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I am submitting herewith a dissertation written by Zhongren Gu entitled "Floating WIM Threshold Concept for Truck Weight Enforcement". I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

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Floating WIM Threshold Concept

for Truck Weight Enforcement

A Dissertation

Presented for the

Doctor of Philosophy Degree

The University of Tennessee, Knoxville

Zhongren Gu

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Dedication

This dissertation is dedicated to my wife, parents, parents in law, brothers, and sister in law for their love, support, and encouragement.

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ABSTRACT

Weigh stations are the primary weight compliance checkpoints for commercial trucks. In the past several decades, states have used weigh-in-motion (WIM) technology to reduce delay and increase enforcement on overweight vehicles. This study offers a detailed analysis of weigh station systems and presents floating-threshold algorithms to improve the efficiency of WIM equipped weigh stations.

This research evaluates weigh station design and operational parameters using queueing theory and found that WIM technology not only enhances the effectiveness and efficiency of weigh station operations but also largely reduces travel delay for trucking companies. The effects of truck demand, truck weight distribution, static scale service time, WIM accuracy, and sorting threshold on weigh station operations have been analyzed. The author shows the importance of transponders in a WIM mainline weigh station operation. The author also proves that the increase of storage spaces within a weigh station may largely increase truck travel delay and does not significantly improve weigh station operations.

This research focuses on the development of floating-threshold algorithms. Since the number of trucks, particularly heavy trucks, has increased rapidly in recent decades, many weigh stations cannot meet the demand even when equipped with WIM systems. This problem is complicated by the fact that truck demands, truck weight distribution, and static scale service time vary by time of day and day of week. The author designed floating-threshold algorithms to automatically adapt to high truck demand and the varying of truck demand, truck weight distribution, and static scale service time, over time. When the queue at the weigh station is long, the threshold value is increased so as to avoid the closure of the weigh station while still catching the worst weight limit offenders. When the queue is short, the threshold value is lowered to increase the number of trucks inspected. Both the traditional fixed-threshold strategy and two floating-threshold strategies were modeled and tested using a microscopic simulation model. The results show that floating-threshold strategies are both more effective in weight enforcement and more efficient for heavy traffic flow and high-variance environments. The finding that different floating-threshold strategies have different effects indicates that it is necessary to make a further study on floating-threshold algorithms.

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1 Introduction

Overweight trucks reduce the lifespan of highway roads and indirectly increase the maintenance costs of these roads. Improvement in the methods for the enforcement of commercial vehicle weight laws may increase the number of overweight vehicles caught, thereby prolonging highway life. Improved enforcement may also reduce the number of illegally operating commercial vehicles.

1.1 Problem overview

A highway is built to serve its function for the period of its design life, usually a period of years. Actually, the roads are designed according to the number of equivalent single axle loads (ESALs) passing before repair or replacement is required. According to the 4th power rule (Huang 1993), strain caused by overweight axles grows exponentially. The 4th power rule states

$$ESAL = \left(\frac{L_x}{L_s}\right)^4$$ **Equation 1-1**

where

Lx: the load in kips on each axle

LS: the load in kips on a standard axle, which is 18 kips

As per the 4th power rule, while an axle load of 20 kips is equivalent to 1.52 ESALs, an axle load of 24 kips is equivalent to 3.16 ESALs. Thus, the weighing of the vehicles is extremely important.

Weight enforcement measures by the State have increased in the last 15 years. The increasing number of trucks operating on interstate highways and the increasing use of weigh-in-motion (WIM) technology for screening trucks are reflected in the higher number of vehicles weighed (Table 1-1).

Although the reported incidences of overweight trucks are less than 1% of the trucks weighed, it is believed that trucks evade the weighing by avoiding the weigh stations and that the actual number of overweight trucks is much greater than that indicated by the weight citation data. WIM data collected at Highway Performance Monitoring (HPMS)

Table 1-1 State Weight Enforcement

Year	Weighed trucks (Including WIM)	Weighed trucks (Excluding WIM)	Weight citations	Violation rate
1985	105,234,000	97,330,000	664,033	0.007
1987	117,900,000	104,452,000	671,259	0.006
1989	146,950,000	124,687,000	692,673	0.006
1991	150,428,000	116,759,000	663,204	0.006
1993	162,615,000	111,889,000	653,492	0.006
1995	169,568,000	111,620,000	654,903	0.006
1997	174,757,174	108,137,433	648,384	0.006
2000	192,991,222	100,103,108	692,988	0.007

(Data from: Office of Freight Management and Operations, FHWA, and Comprehensive Truck Size and Weight Study, FHWA 2000) sites, for example, showed that as many as 20% of the vehicles exceeded legal weight limits (Church and Mergel 2000). Grenzeback et al. (1988) estimated that 15% of all commercial trucks on the Interstate systems were overweight.

Effectively monitoring and controlling truck weights is critical to preserve the life of a road and to minimize pavement maintenance costs. Fekpe et al. (1995) found that pavement costs depended more on the enforcement level than on the weight limit. Strathman and Theisen (2002) stated that on I-5, the incidence of overweight vehicles increased from 2.27% before the closure of a weigh station to 3.67% after closure. After the weigh stations reopened, the incidence of overweight vehicles declined to 3.19%. All these changes were statistically significant at the 95% confidence level.

It is argued that the weight enforcement activities deterred overloading and that eliminating this deterrence would lead to heavier loads (DalPonte, 2000). The studies conducted by several state enforcement agencies also proved this relationship between enforcement level and violation rate (Table 1-2 and Figure 1-1, Taylor et al. 2000). An assessment of potential damage savings to the Texas highway system, particularly I-35 and I-10, showed that an increased enforcement rate of 10% produced an average reduction of 5% in the ESAL accumulations during a 20-year analysis period. The analysis also revealed that each additional 15% increase in the enforcement rate produced an average of 7 to 11% reduction in the accumulated ESALs, which implies that pavement life would be increased and substantial economic benefits could be obtained by increasing weight enforcement levels (Belfield et al. 1999).

Table 1-2 Overweight Violation Rate across State Agency

State	High Enforcement Level Violation Rate	Low Enforcement Level Violation Rate
Virginia (2*)	0.5 to 2.0 %	12 to 27 %
Maryland (2)	1.0 %	34 %
Arizona (2)	1.5 %	30 %
Wisconsin (3)	1.0 %	20 %
Idaho (4)	11.9 %	32 %
Florida (5)	1.4 %	13 %
Montana (6)	1.0 %	29 %

*Number represents number of weigh stations included in study.

Source: Taylor, B., Bergan, A., and Lindgren, N., 2000

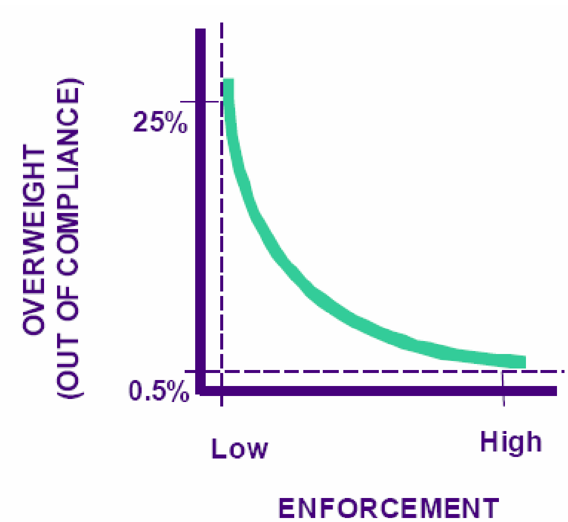

Figure 1-1 Overweight Violation Rate versus Enforcement Level

Source: Taylor, B., Bergan, A., and Lindgren, N., 2000.

1.2 The current situation of the operation of weigh stations

Weigh stations are the primary regulatory compliance checkpoints for commercial trucks in many states. There are over 600 weigh stations located within the United States (Rand McNally, 2005). In 2000, there were about 193 million trucks weighed at these stations (FHWA 2000). However, a large number of weigh stations can not cope with the current traffic levels, resulting in less efficient use of government resources and more travel time for motorists. Weigh station administrators usually close weigh stations to prevent queues from extending onto the mainline. Such a queue spillover can result in an inordinate number of trucks bypassing without compliance checks when weigh stations do not have enough capacity. When trucks are turned away, enforcement levels are reduced and overweight vehicles may possibly continue traveling on the highway. The increased number of trucks on the highway systems also has caused excessive delays at weigh stations, and backups on the entrance ramps create a hazardous condition for freeway traffic.

In response, state enforcement agencies have sought capacity enhancements for the weigh stations. WIM technology, introduced over 50 years ago, significantly increases the capacity of weigh stations. WIM technology weighs trucks without stopping and only requires the trucks with WIM weights above a preset threshold to be weighed by the more accurate static scales. This technology has greatly increased the weight enforcement level and reduced truck delay (Kamyab, A., 1998, Benekohal *et al*., 1999). Road agencies have several options when selecting WIM systems for weight enforcement facilities. The primary options include the placement of WIM systems (i.e. mainline or ramp WIM) and the type of WIM systems (Trischuk et al. 2002). In Tennessee, all the weigh stations use weigh-in-motion technology.

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 the weight that is carried by each wheel, axle, axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces” (ASTM 2002). ASTM classifies four types of WIM systems by speed range, type of application, performance requirements, and other desired characteristics. ASTM Type I and Type II WIM systems are used for traffic data. ASTM Type III and IV WIM systems are used for weight enforcement. As Type IV WIM scales have not yet been approved for use in the United States (ASTM, 2002), U.S. weigh stations must use Type III WIM scales.

The efficiency and effectiveness of a WIM system is determined largely by its accuracy level. If the accuracy is low, the number of vehicles that must be weighed on the static scale increases in order to ensure that the static scale weighs potentially overweight vehicles. In addition, if the WIM underestimates a vehicle’s weight, potentially overweight trucks can bypass the system. The required accuracy level by ASTM is shown in Table 1-3.

There are two solutions for capacity shortage. The first is to physically increase the capacity of a weigh station by building more static scales, which is costly and sometimes infeasible because of specific topology limits. The second method is to decrease the

Table 1-3 Required Accuracy Level by ASTM

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 (2 km / h)				
Axle-Spacing	± 0.5 ft (150 mm)				
Source: ASTM Designation E 1318-02					

number of trucks to be weighed at weigh stations by employing an electronic screen. This method is currently a hot topic both in theoretical research and real application. It uses automatic vehicle identification (AVI) technology to identify the information from an approaching truck. The weight, axle spacing, and other safety information of the trucks with transponders (AVI tags) are checked by a real time database. Usually, electronic screening technology is integrated with mainline WIM technology so that trucks can be checked on the mainline at normal speed. There are three main types of electronic screening systems in the United States: Prepass, Norpass, and Oregon Green Light. Although there are about 350 weigh stations adopting electronic screening technology (Prepass, Norpass, and Oregon Green Light, 2004), the effectiveness of electronic screening is not very obvious because approximately only 0.3% trucks are equipped with transponders (Prepass, Norpass, and Oregon Green Light, accessed April 24th 2004), and transponders are not totally interoperable between different systems.

The number of trucks has increased rapidly in the last decade, 22.45% between 1992 and 1997, 20.22% between 1997 and 2002. While the number of medium and heavy trucks (those weighing more than 6,000 pounds) grew by 18% between 1992 and 1997, the number of trucks in the heavy category (over 50,000 pounds) grew by 37% between 1992 and 1997. Although the number of heavy trucks grew only by 10.7% between 1997 and 2002, the number of trucks with gross weights between 80 kips and 130 kips grew nearly by 50% between 1997 and 2002 (Figure 1-2, Bureau of Transportation Statistics, 2003). In 1998, about 27% of the annual average daily traffic (AADT) on I-40 near Watt Road Weigh and Inspection Station consisted of trucks. The average daily truck volume was more than 21,000 trucks per day (Knoxville Regional Transportation Planning Organization, 2002). Due to the rapid increase in the number of trucks, particularly the heavy trucks, many weigh stations cannot handle the increased workload even when equipped with a WIM system. State enforcement agencies are still trying to arrive at solutions to solve the capacity shortage of weigh stations. I attempt to develop floating-threshold algorithms to alleviate this capacity shortage.

Although WIM technology has been widely adopted for truck weight enforcement and the preset sorting threshold value plays a key role in the application of WIM technology, few studies have been conducted on the selection of a sorting threshold.

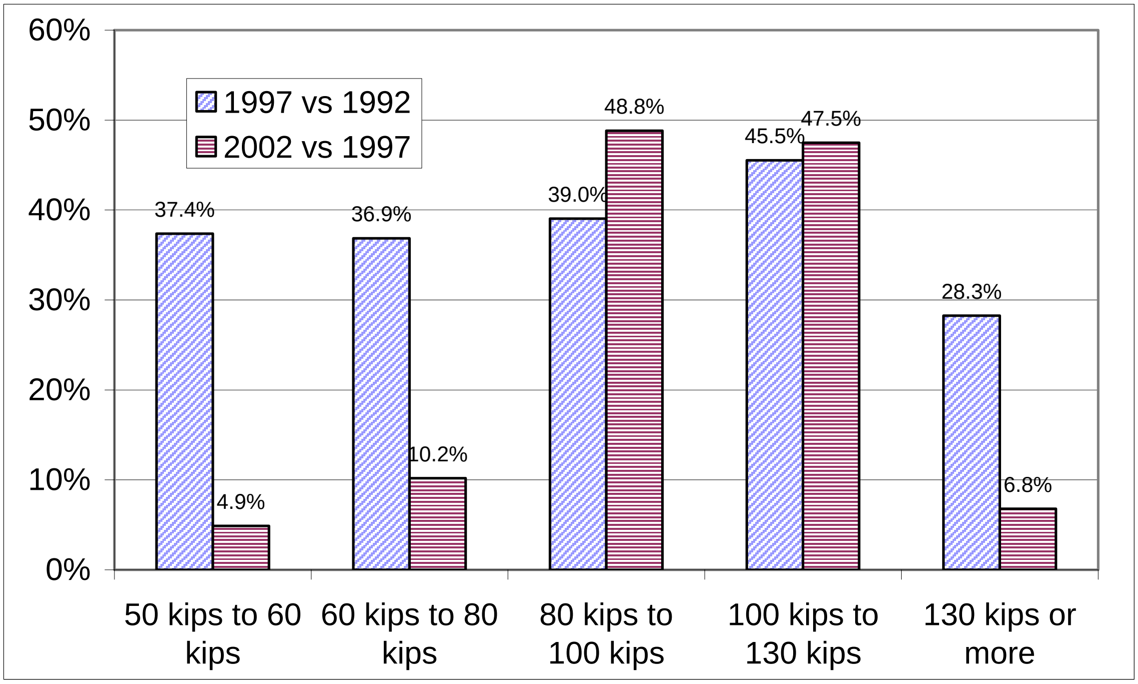

Figure 1-2 Increasing Rate for Heavy Trucks

1.3 Research objectives

This project has three major objectives:

- To theoretically analyze how to select the preset threshold value,
- To analytically compare four weigh station design strategies and theoretically analyze some important weigh station operational parameters, and
- To develop cost-effective floating-threshold algorithms for detecting overweight trucks effectively and efficiently.

1.4 The layout of this dissertation

This dissertation contains 6 chapters. Chapter 1 introduces current weight enforcement issues, current practice of weigh stations, and the research objectives. Chapter 2 presents a brief review of earlier research. Chapter 3 presents the measurements of effectiveness (MOEs) systems for weigh station operations and statistically analyzes truck WIM weight distribution. It also includes statistical research on choosing a suitable sorting threshold. Chapter 4 uses queueing theory to evaluate weigh station design and operational strategies and presents findings about weigh station design and operation. Chapter 5 develops floating sorting threshold algorithms to meet the varying and congested operation environments of a weigh station. Fixed sorting threshold algorithms and floating threshold algorithms are compared for effectiveness and the results show that the floating sorting threshold algorithms are more effective. Chapter 6 summarizes the research and offers suggestions for future research in weight enforcement.

2 Literature Review

2.1 Analysis of the characteristics of weigh station parameters

Just as with other traffic systems, it is very important for weigh station researchers to consider the various components of a weigh station system, and the manner in which they interact to form traffic streams. A traffic system may consist of drivers, vehicles, roads and highways, the general environment, and control device (McShane et al. 1998). The driver characteristics, road system, general environment are not the contents of this project, our research focuses on traffic arrival demand, weight distribution of trucks, service time for overweight and legal weight trucks, the layout of a weigh station, the accuracy of the WIM system, and the sorting threshold of a WIM scale. Several studies have been conducted on the characteristics of truck demand, truck weight distribution, static scale service time, and WIM scale accuracy.

2.1.1 Truck volume variation

After analyzing the data from the Central Traffic Data Base of the Long-Term Pavement Performance (LTPP) project, Hallenbeck et al. (1997) arrived at the following conclusions with respect to the volume of truck traffic:

- Volumes by the day of the week: at most sites, Sunday traffic volume is the lowest for the week for trucks; Saturday truck traffic volume is the second lowest. For weekdays, Monday truck traffic volume is the lowest. The truck traffic volumes for all the other weekdays are similar;

- Volume of traffic by time of day: there is a flat time-of-day distribution for long-haul truck traffic;
- Volume of traffic by the month: at most sites, truck traffic volumes follow different monthly patterns. At the national level, the average monthly trends of trucks are very similar to those of cars;
- Local conditions appear to have an extremely large impact on the time of day and day of week patterns on a given roadway, regardless of road type or level of traffic volume. These variations should be predicted based on field data of a specific road, when necessary.

Stamatiadis and Allen (1997) found that traffic volume variations for Class 9 vehicles changed similarly by day of week, as observed by Hallenbeck et al. (1997). They also found that the variations in the truck traffic volume were not more stable than that for car traffic volumes, when measured in terms of month of year and day of week.

2.1.2 Truck headway distribution

Headway is the time between the passing of a point by successive vehicles, along a lane. The distribution of these headways has been studied, the primary objective being application to capacity estimation, safety analysis, and generation of vehicular traffic in microscopic simulations. Some of these models are based on the selection of various distribution functions, such as the Gamma, Pearson, and Log-normal distributions, while others are based on a mixed distribution (Mahalel and Hakkert, 1983). Al-Ghamdi (2001) divided the traffic flow on freeways into three groups: low flow state, less than 400 vehicles per hour (vph); medium flow state, between 400 and 1200 vph; and, high flow state, more than 1200 vph. He found that negative exponential, shifted exponential, and gamma distributions could well describe headways for low and medium traffic flow on freeways, Erlang distribution seemed to properly fit the high traffic flow state, and Gamma distribution gave a decent fit for large range of flows on arterials (approximately 600 – 1200 vph). Based on the field study at the southbound Dumfries weigh station on I-95 on March 15, 1994, Weng (1995) proved that truck headway was exponentially distributed at the 0.01 level.

Figure 2-1 was created by the data collected at the Westbound Watt Rd. Inspection Station in Knox County, TN on Monday, August 11, 03 from 8:22 until 9:30 AM. The headway exhibited exponential distribution at the 0.05 level.

2.1.3 Truck weight distribution

There are two important issues concerning truck weight distribution. First, the manner in which truck weight changes over time. Second, the manner in which truck weight is distributed among weight categories.

Danlin (1992) used North Carolina's permanent WIM systems in a study of weight distributions throughout the state. He found that there was no significant statistical difference between truck weights on a seasonal basis at a particular site, but there was not enough evidence to decide whether a difference might exist on the weekends.

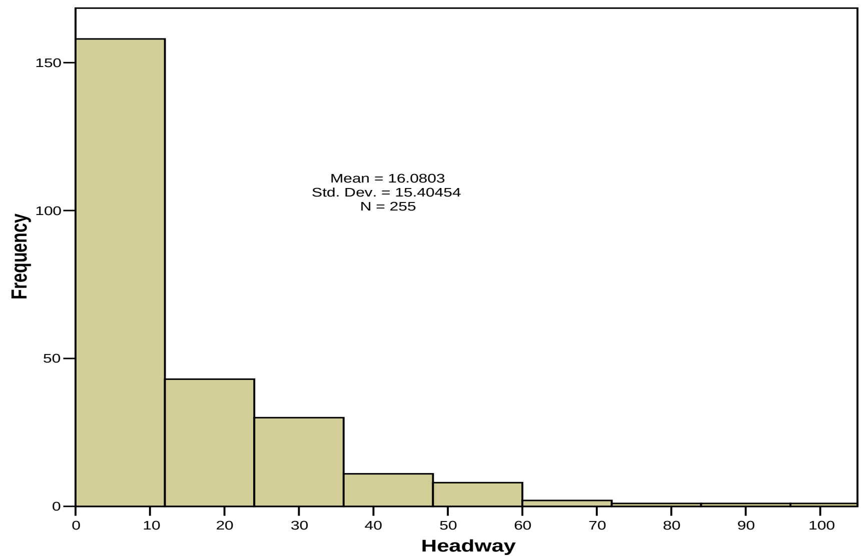

Figure 2-1 Truck Headway

Wu (1996) estimated the truck loading using WIM data and found that the variation in the gross truck-weight distribution was not significant on either a daily or a seasonal basis.

Ahanotu (1999) researched weight data from Georgia and found that WIM data from Advantage I-75 project showed a significant difference between weight distributions at different locations and weight distribution varied significantly in terms of time of day and day of week. This space variation of truck weight distribution can also be proved by the truck weight data from FHWA's Vehicle Travel information System (VTRIS).

Ott and Papagiannakis (1996) analyzed the variations in the measurements of five-axle semitrailer (3-S2) truck steering-axle load and found that the distribution of gross vehicle weight (GVW) of a 3-S2 truck revealed four distinct patterns:

- Bimodal with distinct peaks

- Unimodal/unloaded with a dominant peak corresponding to empty trucks,
- Unimodal/loaded with a dominant peak corresponding to loaded trucks, and
- Others, including main distribution with more than two distinct peaks.

They found that most of the analyzed GVW distributions were bimodal (Table 2-1).

Chou and Ching (1995) analyzed the truckload data in Taiwan. They observed from their data that both gross truck weight and tandem axle weight belong to bimodal distribution whereas single axle weight has only one peak.

This truck gross-weight bimodal distribution method has also been approved by Mohammadi and Shah (1992), Fwa et al. (1992), and Mei et al. (2004). Fwa et al. statistically proved that their gross vehicle weight data belonged to the Weibull distribution while Mei et al. demonstrated their weight data were normally distributed.

2.1.4 WIM accuracy

WIM accuracy depends upon three factors: pavement smoothness, vehicle dynamics, and the integrity of the WIM system [Bergen, 1997]. Errors due to vehicle dynamics are typically isolated to liquid loads, vehicles changing lanes, and peculiar loads. Pavement condition and WIM systematic errors are a much bigger concern.

There are some causes of errors when using a WIM scale (Fekpe, 1993). A major source of errors is the bouncing of vehicles on their tires and suspensions as they travel at speed. Other errors arise from inaccuracies in WIM equipments and calibration problems.

Table 2-1 Frequencies of Four GVW Distributions

Sample Size	*Number of Sites*	*Bi-modal*	*Unimodal/unloaded*	*Unimodal/loaded*	*Others*
N > or = 50	603	71.00%	8.80%	17.60%	2.70%
N > or = 100	297	80.10%	4.00%	14.00%	1.90%

Although it is agreed that WIM loads are an approximation to static loads, WIM loads are only a reference to pavement design, legislation and regulation of size, and weight regulations.

Although the accuracy of the WIM systems has been improved over time, WIM loads are not yet deemed a legal basis for writing a weight-violation ticket. Although, some WIM sites operate at much higher accuracy than others, no systems has yet been proven to consistently yield load and weight values that are within legally acceptable tolerance. WIM scales currently have an accuracy of between 80-94%. For a violation to be enforced, an accuracy of 99% must be achieved (Oak Ridge National Laboratory, 2000). Currently, WIM cannot be used alone for weight enforcement.

Calibration is used to ensure that the estimation of weight by a WIM system is as close to the static scale weight as possible. ASTM (2000) recommends its own calibration procedure. For a well-calibrated WIM system, the mean WIM axle weight is equal to the mean static scale weight (assumed to be true weight). Katz (2001) found that the error density function was consistent with a normal distribution. Specifically, a Chi-square goodness-of-fit test revealed no statistical difference between the error frequency and the normal distribution at the 90% confidence level. Some studies have been conducted with regard to the calibration of WIM systems to meet the accuracy requirements (ASTM 2002, Papagiannakis et al. 1996, McCall and Vodrazka 1997).

2.1.5 Static scale service time

Static scale service time is the time that it takes to weigh all axles of a truck on the static scale. Static scale service time usually determines the capacity of a weigh station.

Weng (1995) tested the static scale service time for four weigh stations and found that three of them exhibited Erlang distribution, and the other one exhibited exponential distribution. Fekpe et al. (1992) also found that the static scale service time they collected, exhibited Erlang distribution.

However, Weng and Fekpe et al. did not divide the static scale service time into subgroups. According to our field study, the static scale service time for overweight trucks is much longer than that for weight-compliant trucks. When an overweight truck is detected, it takes time to make the other necessary checks and write tickets or issue warnings. Our field data collection showed that average static scale service time was about 30 s for legal trucks and 60 s for overweight trucks. Further study on this issue is required.

2.1.6 Weight limitation

The federal government and each state have truck weight and size limitation regulations (FHWA 2000). The current Federal law has set the following limits for the interstate highway systems:

- 20,000 pounds for single axles on the Interstate System,
- 34,000 pounds for tandem axles on the Interstate System,
- Application of the Federal Bridge Formula for other axle groups up to a maximum of 80,000 pounds gross vehicle weight on the Interstate System.

2.2 Weigh station operation and design

In the past, a number of studies were conducted to evaluate weigh station design and operation. This part summarizes the efforts of other researchers in weigh station operation and weigh station simulation. Most of these papers adopted specific weigh station data to study the effectiveness of different factors on weigh station operations, using simulation.

2.2.1 Operational effects of weigh-in-motion systems

Weng (1995) compared and evaluated the effects of WIM systems on traffic operations and weight enforcement. The systems studied included high speed WIM, medium speed WIM, and conventional static scales. Queueing theory and statistics were also introduced. The characteristics of such queueing systems as traffic arrival patterns, weight enforcement processing time distribution, and capacity of the static scales at each weigh station were collected in field studies. The proportion of the vehicle population directed to the static scales after WIM screening was analyzed based on WIM accuracy and truck distribution at or near each weighing facility. After a comprehensive consideration of travel delay, queue, and the avoidance rate of overweight vehicles, optimal weighing systems were proposed for different V / C ratios. As Weng did not analyze the impact of truck weight on the selection of threshold value in this study, her proposed optimal threshold values cannot realistically be used both in reality application and in theoretical research.

2.2.2 Weigh station's capacity enhancement

Kamyab (1998) designed two approaches using which weigh stations can increase their capacity: mainline electronic screening and physical expansion. In mainline electronic screening, a truck with an AVI system is able to send information to a controller that identifies the truck and its WIM weight measurement to determine whether the truck needs to be stopped for further screening. 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. The simulations were performed using Arena, a microscopic, stochastic model for a before and after scenario. Through the simulation results, it was proved that travel times as well as the number of trucks with an unauthorized bypass decreased (not weighed due to the overflow). Physical expansion would solve the problems in a shorter span of time, but electronic screening had the potential to permanently eliminate inefficiencies of WIM stations. Kamyab used only one specific truck demand (440 trucks per hour) and did not mention and truck weight information in this study.

2.2.3 Simulation and analysis of a congested weigh station

Glassco (1999) used the Westa (Weigh Station) simulation model to represent the current and alternate scenarios. Westa is a detailed simulation of truck, car, and other traffic around weigh stations and was coded in C++. Studies were performed for three state agencies as a pilot test of the accuracy and applicability of the Westa model. This study came up with three findings. First, longer ramps did not produce significant improvements of the operations of weigh stations, except for hard deceleration by trucks on the station entrance ramp. Second, greater percentages of transponder-equipped trucks yield greater benefits. However, low market penetration (5 to 10%) is not sufficient to make significant improvements in terms of effectiveness of measures. The minimal rate for trucks equipped with transponders to reduce congestion is 40 to 50%. Third, a WIM scale is very effective in reducing the number of trucks that must be weighed at the static scale. This study was based on the real data of three weigh stations and did not consider the variations in truck weight.

2.2.4 Field and modeling framework for evaluating weigh station operation

Katz (2001) evaluated the performance of a weigh station using the Integration simulation model. His study developed a procedure for relating axle accuracy to gross vehicle accuracy and developed a field and modeling framework for evaluating the operation of a weigh station. The WIM scale operation at the Stephens City weigh station in Virginia was examined to demonstrate the manner in which the field and modeling framework could be applied to evaluate the operation of a weigh station. The field study specifically 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 at the static scales. The study provided 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 was analyzed for various system characteristics. The author concluded that decreasing the threshold in order to improve the level of enforcement would cause greater delay for non-violating truck drivers and 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 percent accurate. The author also found that using a mainline screening system can save a significant amount of time in terms of vehicle-hours of delay. Although Katz proposed a very comprehensive research framework for evaluating weigh station operation, he did not explain the nature of the sorting threshold value and did not consider the impact of truck weight distribution.

