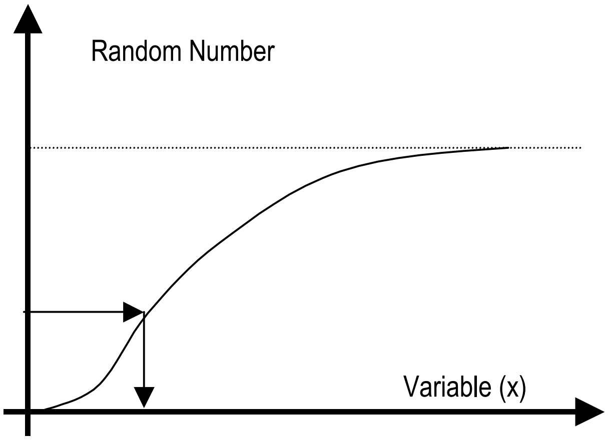


Figure 3-6: Method of Inversion Illustration

3.5.3 Relationship between Gross Vehicle and Axle Weight Accuracy

The relationship between the gross truck weight and its corresponding axle weights can be derived based on the fact that the axle weights are random variables. Using basic statistics the expected value of the gross weight is computed as the summation of the expected axle weights, as demonstrated in Equation 3-1. Furthermore, if the axle weights are assumed to be uncorrelated random variables then the variance of the vehicle gross weight is computed as the summation of the variances of the individual axle weights, as demonstrated in Equation 3-2. This simplifying assumption, while it is not necessarily valid simplifies the computation considerably because the approach does not require estimating the correlation coefficient between axle loads. If it is assumed that the accuracy of the WIM system is similar across the different axles (equal axle variances), then the standard deviation of the gross vehicle weight (square root of variance) can be computed as the square root of the number of axles multiplied by the axle weight standard deviation. Finally, the coefficient of variation (standard deviation divided by mean) for the gross vehicle weight can be computed as the coefficient of variation of the axle weight divided by the square root of the number of vehicle axles, assuming that the expectation of axle weights are approximately equal.

The validity of the proposed procedures was tested by comparing the estimated axle accuracy to ASTM standards, which specify for Type III WIM a gross vehicle weight accuracy of ±6% corresponds to an axle accuracy of ±15%. Given that the majority of trucks are classified as FHWA classification 9 (85% of the Stephens City truck volume), the use of 5 axles in Equation 3-3 would appear to be representative of the majority of trucks. A use of 5 axles for a gross vehicle accuracy of ±6% results in an axle accuracy of ±16%. Consequently, the computation clearly indicates consistency between the proposed analytical procedures and ASTM standards.

To further test the validity of the proposed analytical relationship between the axle and gross weight accuracy, an entire day's worth of data (June 13, 2001) was analyzed. The data included a total of 5,229 trucks of class 9. For each truck the axle and gross vehicle weight was available. In addition, using a Monte Carlo simulation a random number ranging from 0.0 to 1.0 was utilized to generate a random weight with mean equal to the axle weight and a user defined COV that ranged from 2.5% to 10%, as summarized in Table 3.1. The gross vehicle weight was computed by summing all axle weights. The gross vehicle weight error was then computed and compared against the analytical estimate of the gross vehicle weight accuracy. Table 3.1 demonstrates a consistency between the Monte Carlo simulated gross vehicle weight accuracy and the proposed analytical function (error less than 3.8%). Furthermore, the results are consistent for 2, 3, 4, and 5-axle vehicles. It should be noted that the assumptions that were made as part of the analytical derivation were not necessarily present in this validation effort. Specifically, differences in axle weights in the range of 50% or more were observed. In addition, the correlation between axle weights was high ranging from 0.38 to 0.95. However, the proposed analytical procedure still estimates the gross vehicle weight accuracy to a high level of precision (maximum difference of 4%).

$$\overline{w}_T = \sum_{i=1}^{n} \overline{w}_i \tag{3-1}$$

$$\sigma_T = \sqrt{\sum_{i=1}^{n} \sigma_i^2} = \sqrt{n}\sigma_i \tag{3-2}$$

$$COV_T = \frac{\sigma_T}{\overline{w}_T} = \frac{\sqrt{\sum_{i=1}^{n} \sigma_i^2}}{\sum_{i=1}^{n} \overline{w}_T} = \frac{\sqrt{n}\sigma_i}{n\overline{w}_i} = \frac{\sigma_i}{\sqrt{n}\overline{w}_i} = \frac{COV_i}{\sqrt{n}} \tag{3-3}$$

Where:

$\overline{w}_T$	Expected or mean gross vehicle weight
$\overline{w}_i$	Expected or mean weight for axle "i"
σ_T	Standard deviation of gross vehicle weight
σ_i	Weight standard deviation for axle "i"
COV_T	Coefficient of variation of gross vehicle weight
COV_i	Weight coefficient of variation for axle "i"
n	Number of vehicle axles

Table 3.1: Analytical vs. Simulated Axle Weight COV

Comparison of analytical and simulated weight COV

	Two Axles		Three Axles		Four Axles		Five Axles	
Axle Accuracy	Monte Carlo	Analytical	Monte Carlo	Analytical	Monte Carlo	Analytical	Monte Carlo	Analytical
0.025	0.018	0.018	0.015	0.014	0.013	0.013	0.011	0.011
0.050	0.036	0.035	0.030	0.029	0.026	0.025	0.023	0.022
0.075	0.054	0.053	0.044	0.043	0.039	0.038	0.034	0.034
0.100	0.072	0.071	0.059	0.058	0.052	0.050	0.046	0.045

Percent error between analytical and simulated weight COV

Axle Accuracy	Two Axles	Three Axles	Four Axles	Five Axles
0.025	-1.8%	-3.8%	-3.8%	1.6%
0.050	-1.8%	-3.8%	-3.8%	-2.8%
0.075	-1.8%	-1.6%	-3.8%	-1.3%
0.100	-1.8%	-2.1%	-3.8%	-2.8%

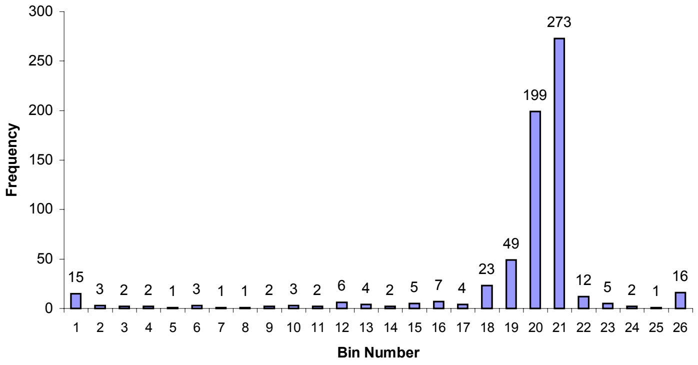
3.5.4 Frequency Distribution for Static Weight Ranges

The second step in the accuracy analysis was to study the frequency distribution for trucks entering the static scale by day-of-week showing frequency with respect to static weight range. Because different time periods were observed each day, it was important to notice the overall distribution trends as opposed to the total frequencies of each distribution. Figure 3-7 shows the frequency distribution for various weight ranges for trucks traveling over the static scale. Trucks that were less than the gross limits were likely to be heavy on one single axle and not the gross vehicle weight. The trucks that carried low gross weights such as the category from 0 to 9,072 kilograms (0 to 20,000 lb) were likely used as “scale checks”. Randomly, the weigh station operator would pull a small truck in to use as a scale check because all wheels can fit on one of the static scale platforms, and then could be compared to splitting up the weights across the platforms. Thus, the front axle of the small truck was placed on one platform, the rear axle was placed on another, and the sum can be compared against the total weight when the truck is weighed on one platform. It is important to note that 36 trucks were found to be over the gross weight limit of 36,290 kg (80,000 lb). Many of these 36 carry permits given by the Virginia Department of Transportation that allow them to drive on selected highways in Virginia because the loads cannot be split up. Also shown is a total among the four days of observation for each weight range. The data does not fit a normal distribution which can be explained because only trucks that are within 5% of legal limits were stopped and the smaller trucks used for scale checks had an effect on the mean static weight.

3.5.5 Relative Errors by Class

In order to determine whether or not the classification of the vehicle played a role in the overestimation or underestimation of weights, the Monday data from the Southbound scale and the Wednesday data from the Northbound scale were analyzed. Truck classes were sorted using the Federal Highway Administration classification scheme. Unfortunately, since almost all of the trucks were considered to be Class 9, it is difficult to give conclusive evidence one way or another. A summary of the vehicle classifications and their relative errors for the two days analyzed is shown in Table 3.2.

Bin	More Than (lb)	Up To (lb)	More Than (kg)	Up To (kg)
1		30000		13608
2	30000	32500	13608	14742
3	32500	35000	14742	15876
4	35000	37500	15876	17010
5	37500	40000	17010	18144
6	40000	42500	18144	19278
7	42500	45000	19278	20412
8	45000	47500	20412	21546
9	47500	50000	21546	22680
10	50000	52500	22680	23813
11	52500	55000	23813	24947
12	55000	57500	24947	26081
13	57500	60000	26081	27215
14	60000	62500	27215	28349
15	62500	65000	28349	29483
16	65000	67500	29483	30617
17	67500	70000	30617	31751
18	70000	72500	31751	32885
19	72500	75000	32885	34019
20	75000	77500	34019	35153
21	77500	80000	35153	36287
22	80000	82500	36287	37421
23	82500	85000	37421	38555
24	85000	87500	38555	39689
25	87500	90000	39689	40823
26	90000		40823	


Static Scale Vehicles during Observation Period

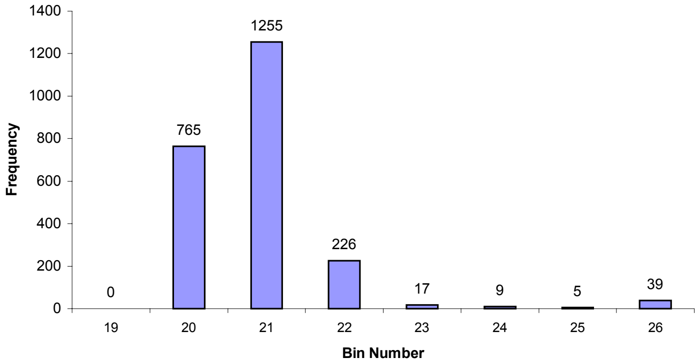

Static Scale Vehicles Over Gross (by WIM) for Observation Week

Figure 3-7: Frequency Distribution for Static Scale Weight Ranges

Table 3.2: Average Relative Errors by Class

Class	Northbound (Wednesday)	Average Relative Error	Southbound (Monday)	Average Relative Error
4	1	-0.015	0	
5	1	0.254	5	-0.097
6	2	0.047	1	-0.100
7	3	-0.051	0	
8	0		1	0.001
9	265	-0.017	123	-0.025
10	5	-0.003	6	-0.027
11	1	-0.123	8	0.029
12	0		2	0.046
13	5	-0.021	5	-0.040
Total	283	-0.016	151	-0.027

Because the Northbound and Southbound scale overall relative errors were different (most likely due to a variance in calibration), it is important to notice how the vehicles in the class compare to the relative errors for the particular scale. For example, in class 10, the Northbound class relative error of –0.003 was higher than the total of –0.016. However, the Southbound class relative error for class 10 was –0.027 which equals the total relative error for the Southbound scale.

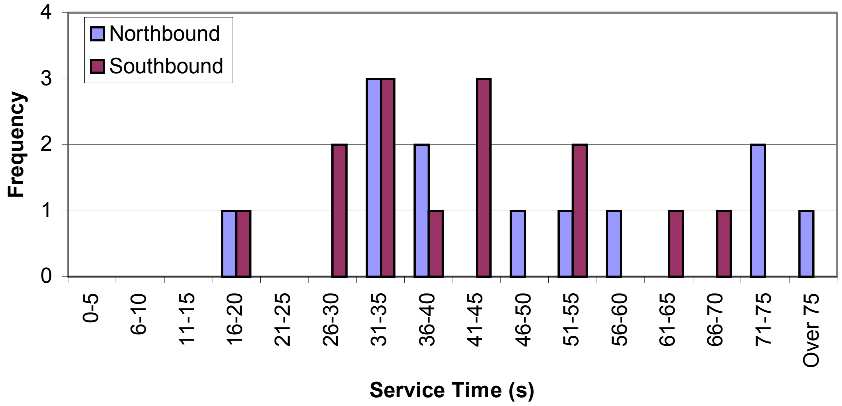
3.6 WEIGH STATION OPERATIONS ANALYSIS

3.6.1 System Operation Overview

The operational aspects of the system can be described by the service time and system time as well as the delays and potential time savings in each case. The service time was defined as the time it took for the weigh station operator to weigh the vehicle and allow the vehicle to proceed. Therefore, for a vehicle in the bypass lane, the service time was zero. Data were collected on Tuesday, May 22, 2001 for three hours in both directions to obtain service time data. It is assumed that the service time is independent of arrival rates and thus a three-hour time period should give a good representation of the service time.

3.6.2 Service Time Analysis

As a facility, 199 trucks used the static scale with an average service time of 15 seconds. Non-violating trucks were trucks which were not found to be exceeding any gross or axle weight laws whereas violating trucks exceed the gross or axle weight that the law allows. Non-violating trucks spent an average of 10 seconds while violating trucks spent an average of 45 seconds at the static scales. For the Northbound scale, 94 trucks arrived with an average service time of 16 seconds. Non-violating trucks had an average delay of 11 seconds at the static scale while violating trucks spent an average of 50 seconds on the static scale. On the Southbound scale, 105 trucks arrived with an average service time of 14 seconds. Non-violating trucks spent an average of 9 seconds while violating trucks spent an average of 40 seconds on the scale. One scale check was performed on the Southbound scale which took 83 seconds. It is interesting to note that the scale house is on the Southbound side and that the average Southbound static scale service times were less. The weigh station operator must look across from the tower to make a visual identification with the truck and therefore perhaps this played a role in service times for Northbound vehicles. Figure 3-8 shows the distributions of service times for both non-violators and violators.


Violating Vehicles

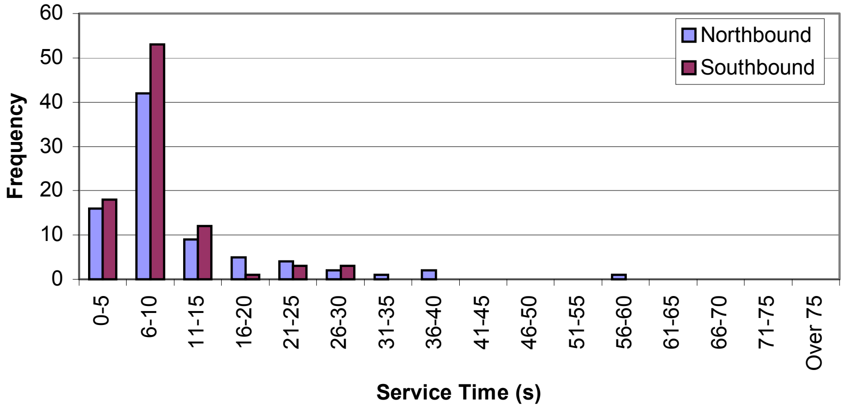

Non-Violating Vehicles

Figure 3-8: Service Times for Non-Violating Vehicles and Violating Vehicles

3.6.3 *System Time Analysis*

The system time for the static scale was defined as the amount of time it took for the vehicle to diverge from the bypass lane to the point where the vehicle merged back with the bypass lane. Because the speed limit for the bypass lane was 68 km/h (40 mph) and the length of the bypass lane was 247 meters (810 feet), the uninterrupted flow of the bypass lane should give a time of 13.8 seconds. Therefore, the delay of the static system would be defined as any amount of service time exceeding 13.8 seconds.

