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16. Abstract

Truck traffic moving through Laredo and El Paso, Texas, includes a large portion of the total number of heavy vehicles entering Texas from Mexico. These trucks have considerable impact on the transportation infrastructure in Texas and other states, and the additional traffic that will be affected by the pending implementation of provisions of the North American Free Trade Agreement (NAFTA) are of special concern. To obtain quantitative data about the number of such trucks and their axle loads, weigh-in-motion (WIM) devices were installed near the north end of the international bridges that cross the Rio Grande at Laredo (1993) and at El Paso (1994).

Data obtained from these WIM systems through the summer of 1996 are presented in summary form in this report. Analysis of the data has been undertaken to characterize the observed truck traffic volume and composition, axle loads, and equivalent single axle loads (ESALs) for northbound trucks entering the U.S. from Mexico at Laredo and at El Paso. A unique configuration of the two-direction WIM system at El Paso, where southbound trucks sometimes form queues over the WIM-system sensors, made it possible to also sample the characteristics of trucks with American trip origin before they crossed the Zaragosa International Bridge into Mexico. This report describes the performance characteristics of this WIM system, its installation, the calibration procedure, and its subsequent operation.

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HEAVY VEHICLE CHARACTERISTICS AT THE LAREDO AND EL PASO PORTS OF ENTRY

by
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and
Clyde E. Lee

Research Report Number 1319-3

Research Project 0-1319
Multimodal Planning and the U.S.-Mexico Free Trade Agreement

conducted for the
TEXAS DEPARTMENT OF TRANSPORTATION
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1996

IMPLEMENTATION RECOMMENDATIONS

The data obtained from two weigh-in-motion (WIM) devices that were installed as part of this research project near the north end of the international bridges that cross the Rio Grande at the City of Laredo (1993) and at El Paso (1994) provide a unique source of information concerning the characteristics of truck traffic at the Texas-Mexico border. Patterns of observed daily truck volumes, truck types, and axle loads have been defined through the summer of 1996. Equivalent single axle load (ESAL) factors have also been developed for each truck type. These data should be used to help assess the current and future impact of border-crossing traffic on the operation and maintenance of highway infrastructure in Texas. Valuable information concerning overloaded trucks is available and should be used in developing appropriate enforcement programs, especially as they relate to NAFTA-induced traffic. Experience gained in procuring, installing, operating, and maintaining the two WIM systems for this project should be applied to future WIM installations, particularly the use of a CRCP slab to provide a long-term foundation for the WIM sensors.

This report was prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

ACKNOWLEDGMENTS

The Weigh-in-Motion (WIM) activities related to Research Project 0-1319, *Multimodal Planning and the U.S.-Free Trade Agreement,* described in this report have been made possible by the special talents and cooperative work of numerous individuals in the Texas Department of Transportation, especially those in the Laredo and El Paso Districts and in the Transportation Planning & Programming Division in Austin, as well as several in the City of Laredo. Manuel F. Aguilera, P.E., Deputy District Engineer, El Paso District, guided the research as Project Director. Joe Aranda, Director of Transportation, City of Laredo coordinated the arrangements between the City and TxDOT, for this research project, to cooperatively install and operate the WIM system during the project and then turn it over to the City. The City of Laredo had a continuously-reinforced concrete pavement slab constructed to accommodate the WIM sensors and provided electric power and a telephone line to the site. Amador Escudero, P.E., City Engineer in Laredo, provided engineering support to the project, especially through frequent, enthusiastic communication with Gabriel Martinez, P.E. Roberto Murillo, P.E., Traffic Engineer for Laredo, and his staff also assisted with traffic control and system installation. Jose L. Arce, Superintendent of Operations, Laredo Bridge System, shared his many years of experience with truck traffic and provided an on-site contact for operating the WIM system near Bridge No. 1. Andrew Ugarte, General Manager, Laredo Bridge System, supported the concept of collecting truck axle load statistical data, and suggested the site for the system. Luis A. Ramirez, P.E., Laredo District Engineer, TxDOT, provided advisory and technical support throughout the project and gave valuable comments concerning the draft of this report. In El Paso, Charles H. Berry, Jr., P.E., Special Projects Engineer, TxDOT, and his assistant Blanca, working directly with Mr. Aguilera, made myriad detailed arrangements for installing, calibrating, and operating the WIM system at the Zaragosa International Bridge, beginning in the fall of 1993. These ranged from having a surveying crew obtain pavement surface profile measurements to making personal contacts with GSA and U.S. Customs officials to solicit their cooperation. Ruben G. Valenzuela, Traffic Signal Technician, and his staff provided invaluable technical support, as did Martin Holguin in transferring the extensive WIM data files throughout the project. Alvin R. Luedecke, P.E., Director, Transportation Planning & Programming Division, TxDOT, and his staff supported the project by using their expertise, developed through many years of experience, and their special equipment resources to install the WIM systems at Laredo and at El Paso. Dean Barrett, Willard Peavy, and several other members of this expert team contributed to the installation of the specially adapted WIM systems for this research application. Sincere appreciation is expressed to the individuals mentioned here, and to others not mentioned specifically, for helping to making it possible to collect the unique sets of truck load data summarized in this report.

DISCLAIMERS

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

Clyde E. Lee, P.E. (Texas No. 20512)
Research Supervisor

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SUMMARY

Truck traffic moving through Laredo and El Paso, Texas, includes a large portion of the total number of heavy vehicles entering Texas from Mexico. These trucks have considerable impact on the transportation infrastructure in Texas and other states, and the additional traffic that will be affected by the pending implementation of provisions of the North American Free Trade Agreement (NAFTA) are of special concern. To obtain quantitative data about the number of such trucks and their axle loads, weigh-in-motion (WIM) devices were installed near the north end of the international bridges that cross the Rio Grande at Laredo (1993) and at El Paso (1994).

Data obtained from these WIM systems through the summer of 1996 are presented in summary form in this report. Analysis of the data has been undertaken to characterize the observed truck traffic volume and composition, axle loads, and equivalent single axle loads (ESALs) for northbound trucks entering the U.S. from Mexico at Laredo and at El Paso. A unique configuration of the two-direction WIM system at El Paso, where southbound trucks sometimes form queues over the WIM-system sensors, made it possible to also sample the characteristics of trucks with American trip origin before they crossed the Zaragosa International Bridge into Mexico. This report describes the performance characteristics of this WIM system, its installation, the calibration procedure, and its subsequent operation.