2.2.5 Evaluation of weigh-in-motion for ITS-CVO applications

Trischuk et al. (2002) investigated the sorting efficiencies of different types of WIM mainline systems commonly used for enforcement of commercial vehicles operation (CVO) using a weigh station micro simulation model, WESTA. In particular, this study investigated the effect WIM system accuracy has on the effectiveness of pre-sorting commercial vehicles prior to approaching a weigh station. To do this, WESTA simulations were performed on a typical commercial weigh station facility with and without mainline WIM across a range of commercial truck volumes (200, 400, and 600 class 9 trucks per hour) and WIM system accuracies (ASTM Type III and Type I WIM). Three evaluation criteria were used in study: (1) the number of compliant trucks that were required to report to the station, (2) the number of overweight trucks that were instructed to the station, and (3) the time for which the weigh station remained open. This study showed improved weight enforcement efficiency with WIM. The improvements in weight enforcement efficiency translated into considerable savings for the weight enforcement agency in terms of improved enforcement effectiveness and protection of the infrastructure, and for the trucking industry in terms of reduced user delay costs. This study also found that higher WIM accuracy resulted in higher agency costs and user delay savings. A major limitation of this study is that the authors did not consider the effect of transponders and used only the legal weight limitations as the sorting threshold.

2.2.6 Evaluation of weigh station design and operational strategies

Gu et al. (2004) simulated the operation of a weigh station by VISSIM, a microscopic, time step, and behavior based traffic simulation software. This study employed simulation to evaluate weigh station design and operational strategies under different design strategies (one static scale, two static scale, ramp WIM scale, and mainline WIM scale) and the effect of threshold, accuracy level of WIM scale, and transponder percentage. The authors found that WIM technology was able to greatly improve the efficiency of the operation of a weigh station. For a mainline WIM weigh station, if the percentage of trucks equipped with transponders is less than 30%, the technology is not effective. Currently, because of the low percentage of trucks equipped with a transponder, the WIM scale on the ramp is the best alternative to increase the capacity of a weigh station. The authors also concluded that WIM scale accuracy and a suitable threshold were very important for the operation of a WIM weigh station.

2.2.7 Evaluation of dynamic weight threshold algorithm for WIM operations

Gu and Han (2005) developed a floating or self-adjusting weight threshold system and tested it using a simulation. To fully utilize the WIM technology and enhance the operational efficiency at WIM sites, the authors devised a dynamic weight threshold (DWT) algorithm. The threshold value is increased when the queue at the weigh station is long, so as to avoid the closure of the weigh station and simultaneously catch the worst weight limit offenders. The threshold value is lowered when the queue at the station is short, in order to maximize the number of trucks inspected. A microscopic simulation model based on a real-world ramp WIM weigh station site was first developed and calibrated. Subsequently, the dynamic threshold adjustment strategy was modeled and tested. The results showed that under a wide range of conditions, the DWT algorithm always outperforms the traditional static threshold operations. Under heavy demand conditions, DWT enables catching of 16 times more overweight trucks than the static operations while keeping the average delay per truck at only 30% of the delay under static operations. In other words, DWT is both more effective in weight enforcement and more efficient for traffic flow.

2.3 Summary

The studies on weigh station parameters have given us a sufficiently clear picture of characteristics of truck demand, truck weight distribution, WIM accuracy, and static scale service time. This study will conduct research based on the characteristics of these weigh station operational parameters.

Although the above mentioned studies provide us with some fundamental knowledge about weigh station operations and design, there exist some limitations in these previous studies because most of them are based on specific weigh stations and their practical operational scenarios. First, the conclusions they arrived at may not have been typical and were limited by their specific scenarios. Second, none of these studies researched the manner in which truck weight distribution affects the operations of a weigh station. Third, none of these studies theoretically researched the selection of the sorting threshold value of a WIM scale. Fourth, because of the quick increase in the number of trucks, particularly heavy trucks, it is necessary to develop a new threshold control algorithm to operate a WIM weigh station effectively and efficiently. This paper attempts to conduct further and broad research regarding these four issues.

Some work has been done in the last two papers by Gu et al. This research will deepen and broaden the scope of the last two studies. In other words, the last two papers are the basis of this study.

3 Measurements of Effectiveness, WIM Weight Distribution, and the Sorting Threshold

3.1 Measurements of effectiveness (MOE)

Different measurements meet different research objectives. It is important to consider the capacity of weigh station and truck delay at weigh stations as well as the number of overweight trucks caught. To measure weight enforcement efforts, Hanscom and Goelzer (1998) established five main measures based on the following criteria: 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. Kamyab (1998) and Katz (2001) used travel times to measure the effectiveness of a weigh station. Glassco (1999) evaluated the effectiveness of a weigh station based on average number of trucks weighed, average number of trucks skipping a weigh station, average time station/scale closed, average queue length, average time to pass a weigh station. Trischuk et al. (2002) analyzed the effectiveness of weigh station operation scenarios based on the percentage of legal trucks required to be weighed by a static scale, the percentage of trucks bypassing a weigh station, the percentage of time a weigh station open, and travel delay costs. Generally, the effectiveness of a weigh station should be measured in terms of its ability to detect and discourage violations. Based on our research objectives, 3 measurements are selected as outlined:

3.1.1 Caught percentage (η)

Caught percentage is defined as the ratio of the number of overweight trucks caught to the total number of overweight trucks.

$$\eta = \frac{Overweight\ Trucks\ Caught}{Total\ Overweight\ Trucks} \times 100\% \qquad \textbf{Equation 3-1}$$

This parameter measures the effectiveness of weight enforcement. Obviously, a higher η value implies a more effective system.

3.1.2 Closure percentage (κ)

Closure percentage is defined as the ratio of weigh station closure times due to overflow to the total weigh station operation times.

$$\kappa = \frac{Weigh\ Station\ Closure\ Times\ Due\ to\ Overflow}{Total\ Weigh\ Station\ Operational\ Times} \times 100\% \qquad \textbf{Equation 3-2}$$

This parameter measures how a weigh station meets its demand. A higher κ value implies that higher percentage of trucks bypass a weigh station due to overflow, thus lowering its enforcement capacity.

3.1.3 Travel delay (τ)

Travel delay is defined as the difference between average travel times of an inspected legal weight truck going through a weigh station and average travel times of a truck on the mainline passing by a weigh station.

$$\tau = \tau_I - \tau_B \qquad \textbf{Equation 3-3}$$

τ_I : *Average Travel Times of an Inspected Legal Truck*

τ_B : *Average Travel Times of a Truck by Mainline*

This parameter measures the average travel delay of an inspected legal truck because of weight enforcement activities. A higher τ value implies that a legal truck can be delayed because of the time spent on inspection. Lesser the τ value, more efficient is the weigh station system.

3.2 Truck WIM scale weight distribution

3.2.1 Truck WIM Scale weight mean and standard deviation

A WIM scale truck weight is arrived at on the basis of its real weight, the accuracy of the WIM scale, and the calibration of this WIM scale. For a well-calibrated WIM scale, it is assumed that for WIM loads of a truck, the mean is μ, and the standard deviation is σ. If it is assumed that the WIM loads of a truck are normally distributed, and the real weight of a truck is X, then its WIM scale weight belongs to Normal (X, $(aX)^2$). Therefore,

$$E(Y) = E[E[Y/X]] = E[X] = \mu \qquad \textbf{Equation 3-4}$$

$$\begin{aligned}\mathrm{Var[Y]} &= \mathrm{E[Var[Y/X]\ ] + Var[E[Y/X]\ ]} \\ &= \mathrm{E[(aX)}^{\ 2}] + Var[X] \\ &= a^2 E[X^2] + \sigma^2 \\ &= a^2(\mu^2 + \sigma^2) + \sigma^2\end{aligned}$$

$$\Rightarrow \qquad Var[Y] = a^2\mu^2 + (a^2+1)\sigma^2 \qquad \textbf{Equation 3-5}$$

where

$X \in A(\mu, \sigma^2)$, $\mathrm{Y} \in \mathrm{N(X,(aX)^2)}$

A : Unnamed distribution of static loads

X : The real truck weight

Y : The weight by WIM scale

a : The parameter of WIM loads standard deviations

Equations 3-1 and 3-2 show that the mean of WIM loads is equal to the mean of static loads and the variances of WIM loads are larger than the variances of static loads. The variances of WIM loads are decided by static weight distribution and accuracy of WIM scales.

The density function of WIM loads can be shown as follows:

$$f_y = \int_0^\infty f_x f_{y/x}\,dx \qquad \textbf{Equation 3-6}$$

where

f_y : the density function of WIM loads distribution

f_x : the density function of static loads distribution

$f_{y/x}$: the joint density function of WIM loads distribution based on static loads.

3.2.2 Truck WIM weight distribution by the Monte Carlo method

Although the mean and standard deviation of WIM loads can be deduced using Equations 3-1 and 3-2, it is very difficult to get the density function of WIM loads by Equation 3-3. For the present research, the Monte Carlo method is used.

Monte Carlo methods are used to solve models that cannot be solved using standard numerical techniques. Instead, an analogous statistical model is constructed for the concerned problem. An experiment is specifically set up to duplicate the features of the problem under study. This resulting calculation process is entirely numerical and is carried out by supplying random numbers into the system and obtaining numerical answers. The RAND Corporation used an electronic roulette wheel to prepare the million-digit book of random number tables (hence the name *Monte Carlo*). 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. The success of this method depends on being able to integrate the density function and to take the inverse of the integrated function. The static loads and WIM loads with 12% error are illustrated in Figure 3-1 and Figure 3-2.

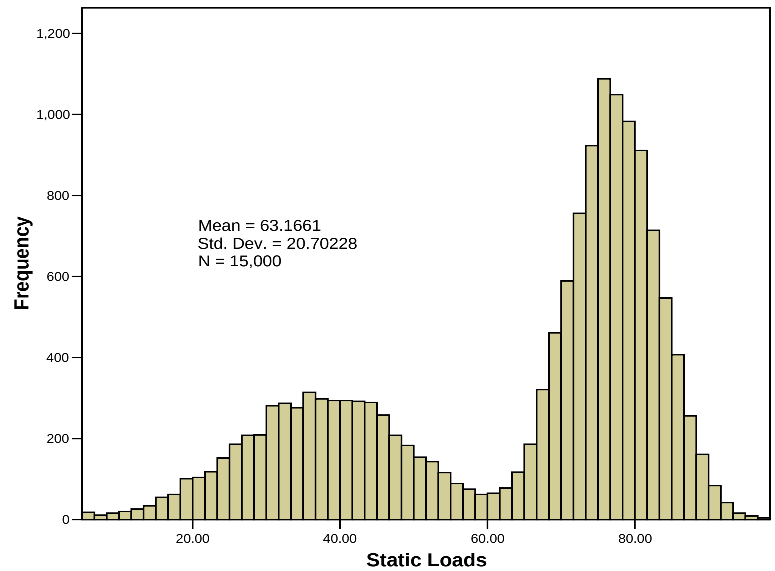

Figure 3-1 Histogram of Static Loads

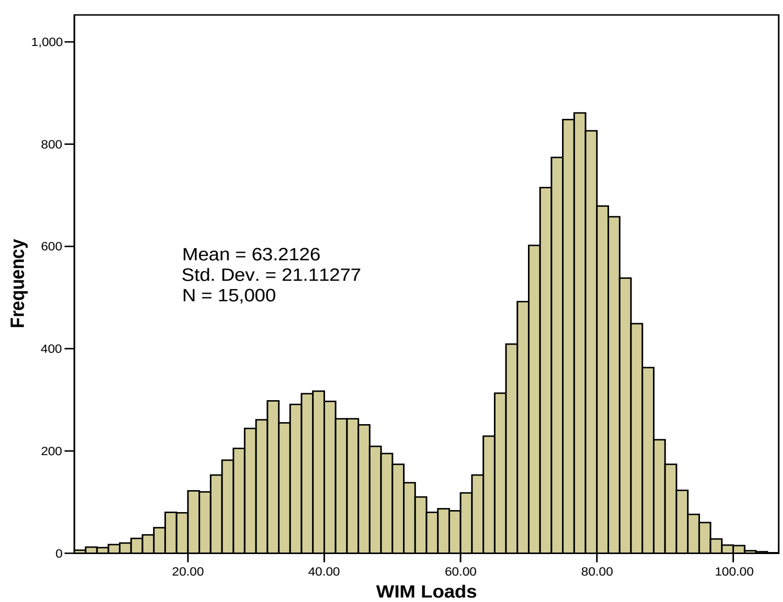

Figure 3-2 Histogram of WIM Loads

3.3 Selection of the value of WIM sorting threshold

A WIM scale sorts passing trucks by threshold value. If a truck's weight is over the threshold, the truck goes to a static scale for further inspection; otherwise, it bypasses the static scale. The lower the threshold, the more is the number of trucks that are likely to queue up for further inspection before the static scale. If the queue length of trucks before a static scale is long enough for trucks to back up on the mainline, the weigh station must be closed, which results in more trucks bypassing the weigh station, and some of them may be overweight. If the threshold is higher, an overweight truck's WIM load is more likely to be lower than the threshold value, thus, the possibility of an overweight truck not being caught is more. Therefore, there should be a tradeoff of the threshold value.

Of the many studies conducted on WIM weigh station operations, only a few have addressed the methods for choosing an appropriate threshold. Some researchers simply use the legal weight limit as the sorting threshold value (Trischuk et al. 2002). Others (Gu et al. 2004 and Katz 2001) have noted that there could exist an optimal threshold value for a specific truck demand.

Obviously, WIM errors bring into question of the selection of the legal weight limit as the sorting threshold. Chou and Chen (2003) mentioned that threshold should be selected based on the accuracy of a WIM scale and the weight limit. They defined the threshold value as

$$W_{TH} = GVW \times Accu \qquad \textbf{Equation 3-7}$$

where

W_{TH}: sorting threshold,

GVW: Legal gross vehicle weight limit, and

Accu: Accuracy of a WIM system

3.3.1 Statistical analysis of the accuracy of a WIM scale

As mentioned above, the error density function of a WIM scale can be viewed as normal distribution density function and the expected WIM loads of a truck equal its static loads if a WIM scale is correctly calibrated. ASTM standards indicate that the requirements for a Type III WIM scale are ± α tolerance (0 < or = α) for β probability of conformity (Figure 3-3). It can be derived that:

$$P(W_{Static} \times (1-\alpha) \le X \le W_{Static} \times (1+\alpha)) = \beta$$
$$\Rightarrow P(W_{Static} \times (1-\alpha) \le X) = \frac{1-\beta}{2}$$
$$\Rightarrow W_{Static} \times (1-\alpha) = W_{Static} + z_{\frac{1-\beta}{2}}\sigma$$

$$\Rightarrow \sigma = \frac{W_{Static} \times \alpha}{z_{\frac{1-\beta}{2}}} \qquad \textbf{Equation 3-8}$$

where

W_{Static} : static weight (axle, tandem, or gross weight) of a truck

α: tolerance of a WIM scale (0=<α), stated as percentage of a static weight

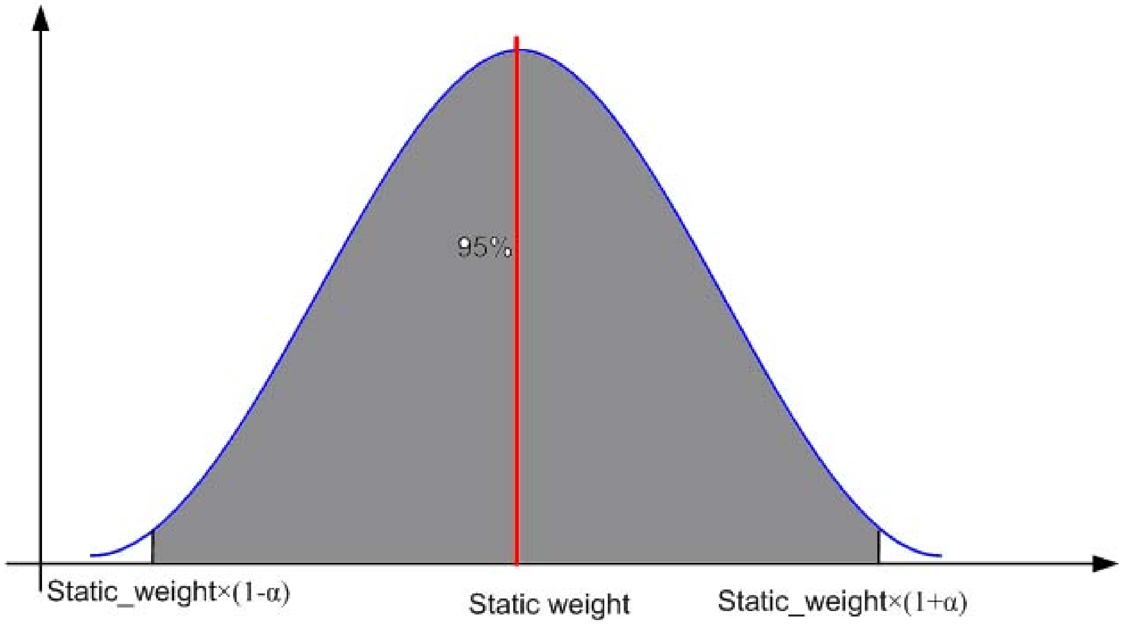

Figure 3-3 WIM Accuracy

β: probability of conformity of a WIM scale

σ: standard deviation of a WIM load

Current ASTM standards indicate that the requirements for a Type III WIM scale are ± α (0 < or = α < 1) for 95% probability of conformity, thus,

$$\sigma = \frac{W_{Static} \times \alpha}{z_{\frac{1-\beta}{2}}} \Rightarrow \sigma = \frac{W_{Static} \times \alpha}{z_{\frac{1-0.95}{2}}}$$

$$\sigma = \frac{W_{Static} \times \alpha}{1.96}$$ **Equation 3-9**

3.3.2 Selection of WIM sorting threshold

The above analysis indicates the manner in which a Type III WIM scale sorts trucks (Figure 3-4). The WIM loads of a truck are normally distributed. The mean of WIM load is equal to the static weight, and the standard deviation is equal to some percentage of its static load. The area to the left of a sorting threshold is the probability of the WIM loads of a truck being less than the sorting threshold, that is, the probability of a truck bypassing a static scale. For an overweight truck, bypass probability means the probability of escaping detection. The area to the right of a sorting threshold is the probability of the WIM loads of a truck being heavier than the sorting threshold, that is, the probability of a truck being sent to a static scale for further inspection.

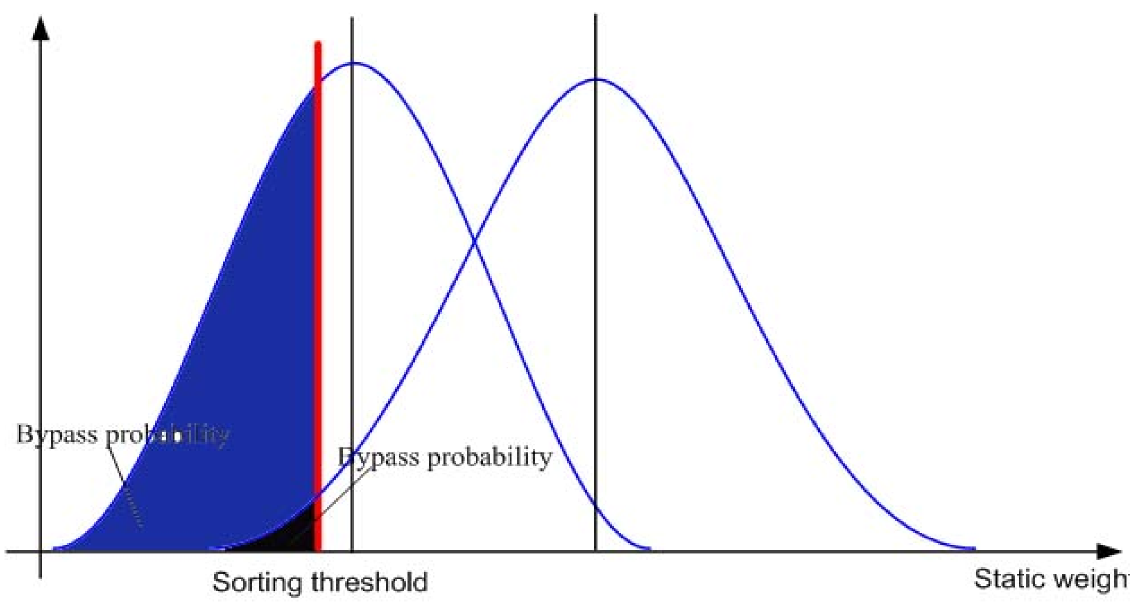

Figure 3-4 Bypass Probability

It is contradictory to select a sorting threshold. A higher threshold would permit more legal weight trucks to bypass a static scale and simultaneously allow more number of overweight trucks to escape detection. A lower threshold would lead to a greater number of overweight trucks being led to a static scale; however, it would also cause legal weight trucks to undergo unnecessary inspection at a static scale.

Statistically, WIM scale errors make it impossible to catch each overweight truck. In order to catch an overweight truck and not to stop a legal weight truck, it is reasonable to set our confidence level (φ) to catch an overweight truck to decide a sorting threshold (shown as Figure 3-5). For a truck whose weight is just over legal weight limit,

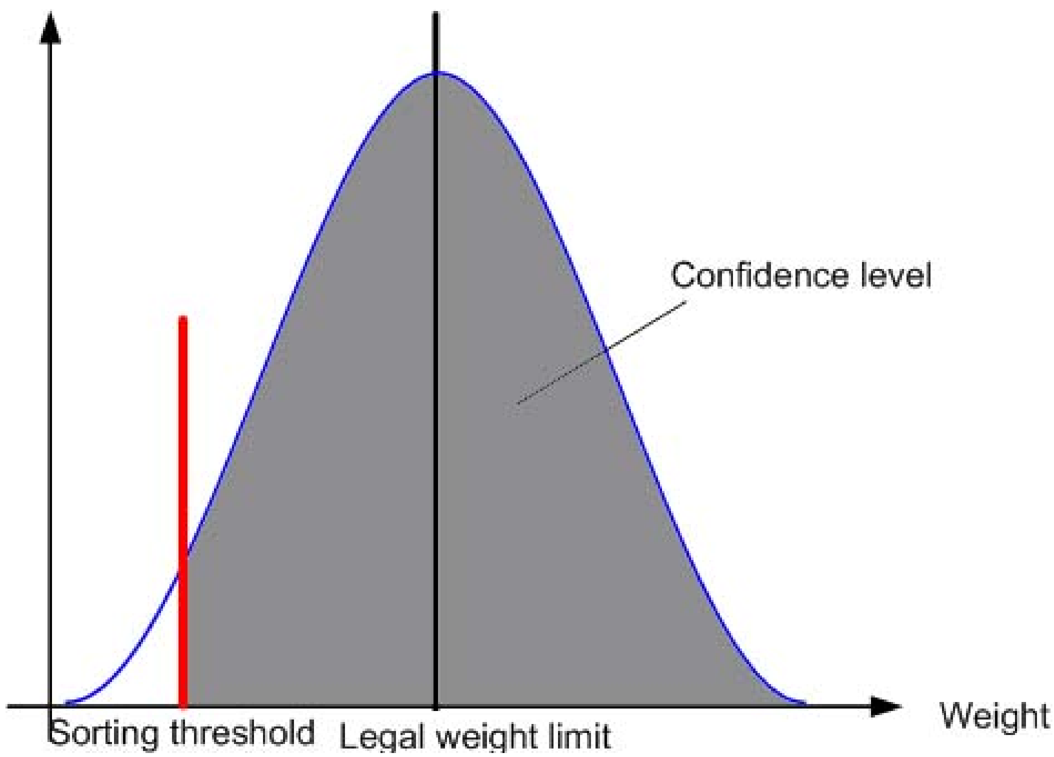

Figure 3-5 Selection of WIM Sorting Threshold

$$P(X \geq W_{TH}) = \varphi$$

Since X belongs to Normal (W_{LT}, $\frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}}$), the sorting threshold is decided by the legal weight limit, the accuracy of WIM scale, and the confidence level of catching an overweight truck.

$$W_{TH} = W_{LT} - \frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi}$$ **Equation 3-10**

where

W_{LT} : legal weight (axle, tandem, or gross weight) limit of a truck

α: tolerance of a WIM scale (0 = or < α), stated as percentage of a static weight

β: probability of conformity of a WIM scale

φ: confidence level of catching a truck just over legal weight limit

σ: standard deviation of a WIM load.

When legal weight limit, β, and φ are known, the relationship between sorting threshold and error level of a WIM scale is linear (Figure 3-6).

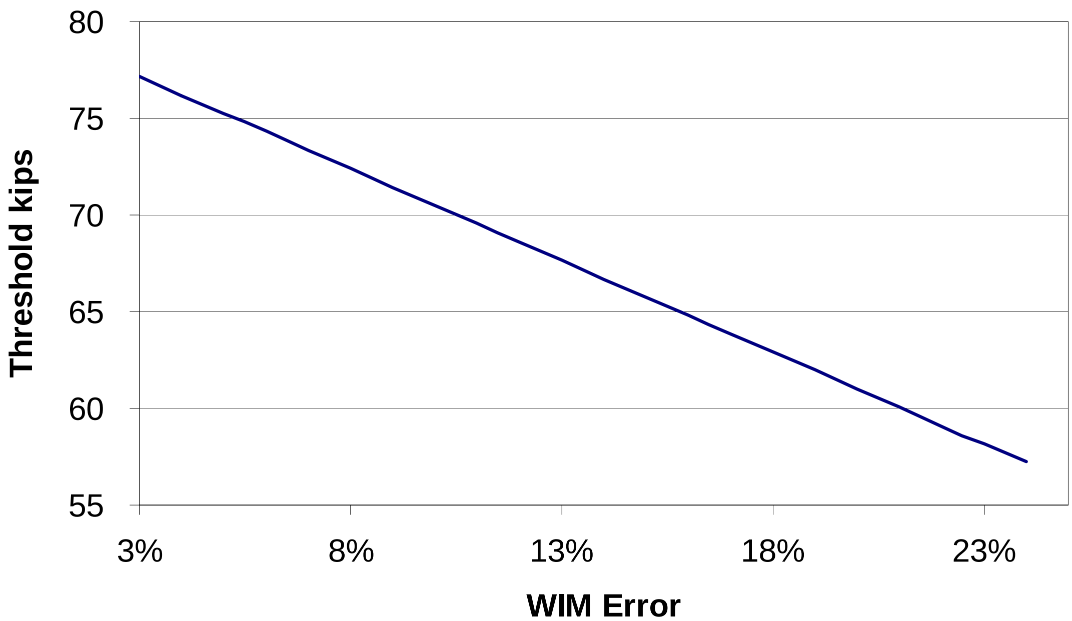

Figure 3-6 Relationship between Sorting Threshold and WIM Error Levels

Chou's equation (Equation 3-4) can be deduced as follows,

$$\text{If } 1-\varphi=\frac{1-\beta}{2},\ \Rightarrow W_{TH}=W_{LT}\times(1-\alpha)$$

This is the same as Equation 3-4.