Table 3.3 summarizes the statistics for the trucks analyzed in the static scale lane. The data taken on Monday occurred with full weigh station operation with both Northbound and Southbound scales open. However, due to construction on pavement slabs on the Southbound side, the data collected on the second visit were on the Northbound side with the Southbound scales closed. Fortunately, this allowed for a comparison between a weigh station with one static scale and a weigh station with two static scales that the weigh station operator must observe. The average system time for full operations was 2 minutes, 20 seconds, which was 17 seconds higher than the average partial system operation time of 2 minutes, 3 seconds. The 17-second difference can be explained by the complications of running two static scales at the same time as opposed to just one scale.

Of particular interest was that out of the 798 trucks weighed, only 125 were violators (or 15.66%). Therefore, in a 100% efficient system, 84.34% of the trucks sent to the static scale could have been spared the extra time and could have continued down the bypass lane. In full operation, out of the 6 hours and 10 minutes that trucks spent in the system, 5 hours and 12 minutes could potentially have been saved. Likewise, in partial operation, out of the 21 hours and 49 minutes spent in the system, 18 hours and 24 minutes could potentially have been saved.

Table 3.3: Summary Static Scale Statistics

Number of Trucks Weighed	798
Number of Violators	125
Violation Rate	15.66%
Average System Time (Full Operation)	0:02:20
Average System Time (Partial Operation)	0:02:03
Total System Time (Full Operation)	6:09:42
Potential Time Savings (Full Operation)	5:11:48
Total System Time (Partial Operation)	21:49:34
Potential Time Savings (Partial Operation)	18:24:29

3.6.4 Effect of Arrival Patterns on System Time

Another important analysis of the time spent in the static system was to determine the effect of static scale arrivals on the average system time. It is important to note that vehicles arriving at the static scale were not Poisson distributed. Trucks seemed to travel in groups and thus at some time periods, several trucks entered the scale and at other time periods, few trucks entered. Weigh station operators noted that truck drivers likely would stop at nearby rest areas and truck stops and leave as a group at the same time. In order to compare similar scenarios, only the data taken on the Northbound scale were analyzed. The data were separated into 5 minute intervals, with the time spent at the static scale versus the number of arrivals, as shown in Figure 3-9. As an overall trend, when the number of arrivals increased, the average service time also increased gradually. This relationship was expected because as more people were arriving at the static scale, queues form and cause delay. However, with less than 5 arrivals per five minute interval, the data points appeared to be fairly even, mostly because trucks would not arrive often enough for a queue to form. The outlying point with 4 arrivals in five minutes with an average service time of about 6 minutes 50 seconds signified that a stream of trucks most likely entered the scale at the same time and not randomly. Also, there might have been a difference in service time because of a violating vehicle or a misunderstanding of the traffic signals by the truck driver. Whether the trucks entered at the same time or that there was an increase in service time, the trucks were forced to queue up for a longer period of time at the static scale.

Arrivals	Average System Time	Observations
1	0:01:39	26
2	0:01:25	35
3	0:01:33	34
4	0:01:38	28
5	0:01:37	31
6	0:02:07	20
7	0:01:52	12
8	0:02:09	2
9	0:03:36	3
10	0:03:19	2

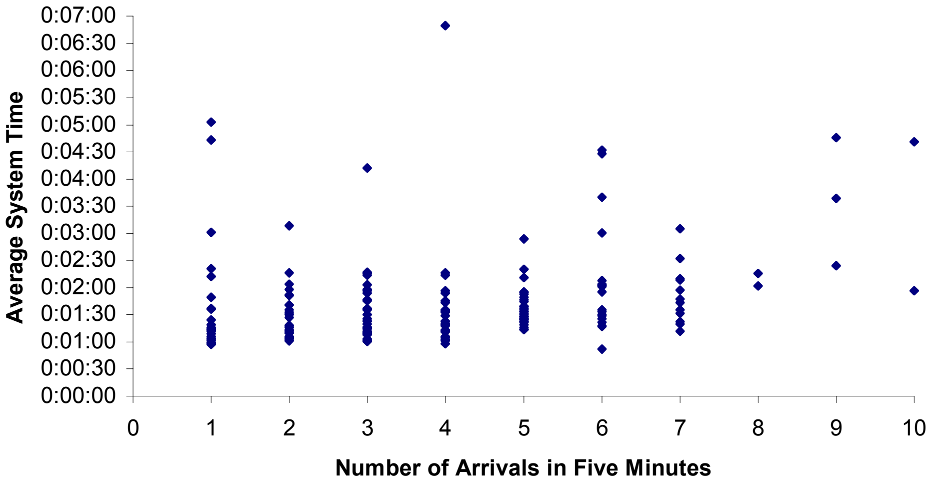


Figure 3-9: Average System Time vs. Number of Arrivals in 5 Minutes

3.7 CONCLUSIONS

Weigh-in-Motion as a system provides a much more efficient weigh station operation in terms of capacity and delay; however, as in any system, it is relatively impossible to have a system that operates with 100% efficiency. If trucks are overweight, the weigh station will inherently force the truck driver to experience some delay. However, trucks that are not overweight and diverted to the static scale will be forced to encounter some unexpected (and unnecessary) delays. The errors in the Weigh-in-Motion scale measurements make it necessary to weigh vehicles that do not only exceed, but are sufficiently close to the maximum limit. Operating the weigh station with a threshold factor of 0.96 as observed on the site is reasonable considering that the WIM scale can be off by as much 7% with 95% probability of conformity. The mean service time at the static scale for non-violating trucks was 10 seconds whereas the mean service time for violating trucks was 45 seconds. The system time ranged from 2 minutes, 3 seconds to 2 minutes, 20 seconds. Of the trucks sent to the static scale, only 16% were violators.

The results indicated that both the northbound and southbound WIM scales were sufficiently calibrated (mean WIM and static scale weights were not statistically different). Furthermore, the use of a normal distribution density function was found to be consistent with the error frequency function. The northbound and southbound scale accuracy was found to not conform to the ASTM standard of ±6% for the gross vehicle weight. Specifically, the accuracy ranged from 6.1 to 7% for a 95% probability of conformity. Finally, this evaluation developed an analytical procedure for relating gross vehicle and axle load accuracies. The proposed analytical procedure, which uses the number of axles in computing the gross weight accuracy, was demonstrated to be consistent with ASTM standards and field data.

CHAPTER FOUR:
A MODELING FRAMEWORK AND CASE STUDY EVALUATION OF WEIGH STATION OPERATIONS

4.1 INTRODUCTION

Chapter four 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. Then, 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.

4.2 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 WIM calibration, the WIM accuracy, the user-defined axle and total weight threshold, and the truck arrival volume. 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 proposed framework validity. Subsequently, the case study utilized geometric, travel time, volume, and speed data to calibrate a model that was used to simulate a 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 were utilized for comparison purposes.

4.3 PROPOSED FRAMEWORK

As was mentioned earlier the proposed framework is composed of two tasks. The first task involves estimating the number of trucks that enter the static scale and bypass lane. These volumes are further classified as violating and non-violating trucks depending on whether they exceed the legal axle 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 applying the approach to the Stephens City case study.

4.3.1 Estimating Truck Volume Breakdown

4.3.1.1 Using Gross Weights

To accurately simulate a WIM facility, it was determined that a means of estimating the volumes distributed to the bypass lane and static scale lane would be required. The methodology used in this study was to determine if the error in a vehicle's weight fit a normal distribution and if so, the number of vehicles per weight class distribution given the arrival rate, truck factor, percent error, and bias can be computed using basic probability theory. The analysis first considered gross weights and not individual axle weights as a test to see if the assumption was reasonable. Then, the individual axle weights were analyzed using a Monte Carlo simulation with 20 trials to obtain the number of vehicles sent to the static scale by both gross weight and axle weight. The resulting difference indicates the amount of error obtained by only analyzing gross weights.

For the first approach in which only gross weights were analyzed, it is assumed that the errors of truck weights follow a normal distribution with a standard deviation of the errors. Figure 4-1 demonstrates the normal distribution trends for various scenarios. For example, when a system has high accuracy, the curve fits tightly around the mean value whereas when a system has low accuracy, the curve is more dispersed around the mean value. In terms of a normal distribution, a calibrated system is one in which the mean of the normal distribution matches the actual mean of truck weights (in the example from the figure, the actual mean is 80) whereas a non-calibrated system has a mean that differs from the actual mean obtained at the static scale. For the purpose of example, imagine that no particular unit is needed. The number 80 might represent pounds, kilograms, or any other measure. The bottom portion of Figure 4-1 represents the methodology used to determine the probability of a given distribution exceeds the weight limits. Each curve represents a set of truck weights and 80 is the limit at which trucks are considered to be violators in this example. The gray areas represent the probability that a truck would be sent to the static scale. The curve with a mean of 67.5 would not have any vehicles sent to the static scale whereas the curve with a mean of 82.5 would have approximately 75% of the vehicles sent to the static scale. The hourly volume of trucks sent to the static scale would simply be the probability of a truck being sent multiplied by the hourly arrival demand of the weigh station.

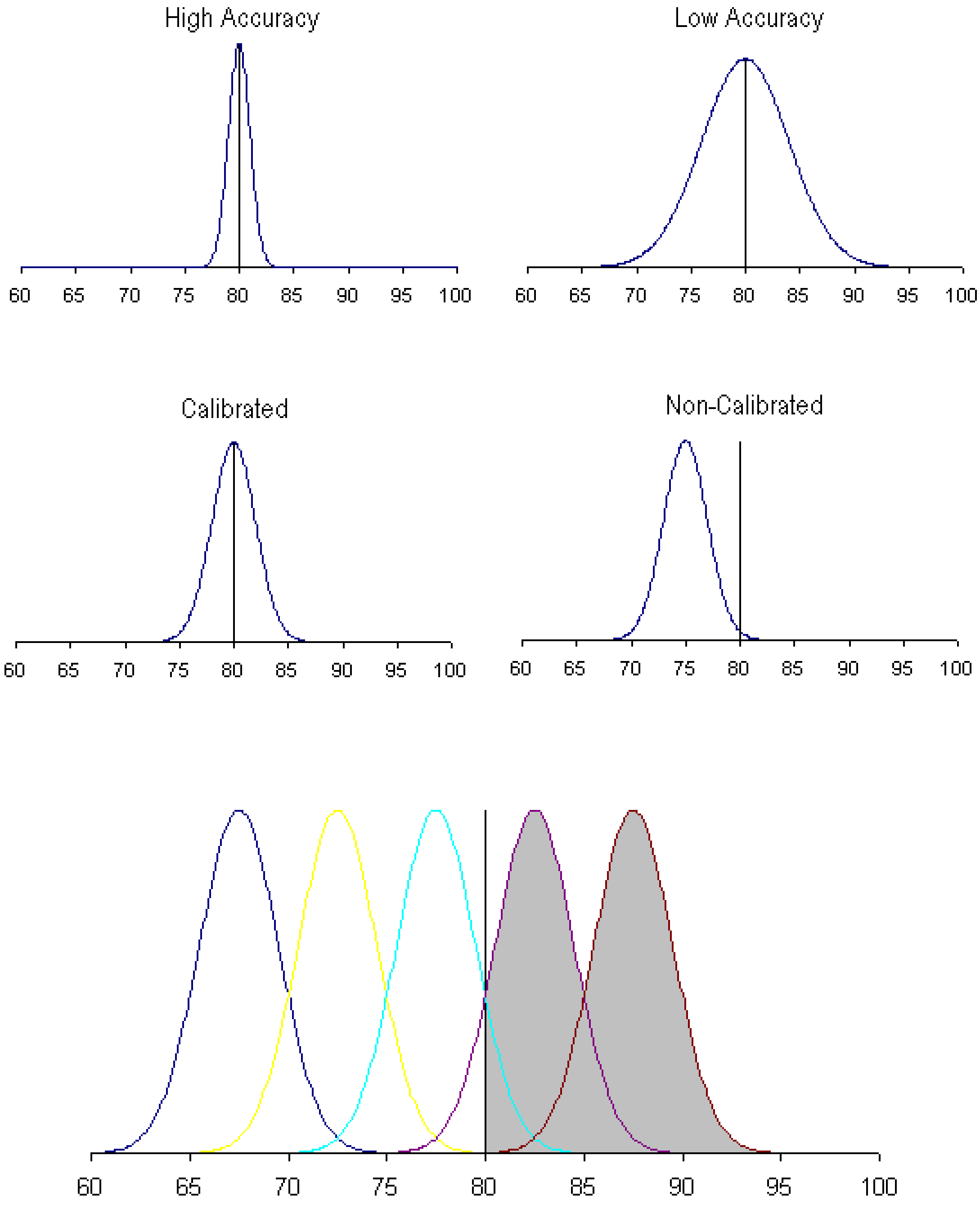


Figure 4-1: Accuracy vs. Calibration (Top), Probability of an Overweight Truck (Bottom)

Input data for the first approach included the threshold, percent error, and bias. The percent error related to the width of the normal distribution in which a low percent error would fall close to the mean value and a high percent error would move away from the mean value. The bias would indicate the calibration of the scale and would direct the curve to shift to the right or shift to the left. A system that underestimates the weight would have a calibration shift to the left whereas a system that overestimates the weight would have a calibration shift to the right.

If the scenarios described previously were used with a bias of zero and a threshold of 1.0 where 80 is the legal limit, the number of trucks sent to the static scale can be determined using the probability of the gray regions. Trucks are weighed and classified in one of the following weight categories: 65-70, 70-75, 75-80, 80-85, and 85-90. The demands of each class would also be known. For example, imagine that 100 trucks represent the class 65-70, 200 trucks represent the class 70-75, 300 trucks represent the class 75-80, 200 trucks represent the class 80-85, and 100 trucks represent the class 85-90. From the curves, the probability that each class would exceed the weight limit would be estimated as described earlier. Using the figure, approximately 0% of the 65-70 class would exceed the limit, 0% of the 70-75 class, 25% of the 75-80 class, 75% of the 80-85 class, and 100% of the 85-90 class. Thus the number of vehicles sent to the static scale can be expressed as (0.00 x 100) + (0.00 x 200) + (0.25 x 300) + (0.75 x 200) + (1.00 x 100) or 325 vehicles.

4.3.1.2 Using Axle Weights

The procedure for determining axle weights is very similar to the procedure of determining gross weights, except that the weights were split up and analyzed by each axle. A monte carlo simulation (as described in Chapter 3) was used to determine the variation from the mean that the weight would be, given a normal distribution. Then, the individual axle weights were analyzed to determine whether or not the vehicle exceeded the gross weight limit of 36,290 kg (80,000 lb), an individual axle weight limit of 9070 kg (20,000 lb), or a tandem axle weight limit of 15,400 kg (34,000 lb). A tandem axle is defined as two individual axles spaced between 102 cm (40 in) and 244 cm (96 in) apart. If the truck exceeds any of the requirements, the driver will be diverted to the static scale. The inputs for the approach were the same as the gross weight approach in which the threshold, percent error, and bias were used.

Given a list of truck data, the monte carlo simulation would determine the estimated weight of the vehicle in a normal distribution of error around the mean weight. Then, using a spreadsheet, a check can be performed to determine if any of the weight requirements were exceeded. If the truck exceeded the limit, then the truck would be sent to the static scale, otherwise the truck would bypass. Instead of the calculation used with a series of trucks as used in the gross weight analysis, each individual truck is analyzed and the total number of trucks sent to the static scale is simply the sum of all individual vehicles that are estimated to exceed the weight limits.

4.3.2 Evaluating Weigh Station Operations

Geometric data as well as the truck volume breakdown were used as inputs to the simulation model. The simulation was run with fifteen periods of random arrivals to calibrate the system to match field conditions. If so, then the simulation would be run with each alternative scenario and the delay would be calculated for each vehicle type. The simulation would be run for various demand levels (100, 200, 300, 400, 500, 600, 700, and 800 veh/h), accuracies (0%, 5%, 10%, 15%, and 20%), and threshold values (0.92, 0.96, and 1.00).