CHAPTER 1. WEIGH-IN-MOTION DEPLOYMENT

1.1. FUNCTIONAL ASPECTS OF WIM

Vehicle weigh-in-motion (WIM) is the process of estimating the motionless (static) weight of a vehicle from measurements of the vertical component of dynamic tire force applied to a sensor on a smooth, level road surface. The static weight and the related dynamic tire force differ in several respects. The dynamic force applied by the vehicle tires to the sensors varies with the vertical acceleration of the various connected masses that comprise the vehicle as the tires interact with the road surface. The static weight is simply the force of gravity acting downward on the motionless mass of the vehicle.

When a vehicle moves over a rough surface, such as a bump on the road, vertical forces are applied to the tires. These forces are transferred to the various vehicle masses through the suspension connectors, causing each mass to accelerate vertically against the force of gravity. When the tire is accelerating upward (bouncing off the road) as it crosses the WIM sensor, the measured tire force can be less than the corresponding static mass; it can be greater when the tire force is accelerating downward. This effect is augmented by an increase in speed and also varies with the mass and suspension characteristics of the moving vehicle. Not all vehicles react to road conditions in the same fashion. Other factors that influence the tire force measurements made by weigh-in-motion devices include vehicle tire inflation pressure and contact area, longitudinal acceleration and environmental conditions, and the accuracy with which the WIM device can measure and convert the vertical component of dynamic tire force to a proportional electrical signal.

The American Society for Testing and Materials (ASTM) has adopted a standard specification for highway weigh-in-motion systems, namely, ASTM E1318 (ASTM 1994). This document also contains user requirements and a test method for evaluating various types of WIM systems (see Appendix D).

The weigh-in-motion system used in this research consists of three basic components: force transducers, vehicle-presence sensors, and the signal processing unit (an on-site computer). The force transducers, which are installed flush with the road surface, consist of a pair of bending metal plates (with special physical characteristics) encased in a rubber-like material. The bending plates deform elastically under a tire-load application, generating tensile strain on the bottom surfaces. The deformation by unit of length (strain) is measured by bonded resistance strain gauges located at critical places on the tension area of the plates. The gauges effect an electrical output signal that is proportional to the vertical force applied (the tire load) to the transducer.

The vehicle presence sensor is an induction loop detector, augmented by an infrared light beam sensor for particular application in El Paso. The speed of a vehicle is determined by the time it takes the front axle on the vehicle to move between the staggered (a known distance apart, longitudinally) weigh pads. Speed is also established in this way for every pair of axles on a vehicle. The average speed of the axle pair is then multiplied by the travel time between the leading and the trailing axle to calculate axle spacing. This method of determining axle spacing improves the calculated values of spacing for accelerating or decelerating vehicles (assuming uniform acceleration), as compared with using only the speed of the front axle, as is done in some WIM systems. Most vehicles observed at Laredo and El Paso were accelerating.

1.2. LAREDO WIM SYSTEM

The weigh-in-motion (WIM) system in Laredo was installed by Texas Department of Transportation (TxDOT) personnel in September 1993. Details of the Laredo system layout, performance, and operation up to July 1994 are presented in Center for Transportation Research (CTR) Report 1319-1 (Leidy 1995). Subsequent operation and maintenance are described in this report.

The Laredo system consists of a one-lane WIM system installed in a specially-constructed, continuously reinforced concrete pavement slab. The slab is 61 m (200 ft) long, 4.27 m (14 ft) wide, and 0.3 m (12 in.) thick. This section of the pavement is part of an existing two-way city street aligned along the north shore of the Rio Grande. Special traffic control measures were taken in an attempt to ensure that northbound traffic moved over the WIM system sensor in the desired lane.

1.2.1. Laredo WIM Calibration

On June 28, 1995, a "check up" calibration was performed on the Laredo WIM system to evaluate the continuing reliability of the data being collected.[4] This process resulted in our making only minor adjustments to the system's operational settings. To carry out the calibration, a special five-axle semi-trailer combination test truck (3S2) was provided by TxDOT. The truck, loaded with two concrete blocks, carried 94 percent of its allowable gross vehicle weight. The reference static axle loads were supplied by the TxDOT personnel (who routinely operate this special WIM-calibration vehicle). Calibration is performed by adjusting selected control parameters in the on-site WIM system microcomputer[5] until the gross vehicle weight and axle loads estimated by the WIM system agree with reference values for the test vehicle, within acceptable tolerances. Verification runs are then made to confirm that repetitive values are in reasonable agreement. Appendix A shows the calibration computations for Laredo and El Paso.

The calibration process involved a total of 17 runs; 13 at a speed of 15 mph and four at 25 mph. On the first trials, five runs were made at an attempted speed of 15 mph to establish the existing condition of the system. On average, the measured gross vehicle weight of the truck was 3.23 percent less than the reference static weight. The tractor tandem axle load was 1.5 percent higher and the trailer tandem axle 3.9 percent higher than the respective reference values. The steering axle had the largest difference, as it was 9.9 percent lower than the reference load.

Adjustments were made to the WIM system settings, and five more runs were performed to evaluate the effect of the changes. This process was repeated with two more runs and one final verification run. This last run, at 15 mph, showed differences of -2.5 percent in the gross weight,

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[4] Two other calibrations were performed on the system before this "check up" calibration (Leidy 1995).

[5] Refer to DAW100 Operation Manual from PAT Equipment Corporation for further details.

-4.6 percent in the steering axle load, -3.9 percent in the tractor tandem load, and -0.51 percent in the trailer tandem load from the respective reference static values. The greatest change was observed in the steering and trailer tandem axle loads (when differences are expressed as a percentage). These values were considered to be within an acceptable range for this speed.