Under this strategy, it is very clear that higher the static loads of an overweight truck, the greater is the possibility of it being caught (Figure 3-7). The caught probability (ω) of overweight trucks and the percentage (*p*) of trucks sent to a static scale can be shown by the following equations:

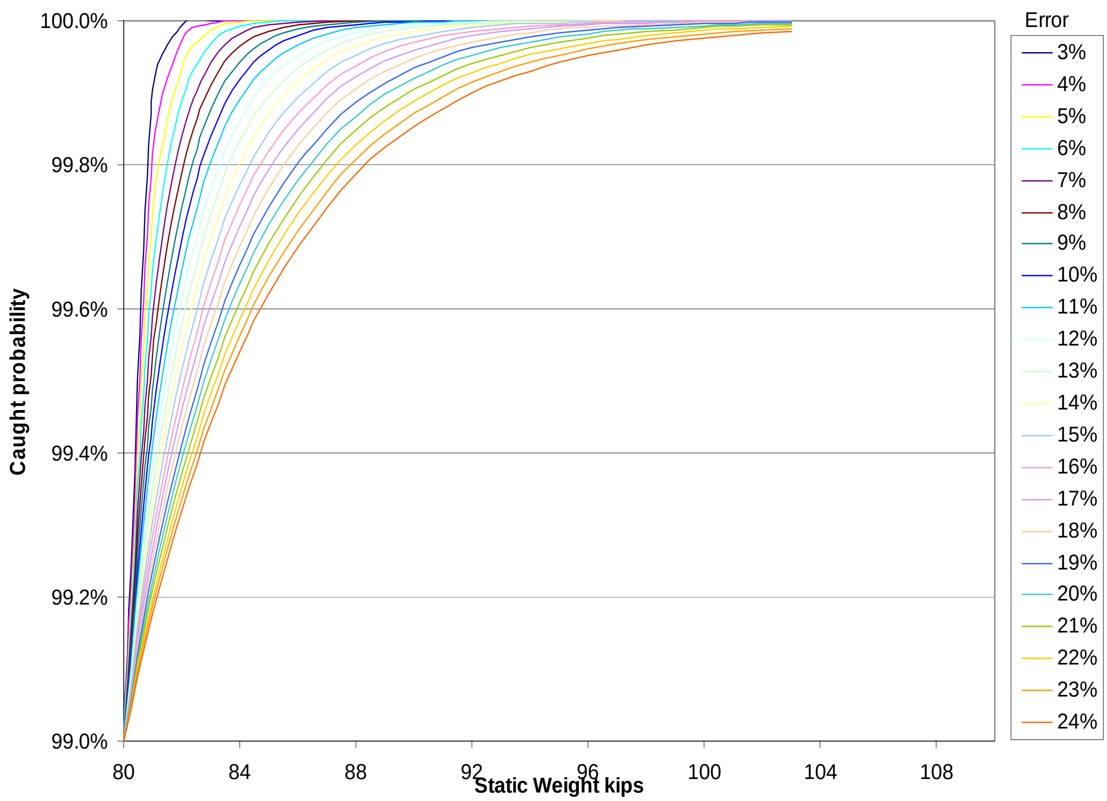

Figure 3-7 Caught Probability of an Overweight Truck under Different Error Levels

$$\omega = \frac{\int_{W_{TH}}^{\infty}\int_{W_{LT}}^{\infty} f_x f_{y/x}\,dxdy}{\int_{W_{LT}}^{\infty} f_x\,dx}$$ **Equation 3-11**

$$p = \int_{W_{TH}}^{\infty}\int_{0}^{\infty} f_x f_{y/x}\,dxdy$$ **Equation 3-12**

where

ω : caught probability, defined as the probability of overweight trucks being caught under a specific sorting threshold, assumed that no overflow happens

p : sent percentage, defined as the percentage of trucks sent to a static scale under a specific sorting threshold, assumed that no overflow happens

w_{TH} : sorting threshold

w_{LT} : legal weight limit

f_x : density function of truck static weight distribution

$f_{y/x}$: joint density function of truck WIM weight distribution based on static weight distribution.

It is obvious that when $\varphi = 99\%$, $\omega \to 1$.

4 Analytical Evaluation of Four Weigh Station Design Strategies and the Effective of Some Important Operational Parameters

Weigh station design and operational strategies determine the performances of a weigh station system. Most researchers have studied weigh station design and operation by simulation method. In this chapter, queueing theory is used to study weigh station design and operational strategies in an effort to find some insights that will benefit the design and operation of a weigh station.

4.1 Introduction to the application of queueing theory in weigh station research

In the following content, Kendall's shorthand notion (Appendix A) will be used to describe queueing Models.

Queueing theory in the past has seldom been utilized for weigh station analysis. Fekpe et al. (1992) applied queueing theory to study the impact of two alternative manpower levels on the performance of continuously operated weigh scales. They used a classic $M/E_k/1$ model to represent the operation of the permanent scale in their study, in which they assumed that truck arrival time interval was exponentially distributed, and static service time followed the Erlang distribution. Weng (1995) also employed $M/E_k/1$

queueing model to study travel delay and queue length and offered her suggestions regarding the manner in which to select a WIM scale system.

These two studies have two limitations. First, both of them assumed that the storage capacity in a weigh station was unlimited, which obviously was not true. Second, they did not make a comprehensive study of the application of WIM technology. Although Weng extended her study to WIM technology, she did not conduct studies on the manner in which weight distribution affects weigh station operations. In this chapter, a more comprehensive study on main factors and layouts of weigh station design and operations will be made.

4.2 Queueing analysis of weigh station systems

When a static scale weigh station cannot cope with its workload, there are three alternatives that can be adopted: building another static scale, WIM on the ramp technologies, and WIM on the mainline technology. When stochastic properties of more general transportation are required, these are generally handled by considering highly simplified, steady-state queues, which permit the use of standard queueing theory. To simplify the analysis, the following assumptions are made:

- Truck arrival patterns: truck arrival follows Poisson distribution with expected arrival rate λ.
- Static scale service patterns: service times by a static scale for all trucks are exponentially distributed with expected service times equal to $1/\mu$.

- Service discipline: the service discipline is FCFS (first come first service). The following truck must wait in line if there is any truck waiting or being served.
- For a weigh station with two static scales, it is assumed that all trucks wait in one line with two service stations.

4.2.1 A weigh station with one static scale

This system is a typical one-node M/M/1/K open queueing system (Figure 4-1). The inter-arrival times (headways) and service times (the time required for a static scale to check a truck) are exponentially distributed. There is only one service station (a static scale) in this type of a weigh station. The system has finite capacity K, which is equal to the waiting positions between a static scale and a mainline plus 1 (a static scale node itself). If the system is full, an approaching truck will decide not to enter this system.

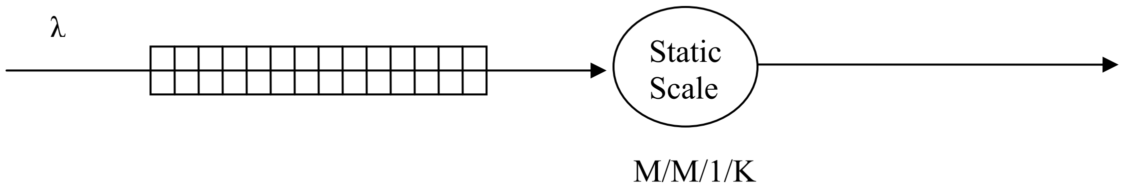

Figure 4-1 Queueing Description of a One Static Scale Weigh Station

4.2.2 A weigh station with two static scales

A two static scale weigh station is a typical two-node M/M/2/K open queueing system (Figure 4-2). The inter-arrival times (headways) and service times (the time required for a truck to be checked by a static scale) are exponentially distributed. There are two parallel service stations in this type of a weigh station. The system has finite storage capacity, equal to the waiting rooms between a static scale and a mainline plus 2 (two static scales node). If the system is full, an approaching truck will decide not to enter this system.

4.2.3 A mainline weigh station

This system (the black and bold portion) can be treated as one-node M/M/1/K open queueing system (Figure 4-3). *p is* designated as the percentage of trucks sent to a static scale under a specific sorting threshold. Arriving trucks are sorted by a WIM scale, and only *p* percentages of trucks enter the queuing system. It can be assumed that truck arrival is a Poisson process having a rate of λ. In terms of the properties of the Poisson process, the arrival input of a static scale is still a Poisson process having a rate of λp (Ross 1985). The inter-arrival times (headways) in this case are distributed generally with expected inter-arrival time equal to $1/(p\lambda)$. The other characteristics of this type of a weigh station are similar to those of a weigh station with one static scale.

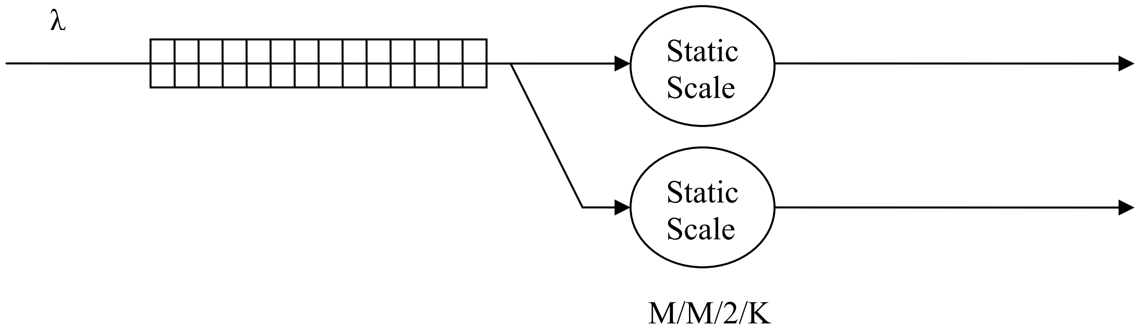

Figure 4-2 Queueing Description of Two Static Scale Weigh Station

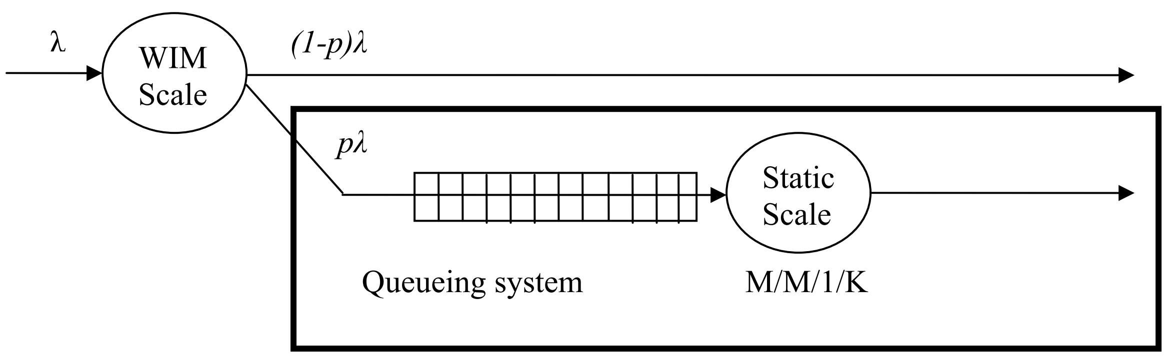

Figure 4-3 Queueing Description of a Mainline WIM Weigh Station

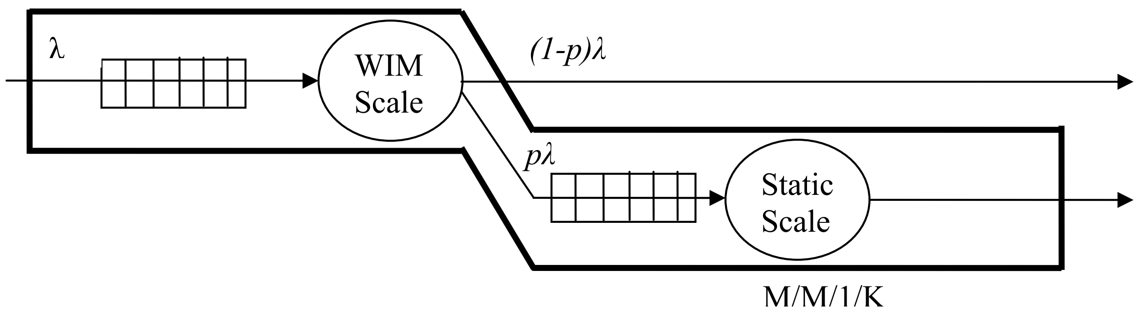

Figure 4-4 Queueing Description of a Ramp WIM Weigh Station

4.2.4 A ramp WIM weigh station

This system can be treated as one-node M/M/1/K open queueing system with blocking and sorting (Figure 4-4). The inter-arrival times (headways) and service times are exponentially distributed. Both the sorting node (a WIM scale) and the service node (a static scale) have finite capacity. The finite capacity of a static scale node may impose a blocking of a WIM scale node when it is full. If the system is full, a coming truck will decide not to enter this system. The percentage of trucks sent to a static scale under a specific sorting threshold is denoted as p. For the static service node, the arrival rate equals $p\lambda$. The storage space between the mainline line and a WIM scale is denoted as C_w and the storage space between a WIM scale and a static scale as Cs. For a static scale, the effective storage capacity equals Cs + pC_w + 1 (Appendix B).

4.2.5 Mathematical analysis of an M/M/c/K queueing system

According to the queueing theory (Gross and Harris, 1998), for an M/M/c/K queueing system,

$$p_n = \begin{cases} \dfrac{\lambda^n}{n!\,\mu^n} p_0 & (1 \le n < c) \\ \dfrac{\lambda^n}{c^{n-c} c!\,\mu^n} p_0 & (c \le n \le K) \end{cases}$$ **Equation 4-1**

$$p_0 = \begin{cases} \left(\sum_{n=0}^{c-1} \dfrac{\lambda^n}{n!\,\mu^n} + \dfrac{\lambda^c}{c!\,\mu^c} \dfrac{1 - \left(\dfrac{\lambda}{c\mu} \right)^{K-c+1}}{1 - \dfrac{\lambda}{c\mu}} \right)^{-1} & \left(\dfrac{\lambda}{c\mu} \ne 1 \right) \\ \left(\sum_{n=0}^{c-1} \dfrac{\lambda^n}{n!\,\mu^n} + \dfrac{\lambda^c}{c!\,\mu^c} (K - c + 1) \right)^{-1} & \left(\dfrac{\lambda}{c\mu} = 1 \right) \end{cases}$$ **Equation 4-2**

$$L = \sum_{n=1}^{K} n p_n$$ **Equation 4-3**

Expected values for system time can be readily obtained using Little's formula:

$$W = \frac{L}{\lambda_{eff}} = \frac{L}{\lambda(1 - p_K)}$$ **Equation 4-4**

For an M/M/1/K queueing system, the above measures of effectiveness can be expressed simply with the following results:

$$p_0 = \begin{cases} \dfrac{1-\rho}{1-\rho^{K+1}} & (\rho \ne 1) \\ \dfrac{1}{K+1} & (\rho = 1) \end{cases}$$ **Equation 4-5**

$$p_n = \begin{cases} \dfrac{(1-\rho)\rho^n}{1-\rho^{K+1}} & (\rho \neq 1) \\ \dfrac{1}{K+1} & (\rho = 1) \end{cases}$$ **Equation 4-6**

$$L = \begin{cases} \dfrac{1}{1-\rho} - \dfrac{1+K\rho^{K+1}}{1-\rho^{K+1}} & (\rho \neq 1) \\ \dfrac{K}{2} & (\rho = 1) \end{cases}$$ **Equation 4-7**

$$W = \begin{cases} \dfrac{\dfrac{1}{1-\rho} - \dfrac{1+K\rho^{K+1}}{1-\rho^{K+1}}}{\left(1 - \dfrac{(1-\rho)\rho^K}{1-\rho^{K+1}}\right)\lambda} & (\rho \neq 1) \\ \dfrac{K+1}{2\lambda} & (\rho = 1) \end{cases}$$ **Equation 4-8**

4.3 Four design strategies

From the above analysis, the result can be obtained as shown in Table 4-1.

It is also known that for a weigh station with WIM technology:

$$p = \int_{W_{TH}}^{\infty} \int_0^{\infty} f_{y/x} f_x \, dx dy$$

$$\omega = \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f_x f_{y/x} \, dx dy}{\int_{W_{LT}}^{\infty} f_x \, dx}$$

Table 4-1 Parameters of Queueing Models for Design Strategies

Strategy	Model	Arrival Rate	Service Rate	Service stations	Traffic intensity ρ	Storage Capacity
One static scale	M/M/1/C	λ	μ	1	λ / μ	C + 1
Two static scales	M/M/2/C	λ	2μ	2	$\lambda / (2\mu)$	C + 2
Ramp WIM	M/M/1/C	$P\lambda$	μ	1	$p\lambda / \mu$	Cs + pCw +1
Mainline WIM	M/M/1/C	$P\lambda$	μ	1	$p\lambda / \mu$	C + 1

C: storage room between the mainline and a static scale, and p: sent percentage.

where

w_{TH} : sorting threshold

W_{LT} : legal weight limit

f_x : density function of static weight distribution of trucks

$f_{y/x}$: joint density function of WIM weight distribution of trucks based on static weight

ω: caught probability, and

p : sent percentage.

A weigh station's purpose is to keep overweight trucks off highway systems. During normal operational periods, there are two main reasons for an overweight truck not being caught when it passes a weigh station. First, an overweight truck can bypass a weigh station if the weigh station is closed because of overflow. This type of an error is denoted as type I, and it equals the loss probability of a queueing system. Second, for a weigh station using WIM technologies, an overweight truck can avoid possible detection in the case of an error by a WIM scale. Due to the inaccuracy of a WIM scale, an overweight truck's WIM loads may get measured as less than the set threshold value and such an overweight truck can continue to move on highway systems without being stopped. This type of error is denoted as type II.

Let us obtain the performances of these four design strategies. For one or two static scales systems, average waiting time (W) is equal to the average number of times a weighed truck spends in the systems. For a weigh station with a WIM scale (on an entrance ramp or mainline), average travel time of a weighed truck (by a WIM scale or a static scale) equals the average traveling time (W) multiplied by p, it is denoted as pW. A fraction or static scale and two static scale systems equal 1- p_k because under this threshold strategy, the caught probability of an overweight and weighed truck is not less than the confidence level, the caught probability of a weighed trucks is approximated to confidence level φ. When φ = 99%, $\omega \rightarrow 1$, it can also be assumed that caught percentage equals 1- p_k. In this chapter, φ was set as 99% except for 4.8. Since, closure equals p_k, caught percentage (η) equals 1-closure percentage (κ). Therefore, in most cases in this chapter, two MOEs—caught percentage and travel delay to measure the effect—are used. The storage space between a static scale and the mainline is denoted as C. For a weigh station with a WIM scale on the entrance lane, $C = \text{int}(C_S + pC_W)$. Table 4-2 shows the performance of these design strategies.

Table 4-2 MOEs of Design Strategies

Case	Caught percentage η	Average travel delay τ
One static scale	$1-\dfrac{(1-\frac{\lambda}{\mu})\left(\frac{\lambda}{\mu}\right)^{C+1}}{1-\left(\frac{\lambda}{\mu}\right)^{C+2}}$	$\left(\dfrac{1}{1-\frac{\lambda}{\mu}}-\dfrac{1+(C+1)\left(\frac{\lambda}{\mu}\right)^{C+2}}{1-\left(\frac{\lambda}{\mu}\right)^{C+2}}\right)\times\dfrac{1}{\lambda\times\left(1-\dfrac{(1-\frac{\lambda}{\mu})\left(\frac{\lambda}{\mu}\right)^{C+1}}{1-\left(\frac{\lambda}{\mu}\right)^{C+2}}\right)}$
Two static scales	$1-\dfrac{\left(\frac{\lambda}{\mu}\right)^{C+2}}{(C+2)!\times\left(1+\frac{\lambda}{\mu}+\dfrac{1-\left(\frac{\lambda}{2\mu}\right)^{C+1}}{2\left(1-\frac{\lambda}{2\mu}\right)}\right)}$	$\left(\frac{1}{\mu}\right)+\dfrac{\left(\frac{\lambda}{\mu}\right)^{3}\left(1-\left(\frac{\lambda}{2\mu}\right)^{C+1}-(1-\frac{\lambda}{2\mu})(C+1)\left(\frac{\lambda}{2\mu}\right)^{C}\right)}{\lambda\left(1-\left(\frac{\lambda}{2\mu}\right)^{2}\right)\times\left(1+\frac{\lambda}{\mu}+\dfrac{1-\left(\frac{\lambda}{2\mu}\right)^{C+1}}{2(1-\frac{\lambda}{2\mu}}\right)\left(1-\dfrac{\left(\frac{\lambda}{\mu}\right)^{C+2}}{(C+2)!\times\left(1+\frac{\lambda}{\mu}+\dfrac{1-\left(\frac{\lambda}{2\mu}\right)^{C+1}}{2(1-\frac{\lambda}{2\mu}}\right)}\right)}$
Ramp WIM	$1-\dfrac{(1-\frac{p\lambda}{\mu})\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+1}}{1-\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+2}}$	$\left(\dfrac{1}{1-\frac{p\lambda}{\mu}}-\dfrac{1+(Cs+pCw+1)\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+2}}{1-\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+2}}\right)\times\dfrac{1}{\lambda\times\left(1-\dfrac{(1-\frac{p\lambda}{\mu})\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+1}}{1-\left(\frac{p\lambda}{\mu}\right)^{Cs+pCw+2}}\right)}$
Mainline WIM	$1-\dfrac{(1-\frac{p\lambda}{\mu})\left(\frac{p\lambda}{\mu}\right)^{C+1}}{1-\left(\frac{p\lambda}{\mu}\right)^{C+2}}$	$\left(\dfrac{1}{1-\frac{p\lambda}{\mu}}-\dfrac{1+(C+1)\left(\frac{p\lambda}{\mu}\right)^{C+2}}{1-\left(\frac{p\lambda}{\mu}\right)^{C+2}}\right)\times\dfrac{1}{\lambda\times\left(1-\dfrac{(1-\frac{p\lambda}{\mu})\left(\frac{p\lambda}{\mu}\right)^{C+1}}{1-\left(\frac{p\lambda}{\mu}\right)^{C+2}}\right)}$

To simplify calculations, any case in which the arrival rate equals the service rate for static scale service stations is excluded, and here $\varphi = 99\%$, $\omega \rightarrow 1$. From the above simplifications, it is obtained that $\eta = 1 - \kappa$.

Table 4-3, Figures 4-5 and 4-6 show the performances of these four design strategies with the following parameters:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight truck
- WIM error: 12% at 95% confidence level
- At least 99% caught confidence level
- Storage spaces of an entrance lane: 15
- Storage spaces between an entrance lane and a static scale: 9, and
- 100% transponder market penetration for a WIM scale on the mainline

The hypothetical scenario shows that both WIM technologies have significant advantages over static scale technologies. Although adding one static scale doubles the capacity, a weigh station with WIM technology is more effective than a weigh station with two static scales. At the same time, WIM technology can sharply decrease truck travel delay, particularly when truck arrival volume is over the capacity of a weigh station with one or two static scales. It is also found that when all trucks are equipped with transponders and WIM accuracy of a mainline WIM scale is the same as that of a ramp WIM scale, a mainline WIM layout can catch more overweight trucks than a ramp WIM if truck

Table 4-3 Effects of Four Design Strategies

Arrival Rate	Caught percentage				Travel delay in Seconds			
	One static scale	Two static scales	Mainline WIM	Ramp WIM	One static scale	Two static scales	Mainline WIM	Ramp WIM
65	100%	100%	100%	100%	65	32	16	16
75	100%	100%	100%	100%	80	33	17	17
85	100%	100%	100%	100%	103	34	18	18
95	100%	100%	100%	100%	142	36	19	19
105	100%	100%	100%	100%	212	37	20	20
115	98%	100%	100%	100%	325	39	21	21
125	94%	100%	100%	100%	453	41	22	22
135	88%	100%	100%	100%	552	44	24	24
145	83%	100%	100%	100%	613	47	25	25
155	77%	100%	100%	100%	648	51	27	27
165	73%	100%	100%	100%	670	57	30	30
175	69%	100%	100%	100%	685	64	32	32
185	65%	100%	100%	100%	695	73	35	35
195	62%	100%	100%	100%	702	86	39	39
205	59%	100%	100%	100%	708	104	44	43
215	56%	99%	100%	100%	712	127	50	48
225	53%	99%	100%	100%	716	156	58	54
235	51%	97%	100%	99%	719	190	68	61
245	49%	95%	100%	99%	721	223	80	69
255	47%	93%	99%	98%	723	254	96	77
265	45%	90%	99%	97%	725	279	116	87
275	44%	87%	98%	96%	727	299	137	96
285	42%	84%	96%	94%	728	315	160	105
295	41%	81%	95%	93%	729	327	183	115
305	39%	79%	92%	91%	731	335	203	123
315	38%	76%	90%	89%	732	342	220	131
325	37%	74%	88%	87%	732	348	235	138

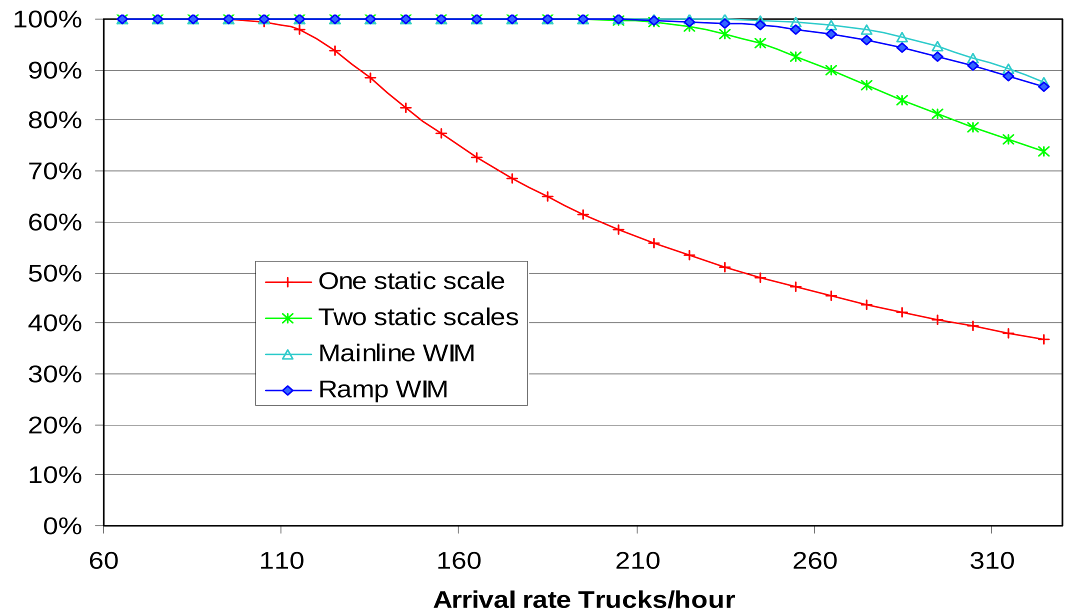

Figure 4-5 Caught Percentage under Design Strategies

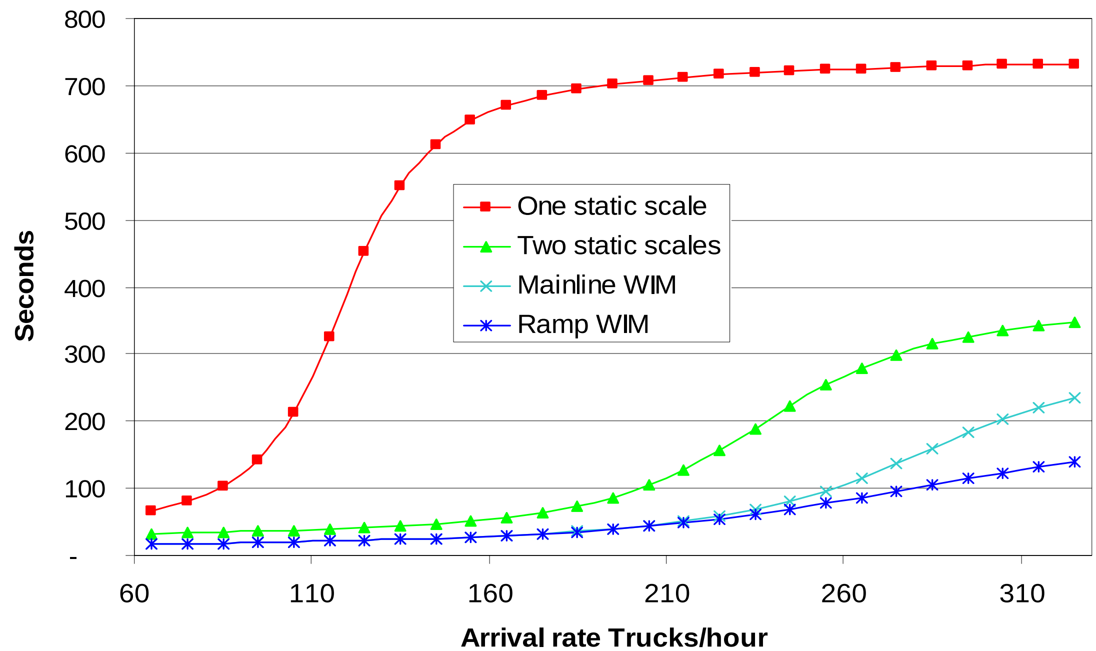

Figure 4-6 Travel Delay under Design Strategies

demand exceeds the weigh station capacity. It seems a little strange that travel delay with a mainline WIM layout is longer than travel delay with a ramp WIM layout when truck demand exceeds the weigh station capacity. This result is because a mainline WIM layout has more effective storage spaces in a weigh station and needs more time to clear waiting trucks than a ramp WIM layout. In reality, a mainline WIM layout should create less travel delay because a bypassed truck can run at normal speed and does not need to enter a weigh station.

4.4 Weight distribution

As mentioned before, for a weigh station with WIM technology, truck weight distribution hugely affects the operation of a weigh station. Truck weight distribution also hugely affects the percentage of trucks *(p)* sent to a static scale for a further check. It also determines an overweight trucks' caught probability *(ω)* (please check Equations 3-8 and 3-9).