A vehicle that traveled through a WIM facility was fit into one of four main categories: static scale violator, static scale non-violator, bypass violator, or bypass non-violator. Static scale violators were vehicles that are sent to the static scale and were violating weight limits. Static scale non-violators were vehicles that were sent to the static scale but were not exceeding any weight limits. Bypass violators were vehicles that were sent to the bypass lane even though the vehicle was violating weight limits. Bypass non-violators were vehicles that were sent to the bypass lane and were not exceeding any weight limits.

In a perfect scenario, the WIM system was designed so that there would only be static scale violators and bypass non-violators. However, due to scale accuracy and calibration, sometimes trucks not exceeding weight limits were sent to the static scale and were thus classified as static scale non-violators. Additionally, some trucks that were exceeding weight limits were sent to the bypass lane and were thus classified as bypass violators.

When evaluating a WIM facility in terms of enforcement, it is important that all violators are sent to the static scale and it is important to minimize the number of bypass violators. However, when evaluating a WIM facility in terms of delay, it is important that all non-violators are sent to the bypass lane and that the delay experienced by static scale non-violators is minimized. Unfortunately, unless a system is 100% accurate with perfect calibration, both enforcement and delay goals cannot be achieved. Therefore, a balance must be reached.

4.3.3 Determining Total Travel Time and Delay

Average delay was obtained for each vehicle class using the Integration simulation model. The Integration model is a microscopic traffic simulation model that tracks individual movements with an update every 1/10th of a second. As a measure of effectiveness, the Integration model uses travel time as an output on a link. According to the Integration User's Guide, link travel time is calculated for any vehicle using a *time card* that is provided at the start of a link and retrieved when a vehicle leaves the link. The difference between the entry and exit times on the *time card* determine the travel time experienced by each vehicle on the link.

The tables that can be generated which show the truck volume breakdown can be used in conjunction with equations to determine travel time and delay characteristics given the values from the delay charts as well as the travel time tables. Vehicles can be classified as a bypass vehicle, static scale non-violator, and static scale violator. The total travel time for any particular vehicle class can be determined using Equation 4-1 where T_x is the total travel time for vehicle class x, D is the demand, P_x is the probability of a truck being of class x (found from the sensitivity analysis), and t_x is the travel time per truck for vehicle class x (found from the travel time tables). Equation 4-2 provides a similar equation for the total travel time for all vehicle classes where t_a is the average travel time per truck for all classes (found from the travel time tables).

$$T_x = D(P_x \times t_x) \qquad [4\text{-}1]$$

$$T_{all} = Dt_a \qquad [4\text{-}2]$$

An important distinction to recognize is that while travel time has already been calculated, it is sometimes necessary to determine the delay encountered as opposed to strictly the travel time experienced. Delay is defined as the difference between the actual travel time and the time it takes to continue on the mainline highway without slowing down or stopping at the weigh station. The average delay per truck can be found using Equation 4-3 in which L_m is the length of the mainline highway parallel to the weigh station facility and s_m is the speed on the mainline highway. Equation 4-4 is of similar structure, but calculates the total delay spent at the facility.

$$Delay_{avg} = t_a - \frac{L_m}{s_m} \qquad [4\text{-}3]$$

$$Delay_{total} = D(t_a - \frac{L_m}{s_m}) \qquad [4\text{-}4]$$

To perform a cost/benefit analysis, it is also important to determine the time cost associated with a particular scenario. Equation 4-5 calculates the average cost of delay per driver and Equation 4-6 calculates the total cost of delay for all drivers where V_t is the value of time as an hourly rate (i.e. dollars per hour).

$$Cost_{avg} = V_t(t_a - \frac{L_m}{s_m}) \qquad [4\text{-}5]$$

$$Cost_{total} = V_t D(t_a - \frac{L_m}{s_m}) \qquad [4\text{-}6]$$

4.4 DATA COLLECTION

Geometric data were obtained by measuring the length of the deceleration lane, approach to the WIM scale, static scale lane, bypass lane, the merge area, and the acceleration lane. 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.

Accuracy data were taken by recording WIM gross weights for each truck that entered the static scale and comparing the WIM weights to the static scale gross weights. System time data were recorded by determining the time it takes for trucks to go from the point where the bypass and static scale lanes diverge to the point where the two lanes merge back together. Video cameras were focused 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 the truck. Service time data were obtained by videotaping the static scale and calculating the amount of time that it took to weigh each truck.

4.5 MODEL CONSTRUCTION AND CALIBRATION

4.5.1 Model Construction

The geometric data and arrival data were both used as inputs into the Integration simulation model. Figure 4-2 illustrates the link-node diagram that was used to analyze the weigh station. The simulation was coded to use node number 1 as the origin node and node number 2 as the destination node. Link numbers 1, 9, and 10 were freeway links. Link number 2 was the deceleration lane off of Interstate 81 leading into the WIM station and link number 3 lead up to the point where the vehicle was sent to the static scale or to the bypass lane. If the vehicle was sent to the bypass lane, link number 4 was used; otherwise link numbers 5 and 6 was used. Node number 12 was the location of the static scale. Next, the vehicles merged back together on link number 7 and used link number 8 to accelerate back to freeway speeds.

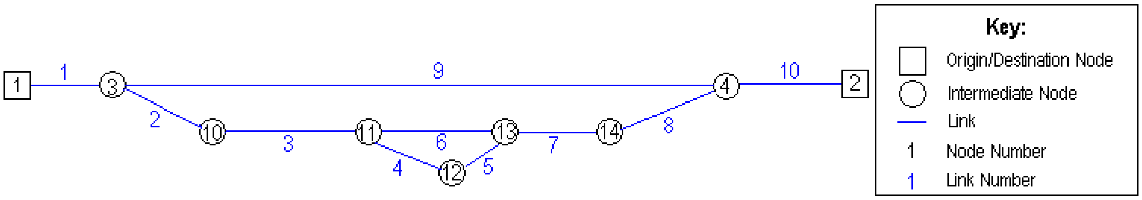


Figure 4-2: Link-Node Diagram

4.5.2 Model Calibration

The system time data collected in the field were used to calibrate the model to accurately simulate the trucks traveling through the weigh station. Table 4.1 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. A speed of 105 mph (65 km/h) was used on link numbers 2 and 8 to match the freeway speed limit. A speed of 65 mph (40 km/h) was used on link numbers 3, 4, and 7 to match the speed limit posted through the WIM facility. Likewise, a speed at capacity of 80% of the freeway speed (on link numbers 2 and 8) and 50% of the WIM facility speed (on link numbers 3, 4, and 7) was coded into the simulation assuming the general characteristics of classic speed-flow relationships. The speed, speed at capacity, and jam density for static scale link numbers 5 and 6 were determined after comparing the simulation model to the known system times.

In order to simulate the truck stopping at the static scale for trucks sent to link numbers 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 laws) would have a 10 second stop with a coefficient of variation of 0.00 and that a violating truck would have a 45 second stop with a coefficient of variation of 0.42. The values for average stop time and the coefficients of variation were obtained by observing field data.

Table 4.1: Link Characteristics

Link No.	Length (m)	Speed (km/h)	Saturation Flow (vph)	Speed at Capacity (km/h)
1	200	105	1800	70
2	176	65	1800	32.5
3	574	65	1800	32.5
4	247	11.5	1800	7.5
5	199	11.5	1800	7.5
6	48	65	1800	32.5
7	334	65	1800	70
8	384	65	1800	7.5
9	1715	105	1800	32.5
10	200	105	1800	70

Fifteen minute periods of field data from five time intervals for three days were used to calibrate the model. The 15 models were chosen with varying arrival rates in order to obtain a wide spread of scenarios. Various link characteristics were simulated until the simulated system time matched the system time obtained in the field study. A speed of 11.5 kilometers per hour, and speed at capacity of 7.5 kilometers per hour generated the best values to correlate with the actual values observed in the field on links four and five. Figure 4-3 shows the actual observed system time data along with the upper and lower 95% confidence limits as well as the system time data obtained after running the simulation model that produced the best values. It could be stated from the data that the model estimated an accurate system time within 95% of the actual value for the 15 time intervals analyzed; therefore, the model is acceptable for use in evaluating alternate scenarios.

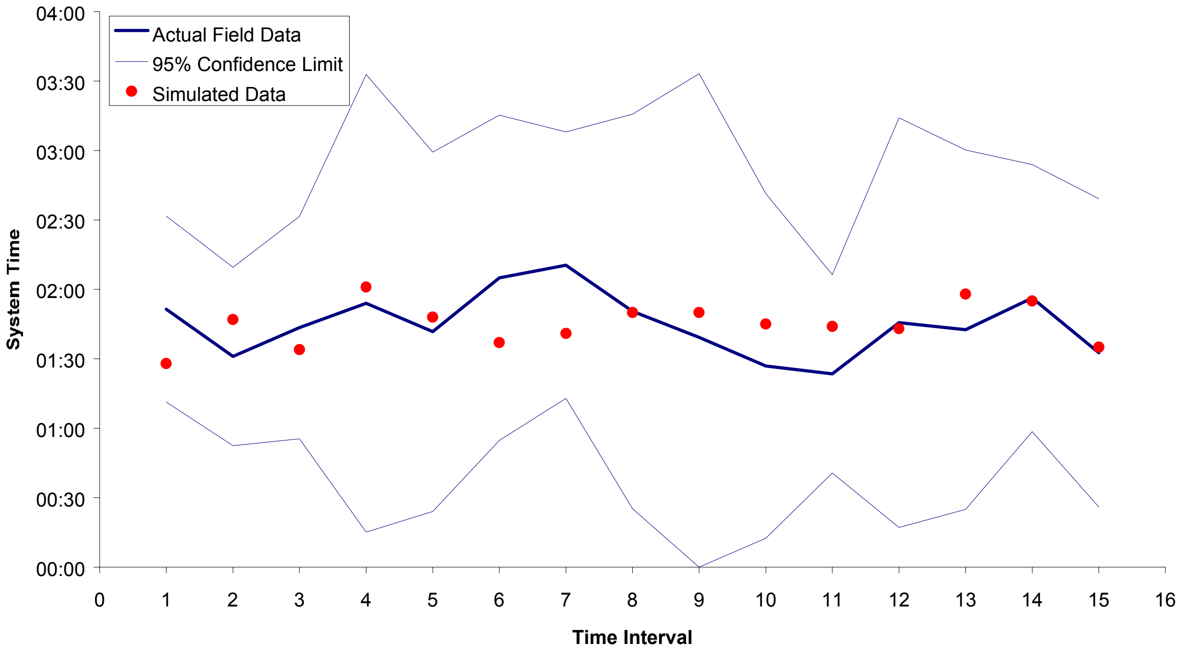


Figure 4-3: Average Simulated and Actual System Time

4.6 SENSITIVITY ANALYSIS

4.6.1 System Volume Distributions

The first sensitivity analysis examined the trends regarding the number of trucks classified as static violators, static non-violators, bypass violators, and bypass non-violators with respect to accuracy, threshold, and calibration. There were three independent variables and therefore cannot graphically be shown on the same chart, thus the analysis was split up into a case where perfect calibration was assumed and a case where the threshold was set to 1.0.

The methodology for determining the WIM system volume distribution was used to estimate the lane distributions for various traffic demands, accuracy levels, calibrations, and thresholds. These sensitivity analyses are described later in this chapter. Distributions were estimated for the following scenarios:

- traffic demands of 100, 200, 300, 400, 500, 600, 700, and 800 vehicles per hour
- accuracy levels of 0%, 5%, 10%, 15%, and 20% deviations from the actual weight
- calibration errors of –10%, -5%, 0%, 5%, and 10% from the actual weight
- threshold values of 0.90, 0.92, 0.94, 0.96, 0.98, 1.00

The distributions were used to perform a sensitivity analysis for truck volumes sent to each lane given various scenarios as well as to perform a sensitivity analysis of the delay estimated from simulation. The 5% accuracy level was used to simulate a load cell system, the 10% accuracy level was used to simulate a bending plate system, and the 15% accuracy level was used to simulate a piezoelectric system.

4.6.1.1 System Volume Distributions Using Gross Weights

The first analysis of system volume distributions involved studying only gross weight violations. A distribution of weights for the trucks using the Stephens City Weigh Station was obtained, as shown in Table 4.2. The WIM system software was used to obtain the weights of 33,712 trucks during the field evaluation. The WIM weights were used in the analysis instead of the static weights because the static weights are only available for trucks that are potentially overweight. However, to correct for the calibration of the WIM scale, a bias factor was added to the model. The next step was to determine the truck factor, percent error, and bias. The threshold was set to be 0.96 during the field study. A percent error of 5% and bias of 1270 kilograms (2800 pounds) was used from observing the field data. The values were placed in the model as well as the frequency distribution of weights in 2270 kilograms (5000 pounds) intervals for the simulation and 910 kilograms (2000 pounds) for the sensitivity analysis. As a comparison to the actual scenario, all trucks that were 96% of the legal limit or higher were sent to the static scale. A normal distribution of the weights was used to estimate the number of vehicles sent to the static scale. This accounted for 2316 trucks over the gross weight of the 33,712. For each interval, the probability of a truck in the particular weight range being sent to the static scale was determined and from these probabilities with a normal distribution, a total of 2361 trucks would be sent to the static scale. Thus, the model appears to be a reasonable estimate for the number of trucks sent to the static scale based on gross weight.

Results of the sensitivity analysis of gross weights when the calibration was assumed to be perfect are shown in Figure 4-4. In the upper-left graph showing the number of static violators with respect to threshold, it can be concluded that as the accuracy of the system improved with any given threshold, the number of static violators in the system increased. However, as the accuracy of the scale was decreased, lowering the threshold sent more of the violators to the static scale. When the accuracy is perfect, 0.9% of the trucks entering the weigh station will be sent to the static scale for violating weight limits.

In the lower-left graph (Figure 4-4), the number of bypass violators with respect to threshold is shown. As the accuracy of the scale was decreased, more trucks were classified as bypass violators. In addition, when the threshold values were closer to 1.0, unless the system was completely accurate, more violators were sent to the bypass lane. In a completely accurate system, the number of bypass violators would be 0. It is also important to note that the static violators and bypass violators are complementary. Therefore, the sum of the static violators and the bypass violators would equal the total violators in the system. In terms of enforcement, bypass violators are not desired in a system.