The 25 mph system settings were next determined with two runs and adjustments were made. Then, two additional runs were used to assess the effect of the changes. At this speed, the WIM system had a difference of -0.35 percent against the reference static gross weight of the truck. The tractor tandem axle group was 1.5 percent above the reference value; the trailer tandem load was -0.82 percent. The steering axle differed from the reference value by -6.42 percent. The WIM system software interpolates between the two speed setting values and uses the measured speed of each vehicle to determine an appropriate factor for use in estimating static weight and axle load for the vehicle.

The determination of accuracy in calculated axle spacing, which depends on the measured speed of each axle, was made by using data from all the calibration runs. Reference values were obtained from on-site tape measurements of the axle spacing of the TxDOT test truck. On average, the WIM system error was +0.03 m (+0.1 ft). There was less than a 1-percent difference for any calculated axle spacing compared with those on the test truck.

1.3. EL PASO WIM SYSTEM

El Paso, one of the largest Customs districts along the U.S-Mexico border, is heavily linked to the maquiladora industry in the northern area of Mexico. The importance of this district is growing as commercial ties strengthen between the two countries. A weigh-in-motion station was conceived in 1993 for El Paso to collect statistical data on the axle-loading characteristics of trucks traveling across the U.S.-Mexico border. The two-lane WIM system was calibrated and commissioned June 1, 1994.

The weigh-in-motion station at El Paso is located between Las Americas Avenue (Loop 375) and the Zaragosa International Bridge. This bridge, which handles commercial truck traffic only, processes over 400,000 trucks a year. The strategic location of the WIM site makes it possible to survey most of the truck traffic crossing the border in both directions on this bridge.

The El Paso WIM system has sensors in two lanes. Lane 1 is referred to as the lane that processes trucks with Mexican origin (northbound traffic). Lane 2 processes the southbound trucks, which have their origin in the U.S. Figure 1.1 shows the locations of both the El Paso and the Laredo WIM sites. Layout of the El Paso and Laredo sites are shown in Figure 1.2. The speed at which most vehicles travel over the WIM sensor is between 15 and 25 mph at both sites.

1.3.1. Installation

Installation of a weigh-in-motion system in El Paso was authorized in December 1993 by TxDOT as an additional task under Research Study 1319. The first field work was accomplished in February 1994.

An on-site inspection of the existing pavement revealed that there was some degree of surface roughness in the area where the weigh-in-motion sensors would be installed. A topographic survey (rod and level survey) in a two-feet grid pattern was therefore performed over an area 61 m (200 ft) long and 3.66 m (12 ft) wide in the southbound and the northbound lanes by El Paso district surveyors. Analysis of these data established the need for pavement surface grinding of the existing continuously reinforced concrete pavement (CRCP) slab to meet the smoothness requirements of ASTM Designation: E1318-94[6]. On April 25, 1994, a subcontract was granted to an independent concrete cutting contractor to level the surface according to the standard. A specialized concrete cutting machine[7] having 27 diamond edge saw blades grinds a 0.91 m (3 ft) width of pavement on each pass. Cuts of up to 0.02 m (0.75 in.) deep (see Fig B.2) were needed in some areas to level the surface. Following this procedure, the road surface met the tolerance of 3.2 mm (1/8 in.) under a 4.88-m (16-ft) straightedge.

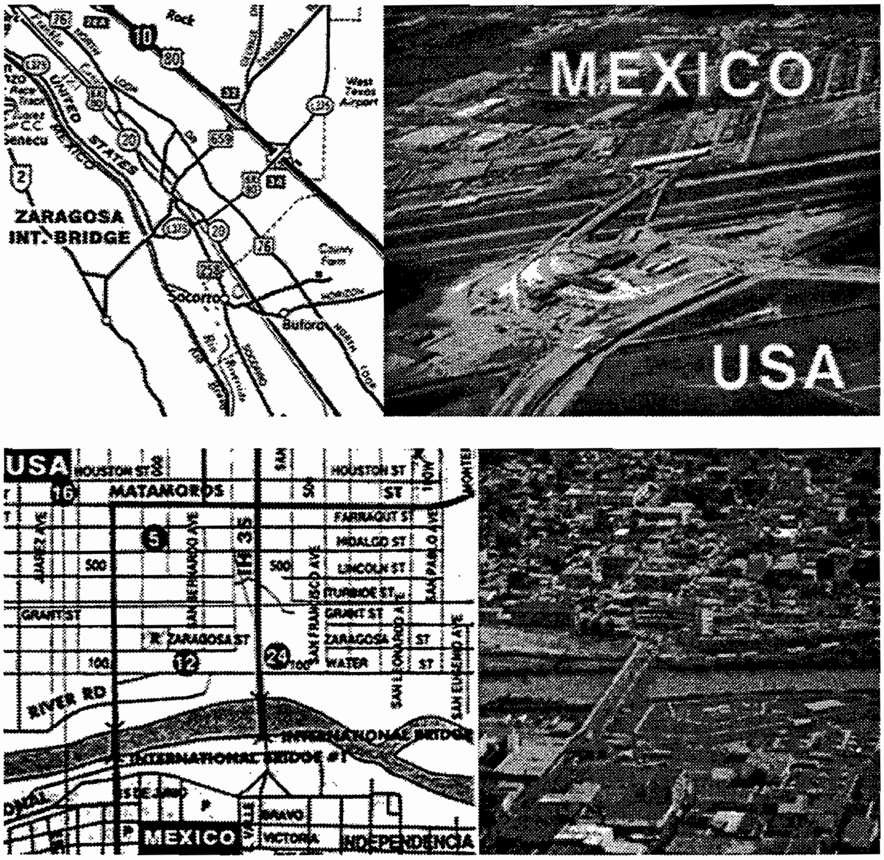

Figure 1.1 Location of the WIM systems: Top picture indicates the Zaragosa International Bridge in El Paso; the bottom picture is the International Bridge No. 1 in Laredo

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[6] Instead of using the proposed 6 m (20 ft) long straightedge prescribed by ASTM, a 4.9 m (16 ft) long straightedge was used.

[7] The concrete cutting machine was connected to a tank truck which carried water used to cool the blades. The water ran from the tank truck to the grinding machine and was sucked back into the tank. Most of the water, along with the cuttings, was collected into the tank truck for proper disposal. Refer to Appendix B.