It is very difficult to define a weight distribution only in terms of its mean and standard deviation. From chapter 2, it can be assumed that the majority of the truck gross weight follows a bimodal distribution. The effect of overweight rate for a ramp WIM weigh station was tested here. The following hypothetical weight data were used to observe the effect of different weight distribution (Table 4-4). Other data are the follows:

Table 4-4 Weight Data

No	Low Weight Part			High Weight Part			Overweight Rate
	Percentage	Mean kips	Standard Deviation.	Percentage	Mean kips	Standard Deviation	
1	35%	37.83	11.41	65%	67.05	6.03	1%
2	35%	37.83	11.41	65%	69.91	6.03	3%
3	35%	37.83	11.41	65%	71.43	6.03	5%
4	35%	37.83	11.41	65%	72.49	6.03	7%
5	35%	37.83	11.41	65%	73.44	6.03	9%
6	35%	37.83	11.41	65%	74.19	6.03	11%
7	35%	37.83	11.41	65%	74.95	6.03	13%
8	35%	37.83	11.41	65%	75.57	6.03	15%
9	35%	37.83	11.41	65%	76.15	6.03	17%
10	35%	37.83	11.41	65%	76.71	6.03	19%
11	35%	37.83	11.41	65%	77.23	6.03	21%

- Service rate: 120 trucks per hour
- WIM error: 12% under 95% confidence level
- At least 99% caught confidence level
- Storage spaces of an entrance lane: 15, and
- Storage spaces between an entrance lane and a static scale: 9

The relationship between overweight rate and *p* is shown in Figure 4-7.

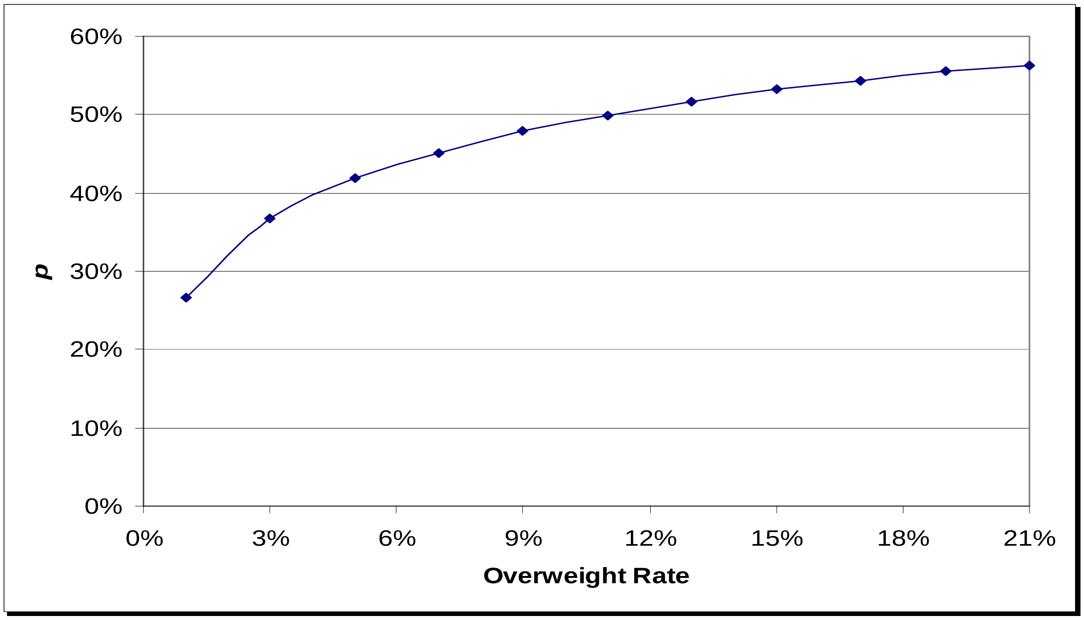

Figure 4-7 Overweight Rate and *p*

The arrival rate for the static scale equals $p\lambda$, and traffic intensity ρ is given by $p\lambda / \mu$. Tables 4-5, 4-6, and Figures 4-8 and 4-9 show the effect of different overweight rates in a hypothetical scenario. When truck demand is low (not more than 150 trucks per hour), almost every overweight truck will be caught because the capacity of the weigh station can meet truck demand. With an increase in truck demand and a higher overweight rate, catching an overweight truck is less likely because the capacity of this weigh station cannot meet truck demand. For every truck demand scenario, travel delay increases with the increase in overweight rate because more trucks are sent to a static scale for further inspection for high overweight rate, even when the weigh station system meets truck demand. It also can be observed that the rate of the effect decreases with the increase of overweight rates.

Table 4-5 Effects of Overweight Rate—Caught Percentage

Overweight Rate	Arrival Rate—trucks / hour						
	50	150	250	350	450	550	650
1%	100.0%	100.0%	100.0%	99.3%	93.4%	81.0%	69.2%
3%	100.0%	100.0%	99.6%	90.1%	72.5%	59.4%	50.3%
5%	100.0%	100.0%	98.4%	81.2%	63.6%	52.1%	44.1%
7%	100.0%	100.0%	96.6%	75.8%	59.1%	48.4%	40.9%
9%	100.0%	100.0%	94.4%	71.4%	55.6%	45.5%	38.5%
11%	100.0%	100.0%	92.4%	68.7%	53.4%	43.7%	37.0%
13%	100.0%	100.0%	90.3%	66.3%	51.6%	42.2%	35.7%
15%	100.0%	100.0%	88.4%	64.4%	50.1%	41.0%	34.7%
17%	100.0%	100.0%	87.1%	63.1%	49.1%	40.1%	34.0%
19%	100.0%	100.0%	85.6%	61.8%	48.1%	39.3%	33.3%
21%	100.0%	99.9%	84.5%	60.9%	47.3%	38.7%	32.8%

Table 4-6 Effects of Overweight Rate—Travel Delay in Seconds

Overweight Rate	Arrival Rate—trucks / hour						
	50	150	250	350	450	550	650
1%	9	12	18	32	60	83	94
3%	13	20	44	102	137	149	154
5%	15	26	73	153	179	188	191
7%	17	31	97	176	197	204	207
9%	18	36	130	210	227	233	236
11%	19	40	149	222	237	243	246
13%	20	44	167	233	247	252	255
15%	21	47	181	243	255	260	263
17%	21	51	205	266	278	283	285
19%	22	54	217	273	284	289	291
21%	22	57	225	278	289	293	296

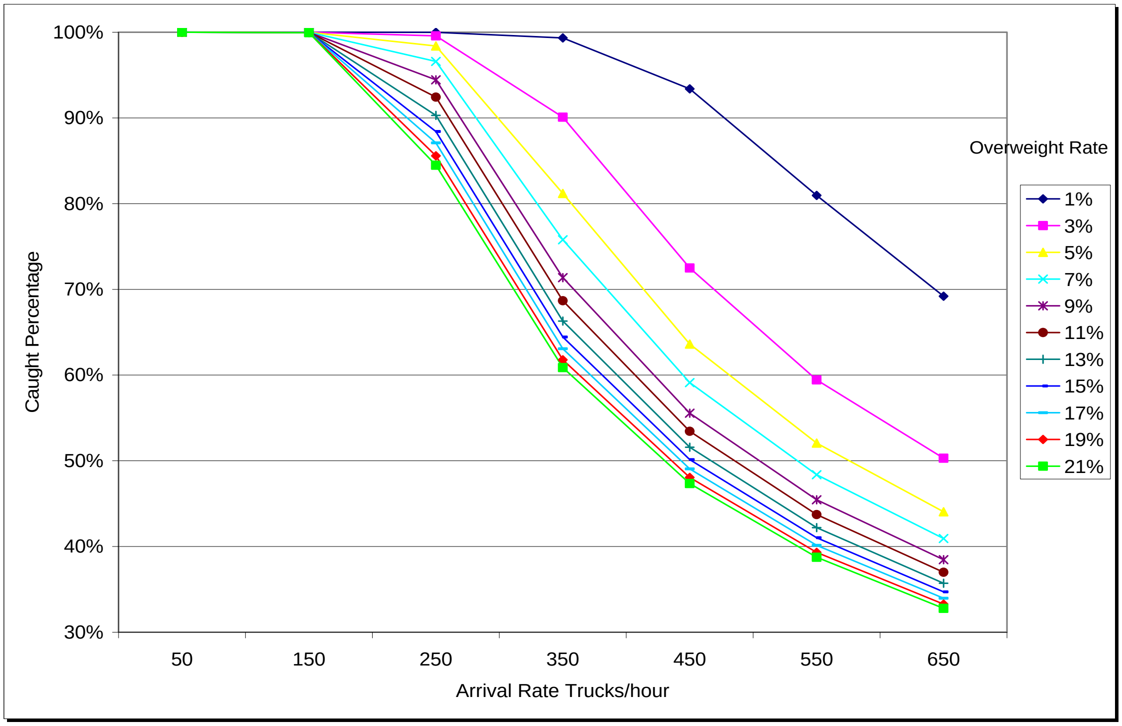

Figure 4-8 Weight Distribution and Caught Percentage

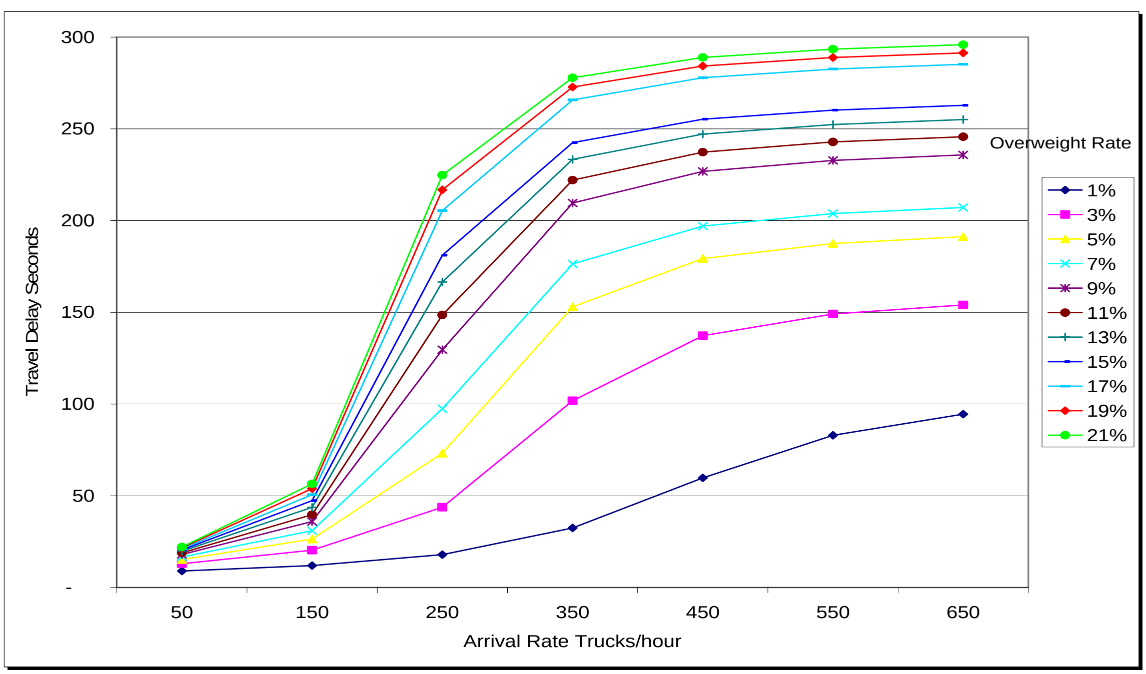

Figure 4-9 Weight Distribution and Travel Delay

The effect decelerates with an increase in the overweight rate. For example, with a truck demand of 350 trucks per hour, the caught percentage difference was 9.3% between overweight rates of 1% and 3% whereas it was 1.5% between overweight rates of 19% and 21%; travel delay difference was 218.8% between overweight rates of 1% and 3% whereas it was 1.8% between overweight rates of 19% and 21%.

4.5 WIM error

For a weigh station with a WIM scale, it is necessary to verify the accuracy of a WIM scale. WIM loads, sorting threshold, and the percentage of trucks sent to a static scale for further checking depend upon the accuracy of a WIM scale. Equations 3-7, 3-8, and 3-9 show sorting threshold (W_{TH}), caught probability (ω), and sent probability (p) of a truck sent to a static scale:

$$W_{TH} = W_{LT} - \frac{W_{LT}}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi}$$

$$\omega = \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}{\int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}$$

$$p = \int_{W_{TH}}^{\infty} \int_{0}^{\infty} f_x f_{y/x} dxdy$$

The traffic intensity (ρ) of a static scale is $\eta\lambda / \mu$.

Caught percentage (η) and travel delay (λ) due to the transponders are given as follows:

$$\alpha = \begin{cases} 1 - \dfrac{(1-\rho)\rho^{C+1}}{1-\rho^{C+2}} & (\rho \neq 1) \\ \dfrac{C+1}{C+2} & (\rho = 1) \end{cases}$$ **Equation 4-9**

$$\gamma = \begin{cases} \dfrac{\dfrac{1}{1-\rho} - \dfrac{1+(C+1)\rho^{C+2}}{1-\rho^{C+2}}}{\left(1 - \dfrac{(1-\rho)\rho^{C=1}}{1-\rho^{C+2}}\right)\eta\lambda} & (\rho \neq 1) \\ \dfrac{C+2}{2\eta\lambda} & (\rho = 1) \end{cases}$$ **Equation 4-10**

The data are as follows, except for WIM accuracy:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight trucks
- At least 99% caught confidence level
- Storage spaces of an entrance lane: 15, and
- Storage spaces between an entrance lane and a static scale: 9

The WIM error data used here are between 3% and 24%, each with a 1% increment.

Tables 4-7 and 4-8, and Figures 4-10 and 4-11 show the measures of effectiveness of WIM error for different truck arrival rates.

Table 4-7 Effect of WIM Error—Caught Percentage

Error Rate	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
3%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
5%	100.0%	100.0%	100.0%	100.0%	100.0%	99.8%
6%	100.0%	100.0%	100.0%	100.0%	99.9%	99.1%
7%	100.0%	100.0%	100.0%	100.0%	99.5%	96.8%
8%	100.0%	100.0%	100.0%	99.9%	98.4%	92.3%
9%	100.0%	100.0%	100.0%	99.7%	96.5%	86.6%
10%	100.0%	100.0%	100.0%	99.2%	92.7%	80.0%
11%	100.0%	100.0%	100.0%	98.2%	88.0%	74.0%
12%	100.0%	100.0%	99.9%	96.7%	82.9%	68.6%
13%	100.0%	100.0%	99.9%	94.4%	78.4%	64.5%
14%	100.0%	100.0%	99.7%	91.8%	74.6%	61.2%
15%	100.0%	100.0%	99.6%	89.6%	71.6%	58.6%
16%	100.0%	100.0%	99.3%	86.6%	68.6%	56.1%
17%	100.0%	100.0%	99.0%	84.0%	66.1%	54.1%
18%	100.0%	100.0%	98.5%	81.4%	63.8%	52.2%
19%	100.0%	100.0%	97.9%	79.2%	62.0%	50.7%
20%	100.0%	100.0%	97.4%	77.2%	60.2%	49.3%
21%	100.0%	100.0%	96.7%	75.4%	58.7%	48.1%
22%	100.0%	100.0%	95.8%	73.6%	57.4%	46.9%
23%	100.0%	100.0%	95.0%	72.2%	56.2%	46.0%
24%	100.0%	100.0%	94.1%	70.8%	55.1%	45.1%

Table 4-8 Effect of WIM Error—Travel Delay in Seconds

Error Rate	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
3%	31	34	38	43	49	57
4%	32	35	40	47	56	69
5%	32	37	43	52	65	86
6%	32	38	46	59	81	119
7%	33	40	51	70	106	166
8%	33	41	55	83	137	215
9%	33	43	61	102	186	280
10%	34	45	68	126	231	316
11%	34	47	77	155	271	340
12%	35	50	88	198	328	386
13%	35	52	99	232	351	396
14%	35	54	111	262	367	403
15%	36	56	125	306	406	438
16%	36	58	141	330	416	442
17%	36	60	156	348	422	445
18%	36	63	173	364	427	447
19%	37	65	189	375	431	449
20%	37	67	214	414	465	481
21%	37	69	230	422	467	482
22%	37	72	247	429	470	483
23%	37	74	262	434	472	484
24%	38	76	276	438	473	485

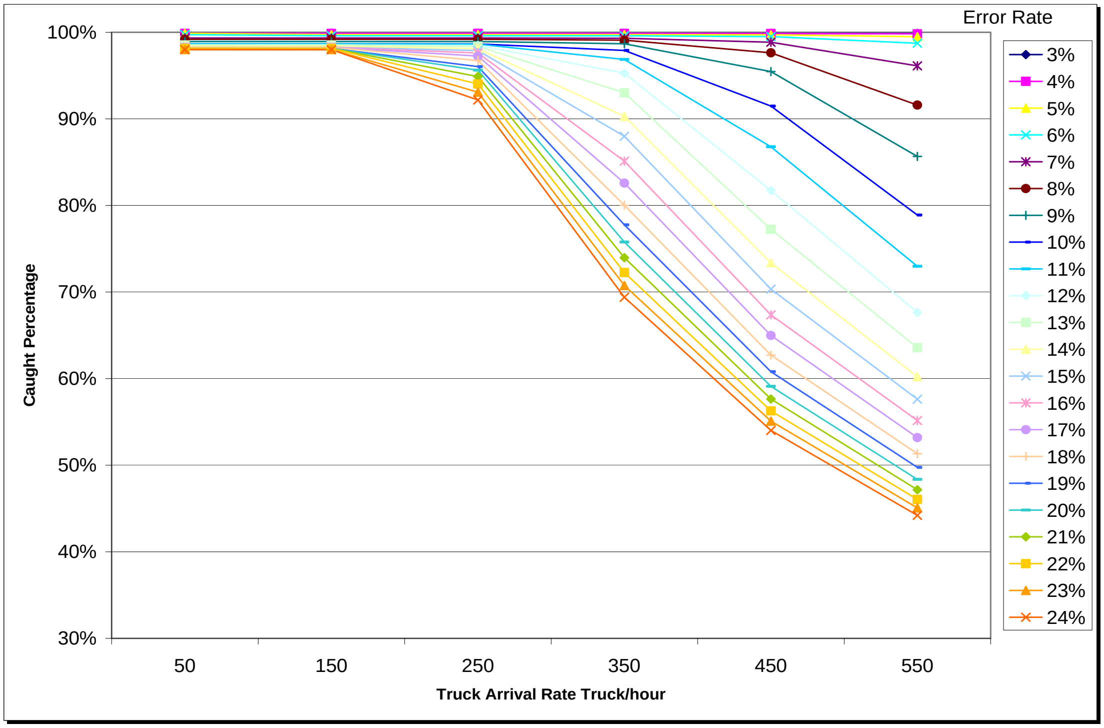

Figure 4-10 WIM Error and Caught Percentage

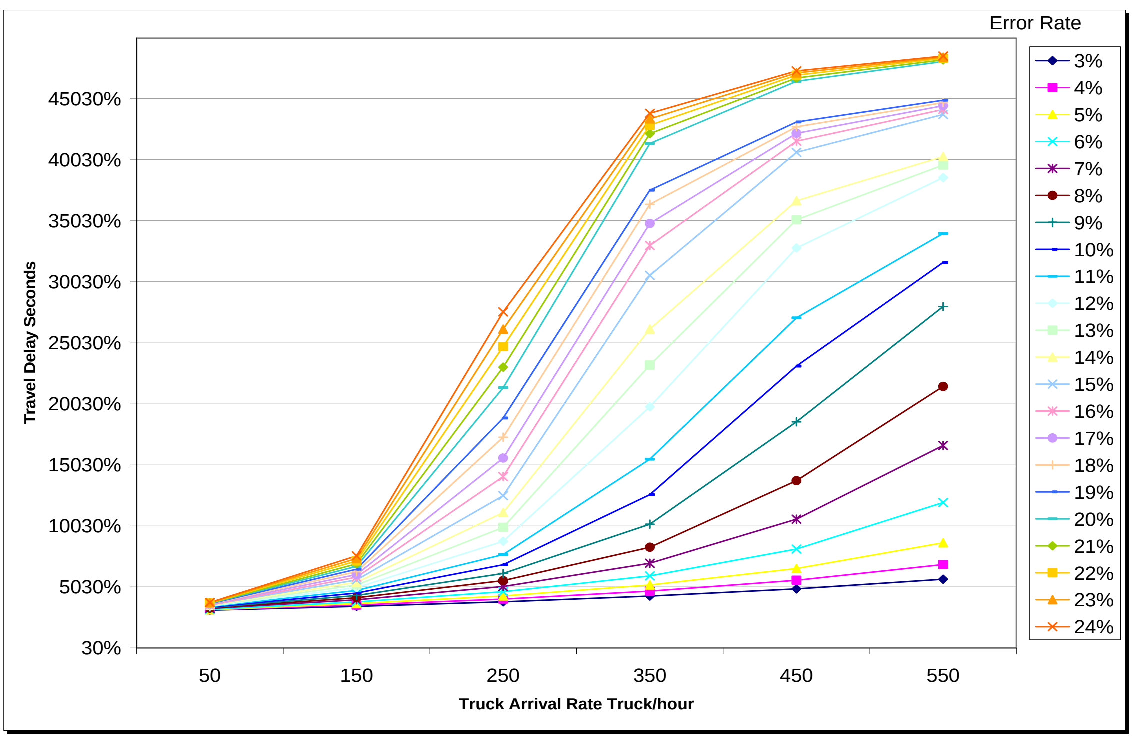

Figure 4-11 WIM Error and Travel Delay

WIM error affects the performances of a weigh station. A higher WIM error leads to a lower caught percentage and higher travel delays. These trends are obvious when truck demand is not less than 350 trucks per hour. For example, for a truck demand of 350 trucks per hour, the WIM error increases from 3% to 24%, caught percentage reduces from 100% to 70.8%, and travel delay increases from 43 s to 438 s. The decreasing rate of caught percentage is less than the increase rate of WIM error whereas the increasing travel delay rate is higher than the increase rate of WIM error.

4.6 Inventory capacity of the static scale ramp

Glassco (1999), showed using the WESTA simulation that longer ramps did not produce significant improvements, except for hard deceleration by trucks on the station entrance ramp; however, the relationship between inventory capacity of the static scale ramp and the operation of a WIM weigh station has not been studied. In this research, the length of a static scale ramp denotes the inventory capacity of a static scale ramp, which refers to storage spaces between the gorge of a static scale ramp and a static scale. The longer the ramp is, the more trucks it can store, which means higher inventory capacity. Our research uses the queueing theory to analyze the effect of both length of a static scale ramp and the length of entrance ramp for different truck demands.

The data used here are as follows, except storage capacity:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight truck
- WIM error: 12% at 95% confidence level, and

- At least 99% caught confidence level.

Tables 4-9 and 4-10, and Figures 4-12 and 4-13 show the measures of effectiveness of static lane storage space under different truck arrival rates (WIM ramp capacity is 11). Tables 4-11 and 4-12, and Figures 4-14 and 4-15 show the measures of effectiveness of WIM ramp lane storage space under different truck arrival rates, static lane storage space capacity is 9. These tables and figures show that in some cases caught percentage does increase with the increase of storage space; however, this improvement is not significant and the storage space increase leads to substantial travel delay. When the truck demand is 350 trucks per hour, the increase in static lane storage space from 1 to 19 increases caught percentage only by 11.3% whereas it increases travel delay by 323.4%. The reason for this is that an increase in storage space does not enhance the capacity of a weigh station but it does extend the possible queue length so that it takes more time to clear the longer queue in the system. These results corroborate the previous simulation studies by Glassco (2001) and Gu et al. (2004). Therefore, when designing a weigh station, the length of the entrance ramp and static scale lane should be related to considerations such as deceleration, truck characteristics, driver's behavior, and so on, except for the performance of a weigh station.

4.7 WIM threshold

In this section, we discuss the manner in which a sorting threshold affects the effectiveness of a weigh station operation. It is concluded that sorting threshold is

Table 4-9 Effect of Static Lane Storage Space—Caught Percentage

Static Lane Storage Space	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
1	100.0%	99.5%	94.4%	82.6%	69.3%	58.3%
3	100.0%	99.9%	97.0%	85.6%	71.0%	59.0%
5	100.0%	100.0%	98.3%	87.5%	71.8%	59.3%
7	100.0%	100.0%	99.0%	88.8%	72.2%	59.4%
9	100.0%	100.0%	99.4%	89.7%	72.4%	59.4%
11	100.0%	100.0%	99.7%	90.4%	72.5%	59.4%
13	100.0%	100.0%	99.8%	90.9%	72.5%	59.4%
15	100.0%	100.0%	99.9%	91.3%	72.6%	59.4%
17	100.0%	100.0%	99.9%	91.6%	72.6%	59.4%
19	100.0%	100.0%	100.0%	91.9%	72.6%	59.4%

Table 4-10 Effect of Static Lane Storage Space—Travel Delay in Seconds

Static Lane Storage Space	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
1	143	217	334	448	531	583
3	143	222	387	589	729	807
5	143	224	427	735	942	1,041
7	143	224	455	886	1,165	1,280
9	143	224	475	1,042	1,395	1,521
11	143	224	489	1,204	1,630	1,762
13	143	224	498	1,370	1,867	2,004
15	143	224	505	1,541	2,107	2,247
17	143	224	509	1,717	2,347	2,489
19	143	224	511	1,897	2,589	2,731

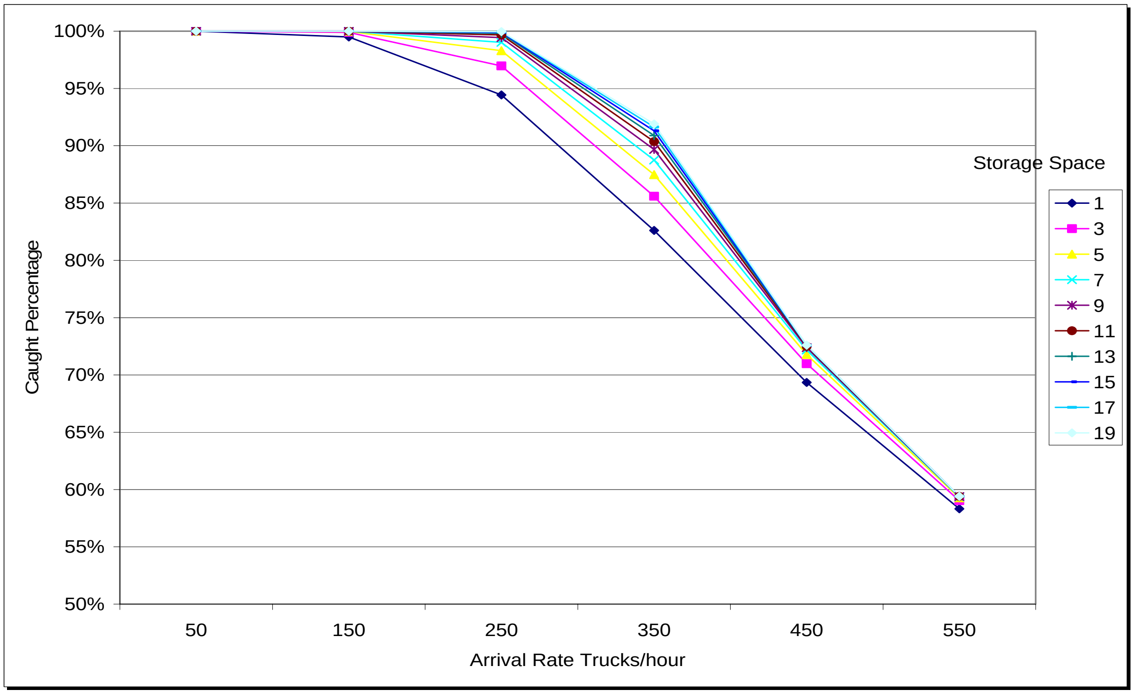

Figure 4-12 Static Lane Storage Space and Caught Percentage

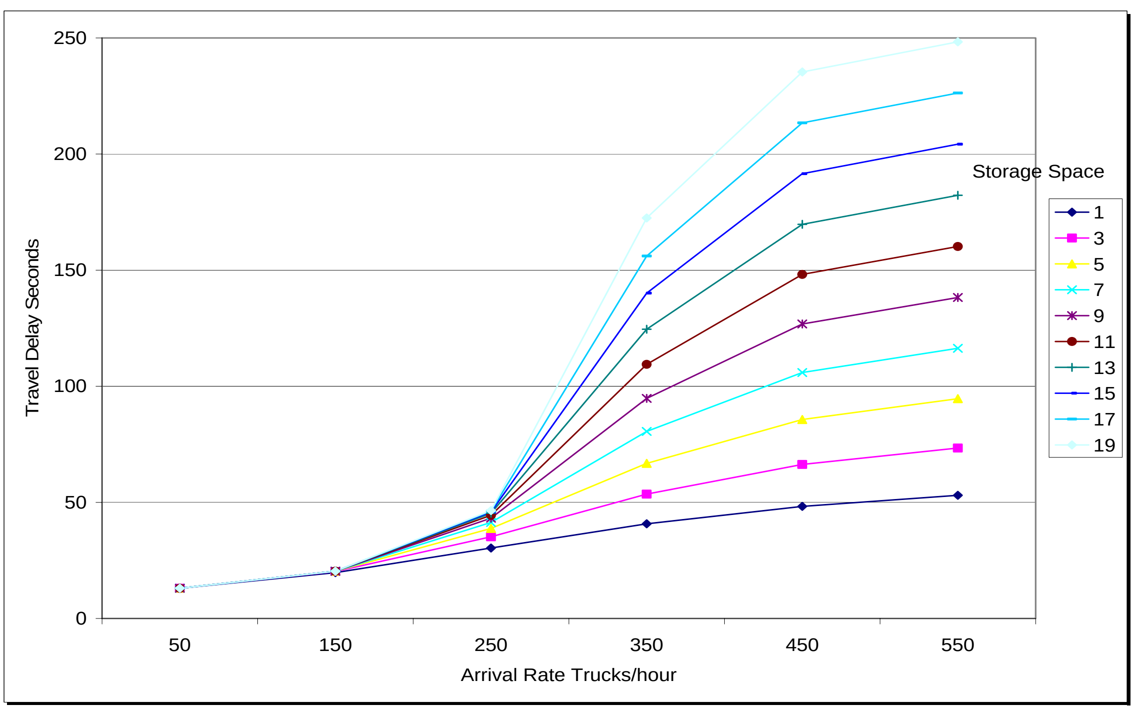

Figure 4-13 Static Lane Storage Space and Travel Delay

Table 4-11 Effect of WIM Ramp Storage Space —Caught Percentage

WIM ramp storage space	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
1	100.0%	100.0%	98.3%	87.5%	71.8%	59.3%
4	100.0%	100.0%	98.7%	88.2%	72.0%	59.3%
7	100.0%	100.0%	99.3%	89.2%	72.3%	59.4%
10	100.0%	100.0%	99.4%	89.7%	72.4%	59.4%
13	100.0%	100.0%	99.6%	90.0%	72.4%	59.4%
16	100.0%	100.0%	99.7%	90.4%	72.5%	59.4%
19	100.0%	100.0%	99.8%	90.6%	72.5%	59.4%
22	100.0%	100.0%	99.8%	90.9%	72.5%	59.4%
25	100.0%	100.0%	99.9%	91.1%	72.6%	59.4%
28	100.0%	100.0%	99.9%	91.3%	72.6%	59.4%
31	100.0%	100.0%	99.9%	91.5%	72.6%	59.4%