Table 4.2: WIM Volume Distribution Model

Truck Factor:	0.96
Critical Gross Weight:	76.8
Sent to Static Scale:	2361
% Error:	0.05
Bias	2.8

Weight Range (lb)	Weight Range (kg)	Frequency	Probability	Static Scale	Bypass
0 to 5000	0 to 2270	0	0.000000	0	0
5001 to 10000	2271 to 4540	32	0.000000	0	32
10001 to 15000	4541 to 6810	375	0.000000	0	375
15001 to 20000	6811 to 9070	634	0.000000	0	634
20001 to 25000	9070 to 11340	446	0.000000	0	446
25001 to 30000	11341 to 13610	1196	0.000000	0	1196
30001 to 35000	13611 to 15880	2133	0.000000	0	2133
35001 to 40000	15881 to 18150	2524	0.000000	0	2524
40001 to 45000	18151 to 20420	2680	0.000000	0	2680
45001 to 50000	20421 to 22680	2812	0.000000	0	2812
50001 to 55000	22681 to 24950	2878	0.000000	0	2878
55001 to 60000	24951 to 27220	2636	0.000000	0	2636
60001 to 65000	27221 to 29490	2349	0.000004	0	2349
65001 to 70000	29491 to 31760	2758	0.002822	8	2750
70001 to 75000	31761 to 34020	5799	0.079536	461	5338
75001 to 80000	34021 to 36290	4164	0.395218	1646	2518
80001 to 85000	36291 to 38560	243	0.796209	193	50
85001 to 90000	38561 to 40830	14	0.969101	14	0
90001 to 95000	40831 to 43100	7	0.997629	7	0
95001 to 100000	43101 to 45360	4	0.999889	4	0
100001 to 105000	45361 to 47630	8	0.999996	8	0
105001 to 110000	47631 to 49900	4	1.000000	4	0
110001 to 115000	49901 to 52170	5	1.000000	5	0
115001 to 120000	52171 to 54440	2	1.000000	2	0
120001 to 125000	54441 to 56700	4	1.000000	4	0
125001 to 130000	56701 to 58970	2	1.000000	2	0
130001 to 135000	58971 to 61240	0	1.000000	0	0
135001 to 140000	61241 to 63510	0	1.000000	0	0
140001 to 145000	63511 to 65780	0	1.000000	0	0
145001 to 150000	65781 to 68040	1	1.000000	1	0
More than 150000	More than 68040	2	1.000000	2	0
Totals		**33712**		**2361**	**31351**

The number of static scale non-violators with respect to threshold is shown in the upper-right graph (Figure 4-4). As the accuracy of the scale was decreased, the number of static non-violators for any given threshold was increased. Additionally, as the threshold was decreased more non-violators were sent to the static scale. Also, as the threshold was decreased, the number of non-violators sent to the static scale for each level of accuracy began to converge to approximately 25%. In terms of delay, non-violating trucks that are sent to the static scale will be forced to encounter unnecessary delays and thus should be minimized.

Results of the sensitivity analysis when the threshold was assumed to be 1.0 are shown in Figure 4-5. The upper-left graph shows the number of static violators with respect to calibration and accuracy. As a trend, when the system accuracy was lowered, the effects of calibration on the number of violators sent to the static scale were not as large. If the system was under-calibrated (vehicle weights are underestimated), fewer violators were sent to the static scale. On the contrary, when the system was over-calibrated (vehicle weights are overestimated), more violators were sent to the static scale. In a perfectly accurate scale, if the calibration were perfect or over-calibrated, all violators would be sent to the static scale.

For Perfect Calibration

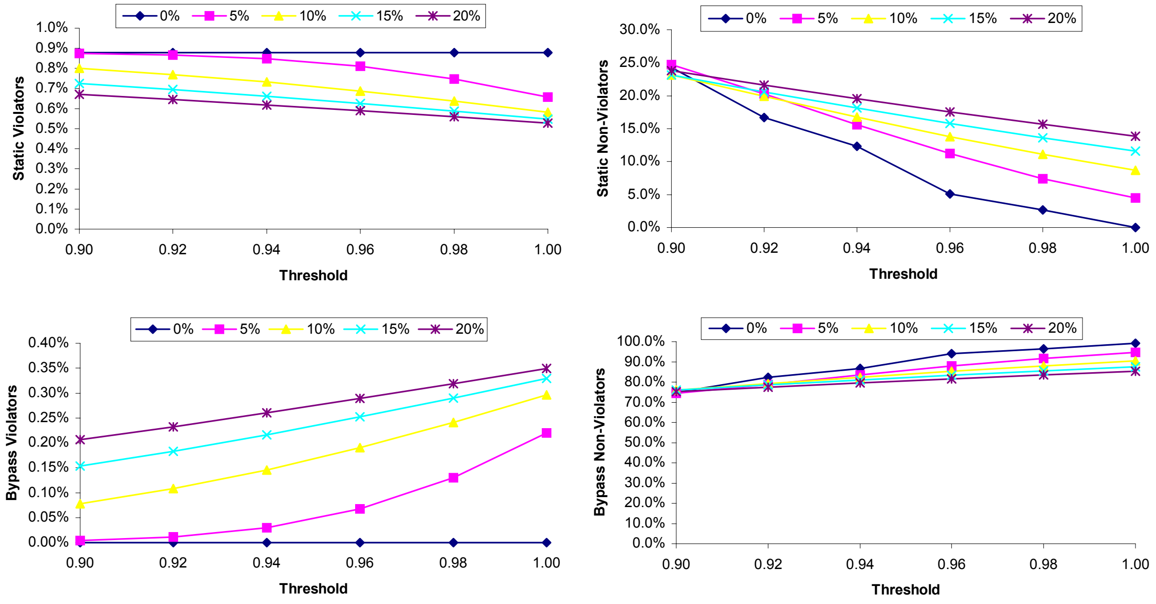


Figure 4-4: Number of Vehicles vs. Threshold given Accuracy (Based on Gross Weight)

For 1.00 Threshold

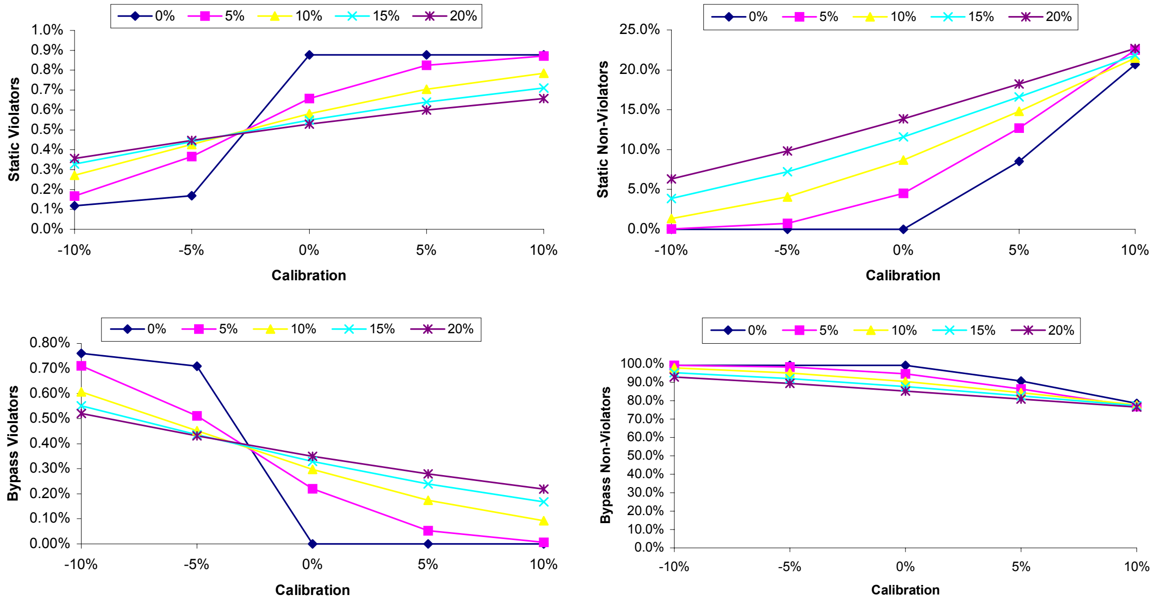


Figure 4-5: Number of Vehicles vs. Calibration given Accuracy (Based on Gross Weight)

The number of violators sent to the bypass lane with respect to calibration is shown in the lower-left graph (Figure 4-5). Because of the complementary relationship between the static violators and bypass violators, the trends were the opposite. When the system was under-calibrated, more violators were sent to the bypass lane. When the system was over-calibrated, fewer violators were sent to the bypass lane. In a perfectly accurate scale, when the calibration was perfect or over-calibrated, there were no violators sent to the bypass lane.

The upper-right graph (Figure 4-5) illustrates the number of non-violators sent to the static scale with respect to calibration. As the calibration was shifted to the right, the number of static non-violators increased. Once the calibration reached a level of 10% over-calibration, the accuracy of the scale no longer had an influence on the number of static scale non-violators and the values converged to just over 20%. In a perfectly accurate scale, no non-violators were sent to the static scale when the scale was under-calibrated or perfectly calibrated.

In the lower-right graph (Figure 4-5), the number of non-violators sent to the bypass lane is shown. Again, this situation is complementary to the upper-right graph. As the calibration shifts to the right, fewer trucks are sent to the bypass lane. When the scale is under-calibrated, or perfectly calibrated, a 100% accurate scale would send 99.1% of the vehicles to the bypass lane correctly as non-violators.

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 4-6 contains a graph showing the percentage of violators missed versus threshold with levels of accuracy as well as a graph showing the percentage of non-violators that experience unnecessary delays.

The data obtained in the sensitivity analysis were used to create charts that a decision maker can use for determining system characteristics necessary to meet enforcement and delay goals. The top graph in Figure 4-6 can be used to determine the optimum threshold to achieve enforcement rate goals. For example, if the DMV wanted to have an enforcement goal of capturing at least 95% of overweight trucks at the static scale, a scale accurate to a degree of ±5% 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 ±5% were chosen with a threshold of 0.94, then 15% of non-violating trucks would experience unnecessary delays on average.

The reverse procedure can be used as well. If the DMV wanted to reduce delays experienced by non-violating vehicles, a goal of only 5% of non-violators being stopped at the static scale might be chosen. The bottom graph of Figure 4-6 suggests that a scale with accuracy ±5% 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% of violators would be able to bypass the static scale.

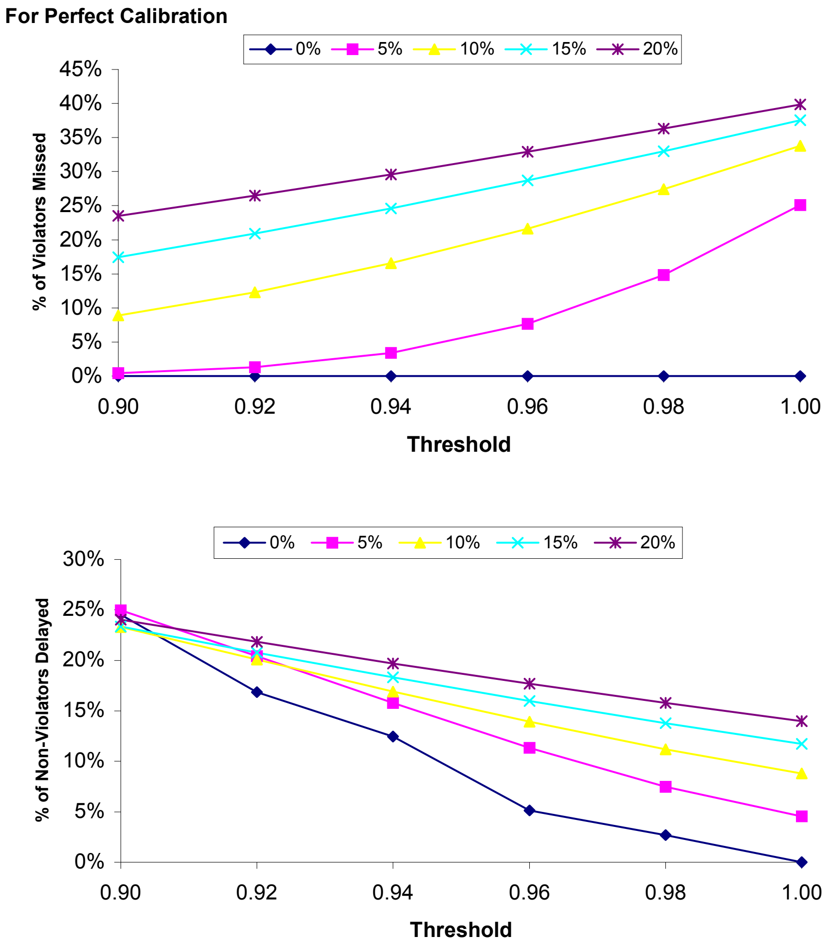


Figure 4-6: Percent of Violators Missed and Percent of Non-Violators Delayed (Based on Gross Weight)

4.6.1.2 System Volume Distributions Using Individual Axle Weights

A truck distribution using one day of data on June 13, 2001 for a total of 6,147 trucks was used. The axle data were evaluated with a Monte Carlo simulation using 20 random numbers for each of the 6,147 trucks. For each truck, a random number was generated and used in conjunction with the normal distribution of the weights to determine a value for the weight of the axle. The procedure was repeated for every axle on every truck. If any of the axles or gross weight laws were violated, 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 calculated to enter the static scale, 20 trials were run to see how closely the values correlated as shown in Figure 4-7. In the sample trial, a ±10% accuracy was used with a threshold of 0.96 and perfect calibration. As shown, all

10 trials produced results of about 15% of the trucks sent to the static scale. Therefore, it could be concluded that although the random numbers were changed, the percentage of trucks sent to the static scale remained fairly constant. Furthermore, these results are consistent with the field results that were presented in Chapter 3. Specifically, the field results demonstrated that between 8 and 16% of the total truck volume was directed to the static scale.

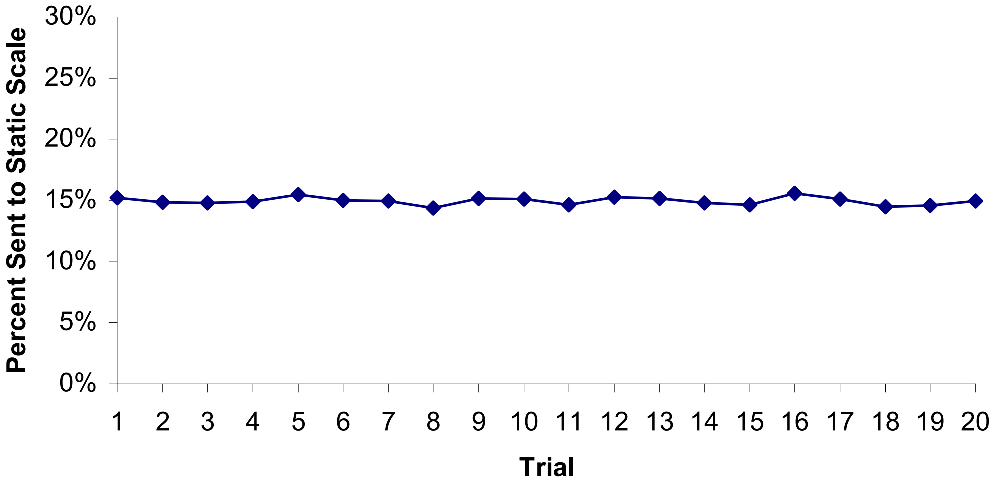


Figure 4-7: Monte Carlo Simulation Results for 20 Trials

The second analysis of truck volume distributions involved analyzing both gross and axle weight violations. To be sure that the random number generated for the Monte Carlo simulation did not play a large role in the sensitivity analysis, 20 trials were performed and the average was taken. The sensitivity analysis results illustrating perfect calibration are shown in Figure 4-8. The upper-left graph showing the number of static violators with respect to threshold shows that as a trend, a more accurate system results in more violators being sent to the static scale. However, as threshold increased, fewer violators were sent to the static scale. With perfect accuracy, about 2.0% of trucks were sent to the static scale. In the lower-left graph of Figure 4-8, the number of bypass violators with respect to threshold is shown. As a trend, when system accuracy was reduced, more violators bypassed the scale. If the scale were completely accurate, there would be no violators sent to the bypass lane.

The upper-right and lower-right graphs of Figure 4-8 show that a more accurate system results in more non-violators being sent to the bypass lane. As threshold was decreased, the number of static and bypass non-violators began to converge whereas with a higher threshold, the accuracy of the system played a large role in determining the number of non-violators sent to the static scale and bypass lanes. If the scale were completely accurate, there wouldn’t be any non-violators sent to the static scale lane.