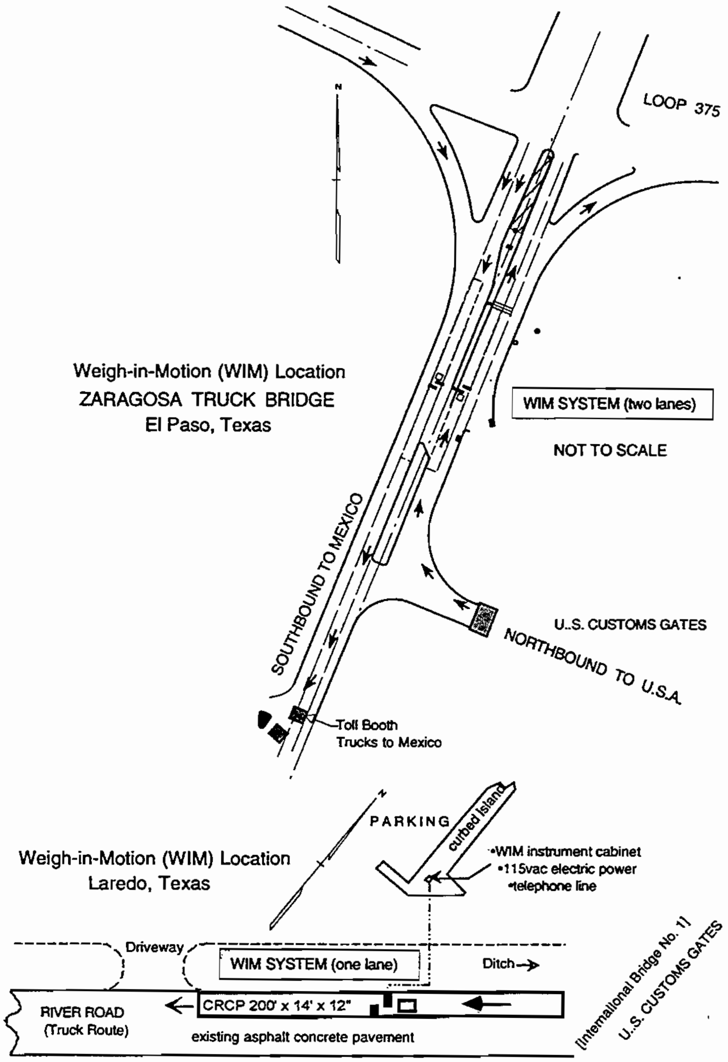

Figure 1.2 Weigh-in-motion (WIM) configuration in Laredo and El Paso

The installation of the four bending-plate tire force transducers (weigh pads) was performed by a TxDOT crew on May 14 and 15, 1994. This process utilized a pavement saw and jack hammer to break away the concrete and create the recesses for the 1.8 x 0.61-m (6 x 2-ft) foundation frames to hold the bending plates. Concrete sawing was also necessary to install the inductance loop detector in each lane and to provide drainage away from the weight pads. The frames were anchored in the recesses and secured with E-bond epoxy. Finally, the bending plates were leveled with the existing pavement surface with shims. Further work was required later to install traffic control devices to guide the trucks over the WIM sensors. Following the installation of the hardware in the road surface and the PAT DAW100 on-site processing computer, the system was calibrated for the first time on June 1, 1994.

Minimum required performance conditions specified that no more than 5 percent of the axle spacing values from the WIM system could be in error by ±1.52 m (±0.5 ft) or more. Additionally, no more than 5 percent of the gross vehicle weights measured by the WIM system could differ from the corresponding reference weight by 10 percent (Lee 1993a).

1.3.2 First Calibration

On June 1, 1994, the Texas Department of Transportation, El Paso District, provided a three-axle single unit (SU) dump truck loaded with gravel and a six-axle semi-trailer combination truck (3S3), with a lift-axle on the semi-trailer carrying a front-end loader. The single unit, three-axle truck was loaded to 97 percent of it allowable axle loads and the six-axle semi-trailer to 76 percent of its allowable gross vehicle weight. The reference weights for the SU were measured on a single-platform certified vehicle scale. By successively positioning selected wheels on the scale platform, with others on the adjacent concrete apron, wheel loads were determined. Each axle-group load on the 3S3 was measured by another five-platform certified vehicle scale in a single-draft weighment. Owing to an unfortunate accident, the laptop computer file that contained the calibration data was lost; however, written records show that the calibration was performed with 21 runs in the southbound lane and 19 in the northbound lane. At the time of the second calibration (see Section 1.3.5) the system was found to be operating with a 5.18-percent difference above the reference gross vehicle weight in the northbound and 5.24 percent above reference in the southbound lane. The test vehicle speed was 5 mph. Average axle spacing distance for the test truck was measured at -0.9 percent difference from the reference value on the southbound lane and -2.2 percent in the northbound lane.

1.3.3. Traffic Flow and Queues

Truck traffic processing at the U.S.-Mexico border deals with permits, customs, and cargo checks, among other transactions. At El Paso, a queue of northbound trucks forms on the Mexican side of the border to pay the bridge toll. These trucks then cross the Zaragosa International Bridge and enter the U.S. Customs yard that is located on the north shore of the Rio Grande. The Customs operation serves as traffic control over the WIM system in Lane 1, generally releasing trucks in single file. Occasionally the traffic signal at Loop 375 (see Fig 1.2) will queue vehicles to a distance long enough to affect the northbound WIM measurements. Vehicles making a right turn at this upstream interchange are, however, occasionally a source of improper WIM measurements. Some drivers start maneuvering into the adjacent right-hand lane beside the WIM sensor while the vehicle's trailer is still moving over the weigh pads. The rear wheels of these vehicles sometimes are off-scale, generating zero tire load in the WIM record. This activity was verified with video images. Special traffic controls are being considered to diminish this occasional source of error. Trucks exhibiting zero wheel load were excluded from the analysis and treated as a part of erroneous data.