Table 4-12 Effect of WIM Ramp Storage Space —Travel Delay in Seconds

WIM ramp storage space	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
1	13	20	39	67	86	95
4	13	20	40	74	96	105
7	13	20	42	88	116	127
10	13	20	43	95	127	138
13	13	20	44	102	137	149
16	13	20	44	109	148	160
19	13	20	45	117	159	171
22	13	20	45	125	170	182
25	13	20	46	132	181	193
28	13	20	46	140	192	204
31	13	20	46	148	202	215

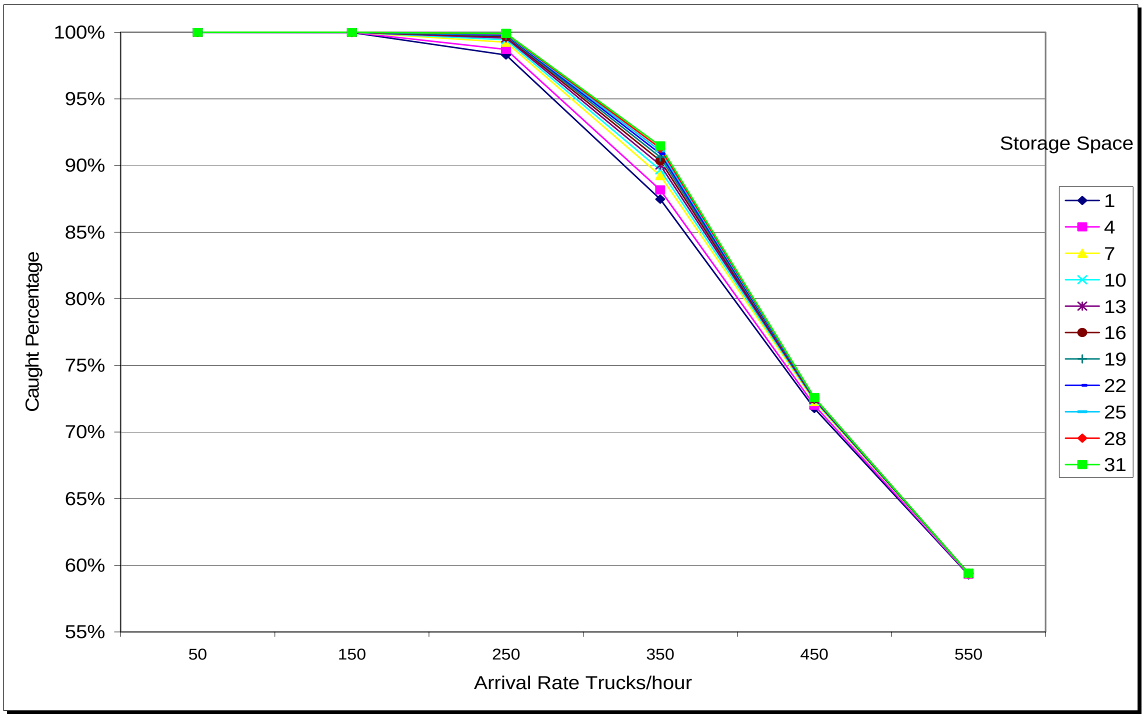

Figure 4-14 WIM Ramp Storage Space and Caught Percentage

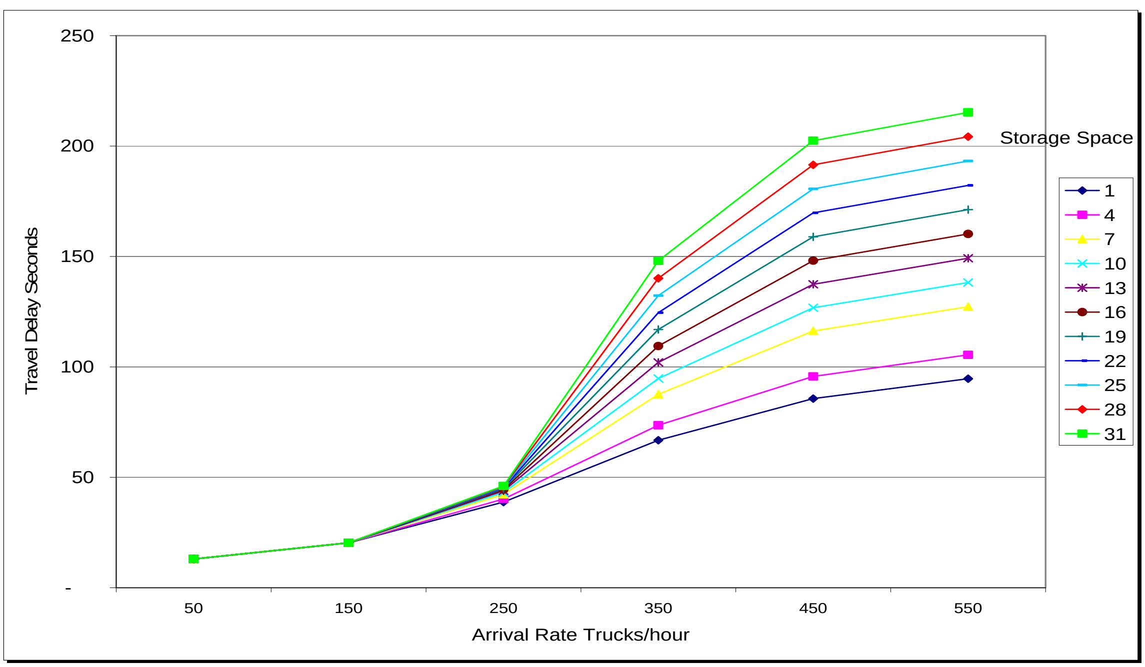

Figure 4-15 WIM Ramp Storage Space and Travel Delay

determined by a weight limit and the accuracy of a WIM scale. It is also necessary to study the manner in which a sorting threshold value affects the operations of a weigh station. For a specific sorting threshold value,

$$\omega = \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}{\int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}$$

$$p = \int_{W_{TH}}^{\infty} \int_{0}^{\infty} f_x f_{y/x} dxdy$$

The traffic intensity (ρ) of a static scale is $p\lambda / \mu$.

The data used here are as follows, except for the caught confidence level:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight truck
- WIM error: 12% at 95% confidence level
- Storage spaces of an entrance lane: 15, and
- Storage spaces between an entrance lane and a static scale: 9.

The results are shown in Tables 4-13, 4-14 and 4-15, and Figures 4-16, 4-17, and 4-18.

Travel delay and closure percentage decreases with an increased sorting threshold whereas caught percentage for overweight trucks showed a different trend. A high sorting threshold decreases the number of trucks sent to a static scale and thus naturally

Table 4-13 Effects of Threshold—Caught Percentage

Threshold kips	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
60	100.0%	100.0%	88.5%	64.3%	50.0%	41.0%
63	100.0%	100.0%	93.2%	69.6%	54.2%	44.3%
66	100.0%	100.0%	97.8%	78.9%	61.7%	50.5%
69	100.0%	100.0%	99.7%	91.7%	74.4%	61.1%
72	97.3%	97.3%	97.3%	96.6%	90.4%	78.1%
75	90.5%	90.5%	90.5%	90.5%	90.3%	88.8%
78	78.2%	78.2%	78.2%	78.2%	78.2%	78.1%
81	59.1%	59.1%	59.1%	59.1%	59.1%	59.1%
82	53.9%	53.9%	53.9%	53.9%	53.9%	53.9%
84	39.0%	39.0%	39.0%	39.0%	39.0%	39.0%
87	20.6%	20.6%	20.6%	20.6%	20.6%	20.6%
90	8.4%	8.4%	8.4%	8.4%	8.4%	8.4%

Table 4-14 Effects of Threshold—Closure Percentage

Threshold kips	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
60	0.0%	0.0%	11.5%	35.7%	50.0%	59.0%
63	0.0%	0.0%	6.8%	30.4%	45.8%	55.7%
66	0.0%	0.0%	2.2%	21.1%	38.3%	49.5%
69	0.0%	0.0%	0.3%	8.3%	25.6%	38.9%
72	0.0%	0.0%	0.0%	0.7%	7.1%	19.8%
75	0.0%	0.0%	0.0%	0.0%	0.3%	1.9%
78	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
81	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
82	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
84	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
87	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
90	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4-15 Effects of Threshold—Travel Delay in Seconds

Threshold kips	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
60	21	48	194	259	272	277
63	19	38	142	218	234	239
66	16	28	83	163	187	194
69	13	19	40	94	131	144
72	9	12	18	34	62	85
75	6	7	9	12	17	27
78	4	4	5	5	6	7
81	2	2	2	2	3	3
82	2	2	2	2	2	2
84	1	1	1	1	1	1
87	0	0	0	0	0	0
90	0	0	0	0	0	0

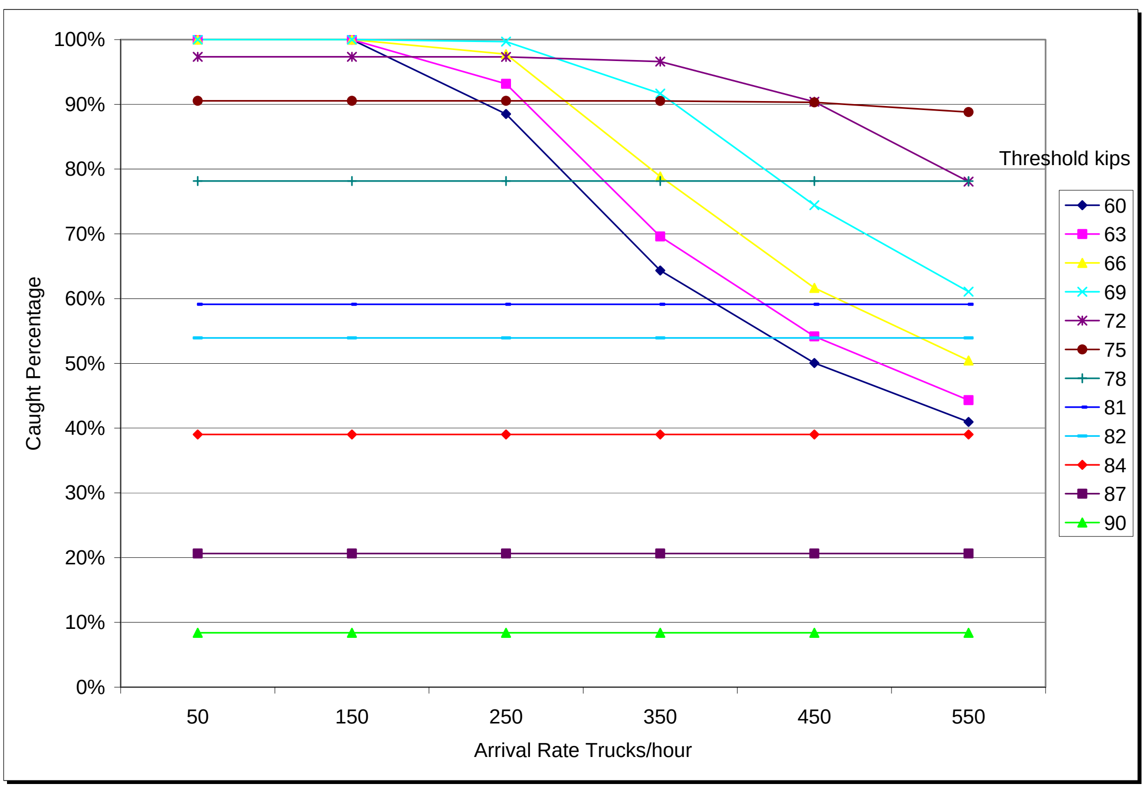

Figure 4-16 Sorting Threshold and Caught Percentage

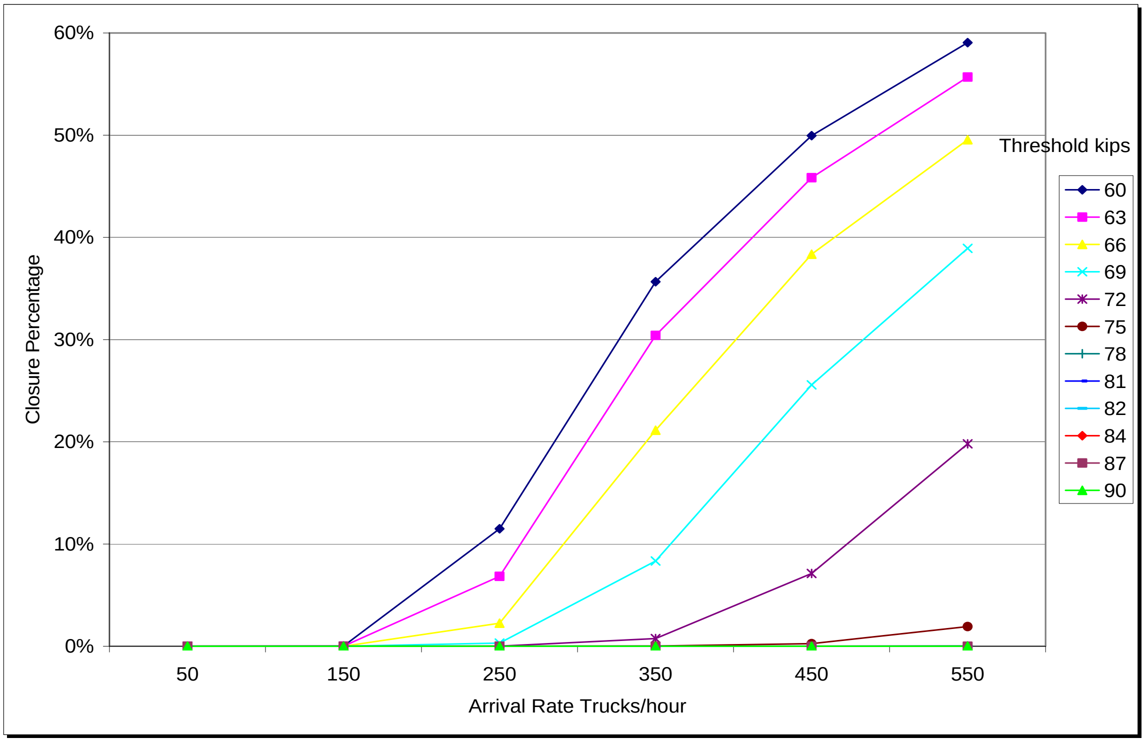

Figure 4-17 Sorting Threshold and Closure Percentage

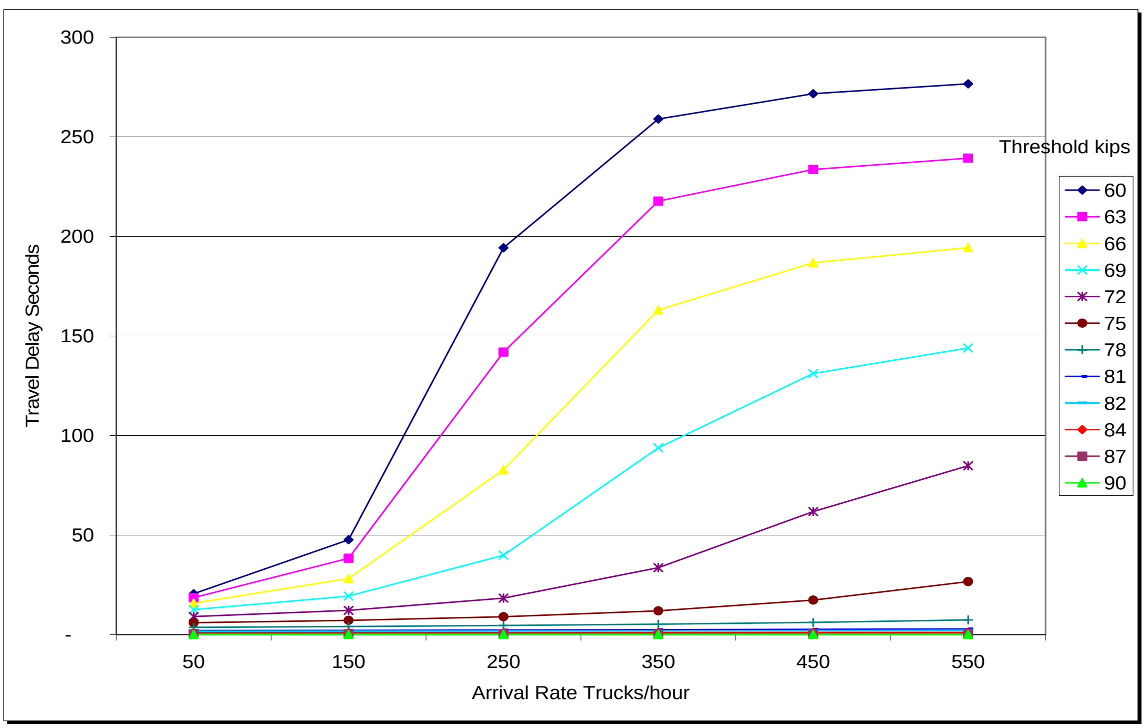

Figure 4-18 Sorting Threshold and Travel Delay

reduces the closure percentage of a weigh station as well as travel delay. Therefore, with respect to these two measures, a higher sorting threshold leads to better performance by a weigh station. The relationship between caught percentage and sorting threshold appears more complex. When truck demand is not more than 150 trucks per hour, sorting threshold values between 60 kips and 69 kips get the highest caught percentage. When truck demand increases to 250 trucks per hour, a 69 kip threshold is the best choice. When truck demand equals 350 trucks per hour, the best sorting threshold is 72 kips, and so on. Since, the main function of a weigh station is to catch overweight trucks, caught percentage is the most important measure for these three MOEs. Considering the other two MOEs (closure percentage and travel delay), the best choices for a sorting threshold are illustrated in Figure 4-19, which shows the optimal threshold changes in terms of truck demand.

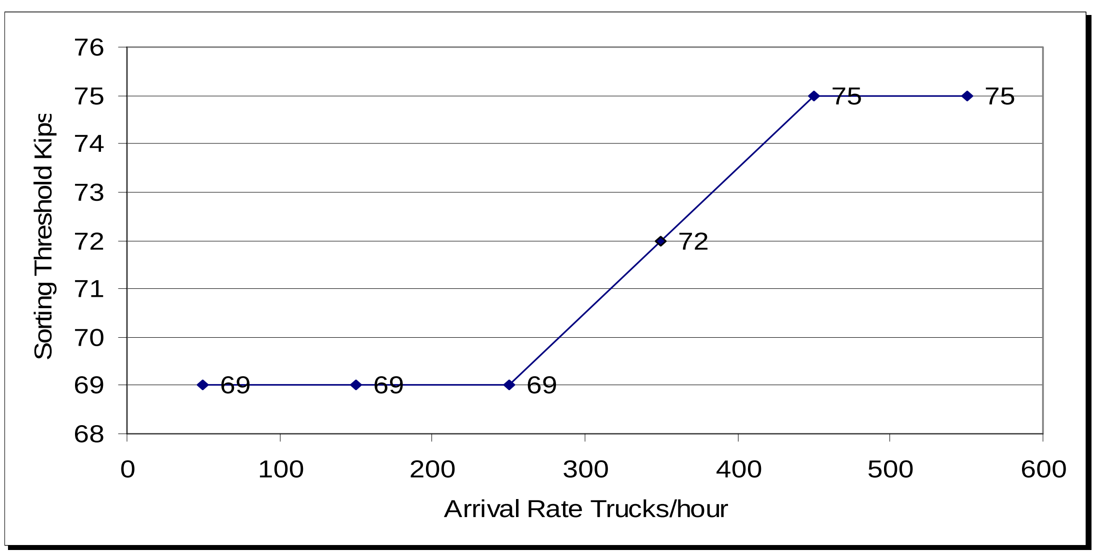

Figure 4-19 Best Choice for Sorting Threshold

4.8 Transponder percentage

For a mainline WIM weigh station, the effect of transponder is very important. Transponder percentage is denoted as ψ. The arrival rate for the static scale equals $(p\psi + (1-\psi))\lambda$, traffic intensity ρ is $(p\psi + (1-\psi))(\lambda/\mu)$. The transponder effect on probability (η) and travel delay (λ) for transponder effect can be shown as the follows:

$$\alpha = \begin{cases} 1 - \dfrac{(1-\rho)\rho^{C+1}}{1-\rho^{C+2}} & (\rho \neq 1) \\ \dfrac{C+1}{C+2} & (\rho = 1) \end{cases}$$ **Equation 4-11**

$$\gamma = \begin{cases} \dfrac{\dfrac{1}{1-\rho} - \dfrac{1+(C+1)\rho^{C+2}}{1-\rho^{C+2}}}{\left(1 - \dfrac{(1-\rho)\rho^{C=1}}{1-\rho^{C+2}}\right)(p\psi + (1-\psi))\lambda} & (\rho \neq 1) \\ \dfrac{C+2}{2(p\psi + (1-\psi))\lambda} & (\rho = 1) \end{cases}$$ **Equation 4-12**

The data used here are as follows, except for the transponder:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight truck
- WIM error: 12% under 95% confidence level
- At least 99% caught confidence level
- Storage spaces of an entrance lane: 15. and
- Storage spaces between an entrance lane and a static scale: 9

Tables 4-16 and 4-17, and Figures 4-20 and 4-21 show the measures of the effectiveness of transponder for different truck arrival rates.

It can be concluded that transponder percentage has a significant impact on the performance of a mainline WIM weigh station. When truck demand is high (not fewer than 250 trucks per hour in this case), an increased transponder percentage will greatly enhance caught percentage and reduce travel delay. For a truck demand of 350 trucks per hour, the caught percentage for 100% transponder percentage is 2.7 times as much as that for 0% transponder percentage, and 100% transponder percentage reduces travel delay by 75.6% compared to 0% transponder percentage. The rate of caught percentage increases with the increase in transponder percentage. For example, when truck demand is 350 trucks per hour, caught percentage is enhanced 3.2% (from 34.3% to 35.2%) with the increase in transponder percentage from 0% to 5% whereas it is enhanced 7.4% (from 85.6% to 91.9%) with an increase in transponder percentage from 95% to 100%.

For a WIM on the mainline weigh station, if more trucks are equipped with transponders, the enforcement level increases. If the arrival rate is 450 trucks per hour, and the percentage of trucks equipped with transponders increases from 0% to 100%, the caught percentage increases from 26.67% to 73.60%, the closure percentage decreases from 73.33% to 27.40%, and travel delay decreases from 709 s to 235 s. Both increased rate of the caught percentage of overweight trucks and the decreased rate of closure probability for a weigh station are larger than increased rate of trucks equipped with transponders, which means that if more trucks are equipped with transponders, the efficiency of this technology increases.