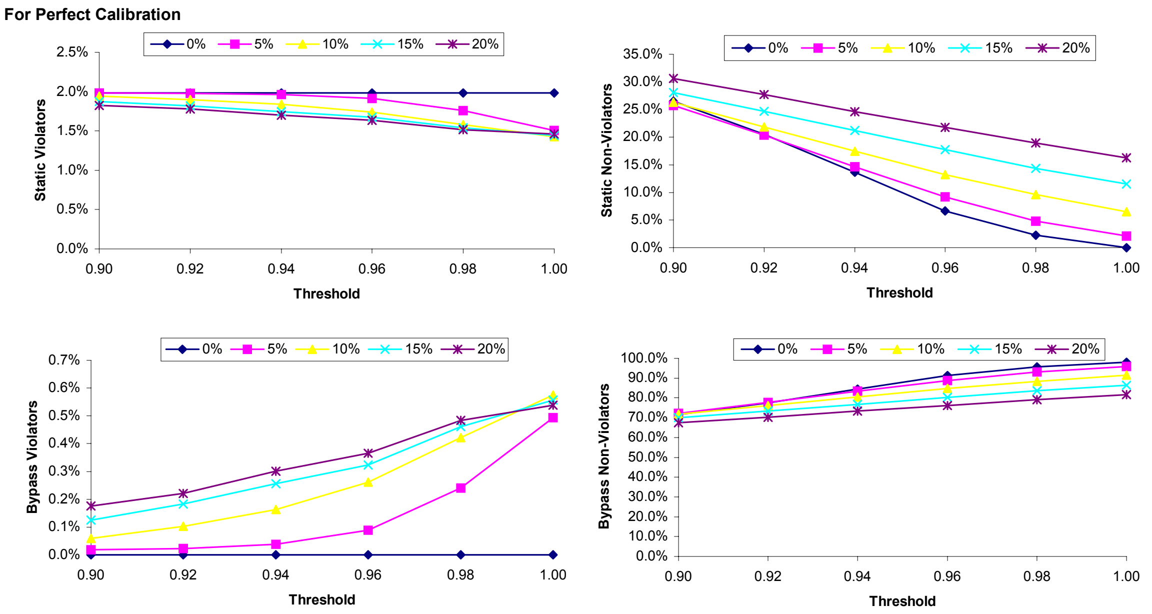


Figure 4-8: Number of Vehicles vs. Threshold given Accuracy (Based on Axle Weight)

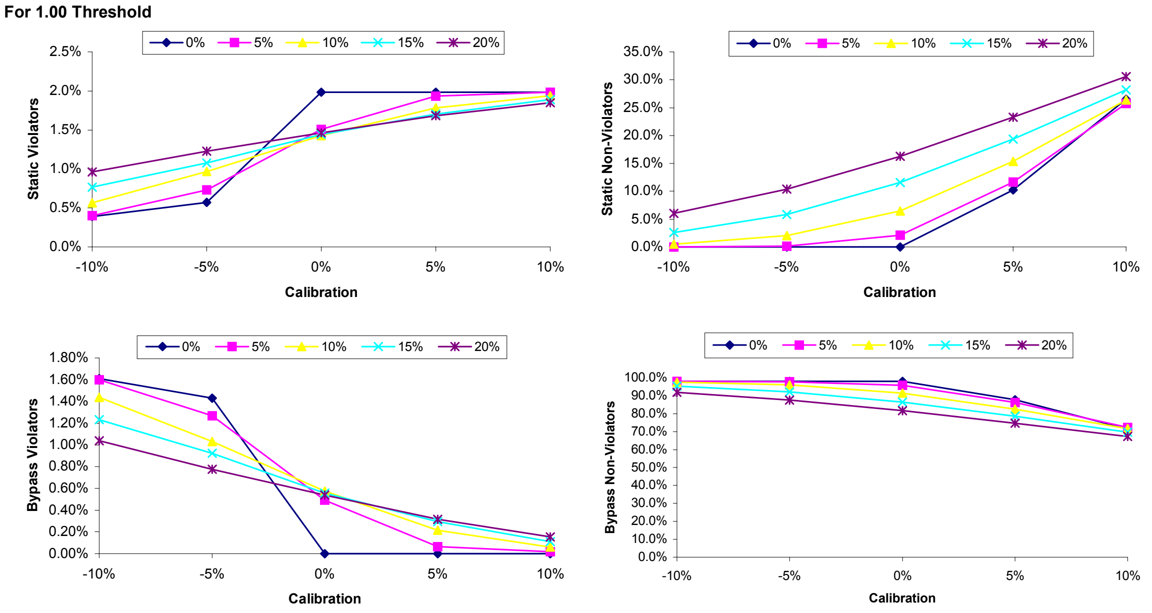


Figure 4-9: Number of Vehicles vs. Calibration given Accuracy (Based on Axle Weight)

The upper-left and lower-left graphs of Figure 4-9 show the effect of calibration on the number of static violators given a threshold of 1.00. Generally, as the calibration error was shifted from left to right, more violators were sent to the static scale and less to the bypass lane. It is interesting to note that if calibration were perfect given a 1.0 threshold, the accuracy of the system did not play a role in the number of violators sent to each scale (except when accuracy was perfect). The effects of calibration also were not as large as the accuracy of the scale was reduced.

The upper-right and lower-right graphs of Figure 4-9 indicate that as calibration was shifted from left to right, more non-violators were sent to the static scale and that less were bypassed. At higher magnitudes of calibration errors, the number of non-violators sent to the static scale and bypass lane began to converge. As expected, the number of non-violators sent to the bypass increased as accuracy was improved.

Figure 4-10 shows the percentage of violators missed and the percent of non-violators delayed given perfect calibration when axle weights are considered which compares to Figure 4-6 when only gross weights are 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, many fewer violators are missed than shown when only gross weights are considered. 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.

4.6.1.3 Gross vs. Axle Weight Analysis

A comparison of the two analyses concluded that it was not appropriate to use gross weight distributions as an estimate for violators and thus an axle weight distribution must be used. The percentage of violators using gross weight as an estimate was only about 0.9% where as the percentage of violators including axle weight was about 2.0%. Overall trends were very similar for the two methodologies; however, the magnitude of the number of vehicles is much different between the two cases. The gross weight analysis was included in order to validate the Monte Carlo simulation approach.

4.6.1.4 Analytical vs. Field Measurements

The axle weight analysis using a Monte Carlo simulation produced results very similar to the actual field data. In the field using one day of data, 13% of trucks were sent to the static scale and using the Monte Carlo simulation, 16% of trucks were sent to the static scale. The slight difference can be easily explained by the stochastic nature of the Monte Carlo simulation. In addition, the field results indicate that 16% of the static scale vehicles were classified as violators, which is very similar to what is estimated using the Monte Carlo simulation (17% of the static scale vehicles were violators). Thus, the Monte Carlo simulation matches very closely with the trends observed in the field.

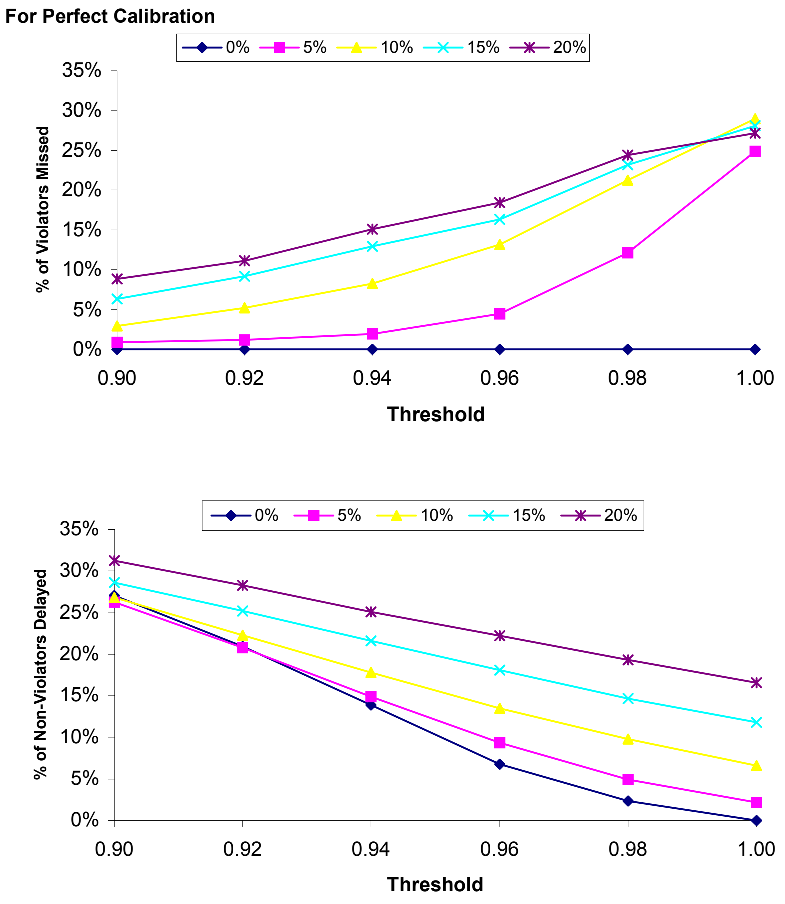


Figure 4-10: Percent of Violators Missed and Percent of Non-Violators Delayed (Based on Axle Weight)

4.6.2 Expected Delay by Trucks

The delay experienced by trucks at the weigh station was estimated using the axle weight analysis in order to match field conditions for both the existing geometric alignment as well as a mainline screening facility. Table 4.3 shows the delay in seconds by vehicle classification for the original scenario using a ramp sorting WIM system. The results are also shown graphically in Figure 4-11 through Figure 4-18.

It is important to note that the travel time expected for a static non-violator at a threshold of 1.00 on a perfectly accurate system for a static scale non-violator would be zero. This scenario exists because when a scale is perfectly accurate, trucks that are not violating weight limits will not be sent to the static scale. Thus, the travel time for this vehicle type is zero.

As expected, when threshold was increased, the average delay per truck decreased since fewer trucks would be sent to the static scale. The difference was much more apparent at higher volumes. For example, at 100 vehicles per hour, a perfectly accurate scale would result 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.

At 100 vehicles per hour, a perfectly accurate scale would expect an average of 129 seconds per truck at a threshold of 0.96 whereas a ±20% accurate scale would expect an average of 144 seconds per truck at the same threshold (difference of 15 seconds). At a demand level of 800 vehicles per hour, a perfectly accurate scale would expect an average of 385 seconds per truck at a threshold of 0.96 whereas a ±20% accurate scale would expect an average of 485 seconds per truck at the same threshold (difference of 100 seconds). Similar to the threshold changes, accuracy changes have travel time differences which were much more apparent at higher volumes.

A weigh station operator can use the resulting charts to determine expected characteristics given certain scenarios. For example, if the expected demand is 500 trucks per hour and the choice is to use a system with ±15% accuracy or ±5% accuracy, it can be stated 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 showing a travel time analysis for a freeway screening system can be found in Table 4.4 and Figure 4-19 through Figure 4-26. The results show that as a whole, using a mainline screening system would save time. At 100 vehicles per hour with a perfectly accurate scale at a threshold of 1.0, the original case resulted in an average travel time of 120 seconds per truck and with the mainline screening scenario, a travel time of 80 seconds would be expected. At a demand of 800 vehicles per hour, the original scenario would expect an average travel time of 354 seconds and the mainline screening would expect an average travel time of 309 seconds for a difference of 45 seconds.

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.

The percentage increase in delay compared to perfect accuracy and a threshold of 1.00 is found in Table 4.5. As the threshold was decreased, there was increased delay and also as the accuracy was reduced, there was also increased delay. It is important to note that freeway screening changes are much more sensitive to demand. In the original case, a demand of 800 vehicles per hour with ±10% accuracy at a threshold of 0.96 calculated a delay of 22% higher than the baseline scenario in the original case whereas in the freeway screening case, the delay was 33% higher. Additionally, the threshold has a very large impact on added delay. For example, in the original case, a perfectly accurate scale with a threshold of 0.92 would have a 17% increase in delay and in the freeway screening, a perfectly accurate scale would have a 29% increase in delay.

4.6.3 Calculating Total Delay

When comparing several alternatives, it is not only important to analyze the average delay per truck, but the total delay in a given time period. As an example, truck arrival distributions for 21 hours for Wednesday, June 13, 2001 on the northbound scale were analyzed. In order to determine the total delay, the data was separated into 15-minute intervals and given equivalent hourly volumes in order to use the tables described earlier in this paper. Then, the hourly arrival rates were grouped into bins of 50 to 150, 150 to 250, 250 to 350, 350 to 450, 450 to 550, and 550 to 650 and given a frequency distribution, shown in Figure 4-27. The delay charts and the equations described in the proposed framework were used to produce the results in Table 4.6.

The table shows information for six different alternatives. The first three use ramp screening and the second three use 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 ±5% accuracy with a threshold of 0.96 and a scale with ±10% 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 of a more accurate system.

4.7 CONCLUSIONS

The methodologies used in this framework can be applied to other WIM systems to determine the effects that 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 goals and delay goals in order for the two to balance out. If there is a high level of enforcement, generally delay is increased. Likewise, if delay is reduced, enforcement is decreased. The threshold also plays a large role in system performance. As the threshold is increased, less delay is incurred but violators are more apt to bypass the static scale.

An analysis using both gross weights and axle weights shows that using only gross weight to determine the number of trucks sent to the bypass lane and static scale is not accurate enough and thus both gross weights and axle weights must be considered. Although a more detailed analysis is involved, it is necessary to analyze axle weights to best capture the true conditions in the field.

Table 4.3: Vehicle Travel Time by Classification (Original Case)

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 4.3 Continued: Vehicle Travel Time by Classification (Original Case)

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

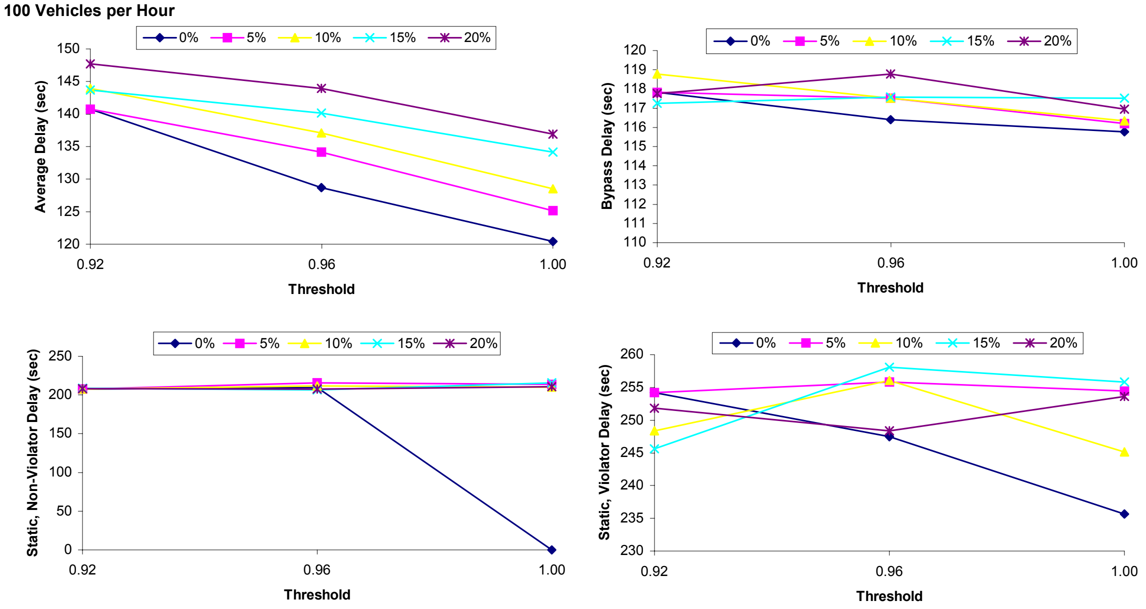


Figure 4-11: Vehicle Travel Time with Demand of 100 veh/h (Original Case)