Southbound trucks approach the Zaragosa International Truck Bridge from the diamond interchange on Loop 375 (see Fig 1.2) and stop at the north end of the bridge to pay bridge toll and to be processed by Mexican authorities. Each truck requires about 2 to 3 minutes' stopped time for this transaction. As the WIM sensors are located only some 76 m (250 ft) upstream from the toll gate, a queue of waiting trucks sometimes makes it impossible for every truck to move steadily over the sensors without stopping. The WIM system measures the average vertical force while a tire is supported by the weigh pad, even if the vehicle stops for a short period of time. This value can be recorded with respect to time. However, when a vehicle stops while over the sensors, calculated values for the number of axles on the vehicle and for the spacing between successive axles cannot be determined from the sensor data. These values are based on an assumption of steady speed or a uniform rate of change of speed (in conventional WIM systems software algorithms).

Information about the loads carried by single, tandem, and tridem axles, as well as by groups of such axles, is needed to estimate the potential damage that will be imposed on pavements and bridges. Therefore, it would be highly desirable to record data from the WIM sensors (a vehicle-presence sensor over the weigh pads plus two tire-force sensors, one for each wheel path) in such a way that an algorithm might be developed to recognize reasonable patterns and sequences of wheel loads that comprise various axle groups.

Recognizing the need for better data processing software, a specification for a new software capable of handling data from the queues was submitted to the manufacturer. This specification required that, in the presence of a standing queue of 15 seconds duration, the WIM system will measure and record only wheel loads and time, but not axle spacing.[8] An auxiliary vehicle-present detector would be integrated into the southbound sensor system. This sensor is described in the following section.

1.3.4. Infrared Light Beam Sensor

An infrared (IR) light beam reflex-type sensor and retroreflector was added to the system to indicate the presence of a vehicle over the weigh pads. The IR light beam is 1.5 m (60 in.) above the road, oriented at approximately 37° with the curb, and extends 19.8 m (65 ft) across the lane (see Fig 1.3). When the light beam is blocked, a vehicle-present signal is generated The IR signal was connected along with a similar signal from the loop detector in a logical OR mode to provide the WIM system with information about trucks occupying the WIM sensors (Lee 1994). The infrared sensor arrangement attempts to detect a gap between trucks but not the small void space between the tractor and the trailer of a combination truck. The operation of the infrared sensor was verified against video images. A camera was aligned in the same position as the infrared light beam. Two video sequences on different days were made, one with a duration of 50 minutes and the second lasting 20 minutes. The traffic conditions varied from vehicles in no queue to stop-and-go situations where trucks stood over the weigh pads for more than 45 seconds while following

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[8] It is not possible to calculate the axle spacing of queued vehicles owing to the inherent restriction that an intermittently stopped vehicle imposes in establishing the relationship of time, distance, and velocity.

the preceding vehicle approximately 1.8 m (6 ft) behind. These are normal operating conditions in the southbound lane during peak traffic periods.