Table 4-16 Effect of Transponder—Caught Percentage

Transponder Percentage	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
0%	100.0%	79.9%	48.0%	34.3%	26.7%	21.8%
5%	100.0%	82.5%	49.6%	35.4%	27.5%	22.5%
10%	100.0%	85.1%	51.2%	36.6%	28.5%	23.3%
15%	100.0%	87.8%	53.0%	37.9%	29.5%	24.1%
20%	100.0%	90.5%	55.0%	39.3%	30.5%	25.0%
25%	100.0%	93.1%	57.0%	40.7%	31.7%	25.9%
30%	100.0%	95.4%	59.2%	42.3%	32.9%	26.9%
35%	100.0%	97.2%	61.7%	44.0%	34.3%	28.0%
40%	100.0%	98.4%	64.3%	45.9%	35.7%	29.2%
45%	100.0%	99.2%	67.1%	47.9%	37.3%	30.5%
50%	100.0%	99.7%	70.2%	50.2%	39.0%	31.9%
55%	100.0%	99.9%	73.6%	52.6%	40.9%	33.5%
60%	100.0%	99.9%	77.3%	55.3%	43.0%	35.2%
65%	100.0%	100.0%	81.4%	58.2%	45.3%	37.1%
70%	100.0%	100.0%	85.8%	61.5%	47.9%	39.2%
75%	100.0%	100.0%	90.3%	65.2%	50.8%	41.5%
80%	100.0%	100.0%	94.5%	69.4%	54.0%	44.2%
85%	100.0%	100.0%	97.6%	74.2%	57.7%	47.2%
90%	100.0%	100.0%	99.2%	79.6%	61.9%	50.7%
95%	100.0%	100.0%	99.8%	85.6%	66.8%	54.7%
100%	100.0%	100.0%	100.0%	91.9%	72.6%	59.4%

Table 4-17 Effect of Transponder—Travel Delay in Seconds

Transponder Percentage	Arrival Rate—trucks / hour					
	50	150	250	350	450	550
0%	51	603	692	704	709	712
5%	49	566	669	681	686	689
10%	46	526	645	658	663	666
15%	44	480	621	635	640	643
20%	41	430	597	612	617	620
25%	39	376	573	589	594	597
30%	37	319	548	565	571	574
35%	35	262	523	542	548	551
40%	33	210	497	519	525	529
45%	31	165	471	495	502	506
50%	29	129	444	472	479	483
55%	27	102	415	448	456	460
60%	25	82	384	424	433	437
65%	23	67	349	399	409	413
70%	22	55	309	374	386	390
75%	20	46	261	349	362	367
80%	19	39	205	322	338	344
85%	17	33	149	293	314	320
90%	16	28	101	261	289	297
95%	14	24	67	222	263	273
100%	13	20	46	172	235	248

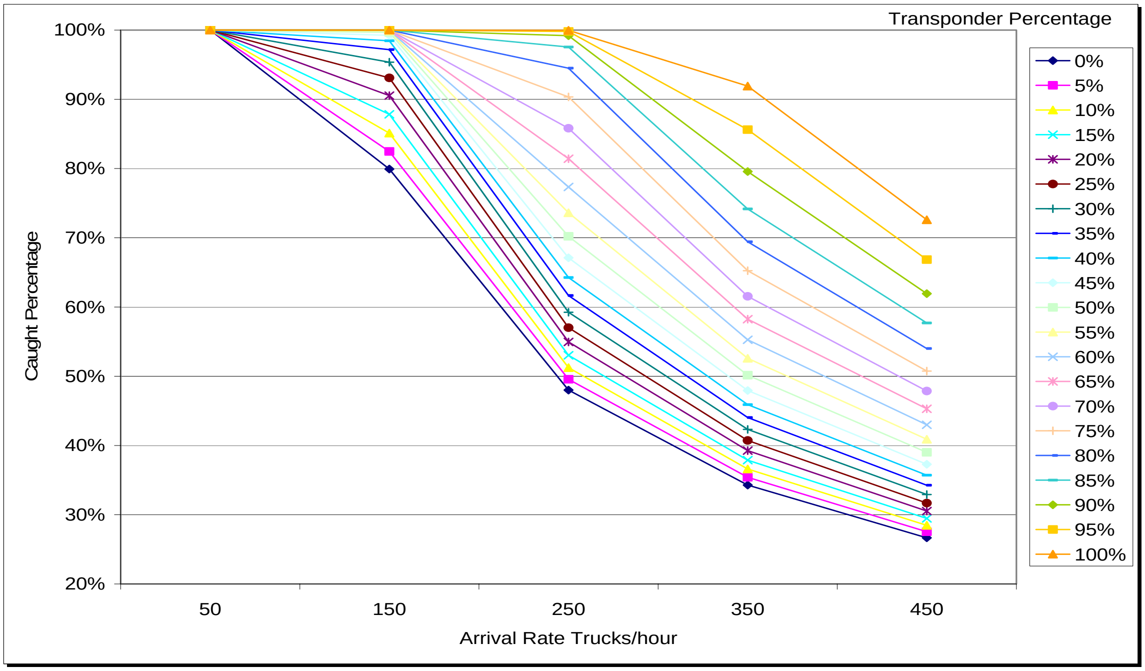

Figure 4-20 Transponder and Caught Percentage

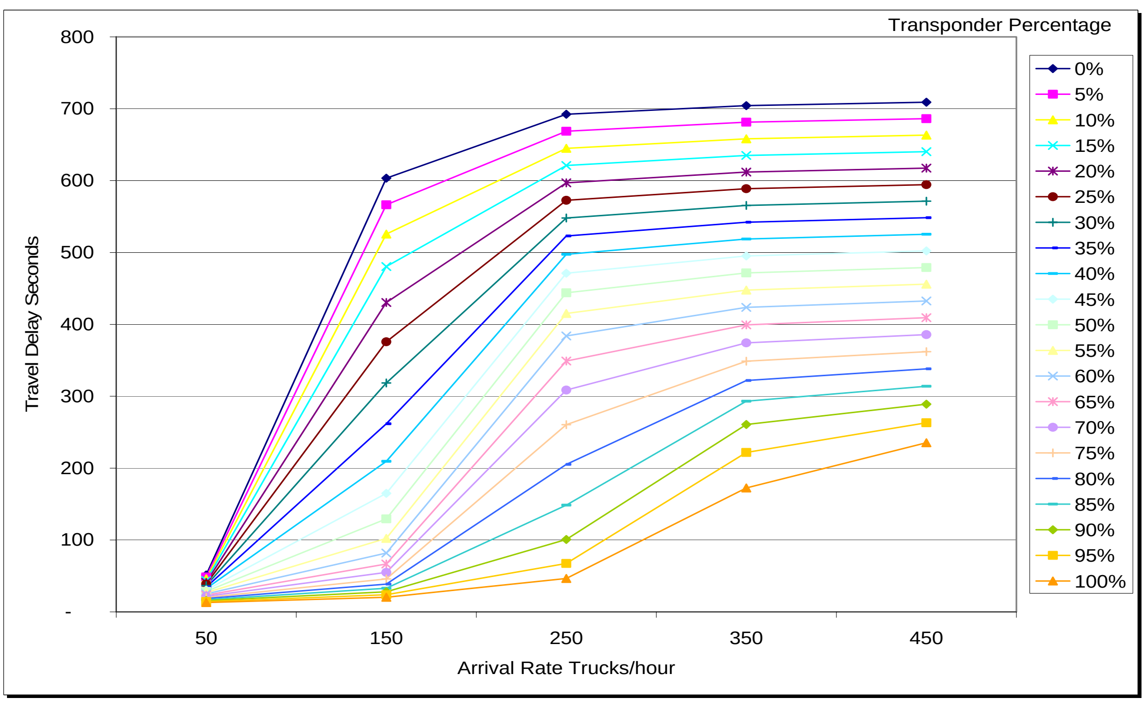

Figure 4-21 Transponder and Travel Delay

4.9 Summary

This chapter used the queueing theory to analyze weigh station design strategies and the effect of some important operational parameters. From the results of the analysis, it can be concluded that:

1. WIM technology can greatly improve the efficiency of weigh station operation. WIM technology can not only greatly decrease truck travel delay and reduce the probability of weigh station closure due to overflow but also increase the possibility of catching overweight trucks. This technology benefits both weigh station operators and trucking companies.
2. The percentage of trucks equipped with transponders has a strong impact on the effect of WIM technology for a mainline WIM weigh station. Currently, because of the low percentage of trucks equipped with transponders, a ramp WIM weigh station should be a better alternative than a mainline WIM weigh station in order to increase weigh station productivity.
3. Weight distribution has an immense influence on the capacity of a WIM weigh station. For a specific threshold and WIM error, weight distribution decides the percentage of trucks sent to a static scale for further inspection. Higher the percentage of trucks sent to a static scale, fewer is the number of trucks a weigh station can handle.
4. The accuracy of a WIM scale is very important for WIM weigh station operation. Since WIM scales accuracy and legal weight limits decide the

sorting threshold and the legal threshold weight limit seldom changes, the accuracy of WIM scales plays a key role in the application of WIM technology.

5. Storage spaces in a weigh station system do not significantly affect the effect of catching overweight trucks while causing long travel delay when traffic density is heavy.
6. For each scenario, an optimal threshold could exist. A low threshold causes longer delays for legal weight trucks and a higher risk of overweight trucks bypassing a weigh station due to weigh station overflow; on the other hand, although a high threshold reduces travel delay of trucks drivers, it may allow overweight trucks to go though a weigh station without being identified because of WIM scale error.

5 Floating-threshold Control Algorithm

Although WIM technology has been used for more than 50 years; there has been little research into the selection of a threshold value. Gu et al. (2004) and Katz (2002) both mentioned that an optimal threshold could exist for a weigh station with WIM technology. Weng (1995) attempted to find an optimal threshold based on a V/C ratio. Although these studies offer some insight regarding the threshold value, none of them have analyzed the essence of the problem theoretically. This study attempts to conduct a systematic study of weigh station systems using queueing theory and statistical analysis to find a good threshold strategy and develop floating-threshold algorithms to adapt to the changes of truck demand, WIM error level, service time distribution, and truck weight distribution.

5.1 Floating-threshold algorithm development

The performance of WIM technology depends on such factors as traffic volume, service capacity, weight distribution, WIM error, legal weight limit, weigh station layout, and weight station geometry. To the best of our knowledge, till date, few studies have identified the effect of weight distribution on WIM technology performance. This study is the first attempt to systematically investigate the sensitivities of WIM technology with respect with all these variables.

Let us review our fixed-threshold algorithms. In Chapter 3, it was shown that a sorting threshold value could be derived based on legal weight limit, WIM accuracy, and the confidence level,

$$W_{TH} = W_{LT} - \frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi}$$

where

W_{LT} : legal weight (axle, tandem, or gross weight) limit of a truck

α: tolerance of a WIM scale ($0 = < \alpha$), stated as a percentage of a static weight

β: probability of conformity of a WIM scale

φ: confidence level of catching a truck just over legal weight limit, and

σ: standard deviation of a WIM load.

Based on this strategy,

$$\omega = \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f_x f_{y/x} dx dy}{\int_{W_{LT}}^{\infty} f_x dx}$$

$$p = \int_{W_{TH}}^{\infty} \int_{0}^{\infty} f_x f_{y/x} dx dy$$

$$\rho = p\lambda / \mu$$

where

ω : caught probability, defined as the probability of overweight trucks being caught under a specific sorting threshold, assuming that no overflow happens

p : sent percentage, defined as the percentage of trucks sent to a static scale under a specific sorting threshold, assuming that no overflow happens

ρ: traffic intensity,

λ: average truck arrival rate

μ: average static scale service rate

w_{TH} : sorting threshold

w_{LT} : legal weight limit

f_x : density function of truck static weight distribution, and

$f_{y/x}$: joint density function of truck WIM weight distribution based on static weight distribution.

When the density of the traffic intensity is close to 1, this queueing system becomes unstable. The hypothetical data used in Chapter 4 are still used here:

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% truck overweight
- WIM error: 12% under 95% confidence level, and
- 99% caught confidence level for a truck whose weight is just over legal weight limit.

In this case, approximately 25% of the trucks' WIM loads were over the sorting threshold, which means that this system cannot handle the truck volume when truck volume is equal to or over 480 trucks / hour. In reality, this problem is a constant occurrence on some congested interstate weigh stations.

There are two methods to solve this problem. First, one static scale lane can be added to quickly increase the capacity of a weigh station. However, this addition needs both capital investment and labor. Furthermore, topological limitations can make the addition of a static scale lane impossible. A second alternative is to develop an optimal sorting threshold to maximize caught percentage and minimize closure percentage for a weigh station and travel delay for truck drivers.

In Chapter 3, it is concluded that caught percentage for a ramp WIM weigh station as per the fixed-threshold strategy is as follows.

$$Caught\ \ Percentage\,(\eta) = \left(1 - p(C+1)\right) \times \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f_{y/x} f_x \, dxdy}{\int_{W_{LT}}^{\infty} f_x \, dx} \quad \textbf{Equation 5-1}$$

where

P(C + 1): weigh station close percentage

The objective is to catch as many overweight trucks as possible, so

$$Maximize\ \left(1 - p(C+1)\right) \times \frac{\int_{W_{TH}}^{\infty} \int_{W_{LT}}^{\infty} f(y/x) f(x) \, dxdy}{\int_{W_{LT}}^{\infty} f(x) \, dx}$$

From the above equation, it can be concluded that the value of the threshold is decided by

- Legal weight limit
- WIM accuracy
- Weight distribution
- Truck arrival rate
- Truck service time at a static scale, and
- Other factors (such as the length of the entrance lane and the static scale lane.)

For a specific scenario (known weight distribution, known WIM accuracy, known truck arrival rate, known truck service time), maximizing caught percentage will establish an optimal threshold value, while considering travel delay for truck drivers and closure percentage of a weigh station.

In reality, these parameters vary according to time and space. For instance, truck arrival rate changes by hour of day, day of month, and month of year. These variances make it impossible to arrive at an optimal threshold that is suitable for all the cases. It is necessary and important to find a flexible strategy to be applied in dynamic situations.

Dynamic (state-dependent) control policies can offer significant improvements over less responsive strategies. In contrast with static strategies, which are usually based on fixed estimates of system parameters, dynamic policies depend on the current states of the system. For example, dynamic routing may be useful for a weigh station where traffic patterns and weight distributions vary over time. Based on dynamic control theory, a floating-threshold strategy can be developed to adapt to variations in traffic volumes, weight distributions, and WIM accuracy.

Queue length before a static scale is a good reference to the floating-threshold strategy. The number of trucks waiting for service before a static scale is decided by the interactions among parameters like truck arrival, truck weight distribution, static service capacity, weight legal limit, and even sorting threshold itself. The queue length is also the deciding factor regarding the closure of a weigh station. Therefore, it is reasonable to adjust the threshold value according to the number of trucks waiting for service before a static scale.

5.2 Theoretical analysis of floating-threshold algorithm control

In our floating-threshold strategy, the sorting threshold value changes dynamically based on the queue length before the static scale. Based on this mechanism, when the queue length is low, a low threshold is applied; when the queue length is high, a high threshold is used to catch higher possible overweight trucks. For a ramp WIM weigh station, queue length between a static scale and a WIM scale is applied as the independent variable. The floating-threshold algorithm can be expressed as follows:

$$W_{TH} = \begin{cases} f(n) & \text{n <= Cs} \\ f(Cs) & n > Cs \end{cases}$$ **Equation 5-2**

where

W_{TH}: sorting threshold value

n: the number of trucks waiting before a static scale. n is a non-negative integer

Cs: the storage capacity of a static scale lane

From the above analysis, it can be derived that f(n) must be discrete, monotonic, and increasing.

If n trucks are waiting before the static scale, the sorting threshold is f(n), the percentage of trucks sent to the static scale can be expressed as follows:

$$p(n) = \int_{W_{TH}}^{\infty}\int_{0}^{\infty} f_x f_{y/x} dxdy = \int_{W_{TH}}^{\infty} f_z dz$$

$$\omega(n) = \frac{\int_{W_{TH}}^{\infty}\int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}{\int_{W_{LT}}^{\infty} f_x f_{y/x} dxdy}$$

where

p(n): the inverse percentage distribution function of WIM loads

ω(n) : caught probability

w_{TH} : sorting threshold

w_{LT} : legal weight limit

f_x : density function of truck static weight distribution. and

$f_{y/x}$: joint density function of truck WIM weight distribution based on static weight distribution.

In this case, the arrival rate depends on the state of the system (the number of trucks in the system). It is assumed that truck arrival for a weigh station system is λ. The mean truck arrival to the static scale (λs_n) depends on the number of trucks before the static scale n. Furthermore, there is a limit on the number in the system. Thus, mean truck arrival to the static scale (λs_n) is

$$\lambda s_n = \begin{cases} \lambda \times p(n) & n <= Cs \\ \lambda \times p(Cs) & n > Cs \end{cases}$$ **Equation 5-3**

In addition, the mean static service rate is

$$\mu_n = \mu$$ **Equation 5-4**

If the arrival process follows the Poisson distribution and the static scale service time follows an exponential distribution, the state of the weigh station system can be obtained at the follows:

$$P_n = \frac{\lambda s_{n-1} \lambda s_{n-2} \cdots \lambda s_0}{\mu^n} P_0 = \left(\frac{\lambda}{\mu}\right)^{n} P_0 \prod_{i=0}^{n-1} p(i) \quad (n \geq 1)$$ **Equation 5-5**

(Gross and Harris, 1985)

The effective storage space for a ramp WIM weigh station is denoted as C. From the boundary condition: $\sum_{n=0}^{C+1} p_n = 1$, idle probability (P_0), the average queue size (*L)*, and the effective arrival rate (λs_{eff}) can be derived as the follows:

$$P_0 = \frac{1}{1 + \sum_{n=1}^{C+1} \left(\frac{\lambda}{\mu}\right)^{n} \prod_{i=0}^{n-1} p(i)}$$ **Equation 5-6**

$$L = \sum_{n=0}^{C+1} n P_n$$ **Equation 5-7**

$$\lambda s_{eff} = \sum_{n=0}^{C} \lambda s_n P_n = \lambda \sum_{n=0}^{C} p(n) P_n$$ **Equation 5-8**

The caught percentage (η), closure percentage (κ), and travel delay (τ) can be deduced as the follows:

$$\eta = \sum_{n=0}^{C} w(n) P_n$$ **Equation 5-9**

$$\kappa = P_{C+1}$$ **Equation 5-10**

$$\tau = \frac{L}{\lambda s_{eff}} \sum_{n=0}^{C} \left(Pn \times p(n)\right) = \frac{L}{\lambda}$$ **Equation 5-11**

Although the queueing theory can exactly analyze the operational processes of a weigh station, for complex problems, the queueing theory is difficult to apply or it gives a poor approximation of a weigh station system, due to its reliance on the assumptions of theoretical probability distributions. In the weigh station system, the WIM loads distribution cannot be deduced by mathematical methods. The static scale service time of a legal weight truck is different from that of an overweight truck. Floating-threshold strategies force a truck to dynamically select its route in a weigh station system, which makes the system more complex. Some important characteristics (speed, space) of trucks cannot be exactly analyzed by queueing models. Other methods could be more suitable to evaluate our strategies.

5.3 Simulation based evaluations

In order to identify the effects of floating-threshold algorithms, one can perform either field tests or simulation experiments. Although, field operational tests can be used for the evaluating any traffic control system, they tend to be prohibitively expensive, time consuming, and sometimes infeasible. For instance, the test results depend on uncontrollable elements (e.g. weather conditions, travel demand, incidents) and their confounding effects can make an accurate analysis of the impacts of WIM technology impossible. Considering that it may not be possible to control these variables in a field test, simulation provides an ideal alternative to evaluate the performance of ramp control algorithms over a range of values for those variables. In recent years, simulation has emerged as an alternative tool to evaluate the performance of traffic controls and to select an appropriate design. Simulation studies can also be used to analyze the robustness of a design by evaluating a range of scenarios and calibrating control parameters. A number of studies have simulated weigh station operations for different scenarios. This study will make a theoretical analysis of our WIM threshold control algorithm and then evaluate this algorithm by simulation experiments.

5.3.1 Simulation model construction

A weigh station is a complex control system. A weigh station system comprises inputs, its simulation model, and outputs. The inputs consist of arrival demand, the weight distribution of trucks, service time for overweight and non-overweight trucks, geometric configuration of a weigh station, the accuracy of the WIM system, and the threshold value of the WIM scale. The simulation model refers to the selected traffic simulation software. The MOEs are attained to evaluate the different algorithms (Figure 5-1).

5.3.2 Simulation software selection

The traffic simulation models are categorized according to type (macroscopic, microscopic, or mesoscopic) and functionality (highway, signal, integrated). Obviously, for the purpose of our simulation, a microscopic simulation model of highway traffic is suitable. Traffic flow in a weigh station system emerges from a complex interactive effect between the mainline, bypass-lane, and static-scale-lane traffic and depends on several factors such as drive behavior, road geometry, and vehicle characteristics. Macroscopic or mesoscopic simulators are based on a coarse representation of traffic flow that fails to represent these interactions among vehicles. Thus, macroscopic or

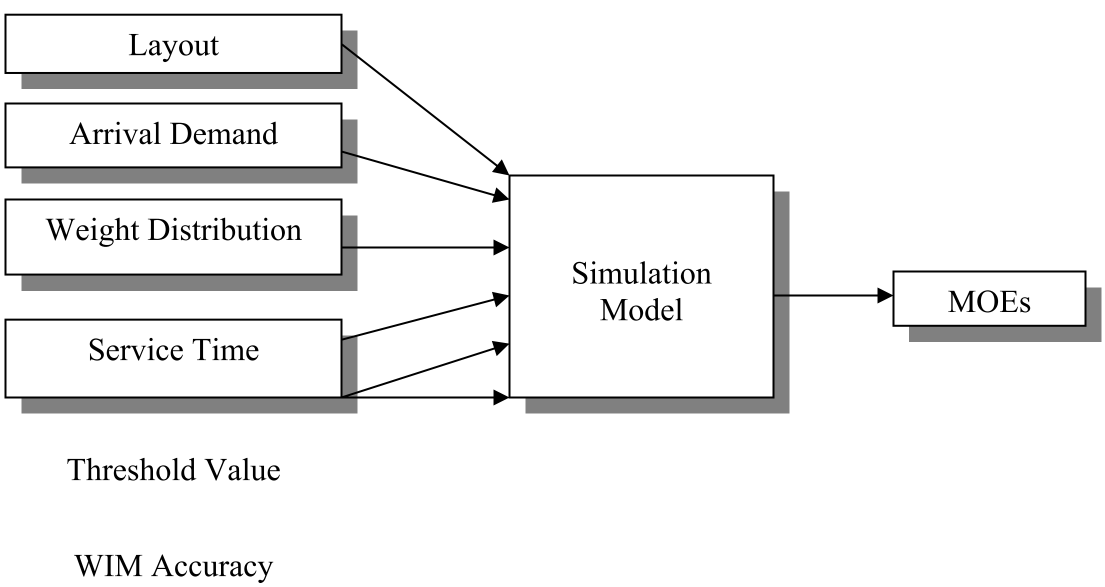

Figure 5-1 Simulation Model

mesoscopic simulations may not be adequate to evaluate the performance of weigh station control algorithms. Microscopic simulation is more suited to our purposes. In this simulation model, a truck needs to change its route dynamically based on the weigh station status, the weight on the WIM scale, the threshold of the WIM scale, the actual truck weight, and the legal weight limitations.

Most simulation models, such as CORSIM and Integration, cannot implement these features. Fortunately, VISSIM can do so with its built-in Vehicle Actuated Programming (VAP) function. The VISSIM traffic simulation model was developed in Germany by PTV AG and is a stochastic and microscopic traffic simulation model. VISSIM consists of two different programs: 1) the traffic simulator, and 2) signal state generator. The traffic simulator comprises car following logic and lane changing logic. The signal state generator is signal control that receives detector information from the traffic simulator, determines the signal status, and sends the status to the traffic simulator. In VISSIM, the vehicle and driver characteristics are built-in. Users can also introduce their own models of vehicle characteristics and driver characteristics. Geometric layout, traffic demand, and traffic composition can be easily input into the model (Figure 5-2).

5.3.3 Simulation model verification

The simulation model results are compared to theoretical results of the queueing theory to verify the effectiveness of this simulation model. A ramp WIM weigh station layout was selected because it is the most widely used WIM layout. The simulation data used the following parameters:

Figure 5-2 Graph of Weigh Station Simulation by VISSIM

- Service rate: 120 trucks per hour
- Truck weight distribution: 5% overweight truck
- WIM error: 12% under 95% conformity level
- At least 99% caught confidence level
- Storage spaces of an entrance lane: 15
- Storage spaces between an entrance lane and a static scale: 9

Each truck volume scenario was replicated 15 times. Table 5-1, Figures 5-3, 5-4 show the simulation results and the theoretical analysis results using queueing theory.

Table 5-1 Comparisons between Simulation and Theoretical Analysis

Truck Volume trucks / hour	Caught Percentage		Travel Delay in Seconds		Difference	
	Simulation	Theory	Simulation	Theory	Simulation	Theory
50	101.3%	100.0%	16	15	1.3%	8.1%
150	99.5%	100.0%	26	26	0.5%	1.3%
250	98.2%	98.4%	79	73	0.2%	8.5%
350	78.7%	81.2%	144	153	3.1%	5.9%
450	63.8%	63.6%	157	179	0.3%	12.4%
550	50.8%	52.1%	162	188	2.5%	13.6%
650	42.4%	44.1%	161	191	3.9%	15.6%

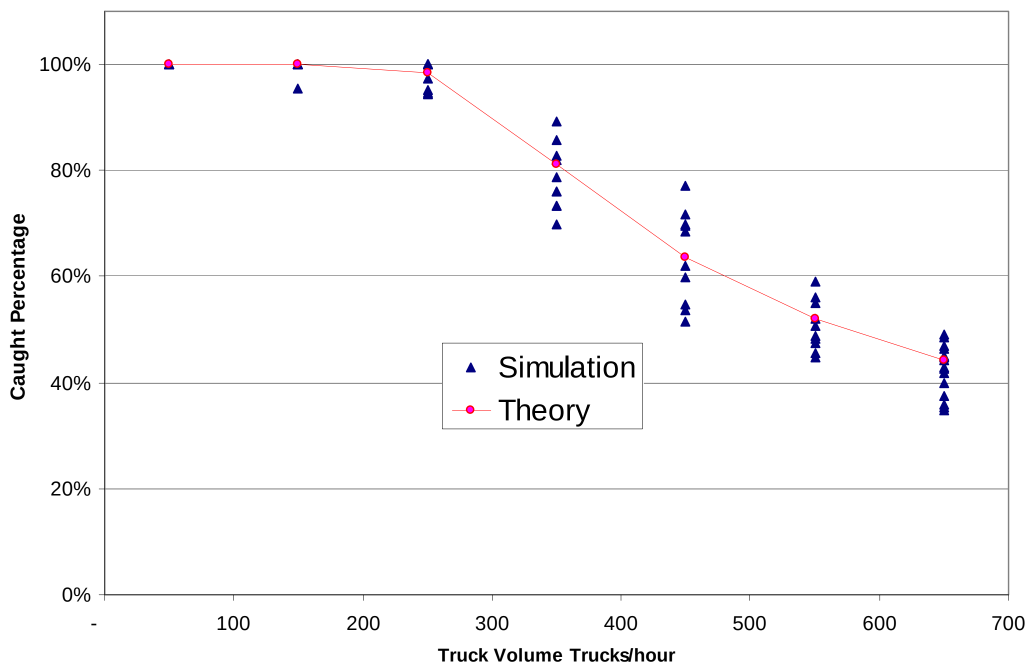

Figure 5-3 Caught Percentage between Simulation and Theory

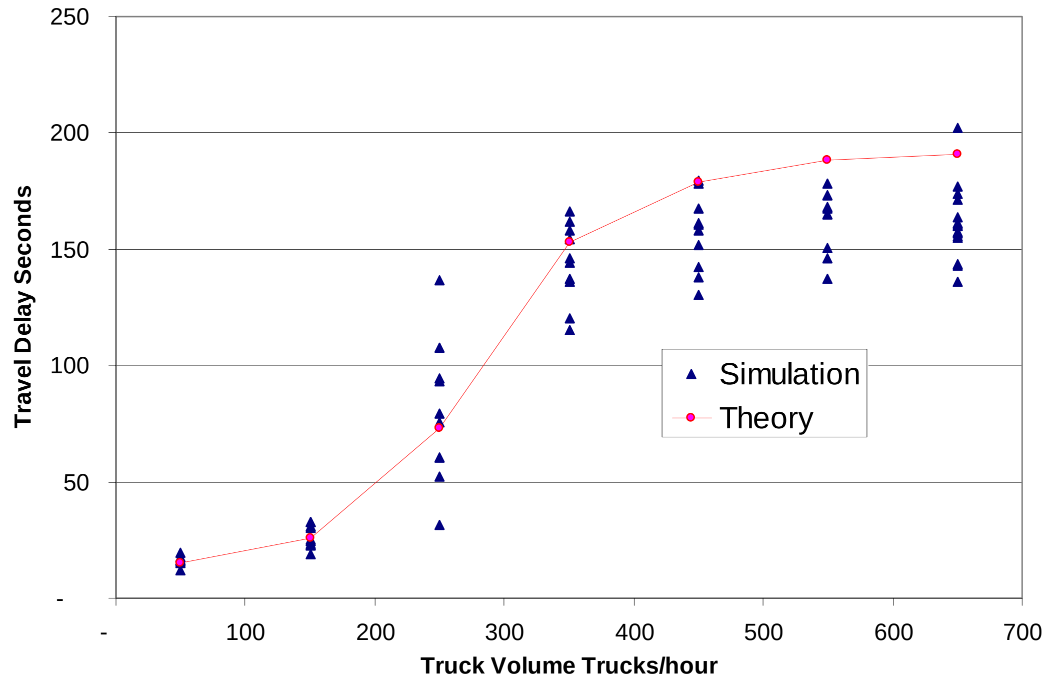

Figure 5-4 Travel Delay between Simulation and Theory

The percentage differences between the simulation model results and the theoretical results for caught percentage are less than 4%, which shows that the simulation models are very good for these cases. The percentage differences between the simulation model results and the theoretical results for travel delay are less than 15.6%. In a simulation environment, travel time includes not only the waiting time and service time, but also vehicle running time. Statistical tests also proved that at 95% confidence level the theoretical results are acceptable as the mean of the simulated results. The simulation model can be used for evaluating a weigh station operation based on the above analysis.

5.4 Threshold control algorithms

A fixed-threshold algorithm and two floating-threshold algorithms will be evaluated on the basis of their traffic responsiveness. The performances of these two algorithms have been analyzed earlier. Whereas the fixed-threshold algorithm primarily considers weight limit and WIM accuracy, floating-threshold algorithms also try to take into account truck volume, truck weight distribution, and static service time. Both algorithms use real time traffic data as input as these are easy to obtain. At the same time, two kinds of floating algorithms: the linear model and the logarithmic model will be introduced.

5.4.1 Fixed-threshold algorithm

As stated in chapter 4, for the fixed-threshold algorithm, the sorting threshold (W_{TH}) depends on the legal weight limit (W_{LT}) and WIM accuracy.

$$W_{TH} = W_{LT} - \frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi} \qquad \textbf{Equation 5-12}$$

where

α: the error of a WIM scale, stated as percentage of a static weight,

β: the confidence level of a WIM scale, and

φ: the confidence level of catching a truck just over the legal weight limit.

5.4.2 Linear model

In this algorithm, the sorting threshold changes linearly with the number of trucks waiting for service before the static scale.

$$W_{TH} = \begin{cases} W_{TH\min} + \Delta W_{TH} \times L & \mathrm{L} \le \mathrm{C} \\ W_{TH\max} & \mathrm{L} > \mathrm{C} \end{cases} \qquad \textbf{Equation 5-13}$$

where

W_{TH} : the actual, or new, weight threshold value of the WIM sorter

$W_{TH\min}$: the minimum weight threshold value of the WIM sorter

$W_{TH\max}$: the maximum weight threshold value of the WIM sorter

ΔW_{TH} : the weight threshold incremental value per additional truck in queue

C: the storage capacity between a static scale and a WIM scale, and

L: the number of trucks waiting in queue.