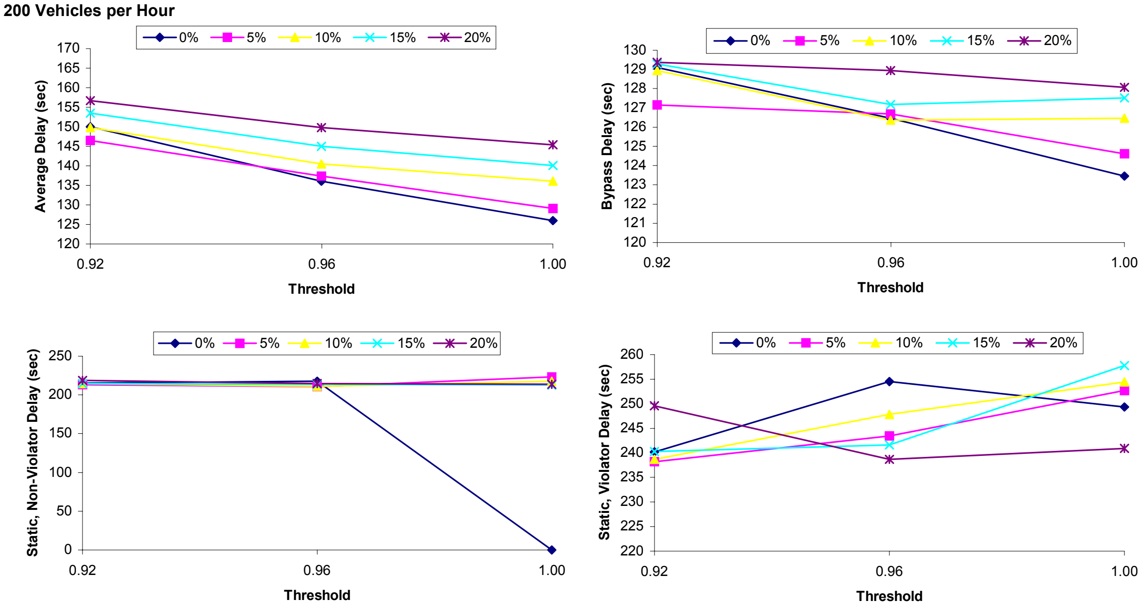


Figure 4-12: Vehicle Travel Time with Demand of 200 veh/h (Original Case)

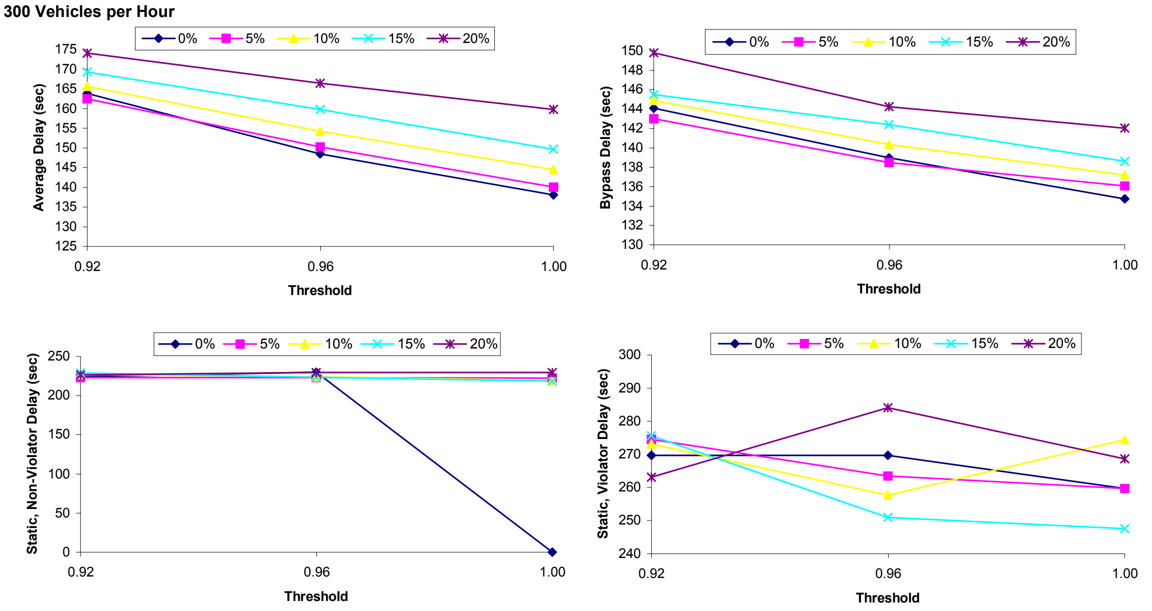


Figure 4-13: Vehicle Travel Time with Demand of 300 veh/h (Original Case)

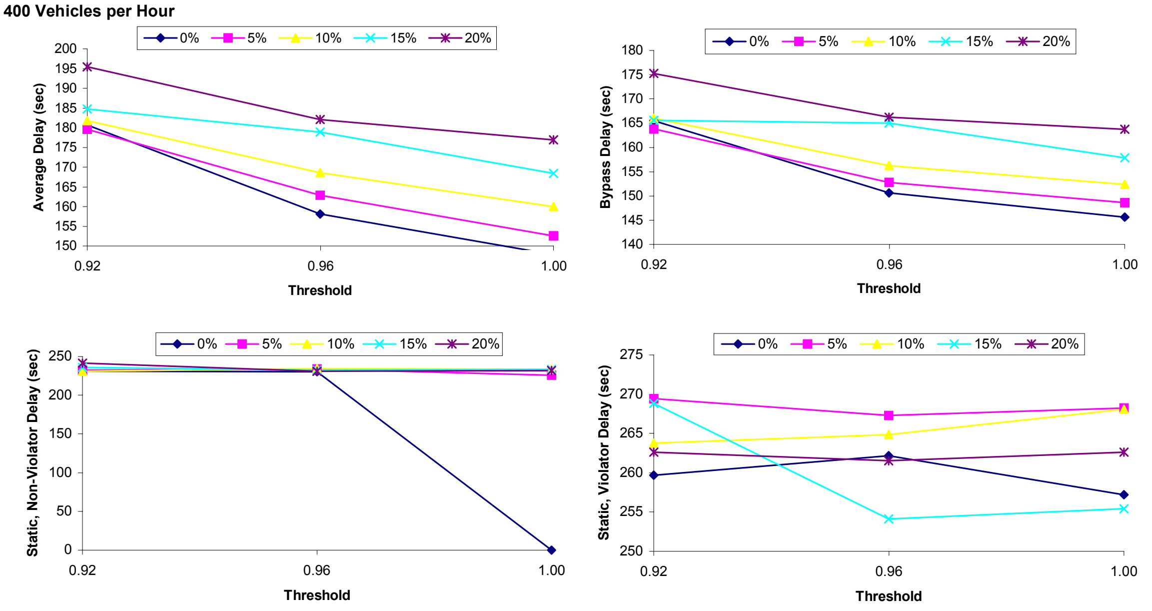


Figure 4-14: Vehicle Travel Time with Demand of 400 veh/h (Original Case)

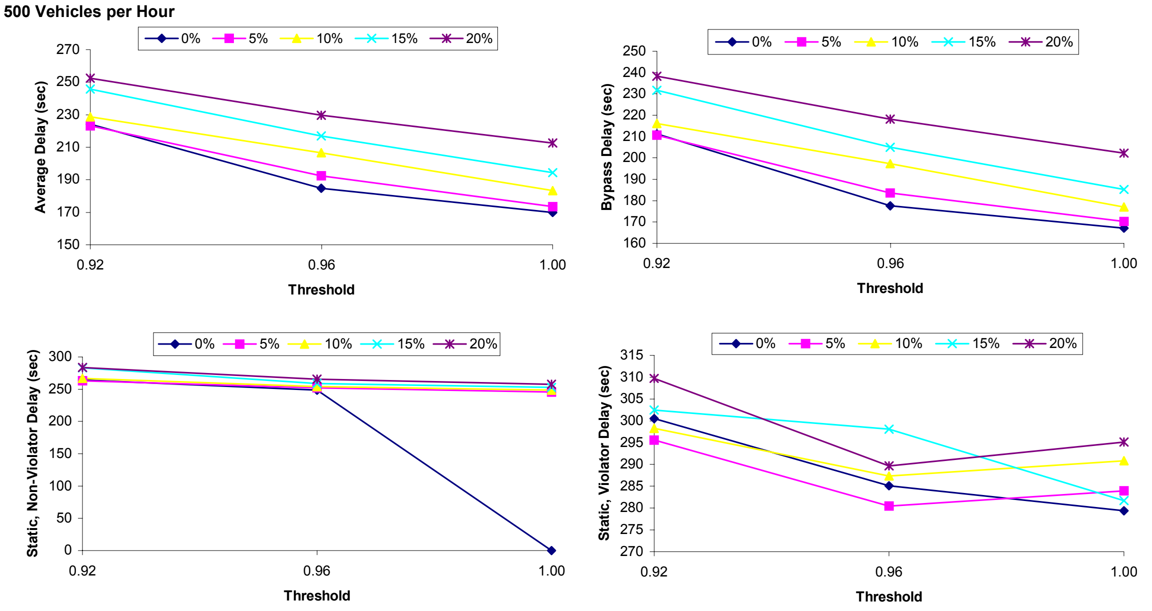


Figure 4-15: Vehicle Travel Time with Demand of 500 veh/h (Original Case)

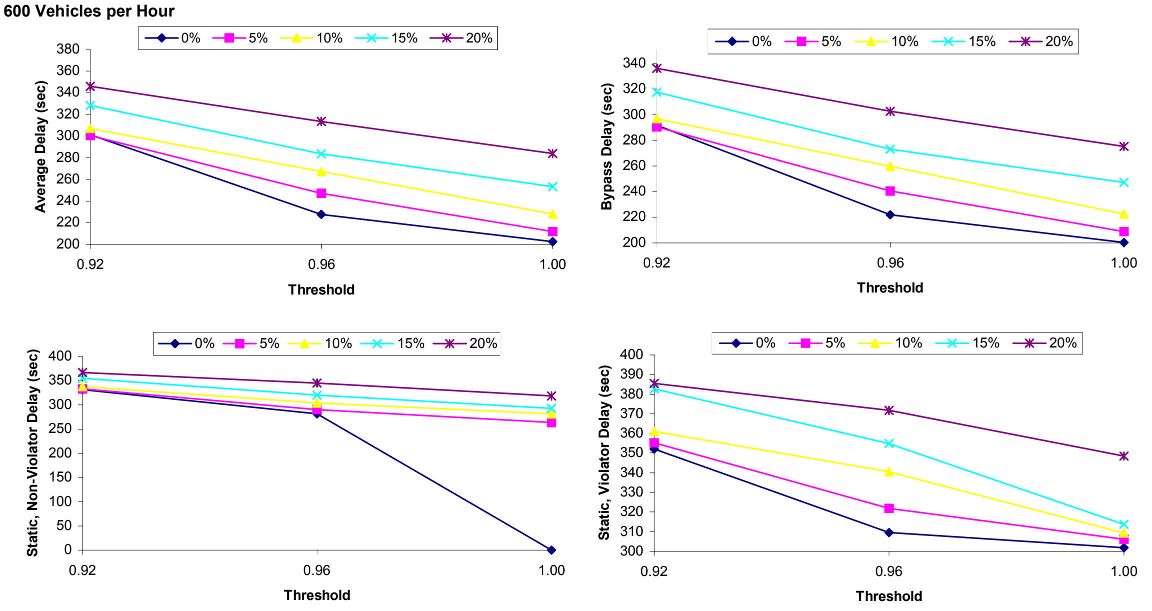


Figure 4-16: Vehicle Travel Time with Demand of 600 veh/h (Original Case)

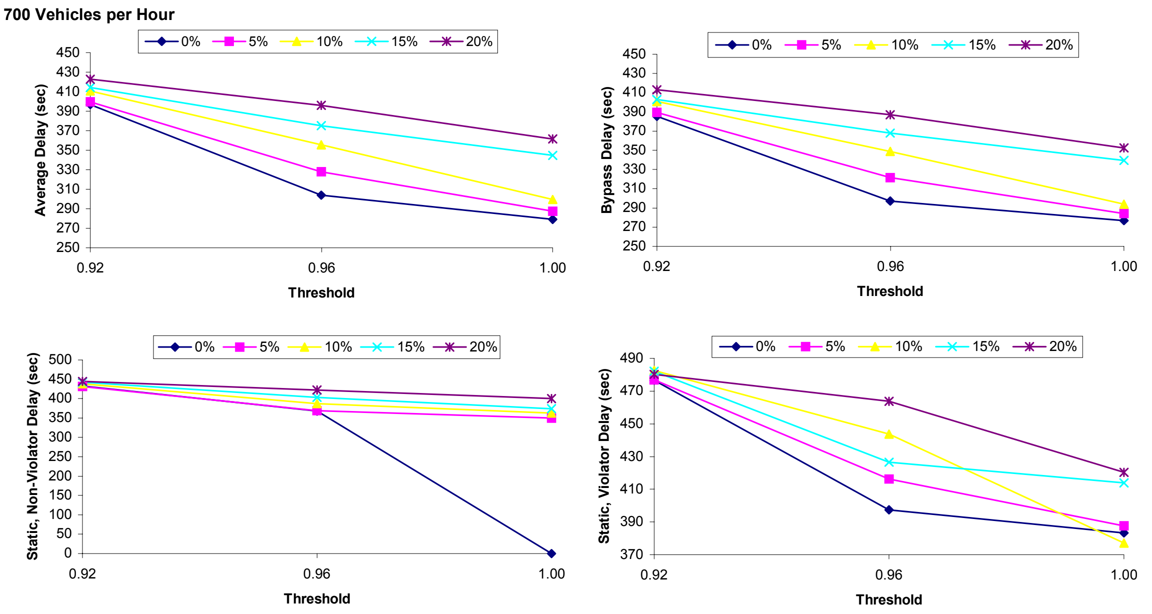


Figure 4-17: Vehicle Travel Time with Demand of 700 veh/h (Original Case)

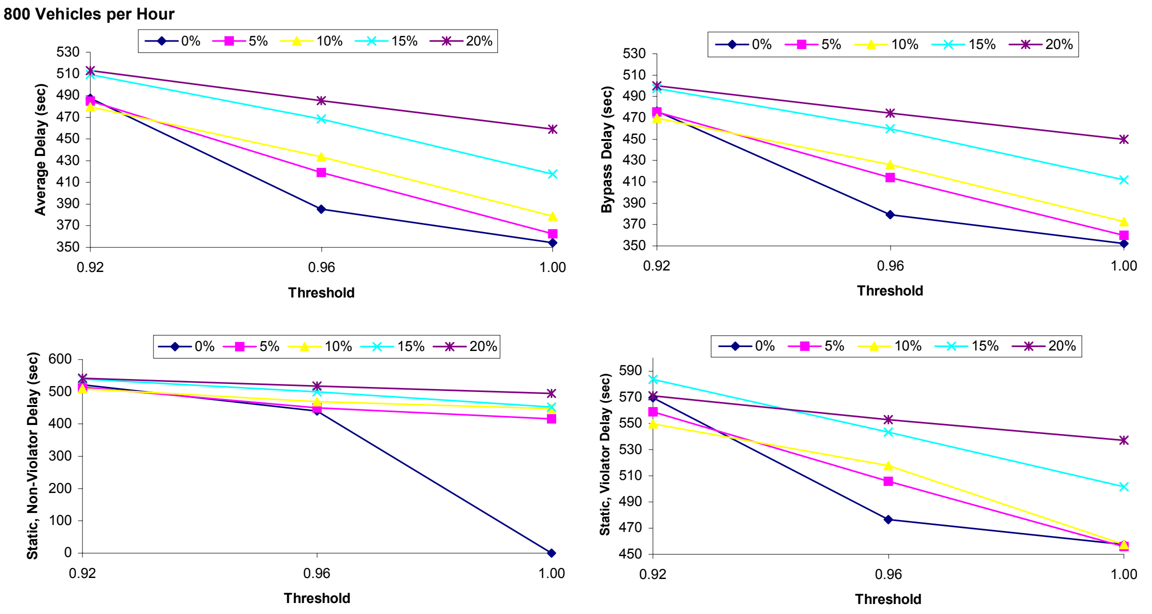


Figure 4-18: Vehicle Travel Time with Demand of 800 veh/h (Original Case)