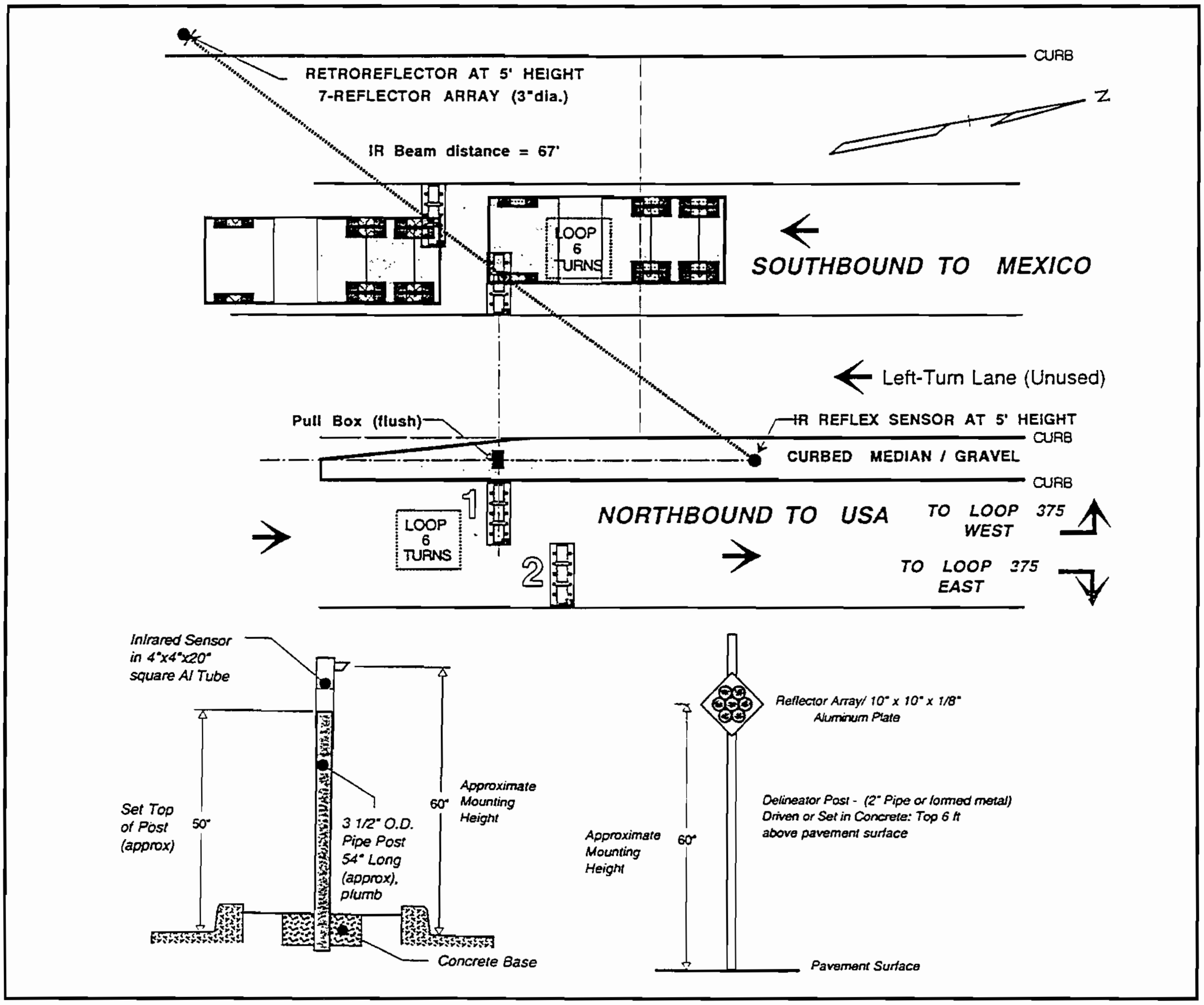

Figure 1.3 Infrared light beam sensor in the southbound lane in El Paso

The first video tape session proved to be inconclusive owing to a disparity in the time records between the WIM computer and the video camera. However, some vehicle-record matching was possible. The test indicated that about 90 percent of the vehicles were properly detected. In the second tape session, all vehicles were correctly detected. After the installation of the IR sensor, the number of misclassified vehicles was significantly reduced. The infrared light beam sensor has functioned continually since it was installed in September 1994. Work on the development of an algorithm to group axles from the recorded data is continuing. The infrared light beam, along with the new software, provided additional resources to classify vehicles under the existing conditions in the southbound lane in El Paso. On August 12, 1994, a second calibration was performed to evaluate the continuing reliability of the data being collected.

1.3.5. Second Calibration

As with the first calibration, a three-axle dump truck and a six-axle platform truck were provided by TxDOT's El Paso District. The three-axle truck was loaded above capacity, while the six-axle truck was loaded up to 73 percent of its allowable gross vehicle weight. During a two-day calibration process, a total of 119 runs were performed with the two trucks on the northbound lane and 115 in the southbound lane.

As mentioned before, the weight measurements are dependent on the speed of the passing vehicle, owing to the inherent dynamics of in-motion weighing. Therefore, the calibration measurements for the system were performed in three different operating speed ranges, namely, 10, 17, and 25 mph on the northbound lane (Lane 1) and 10, 20, and 30 mph on the southbound lane (Lane 2). The accuracy achieved varies with the speed. Table 1.1 shows the percentage of difference from the reference static gross vehicle weight for the traffic speed ranges.

Table 1.1 Accuracy of El Paso WIM

	Speed (mph)	Percent Difference from Reference GVW
Lane 1	10	+3.76
	17	+0.02
Lane 2	10	+1.23
	20	-3.41

Based on the assumption that the calibration truck was "load balanced" on 50 percent of its weight to the right and 50 percent to its left,[9] two calibration factors were determined. The set of adjustments have the effect of modifying the right and left wheel load measurements. The corrections were made from 31 runs in Lane 1 and 33 runs in Lane 2. The new capabilities for queuing processing in the software were evaluated through a stop-and-go test.

Using the three-axle truck, the test was performed to simulate the queuing problem on the southbound lane. This test consisted of five different runs where the right wheel of the first axle of the truck was standing on the leading weight pad for 10, 30, 60, 120, and 300 seconds. After this, the truck was moved to the trailing weigh pad and the process was repeated. Under these conditions, the measured weights were on the average 3.3 percent higher than the reference static GVW.

1.4. DATA ACQUISITION AND PROCESSING

The DAW100 unit for the WIM systems at Laredo and El Paso is equipped with a 9600-baud external modem for remote data collection and transmittal. Both systems have the capability of storing approximately 30 days of data. The stored information at Laredo is gathered every two

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[9] This is a safe assumption since the truck was carefully and specially loaded for the calibration.

weeks via modem from The University of Texas at Austin. To minimize costs, the collected data at El Paso is retrieved via modem at the TxDOT district office in El Paso and mailed on floppy disks to The University of Texas at Austin.

The information downloaded from the on-site processing unit is in standard binary format. The data is decoded to ASCII format (on a personal computer) using a file processing software developed by Liren Huang.[10] Further data processing is completed using Microsoft Excel software.

1.4.1. Data Irregularities

Although the WIM system for this study has been operating continuously for over 2 years, not all data were used for this report. For example, during system malfunctioning, the information was erroneous or not collected. Some of these malfunctions were repaired within a few days; others required total system shutdown, which prevented data collection for weeks at the time.

A reoccurring problem with one of the weigh pads in the Laredo WIM (a problem that went undetected for several months) limited the number of trucks weighed daily. In this case, the monthly volume of crossing vehicles measured was affected (though it was possible to determine vehicle loading characteristics with smaller samples).

In El Paso, some data were lost as a result of system overflow. The storage capacity reached its maximum capacity, and information was automatically overwritten by the new information. The truck volume in the northbound lane of El Paso is affected by the vehicles running off scale. Also, several empty vehicles stop in the service lane to close the cargo compartment doors. These vehicles cross with their doors open to expedite the inspection process. In the southbound lane the queuing problem creates a major vehicle classification problem. Information of several vehicles in queue are recorded as a single vehicle.

The processing unit records passing vehicles to a maximum of eleven axles. However, when a queue is present and two or more vehicles are falsely grouped as one, the computer will record the maximum axles possible. If a vehicle is still present, it will create a new record for the remainder of the vehicle. Such problems can complicate proper data analysis.

Ten weekdays were selected to reclassify vehicles through visual data inspection. This process consisted of examining the loads and axle spacing of all recorded vehicles each day and establishing, using the best possible judgment, the classification of the vehicle. This analysis showed that none of the seven-axle trucks recorded was actually a seven-axle truck. Most of them consisted of five-axle trucks tailgated by a car. The large majority (up to 95 percent) of the ten-axle truck records comprised two five-axle trucks recorded as one. Also, the eleven-axle truck records, which comprised over 75 percent of the improperly classified vehicles, included at least one five-axle truck (most commonly two) and part of some other vehicle. The eight- and nine-axle trucks were part of previous vehicles and were recorded as such when the gap with the following vehicle was large enough to differentiate them. Trucks classifications of two-, three-, four-, and six-axle are questionable, since some were part of the preceding vehicle. Data analysis showed that vehicles

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[10] Liren Huang is a Research Associate at the Center for Transportation Research, The University of Texas at Austin.

classified as five-axle trucks were truly of such vehicle class. Only two of the approximately 5,000 five-axle trucks were a three-axle truck tailgated by a car. In addition, around 330 five-axle trucks a day were being combined with other vehicles into erroneous classes. The analysis presented in this report for the southbound traffic at El Paso is limited to five-axle trucks. The actual volume is between 1.4 and 1.6 times larger than the vehicles counted. Since significantly fewer vehicles were counted in the southbound lane, no direct comparison is possible with the northbound lane in terms of volume, although the loads and traffic pattern are representative. The classifications for other vehicle types is highly unreliable and it was not possible to establish a pattern for those vehicle types.