5.4.3 Logarithmic model

For this algorithm, the sorting threshold logarithmically changes with the number of trucks waiting for service before the static scale.

$$W_{TH} = \begin{cases} W_{TH\min} + \Delta W_{TH} \times \log(L) & \text{L} \le \text{C} \\ W_{TH\max} & \text{L} > \text{C} \end{cases}$$ **Equation 5-14**

where

W_{TH} : the actual, or new, weight threshold value of the WIM sorter

$W_{TH\min}$: the minimum weight threshold value of the WIM sorter

$W_{TH\max}$: the maximum weight threshold value of the WIM sorter

ΔW_{TH} : the weight threshold incremental value per additional truck in queue

C: the storage capacity between a static scale and a WIM scale, and

L: the number of trucks waiting in queue.

The relationships between the three algorithms are shown as Figure 5-5.

5.5 Calibration of input parameters

It is necessary to calibrate the input parameters for each control algorithm. Based on the analysis in Chapter 3, for a fixed-threshold algorithm, the control input parameters are calibrated as shown in Equation 5-15. Since the main task of a weigh station is to catch overweight trucks, the caught percentage should be the most important measurement in determining the value of the sorting threshold. For a floating-threshold value, the sorting

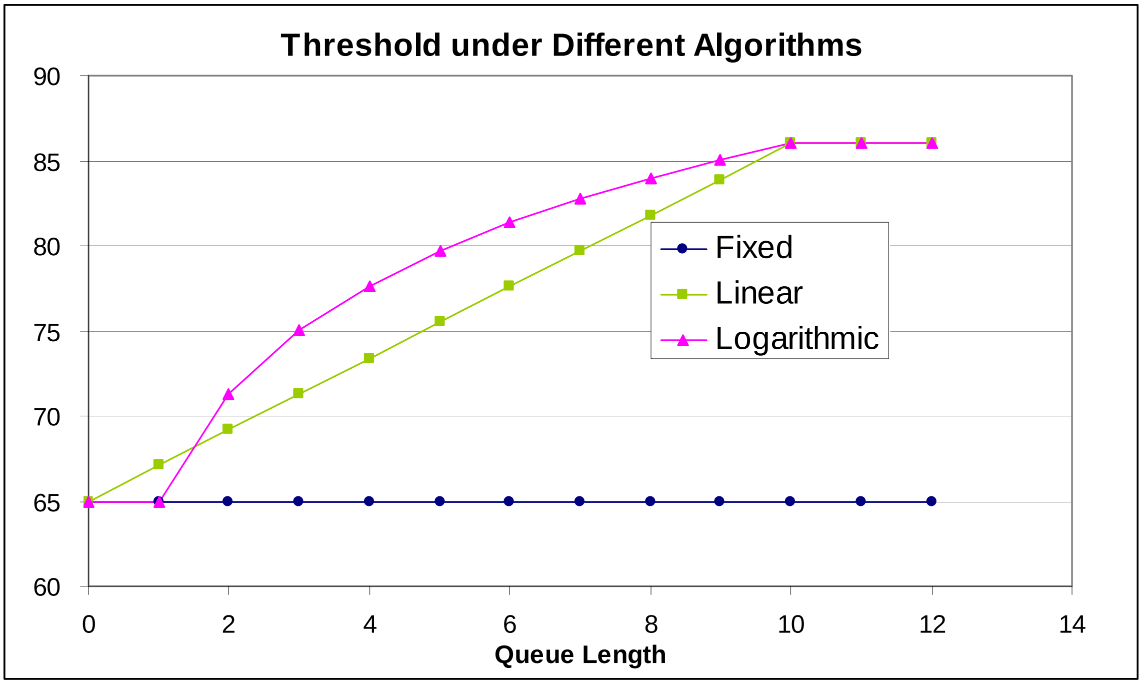

Figure 5-5 Threshold under Different Algorithms

threshold determines the caught percentage of overweight trucks. Higher the value of the sorting threshold used, lower is the probability of catching an overweight truck. The sorting threshold range should be decided by two principles:

- The minimum value should be set such that at 99%, a truck whose weight is just over legal weight limit will be caught.
- The maximum value should be set at 20% to catch a truck whose weight is just over the legal weight limit.
- If the WIM error is normally distributed, the minimum sorting threshold ($W_{TH\min}$) is the same as the fixed-threshold value

$$W_{TH\,\min} = W_{LT} - \frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi_{\max}}$$ **Equation 5-15**

where

$\varphi_{\max}$: the highest confidence level of catching a truck whose weight is just over the legal weight limit.

The maximum sorting threshold ($W_{TH\,\max}$) is

$$W_{TH\,\max} = W_{LT} - \frac{W_{LT} \times \alpha}{z_{\frac{1-\beta}{2}}} \times z_{1-\varphi_{\min}}$$

where

$\varphi_{\min}$: the lowest confidence level of catching a truck whose weight is just over the legal weight limit

After the minimum and maximum of the sorting threshold have been set, it is very easy to get the two parameters of linear and logarithmic algorithms.

Since truck arrival rate, service capacity, and truck weight distribution vary with time of day and regionally as well, and this strategy can automatically adapt to these varying parameters, this strategy has great advantages.

5.6 Experimental design

5.6.1 Experimental inputs

Running a VISSIM weigh station simulation required several inputs. The input variables used include (Table 5-2):

a) Running time length. The simulation should run for a constant arrival rate for 3 hours and 10 minutes. The first 10 minutes were for warming up. The MOEs data were collected in the remaining 3 hours.

b) Weigh station layout: the layout in this simulation was modeled on the Watt Road Weigh Station, which is located on I-40, Knoxville, TN. This weigh station includes a mainline WIM scale, a static scale, a bypass lane, and an entrance lane. It is also easy to model a geometric layout in VISSIM.

c) Truck demand: although VISSIM can incorporate any class of vehicles and load spectra, only Class 9 vehicles were modeled in this simulation. Moreover, six levels of truck demand were considered here: 150, 300, 450, 600, 750, and 900 trucks per hour.

d) Weight distribution: the gross vehicle weight data for Class 9 vehicles used in this study were taken from 2003 FHWA CA rural interstate weight data. The overweight rates for the weight distribution were 1%, 5%, 10%, and 20%.

e) WIM error: three tolerance levels of WIM error based on 95% probability of conformity were selected here: 6%, 12%, and 24%.

Table 5-2 Experimental Factors

No	Name	Level	Description
1	Truck demand	6	1. 150 trucks per hour, 2. 300 trucks per hour, 3. 450 trucks per hour, 4. 600 trucks per hour, 5. 750 trucks per hour, and 6. 900 trucks per hour.
2	Weight distribution	4	Overweight rate: 1. 1%, 2. 5%, 3. 10%, and 4. 20%.
3	WIM error	3	1. 6%, 2. 12%, and 3. 24%.
4	Static service time distribution	2	• Exponential distribution: • Mean: 1. Legal weight trucks:30 seconds; Overweight truck: 60 seconds 2. Legal weight trucks:15 seconds Overweight truck: 30 seconds
5	Threshold control algorithms	3	1. Fixed 2. Linear 3. Logarithmic

f) Static scale service time: the field study shows that static service times for legal weight trucks and overweight trucks are different. This simulation proposed two levels of average static scale service time: legal weight trucks at 30 seconds and overweight truck at 60 seconds; and legal weight trucks at 15 seconds and overweight truck at 30 seconds. Static scale service times were assumed to be exponentially distributed.

g) Legal weight limits: the federal legal weight limit (80 kips) was used as the maximum legal weight limit for gross vehicle weight.

h) Threshold control strategies: three threshold control strategies were considered for experimental design: one fixed-threshold strategy and two floating-threshold strategies.

A full factorial design was adopted for this research. Compared to other factorial designs, full factorial designs have the following advantages: 1) orthogonality, 2) elimination of aliasing concerns, and 3) ability to investigate all main factors and all interactions. The obvious disadvantage is the cost, time, and resources required to make all the runs required by a full factorial design, particularly when the numbers and levels of factors are large (Schmidt and Launsby, 1997). Due to the interactions among these factors and the low cost and time in using a simulation, full factorial designs were used here.

For all the experimental factors and their levels discussed earlier, the number of scenarios for a full factorial design for each control algorithm should equal (6 levels of truck demand) × (4 levels of weight distribution) × (3 levels of WIM error) × (2 levels of static service time) = 144. Thus, the total scenarios for this experiment should be (3 control algorithms) × 144 = 432. Ten replications of each scenario have been made randomly to produce results with error percentages within acceptable limits. For this study, a total 4,320 replications were made.

5.7 Simulation results analysis

5.7.1 Effect of truck demand

First, the performances of these three algorithms under different truck demands were compared. Linear floating algorithm was ideal for implementation in this situation. It can be observed from Figures 5-6, 5-7, 5-8, and from among these three algorithms that the linear floating-threshold algorithm performed best, the logarithmic floating-threshold algorithms were second, and the fixed floating-threshold algorithm was placed third in terms of performance. Higher the truck demand, the better the floating algorithms performed over the fixed algorithm. When truck demand equaled 150 trucks per hour, caught percentage and close percentage for these three algorithms were nearly equal. When truck demand was 200 trucks per hour, the linear floating algorithm improved caught percentage by 11.1% and logarithmic floating algorithm improved caught percentage by 9.4%. Closure percentage was very low (less than 1.5%) when truck demand was not more than 750 trucks per hour, for linear floating algorithm. The two floating-threshold algorithms also greatly reduced travel delay for each truck demand level. Travel delay also appears steady for each floating algorithm under different truck demand levels. Average travel delay ranged from 44 seconds to 47 seconds for linear algorithm and from 61 seconds to 85 seconds for the logarithmic algorithm and increased quickly with an increase in truck demand.

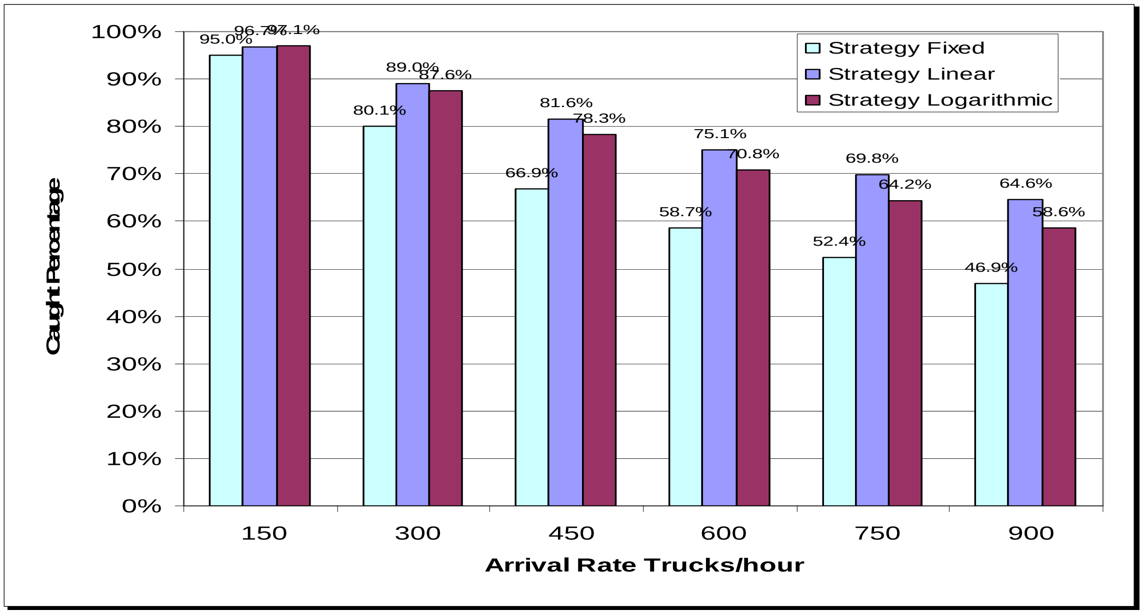

Figure 5-6 Caught Percentage under Truck Demand

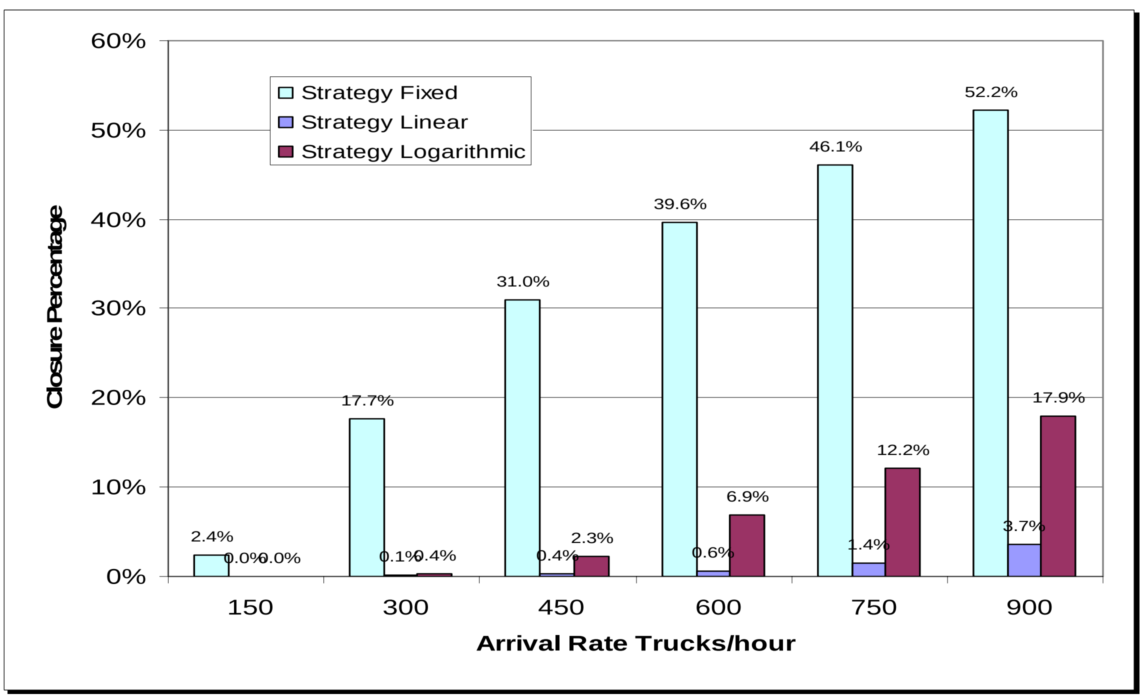

Figure 5-7 Closure Percentage under Truck Demand

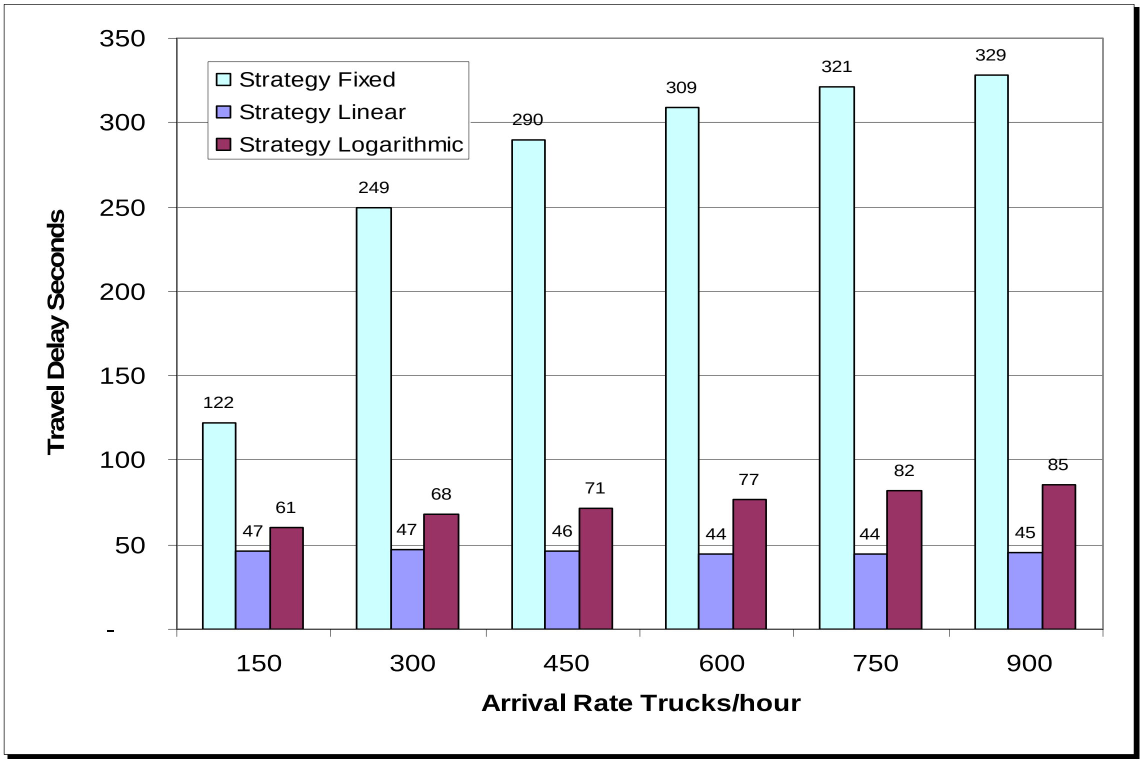

Figure 5-8 Travel Delay under Truck Demand

5.7.2 Effect of WIM accuracy

Now the performance of these three algorithms under different WIM error levels can be compared. In this situation, the linear floating algorithm was also ideal for implementation. Since, the threshold values were selected based on the accuracy of WIM scales, the differences of effectiveness between different levels of WIM error were not too large. Figures 5-9, 5-10, and 5-11 showed that the linear floating-threshold algorithm performed best, the logarithmic floating-threshold algorithms were the second best, and the fixed floating-threshold algorithm was third in terms of performance. Both the floating-threshold algorithms increased caught percentage and greatly reduced weigh

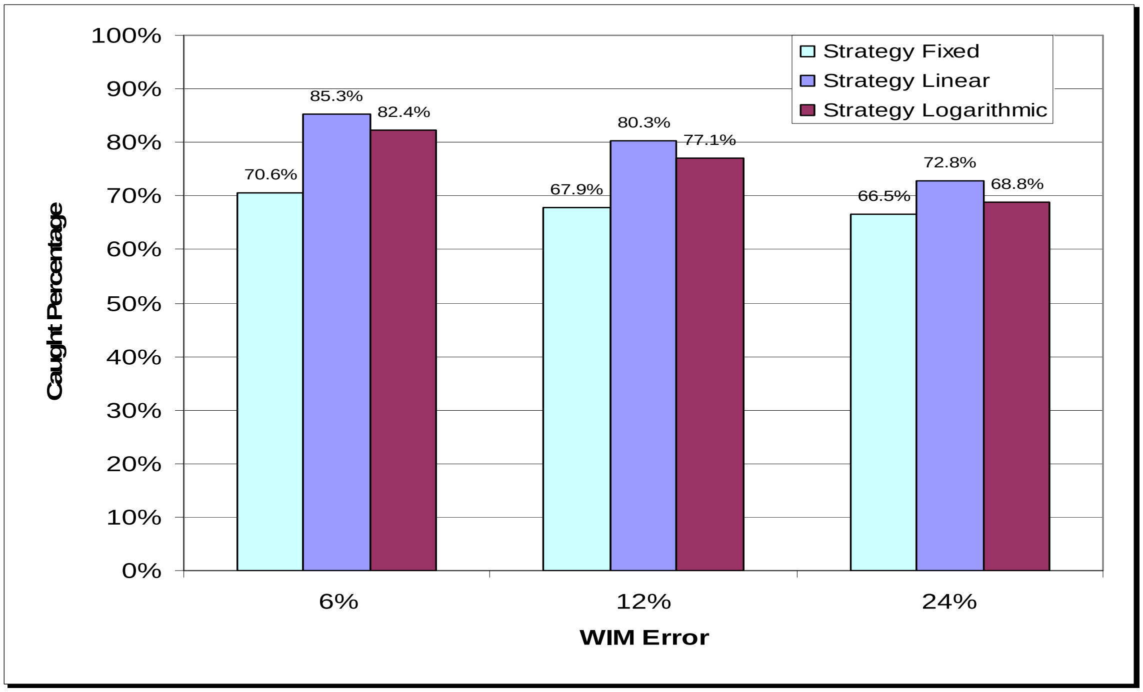

Figure 5-9 Caught Percentage under WIM Error

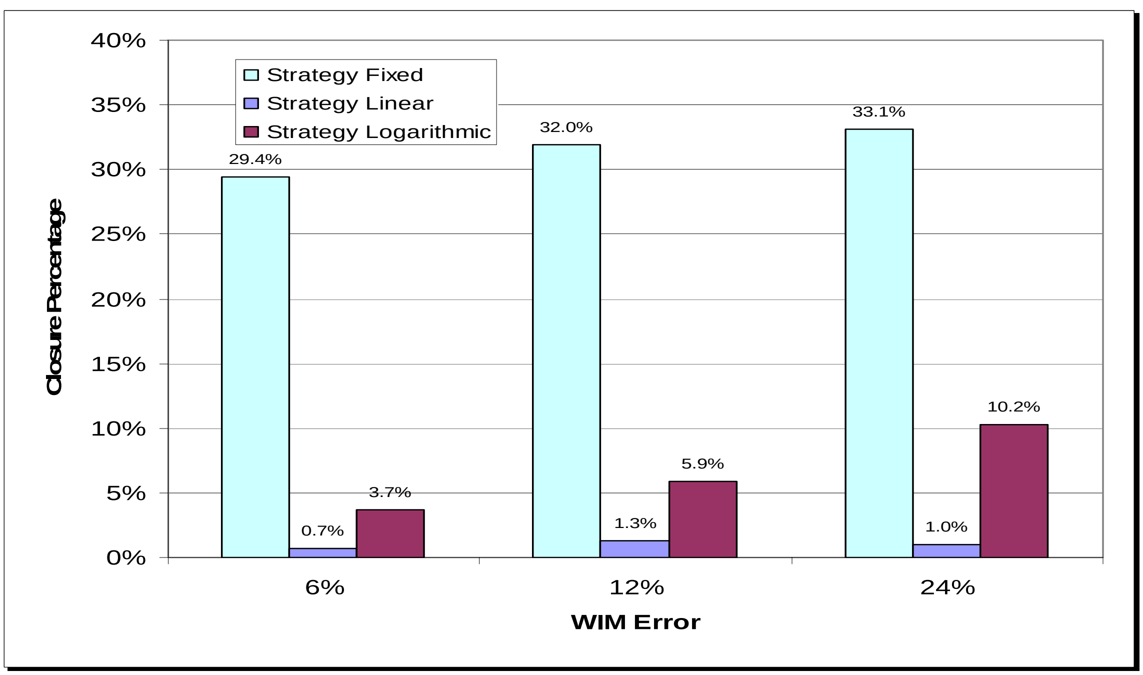

Figure 5-10 Closure Percentage under WIM Error

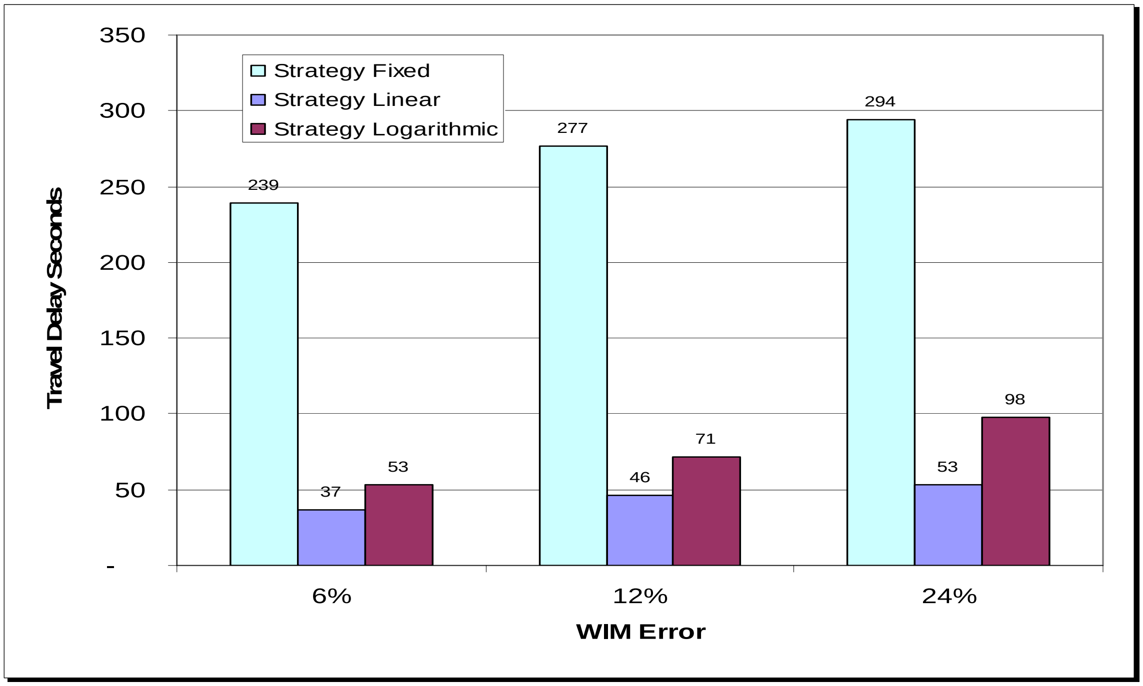

Figure 5-11 Travel Delay under WIM Error

station closure and average travel delay. The rate of improvement was reduced when WIM error increased. For example, compared to a fixed-threshold algorithm, a linear floating algorithm raised caught percentage by 30% when WIM error equaled 6% and 9.5% when WIM error was 24%. Furthermore, the performance for all three algorithms changed only slightly with the increase in WIM error, which means that the threshold algorithms, which take WIM error into account, are suitable for different WIM levels.

5.7.3 Effect of truck weight distribution

The performances of these three algorithms for different weight distribution levels are very similar to those for different truck demand levels. The linear floating algorithm was ideal for implementation in this situation as well. Among these three algorithms, the linear floating-threshold algorithm performed best, the logarithmic floating-threshold algorithms second, and the fixed floating-threshold algorithm was third in terms of performance. Higher the overweight rate, better the floating algorithms performed over the fixed algorithm. When the overweight rate was 1%, caught percentage, closure percentage, and travel delay for these three algorithms were nearly equal. Closure percentage and travel delay seemed steady for each floating algorithm for a low overweight rate, particularly for linear floating algorithm (Figures 5-12, 5-13, and 5-14).