Table 4.4: Vehicle Travel Time by Classification (Mainline Screening Case)

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	92.6
±10%	Bypass	82.3	80.4	81.0
	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 4.4 Continued: Vehicle Travel Time by Classification (Mainline Screening Case)

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

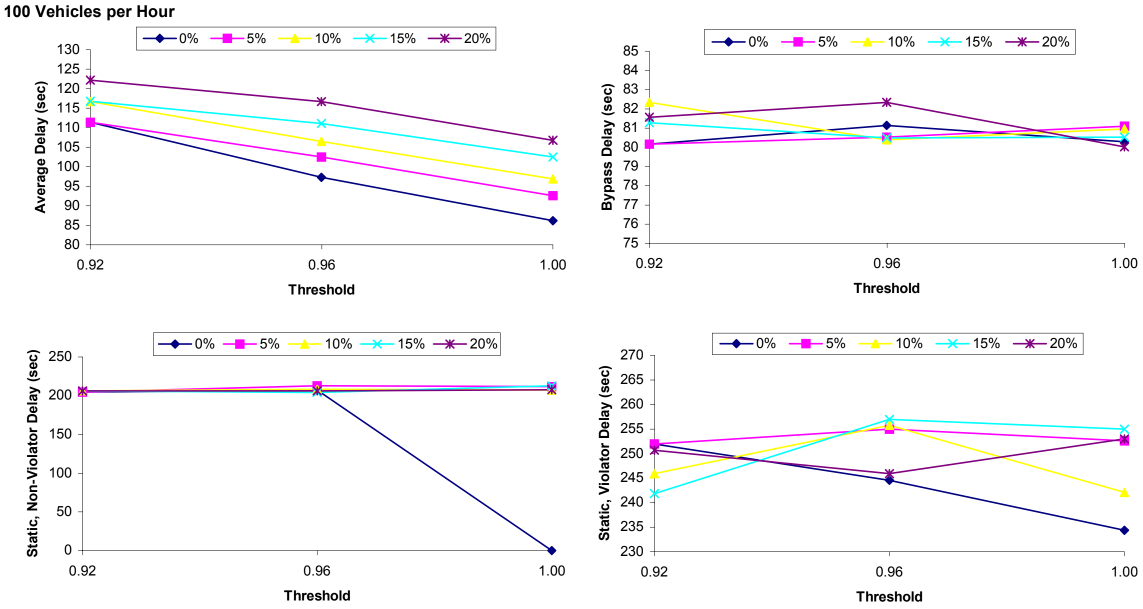


Figure 4-19: Vehicle Travel Time with Demand of 100 veh/h (Mainline Screening Case)

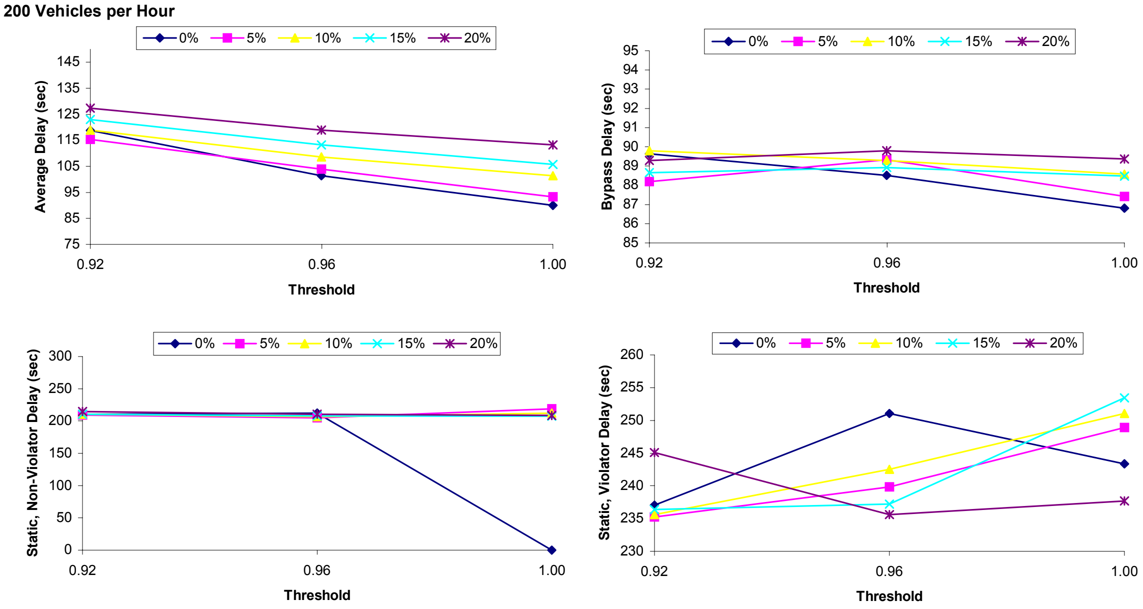


Figure 4-20: Vehicle Travel Time with Demand of 200 veh/h (Mainline Screening Case)

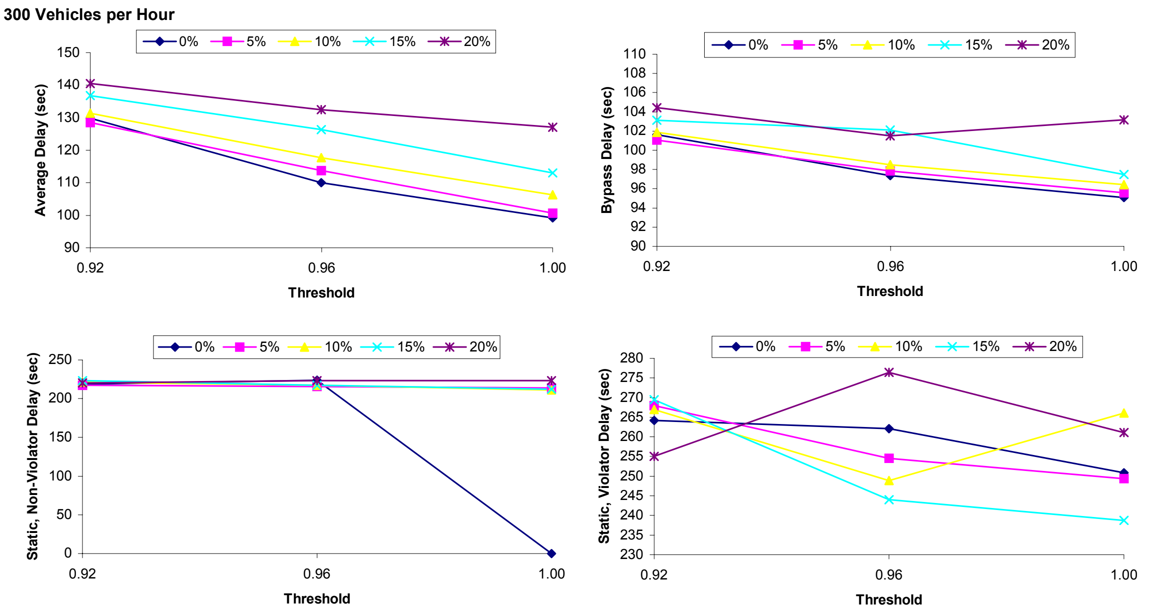


Figure 4-21: Vehicle Travel Time with Demand of 300 veh/h (Mainline Screening Case)

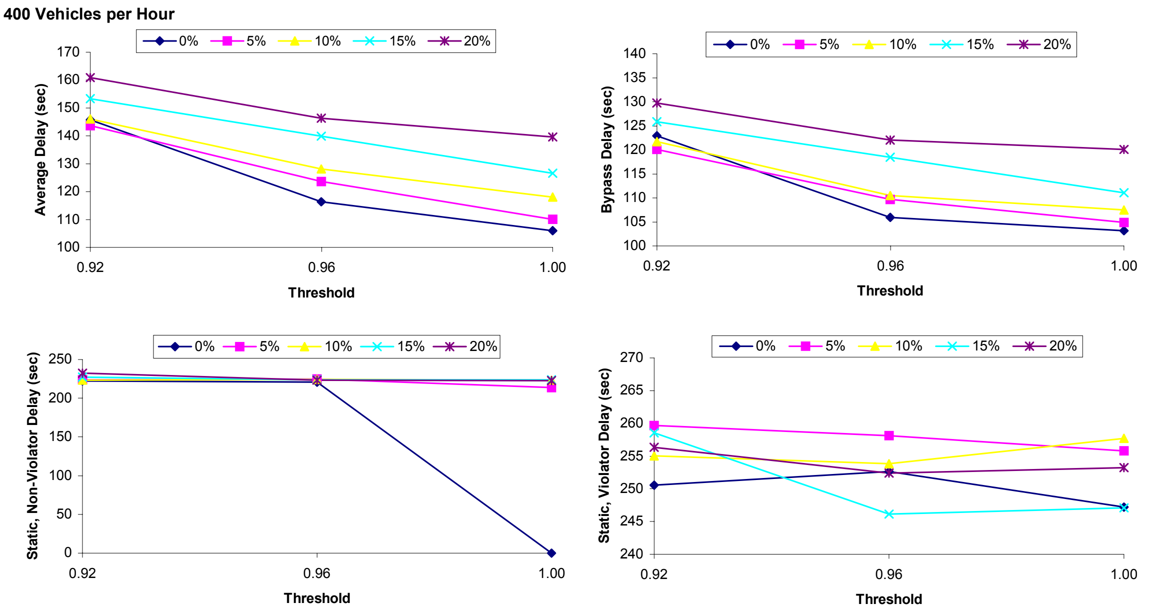


Figure 4-22: Vehicle Travel Time with Demand of 400 veh/h (Mainline Screening Case)

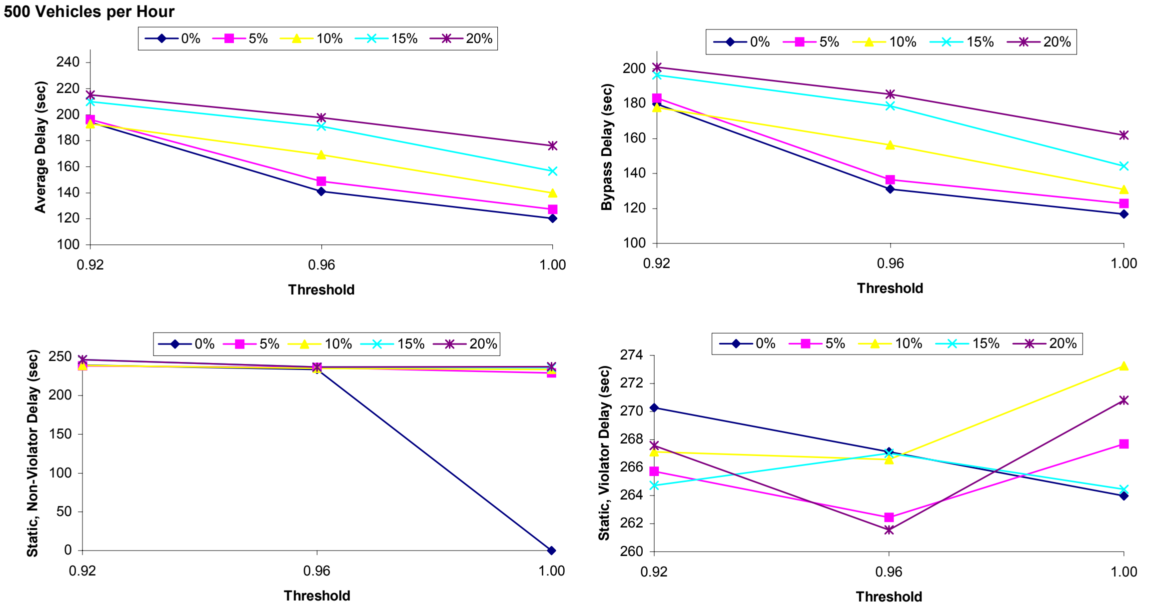


Figure 4-23: Vehicle Travel Time with Demand of 500 veh/h (Mainline Screening Case)

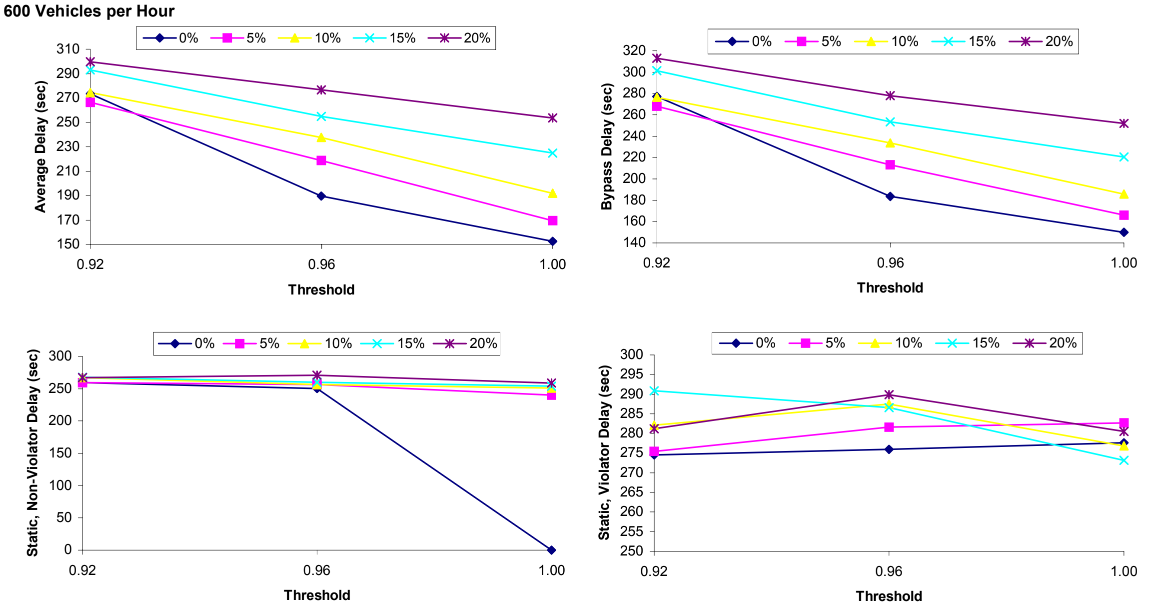


Figure 4-24: Vehicle Travel Time with Demand of 600 veh/h (Mainline Screening Case)