1.4.2 Traffic Impact on Pavement

Pavement deterioration takes place in a multi-factor environment. The roadbed soil, construction material, drainage, environmental conditions, and traffic all have significant impact on pavement performance. This section describes how traffic damage is assessed.

In 1958, the American Association of State Highway Officials (AASHO) conducted a large-scale road test to determine the relative damaging effects of various axle loads on different pavement types. In this test, AASHO developed the concept of expressing the relative damage caused by one pass of a given axle type and load in terms of the equivalent number of passes of a standard axle type and load. An equivalent single axle load (ESAL) factor was thus defined as the number of passes of a standard (usually 18-kip[11]) single axle needed to equal the damage to a particular pavement structure caused by one pass of a given axle type (e.g., single, tandem, tridem, or steering) when it applies its observed (or assumed) load to the pavement. Under these conditions, an 18-kip single-axle load application will produce a unity value of relative damage. An 18-kip ESAL factor for any other given load is determined by the ratio of the damage caused by the 18-kip single axle load application, ($W_{t_{18}}$) against damage caused by the selected axle load application (W_{t_i}):

$$\text{ESAL factor} = \frac{W_{t_{18}}}{W_{t_i}} = \frac{\text{18-kip single axle load application}}{t_i \text{ axle load application}}$$

The ESAL factor relationship was found to increase exponentially approximately to the fourth power as the load increased. This implies that a single axle loaded 2 kip above the allowed 20 kip creates $(22/20)^4 = 1.5$ times the damage caused by the legally loaded axle.

The equivalence factor is influenced by the thickness and type of pavement, roadbed characteristics, axle configuration, and expected pavement performance. The expected pavement performance is a measure of pavement structural and functional conditions. The structural

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[11] 1 kip = 1,000 lbf = 4.448 kN. NOTE: In this application, the load produces a vertically downward force because of the influence of gravity acting on a mass; therefore, the load is expressed in mass units, lb. Vehicle scales and axle-load scales used to weigh trucks are adjusted under field standard test weights to indicate mass units, i.e., lb (avoirdupois) or kg. One avoirdupois lb=0.453 592 37 kg. To calculate force, multiply mass by acceleration due to the local force of gravity (nominally, 32.174 ft/s^2 or 9.807 m/s^2). A newton, N, is the external force that will accelerate a 1 kg mass at 1 m/s^2.

performance assesses the ability of a pavement to support load. Areas such as occurrence of cracking, raveling, and faulting (among others) are included here. The functional performance encompasses how the users perceive the pavement quality (e.g., riding comfort). This subjective characteristic is quantified, mostly, by measuring pavement roughness throughout the pavement life. An index ranging from 0 to 5, where 5 indicates the highest performance or serviceability, is established for the initial and final pavement conditions. The total change of this index, namely, Present Serviceability Index (PSI), is incorporated into the pavement damage relationship.

The number of axle load applications required to achieve terminal serviceability, P_t, for flexible pavement is express as:

$$\log W_t = 5.93 + 9.36 \log(SN+1) - 4.79 \log(L_1 + L_2) + 4.33 \log L_2 + \frac{\log(\Delta PSI)}{0.40 + \frac{0.081(L_1 + L_2)^{3.23}}{(SN + 1)^{5.19} L_2^{3.23}}}$$

Similarly, for rigid pavements:

$$\log W_t = 5.85 + 7.35 \log(D + 1) - 4.62 \log(L_1 + L_2) + 3.28 \log L_2 + \frac{\log(\Delta PSI)}{1.0 + \frac{3.63(L_1 + L_2)^{5.20}}{(D + 1)^{8.46} L_2^{3.52}}}$$

where:

W_t = number of dual-tire axle load applications at the end of time t,

P_t = serviceability at the end of time t,

ΔPSI = ratio of the loss in serviceability, $\left[\frac{4.2 - P_t}{4.2 - 1.5}\right]$ for flexible, $\left[\frac{4.5 - P_t}{4.5 - 1.5}\right]$ for rigid,

SN = abstract number expressing the structural strength of a pavement required for a given combination of soil support, construction material, total traffic in ESALs, terminal serviceability, and environment. (AASHTO 93),

D = thickness of concrete pavement slab,

L_1 = axle group load, and

L_2 = axle group code (1 for single axle group, 2 for tandem axle group, and 3 for tridem axle group).

(These formulas are units dependent and must be used in inches and kip.)

It is apparent from these equations that the total weight of the vehicle is not relevant to the pavement deterioration calculation but, rather, to the actual load in the specific axle group (all other conditions being equal). As the number of axles increases in the axle group classification, more load is allowed on them, since the load is being distributed.

When the legal load limit of Mexican trucks is examined against that of U.S. trucks, it is evident that the differences existing between the two countries escalate in terms of pavement damage. For example, a Mexican tridem axle legally loaded (49.6 kip) will produce twice the damage of its U.S. counterpart (42.0 kip). Notice that the difference between the two loads is only 18 percent.

CHAPTER 2. TRUCK COUNT PROFILES

Analysis of the data presented here encompasses the time frame of August 1994 to August 1995 at the Laredo weigh-in-motion site. El Paso WIM data extend for an additional month, until September 1995. For both sites, 449,886 trucks were weighed during this period. The data include weekday truck traffic only. Weekend traffic was excluded because it represents only a small fraction of the weekday traffic. Saturday traffic is about one-quarter of that on a regular working day, while Sunday traffic is around half of that recorded on a Saturday. Also, most holidays were excluded because they are atypical compared with working days. Most noteworthy is the fact that both U.S. and Mexican holidays influence the traffic volume at the ports of entry.