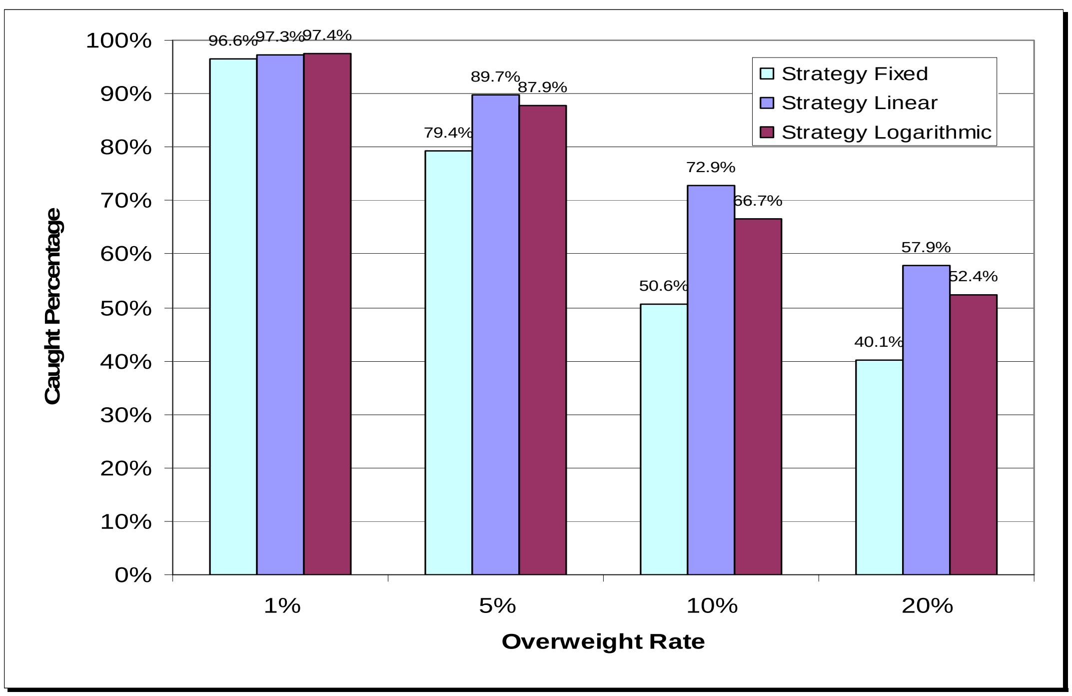

Figure 5-12 Caught Percentage under Weight Distribution

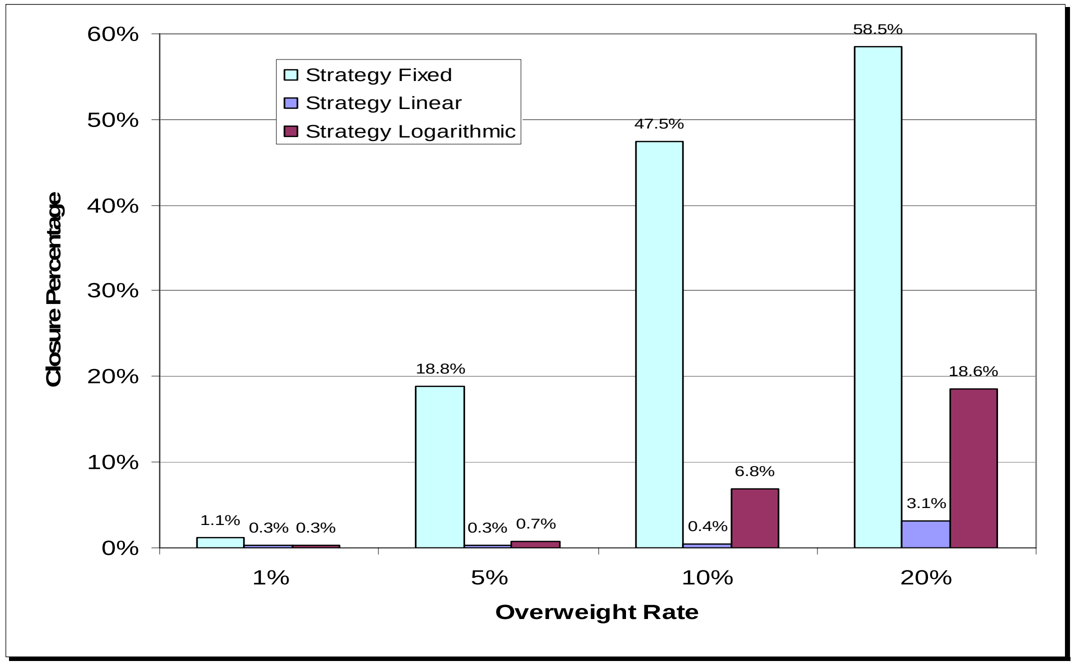

Figure 5-13 Closure Percentage under Weight Distribution

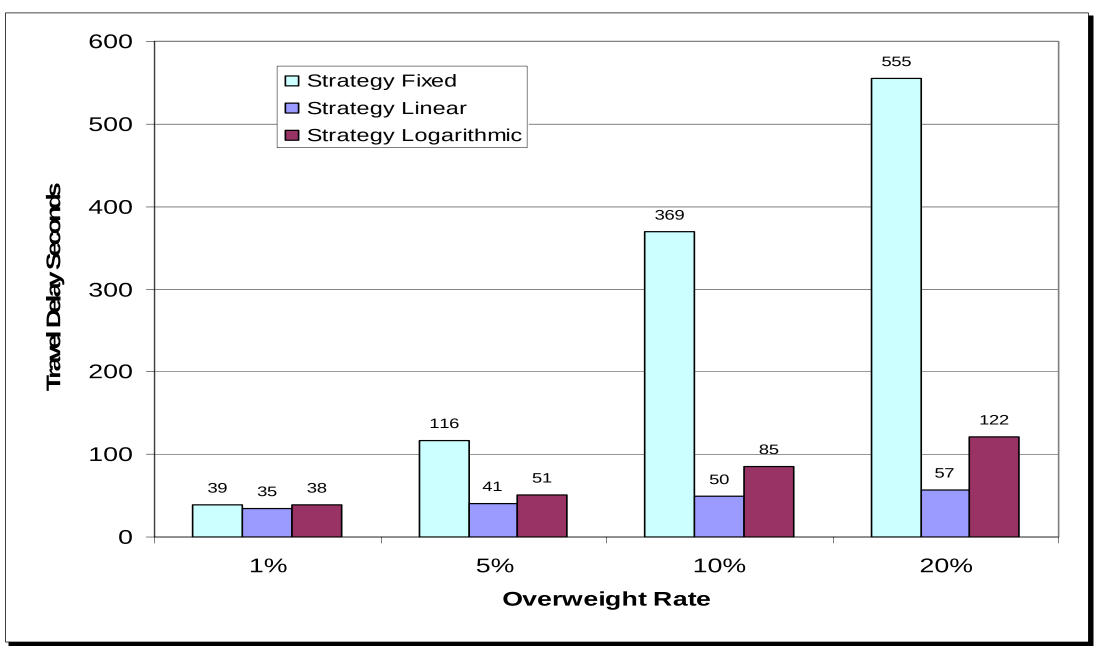

Figure 5-14 Travel Delay under Weight Distribution

5.7.4 Effect of static scale service time

Finally, the performances of these three algorithms under different static service times were analyzed. The linear floating algorithm was ideal for implementation in this situation also (Figures 5-15, 5-16, 5-17). Compared to the fixed-threshold algorithm, the linear floating algorithm increased the caught percentage (10.7%), reduced the closure percentage (98%), and decreased travel delay (77.0%) when average static service time (Level 1) was 15 s for legal trucks and 30 s for overweight trucks. If the service time was longer, greater improvements could be achieved.

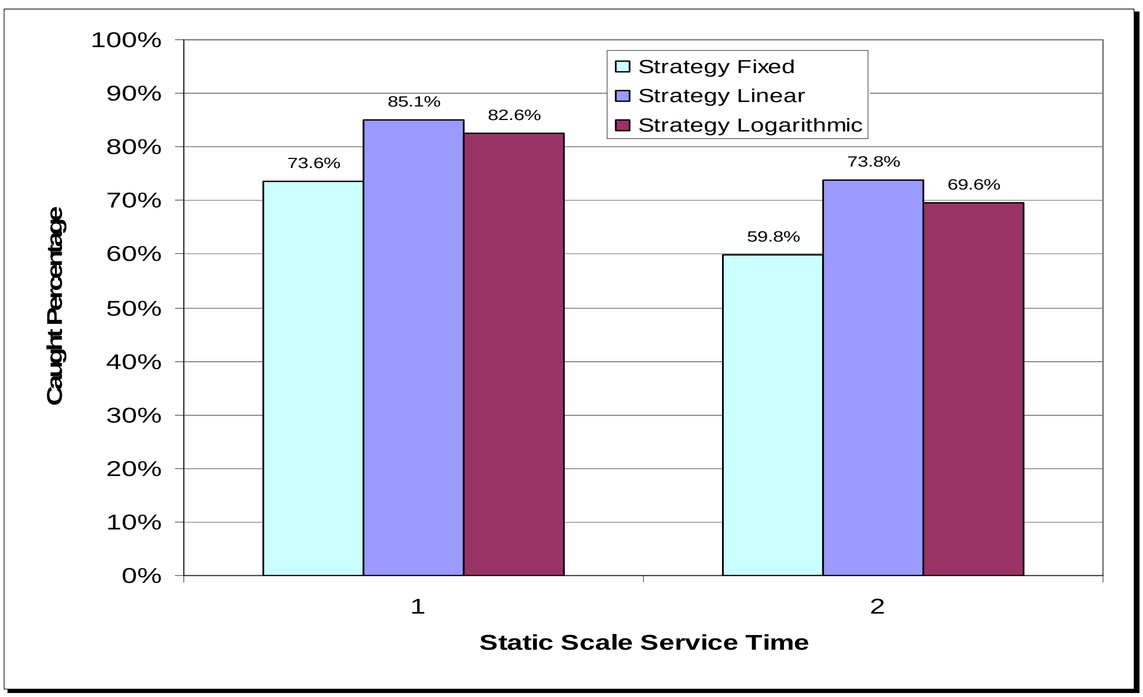

Figure 5-15 Caught Percentage under Service Time

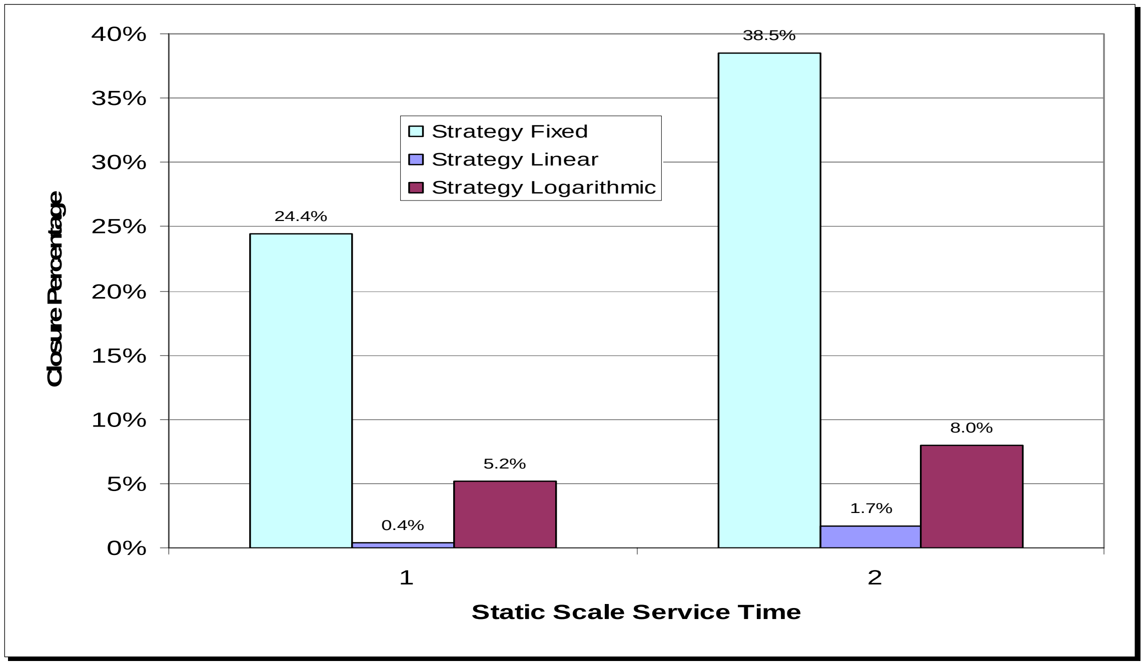

Figure 5-16 Closure Percentage under Service Time

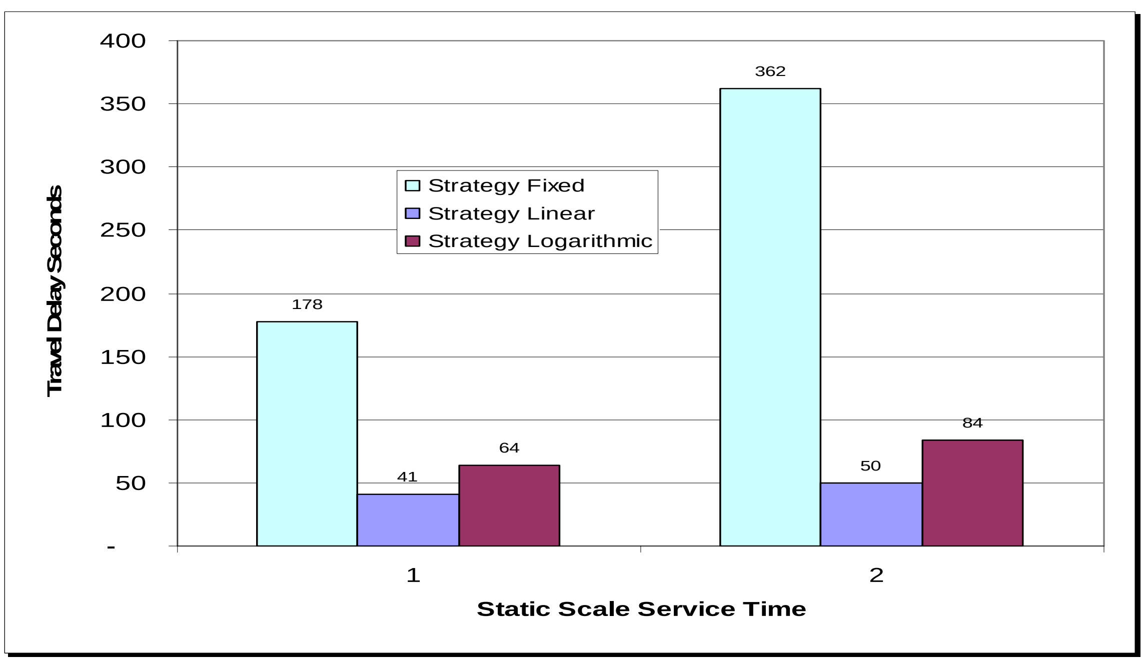

Figure 5-17 Travel Delay Percentage under Service Time

5.8 Statistical analysis of control strategies

While the above analysis implicitly demonstrates the effect of experimental factors on algorithm performance, an analysis of variances (ANOVA) analysis of the results statistically explains the impacts of different algorithms.

5.8.1 Caught percentage

The difference in caught percentage among these three algorithms can be analyzed in relation to the AVOVA table (Table 5-3), which partitions all the variations of a sample into components. The ratio of the mean square components forms an *F*-ratio that evaluates the effectiveness of the model fit. The observed significance probabilities (<0.001) show that the average caught percentages among these three algorithms were not equal. The Means for One-way table (Table 5-4) and The Means Comparisons table (Table 5-5) further show that average caught percentage for the linear algorithm was the highest; the average caught percentage for logarithmic algorithm was second; and the average caught percentage for fixed algorithm was the lowest. This implied that more number of overweight trucks is likely to be caught using the linear algorithm.

Table 5-3 Analysis of Variance for Caught Percentage

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob. > F
Strategy	2	12.66873	6.33436	86.6911	<.0001
Error	4317	315.43538	0.07307		
C. Total	4319	328.10410			

Table 5-4 Average Caught Percentage

Level	Number	Mean	Std. Error	Lower 95%	Upper 95%
Fixed	1440	0.666684	0.00712	0.65272	0.68065
Linear	1440	0.794658	0.00712	0.78069	0.80862
Logarithmic	1440	0.760895	0.00712	0.74693	0.77486

Std. Error uses a pooled estimate of error variance

Table 5-5 Average Caught Percentage Comparisons

Level	- Level	Difference	Lower CL	Upper CL	p-Value
Linear	Fixed	0.1279744	0.1082244	0.1477245	2.507e – 36
Logarithmic	Fixed	0.0942113	0.0744613	0.1139614	1.345e – 20
Linear	Logarithmic	0.0337631	0.0140131	0.0535132	0.0008105

5.8.2 Closure percentage

Again, for analyzing the closure percentage of these three algorithms, the ANOVA table (Table 5-6) partitions all the variations of a sample into components. The ratio of the mean square components forms an *F*-ratio that evaluates the effectiveness of the model fit. The observed significance probabilities (<0.001) show that the average closure percentage among these three algorithms is not equal. The Means for One-way ANOVA table (Table 5-7) and The Means Comparisons table (Table 5-8) further shows that average closure percentage for the fixed algorithm is the highest, the average closure percentage for logarithmic algorithm is second, and the average closure percentage for linear algorithm is the lowest. This implies that more number of overweight trucks could bypass a weight station without inspection, on using the fixed algorithm.

Table 5-6 Analysis of Variance for Closure Percentage

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob. > F
Strategy	2	75.74271	37.8714	922.5293	0.0000
Error	4317	177.21998	0.0411		
Total	4319	252.96269			

Table 5-7 Average Closure Percentage

Level	Number	Mean	Std. Error	Lower 95%	Upper 95%
Fixed	1440	0.314884	0.00534	0.3044	0.32535
Linear	1440	0.010232	0.00534	-0.0002	0.02070
Logarithmic	1440	0.066177	0.00534	0.0557	0.07664

Table 5-8 Average Closure Percentage Comparisons

Level	- Level	Difference	Lower CL	Upper CL	p-Value
Fixed	Linear	0.3046516	0.2898479	0.3194553	2.67e – 302
Fixed	Logarithmic	0.2487063	0.2339027	0.2635100	1.89e – 212
Logarithmic	Linear	0.0559453	0.0411416	0.0707489	1.522e – 13

5.8.3 Travel delay

Finally, the closure percentage of these three algorithms (Table 5-9) was analyzed. The ratio of the mean square components forms an *F*-ratio that evaluates the effectiveness of the model fit. The observed significance probabilities (0.000) show that the average travel delay among these three algorithms is not equal. The Means for One-way ANOVA table (Table 5-10) and The Means Comparisons table (Table 5-11) further shows that average travel delay for the fixed algorithm was the highest, average travel delay for the logarithmic floating algorithm was second, and average travel delay for the linear algorithm was the lowest. This implies that the fixed algorithm causes legal trucks to spend more time in going through a weigh station.

Table 5-9 Analysis of Variance for Travel Delay

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob. > F
Strategy	2	42977955	21488978	933.6978	0.0000
Error	4317	99355397	23014.917		
C. Total	4319	142333352			

Table 5-10 Average Travel Delay

Level	Number	Mean	Std. Error	Lower 95%	Upper 95%
Fixed	1440	269.968	3.9978	262.13	277.81
Linear	1440	45.563	3.9978	37.73	53.40
Logarithmic	1440	74.096	3.9978	66.26	81.93

Table 5-11 Average Travel Delay Comparisons

Level	- Level	Difference	Lower CL	Upper CL	p-Value
Fixed	Linear	224.4049	213.3206	235.4892	5.46e – 294
Fixed	Logarithmic	195.8716	184.7873	206.9559	2.82e – 232
Logarithmic	Linear	28.5333	17.4490	39.6176	4.6781e – 7

5.9 Summary

The above analysis makes it clear that floating-threshold algorithms can provide the means to operate a WIM weigh station more effectively and efficiently than the fixed-threshold algorithm. Two types of floating-threshold algorithms were introduced in this chapter to adapt to the variations and changes among truck demand, truck weight distribution, static scale service time, and WIM error. In most cases, the floating-threshold algorithms resulted in a more effective performance than the fixed-threshold algorithm. The figures show the results that were arrived at intuitively and these results have been statistically confirmed. The floating-threshold algorithms not only increase a weigh station's capacity to catch overweight trucks, but also significantly decrease travel delay for truck drivers. Floating algorithms also can automatically adapt to the variations and changes in the characteristics of weigh station systems. At a WIM weigh station using a floating-threshold algorithm, weigh station overflow can be sharply decreased, which means that this algorithm can keep a weigh station operating without interruption. Actually, the results reveal that weigh station overflow seldom occurred when a linear floating-threshold algorithm was applied.

Additionally, different floating-threshold algorithms performed differently. In the above cases, the linear floating algorithm was slightly better than the logarithmic floating algorithm, suggesting that it is necessary to find an effective and efficient floating-threshold algorithm that is suitable for different scenarios.

6 Conclusions and Directions for Future Research

This chapter will present a summary of this study, draw a number of conclusions that are based on the outcome of this research, and discuss some directions for future research.

6.1 Conclusions

This research evaluated weigh station design strategies and the effect of several operational parameters using queueing theory. Floating-threshold algorithms were developed to adapt to the varying in traffic demand, weight distribution, WIM error, and static service time. Conclusions from this study can be summarized as follows:

1. WIM technology can greatly improve the efficiency and effectiveness of weigh station operation. WIM technology can not only greatly decrease truck travel delay and reduce weigh station overflow but also can increase the possibility of catching overweight trucks. Since, it can enhance weight enforcement and reduce truck traveling times spent at a weigh station, WIM technology benefits both weigh station operators and trucking companies.
2. Weight distribution, truck arrival demand, static scale service rate, and WIM accuracy are the most important parameters for a weigh station system. These four factors determine the sorting threshold value, weight station operation performance, and even the layout of a weigh station.

3. The percentage of trucks equipped with transponders has a major impact on the effectiveness of the operations of a mainline WIM weigh station. Currently, because of the low percentage of trucks equipped with transponders, a ramp WIM weigh station is probably a better alternative to increase the productivity of a weigh station compared to a WIM mainline weigh station.
4. Storage spaces in a weigh station system do not significantly affect the effect of catching overweight trucks while causing long travel delay when traffic density is heavy. Designers should consider other requirements, such as decelerations and topology to determine the length of storage spaces.
5. Selecting a sorting threshold based on WIM accuracy and legal weight limits is effective and feasible. A low threshold will increase travel delay for legal weight trucks and raise the risk that overweight trucks will bypass a weigh station because of overflow. On the other hand, because of the error of the WIM scale, a high threshold reduces travel delay of trucks drivers, but it may allow overweight trucks go though a weigh station without being identified. The fixed-threshold algorithm based on legal weight limit and WIM accuracy is very effective, simple, and easy to implement.
6. Floating-threshold algorithms are good choice for WIM weigh station operations. A fixed weight threshold lacks flexibility to respond to the varying truck demand and weight. When truck traffic is heavy, a low

fixed-threshold may direct too many legal weight trucks to the static scale and cause unnecessarily queueing and delay. Conversely, a high fixed-threshold may allow too many weight offenders to slip through the cracks. In light of these findings, this research presents floating-threshold adjusting algorithms to address these issues. The research results show that the floating-threshold strategy is a better and smarter approach to improving the efficiency and effectiveness of weigh station operations. This strategy can be applied to both low and high truck demand, light and heavy truck weight, low and high WIM accuracy, and slow and quick static scale service speed. The implementation of such a strategy does not require costly capital hardware investment or a lengthy construction and installation. The resultant savings in time and money should not be overlooked.

6.2 Recommendations for future research

This study points toward many possible areas for future improvements to data models and procedures developed in this study. Further study regarding the vehicle gross weight, axle weight, tandem axle weight, and vehicle size is required. This research framework offers a general structure to study weigh station systems using gross vehicle weight. This framework, however, may be a little coarse for weigh station systems. Current federal TS&W regulations require a permanent weigh station to check axle weight, tandem weight, and size of a truck as well. At the same time, a weigh station also randomly selects some trucks to pull in for a check. Additionally, truck weight distribution is a little complex. Two truck weight distributions with the same overweight rate can lead to different effects. The overweight rate is not only decided by average truck weight but also by weight variance. These inspections and activities do affect the performance of our algorithms but should not alter our conclusions.

Further development of floating-threshold algorithms is necessary. It has been proved that floating-threshold algorithms can improve weigh station operational efficiency and effectiveness. This study also found that different floating-threshold algorithms have different performances on weigh station operations. This study did not conduct further research on the suitability of algorithms for a specific scenario. Since the parameters of each floating algorithm should also affect the results, further study in these two fields is required.

Cost-effective analysis is also necessary. Although our floating-threshold algorithms do not require a large capital investment, some detectors will have to be set up along a static scale lane and the current WIM control algorithm will require minor revision. A cost-effective analysis should help to show the value of floating-threshold algorithms.

It must be pointed out that there are several methods to enforce federal TS&W regulations and keep overweight trucks from highway systems. Overweight-truck drivers often attempt to avoid a permanent weigh station using a bypass route or by traveling through a permanent weigh station when it is closed. Proper site selection and extended operation time have proved very effective to reduce the incidences of overweight trucks.

The location of a weigh station is controlled not only by construction costs, topography, highway alignment, and geometrics, but also by effectiveness of weight enforcement.

Recently, Green et al. (2002) developed a virtual weigh station system by using INDOT existing WIM equipment, laptop computers, and wireless communication equipment to improve the official's ability to recognize an overweight truck.

Pre-clearance systems also have widely applied and incorporated WIM technologies into Commercial Vehicle Information Systems and Networks (CVISN) with Automatic Vehicle Identification (AVI) technologies (Oursler and Severson, 2001). With the integration of AVI and WIM technologies, weight and size information of a truck are electronically identified at normal traffic speed. Those trucks that pass all the checks need not to be pulled into a weigh station. Weigh station personnel can focus on trucks that cannot be identified or cannot pass all the checks. This method will significantly reduce the number of trucks to be checked. Currently, three major CVISN pre-clearance weigh station systems—Prepass, Norpass, and Oregon Green Light—have been operated in North America. The achievements of this technology have been proved by experience.

Most importantly, none of these alternatives can totally replace the other ones. The above approaches are complimentary. A comprehensive program can improve the effectiveness of weight enforcement.

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APPENDIXES

APPENDIX A Kendall's Shorthand Notion

Kendall's shorthand notion A/B/C/X/Y is now widely used to describe queueing models (Copper, 1981). In this notation, A is shorthand for the distribution of the arrival process, B for the service pattern as described by the probability distribution for the service time, C indicates the number of parallel servers in the system, X indicates the restriction on system capacity, and Y indicates the queue discipline. Some standard symbols for these characteristics are presented in Table B-1. For example, M/G/1/7/FCFS indicates a queueing process with exponential inter-arrival times, general distribution service times, just one server in the system, at most seven are allowed in the system, and first-come, first-service queue discipline. In many situations, only the first three symbols are used. Current practice is to omit the service capacity symbol if no restriction is imposed and to omit the queue discipline if it is first come, first served. Since, the queue discipline of a weigh station always is FCFS, the last one is omitted and the first four symbols are used in the description of a weigh station system.

Table A-1 Queueing Notation A/B/C/X/Y

Characteristic	Symbol	Explanation
Interarrival-time Distribution (A) Service-time distribution (B)	M	Exponential
	D	Deterministic
	E_k	Erlang type k (k = 1, 2…)
	H_k	Mixture of k exponentials
	PH	Phase type
	G	General
Number of parallel servers(C)	1, 2…, ∞	
Restriction on system capacity (X)	1, 2…, ∞	
Queue discipline (Y)	FCFS	First come, first served
	LCFS	Last come, first served
	RSS	Random selection for service
	PR	Priority
	GD	General discipline

Source: Gross and Harris, *Fundamentals of Queueing Theory, Third Edition*, p8

APPENDIX B Effective Storage Space of a Ramp WIM Weigh Station

Extend simulation was used to test the effective storage space of a ramp WIM weigh station compared with queueing theory with effective storage space.

The data used are the follows:

Part	Percentage	Mean Kips	Standard deviation
Low	45.00%	37.83	11.41
High	55.00%	73.76	6.03

Arrival Rate—trucks per hour	Service rate—trucks per hour	Static Scale Lane	WIM Entrance Lane	WIM Error Rate	Sorting Threshold kips	Percentage Further Checked
300	90	5	9	12%	70.4	36.45%

Effective storage space: $5 + 9 \times 36.45\% + 1 = 9.28 \approx 9$

Simulation test results are as follows:

Test No	Queue Length	Waiting Time in Seconds	Caught Percentage	Bypass Percentage
1	10.08	284.83	66.96%	32.25%
2	10.06	280.98	67.14%	31.19%
3	10.35	295.30	65.40%	33.42%
4	10.13	286.06	66.83%	32.18%
5	10.13	284.94	67.66%	31.43%
6	10.06	283.83	66.50%	31.77%
7	10.44	296.34	66.55%	33.50%
8	10.14	285.04	65.76%	32.86%
9	9.97	281.69	66.37%	31.89%
10	10.04	282.01	68.45%	31.52%

The summary of simulation test:

Item	Queue Length	Waiting Time in Seconds	Caught Percentage	Bypass Percentage
Simulation Average	10.14	286.10	66.76%	32.20%
Standard Deviation	0.15	5.39	0.88%	0.81%
Upper 95 % mean	10.42	296.66	68.49%	33.80%
Lower 95% mean	9.86	275.54	65.04%	30.60%
Queueing Theory	9.98	281.01	67.96%	31.53%

Since, all the four measurements of queuing theory are falling between the upper and lower 95% values, it can be concluded that the effective storage assumption is feasible.

VITA

Zhongren Gu was born in Jiangsu Province, China on October 23rd 1971. He received his bachelor's degree in transportation management engineering from Northern Jiaotong University (now Beijing Jiaotong University) in 1993. He worked as a traffic engineer for a road transportation company from 1993 to 1995. Zhongren returned to Northern Jiaotong University in 1995 and earned his master's degree in transportation management and engineering in 1998. After his graduation, he joined Sintrans, one of the largest forwarding companies in the world and one of the largest Third Party Logistics companies in China. In 2001, Zhongren attended the Department of Civil and Environmental Engineering at University of Tennessee, Knoxville (UTK) in pursuit of a Ph.D. degree in transportation engineering. At UTK, Zhongren's research focused on Intelligent Transportation Systems, traffic simulation, supply chain management, and logistics systems design.

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