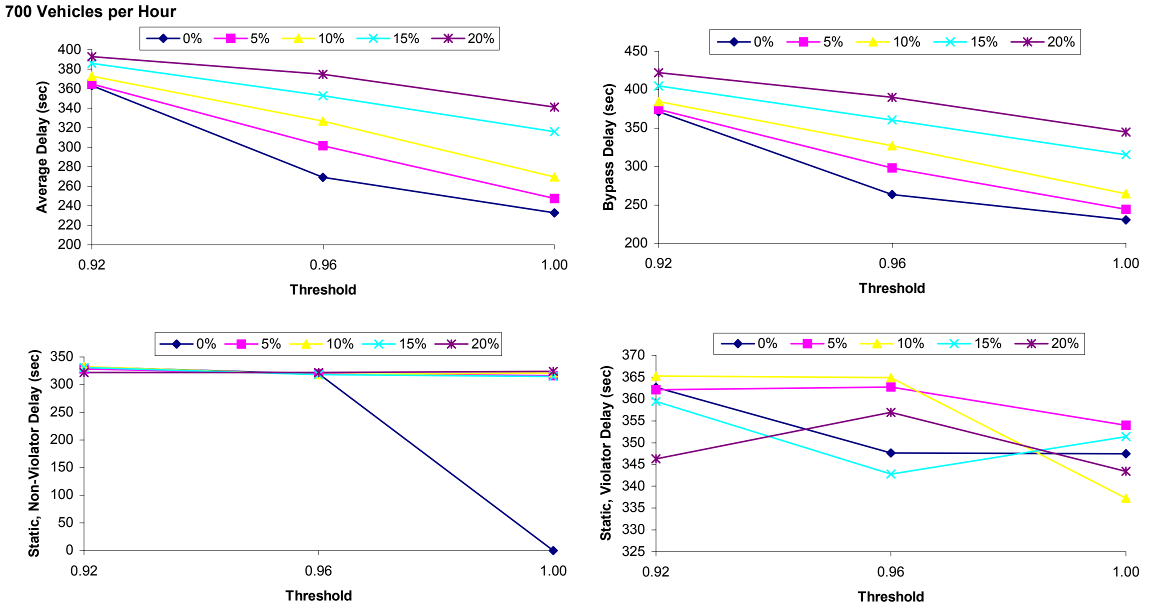


Figure 4-25: Vehicle Travel Time with Demand of 700 veh/h (Mainline Screening Case)

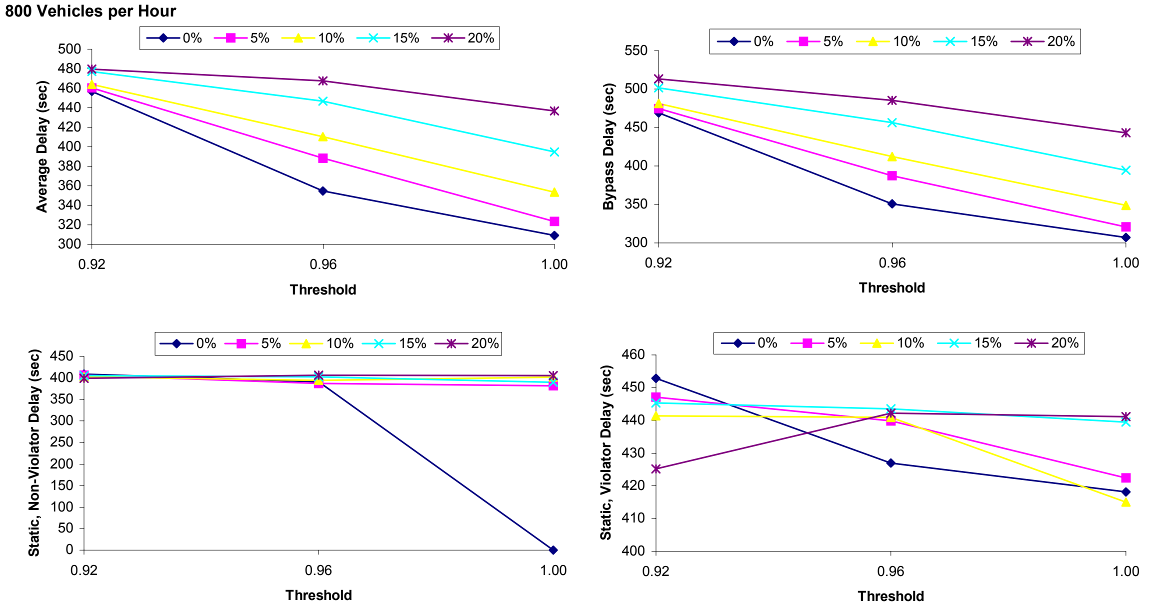


Figure 4-26: Vehicle Travel Time with Demand of 800 veh/h (Mainline Screening Case)

Table 4.5: Percent Increase in Delay compared to Perfect Accuracy and 1.00 Threshold

Original Case

Volume	Accuracy	Threshold		
		0.92	0.96	1.00
100	±0%	17%	7%	0%
	±5%	17%	11%	4%
	±10%	20%	14%	7%
	±15%	19%	16%	11%
	±20%	23%	20%	14%
200	±0%	19%	8%	0%
	±5%	16%	9%	2%
	±10%	19%	12%	8%
	±15%	22%	15%	11%
	±20%	24%	19%	15%
300	±0%	19%	8%	0%
	±5%	18%	9%	1%
	±10%	20%	12%	5%
	±15%	23%	16%	8%
	±20%	26%	21%	16%
400	±0%	22%	7%	0%
	±5%	21%	10%	3%
	±10%	23%	14%	8%
	±15%	25%	21%	14%
	±20%	32%	23%	20%
500	±0%	32%	9%	0%
	±5%	31%	13%	2%
	±10%	35%	22%	8%
	±15%	45%	28%	14%
	±20%	49%	35%	25%
600	±0%	49%	12%	0%
	±5%	48%	22%	5%
	±10%	52%	32%	13%
	±15%	62%	40%	25%
	±20%	71%	55%	40%
700	±0%	42%	9%	0%
	±5%	43%	18%	3%
	±10%	47%	27%	7%
	±15%	48%	34%	23%
	±20%	51%	42%	30%
800	±0%	38%	9%	0%
	±5%	37%	18%	2%
	±10%	35%	22%	7%
	±15%	44%	32%	18%
	±20%	45%	37%	30%

Freeway Screening

Volume	Accuracy	Threshold		
		0.92	0.96	1.00
100	±0%	29%	13%	0%
	±5%	29%	19%	7%
	±10%	35%	24%	12%
	±15%	36%	29%	19%
	±20%	42%	35%	24%
200	±0%	32%	13%	0%
	±5%	28%	16%	4%
	±10%	32%	21%	13%
	±15%	37%	26%	18%
	±20%	42%	32%	26%
300	±0%	31%	11%	0%
	±5%	30%	15%	2%
	±10%	32%	19%	7%
	±15%	38%	27%	14%
	±20%	42%	34%	28%
400	±0%	38%	10%	0%
	±5%	35%	17%	4%
	±10%	38%	21%	11%
	±15%	45%	32%	19%
	±20%	52%	38%	32%
500	±0%	61%	17%	0%
	±5%	63%	24%	6%
	±10%	60%	41%	16%
	±15%	75%	59%	30%
	±20%	79%	64%	46%
600	±0%	79%	25%	0%
	±5%	75%	43%	11%
	±10%	80%	56%	26%
	±15%	92%	67%	48%
	±20%	97%	81%	67%
700	±0%	56%	16%	0%
	±5%	57%	29%	6%
	±10%	60%	40%	16%
	±15%	66%	51%	36%
	±20%	69%	61%	46%
800	±0%	48%	15%	0%
	±5%	49%	26%	5%
	±10%	50%	33%	14%
	±15%	54%	44%	28%
	±20%	55%	51%	41%

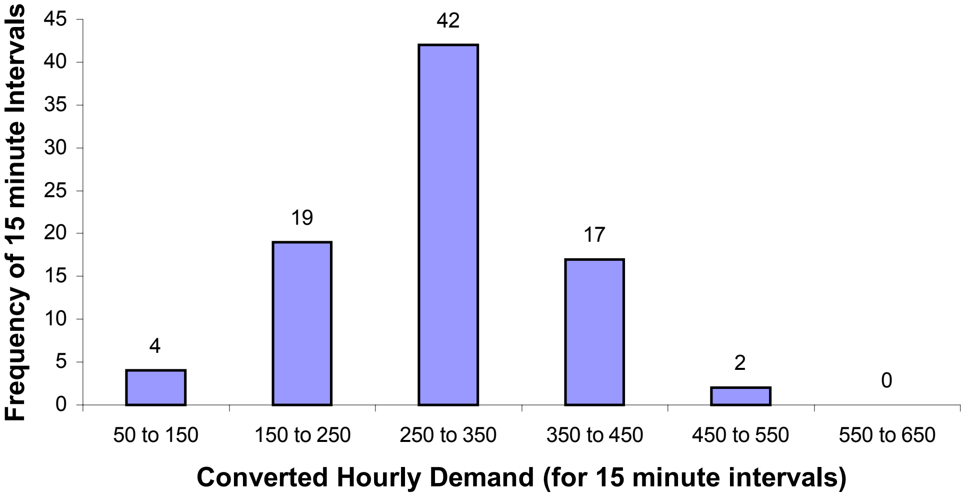


Figure 4-27: Frequency Distribution of Demand Levels

Table 4.6: 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
Total Delay for 21 hour day (veh-hr)		553	643	742	281	390	523

Case A: Ramp Screening with ±0% accuracy, 1.0 threshold
Case B: Ramp Screening with ±5% accuracy, 0.96 threshold
Case C: Ramp Screening with ±10% accuracy, 0.92 threshold
Case D: Freeway Screening with ±0% accuracy, 1.0 threshold
Case E: Freeway Screening with ±5% accuracy, 0.96 threshold
Case F: Freeway Screening with ±10% accuracy, 0.92 threshold

CHAPTER FIVE:
RESEARCH FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 RESEARCH FINDINGS

In this study, the data collection process precluded the collections of static axle weights in conducting the accuracy analysis. Consequently, an analytical procedure for deriving the relationship between the gross vehicle weight and axle weight was developed. The analytical procedure makes a number of simplifying assumptions that include (a) assuming that the axle weights are independent random variables, (b) the axle weight accuracy is equal across the different axles, and (c) that the truck axle weights are not significantly different. Equation 5-1 can be used to relate the standard deviation of the gross weight (σ_T) to the standard deviation of the axle weight (σ_i) for a vehicle with “n” axles. The methodology was applied on one day of WIM data using a Monte Carlo simulation and the final result indicated an error of less than 3.8% between the simulated and estimated total weight accuracy. Although in the validation effort the truck axle weights varied considerably and the truck axle weights were not necessarily independent, the proposed analytical approach still provided gross vehicle weight accuracy within a minor margin of error. Therefore, the approach seems reasonable and was used to estimate axle weight accuracy from gross weight accuracy measurements. Additionally, the results are consistent with ASTM standards for gross and axle weight accuracy requirements.

$$\sigma_T = \sqrt{\sum_{i=1}^{n} \sigma_i^2} = \sqrt{n}\sigma_i \qquad [5\text{-}1]$$

The field evaluation of the Stephens City weigh station operations concluded the following:

a) Northbound and southbound WIM scales were sufficiently calibrated.
b) The WIM weight error density function can be represented using a normal distribution.
c) Northbound and southbound scale accuracy was found to not conform to the ASTM standard of ±6% for the gross vehicle weight (accuracy ranged from 6.1% to 7.0% for a 95% probability of conformity).
d) Average service time was 10 seconds for non-violating trucks and 45 seconds for violating trucks with an overall average of 15 seconds.
e) Average system time ranged from 2 minutes and 3 seconds to 2 minutes and 20 seconds.
f) Only 16% of the vehicles that were diverted to the static scale were violators.
g) Volumes over the 17-hour period over the analysis week were as few as 2150 veh/h for Saturday and peaked up to 4897 veh/h on Wednesday before decreasing.
h) The percentage of trucks sent to the static scale ranged from 8% to 16%.
i) Average hourly flow to the weigh station ranged from 53 to 400 veh/h.

The framework involved for modeling evaluation required that a method be developed to estimate the number of vehicles that would be sent by the WIM system for varying scenarios. A Monte Carlo simulation was used in which trucks were evaluated using a normal distribution of error around axle weights to determine whether or not the vehicle would be sent to the static scale. The results of the sensitivity analysis with varying accuracy and threshold were used as inputs for the INTEGRATION microscopic simulation model to calculate the travel time for each classification of vehicle using both a traditional ramp sorting system and a mainline screening system.

The results for the modeling evaluation concluded the following:

a) The INTEGRATION model results provided travel times that were within a 95% confidence interval of actual field conditions for fifteen different time intervals.
b) Using a gross weight analysis, 0.9% of vehicles would be violators.
c) Using an axle weight analysis as the actual WIM system does, 2.0% would be violators, thus a gross weight analysis is not a good estimate of actual field conditions.
d) Decreasing the threshold in order to improve the level of enforcement will cause a higher amount of delay for non-violating truck drivers unless the system is 100% accurate (with a 0.90 threshold, about 30% of non-violating trucks would experience unnecessary delays).
e) Increasing the threshold in order to reduce delay will result in a decreased level of enforcement as more violators will enter the bypass lane unless the system is 100% accurate (with a 1.00 threshold, up to 30% of violating trucks would be able to bypass the scale).
f) Using a mainline screening system can save a significant amount of time in terms of vehicle-hours of delay (i.e. at a demand of 300 vehicles per hour with ±5% accuracy and a threshold of 0.96, given a 17-hour period of data, 643 vehicle-hours of delay would occur in the original case as opposed to only 390 vehicle-hours of delay in the mainline screening case).

5.2 CONCLUSIONS

In this thesis, the quality of weigh station operations at the Stephens City Weigh Station was quantified in terms of the accuracy that the WIM system produced. The framework developed in the field evaluation can be used to evaluate other weigh stations in a similar manner. Additionally, a framework was developed for modeling weigh station operations at the Stephens City Weigh Station. The model can be adapted to test alternate arrangements in other weigh station facilities for utilization by a decision maker in order to determine what type of WIM system is needed to fit their particular situation.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Further validation of the proposed analytical procedure for relating axle and gross vehicle weights using field data is required. These validation efforts would require both WIM and static axle weights.

Weigh-in-Motion technology has been developed that would allow trucks to be screened at highway speeds and be pulled into the weigh station if the truck is overweight. Otherwise, they would continue on the highway. Although this scenario would reduce delay, having a highly accurate system would help control the static scale delay even further, which is a very significant portion of the total delay at a WIM facility.

In order to have a better understanding of the accuracy of the system, it is recommended that more data be obtained in other time periods throughout the year to see how weather conditions have an effect on the accuracy. It is also believed that human error may play a role in terms of drivers driving over the WIM scale, and thus this topic should be given some consideration as well.

Further research in delay characterizations at weigh stations could possibly lead to a procedure for determining a level of service criteria for weigh station facilities. Level of service criteria would be beneficial to departments of transportation and other transportation agencies in determining how to make use of funding for commercial vehicle enforcement. If it can be proven that installing a more accurate system would improve operations, the transportation agency might be willing to invest more money into the system.

In further studies, it is recommended that a detailed cost/benefit analysis be performed in order to understand the overall advantages of one scale over another not only by travel time savings as this study shows, but evaluating the economics of a system as well.

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VITA

Bryan Katz was born in Somerville, New Jersey to Alan and Marcia Katz. After living in New Jersey and Connecticut for a short period, he moved to beautiful Haymarket, Virginia in 1985. In 1997, he graduated from Stonewall Jackson High School in Manassas, Virginia with an International Baccalaureate diploma and went on to pursue a Bachelor of Science in Civil Engineering at Virginia Tech. At Virginia Tech, he became active in the American Society of Civil Engineers and the Institute of Transportation Engineers. He graduated with his Bachelor's Degree in 2000 and stayed at Virginia Tech to pursue a Master's. While working on both his Bachelor's and Master's degrees, he has been an Engineer with HNTB Corporation in the Construction Services Group as a consultant to the Virginia Department of Transportation on the US Highway 460 Christiansburg Bypass Program. Bryan is the 2001 recipient of the Mid Atlantic Universities Transportation Center (MAUTC) Outstanding Student Award. Upon completion of his Master's Degree in December 2001, Bryan plans to begin working for Science Applications International Corporation (SAIC) in Northern Virginia.