Since data are collected continuously at both WIM sites, additional data were included after the first period of data analysis. These data were collected from January 1996 to July 1996 in El Paso, and from March 1996 to June 1996 in Laredo. The information obtained during this period is presented separately.

As mentioned before, equipment and traffic flow problems impeded continuous data collection in some instances, though a sufficient amount of reliable information was gathered to characterize traffic count and load patterns at Laredo and El Paso. As noted in the next section, the daily traffic count is fairly stable, and even when small samples are collected in a month a consistent pattern is detected.

2.1. ANALYSIS OF TRUCK COUNT DATA

Commercial truck traffic crossing the southern border of Texas shows an increasing, steady flow of vehicles. Large observed variations are associated with WIM device malfunction in most cases. Figures 2.1 and 2.2, presented to illustrate this situation, show the average number of vehicles counted per day during the month plotted against the calendar day of the month. They also detail the five types of trucks predominantly observed at both sites. Appendix C contains the same kind of graphic daily count data for all the months covered in this study, including erroneous records.

Figure 2.1 shows Laredo's daily traffic for January 1995. The number of trucks crossing the weigh-in-motion station during any weekday is fairly constant. January 24 represents an unusually low volume compared with that for the rest of the month. During that day a large number of erroneous data files was generated by the WIM system (represented by the "err" series). The coincidence of these two events explains part of the variability observed in the data for that specific day. A reverse situation is observed on January 11 and 31. These two days registered the smallest amount of erroneous data, and they also represent the highest traffic count.

Figure 2.2 illustrates a different case. It shows a distribution of erroneous data through time that coincides with large variations in daily vehicle count. The significant aspect of the data shown in this figure is that the "err" distribution and the five-axle truck distribution are mirror images. The implication is that most of the erroneous data are composed of five-axle trucks. Five-axle trucks accounted for 68 percent of all trucks counted during February 1995.

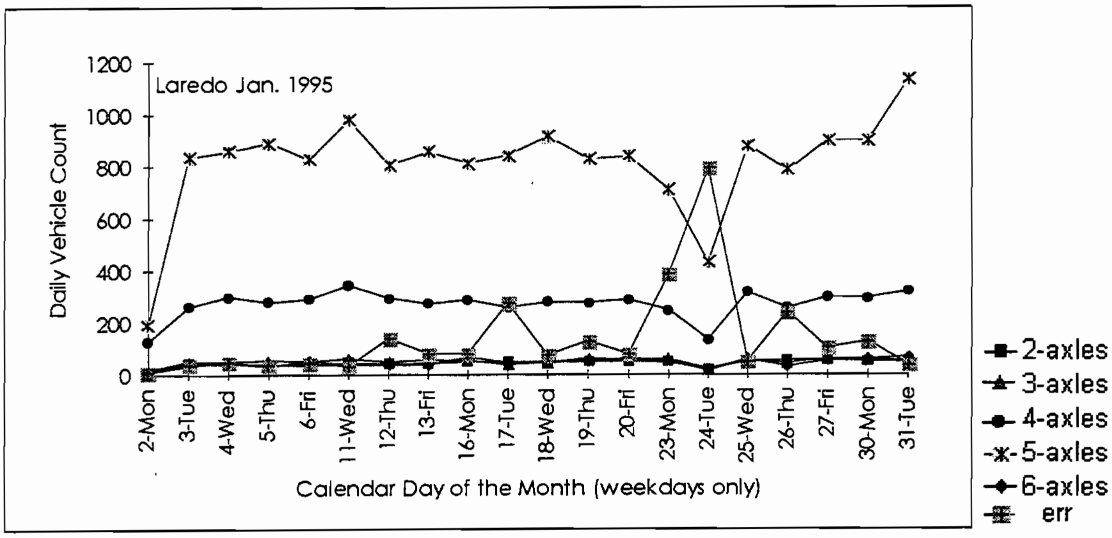


Figure 2.1 Laredo January 1995 daily truck count

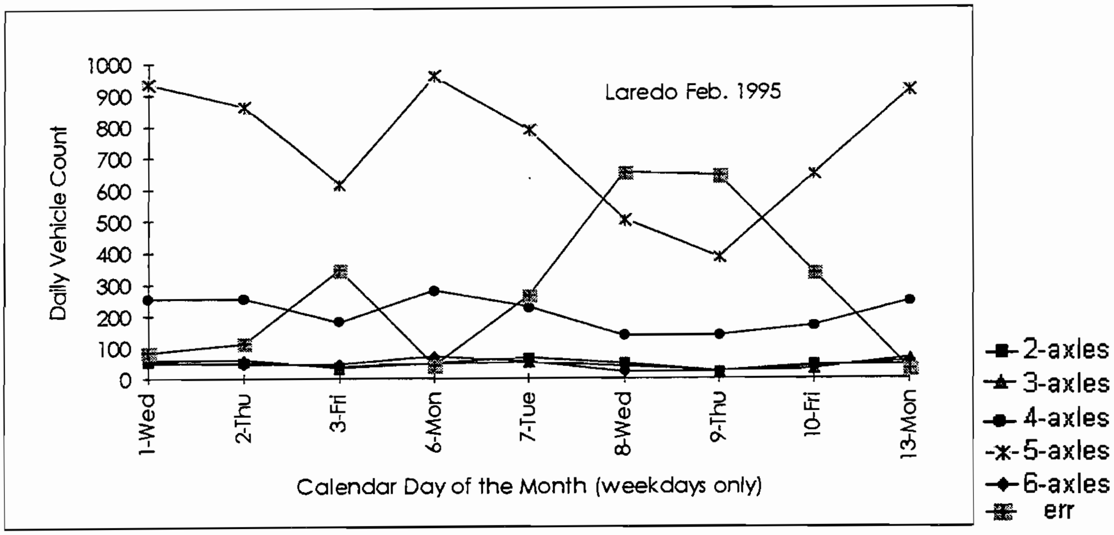


Figure 2.2 Laredo February 1995 daily truck count

Erroneous data fluctuates in proportion to the number of vehicles counted during the day. Even though in some months the erroneous data may represent a large proportion of the vehicle count, they do not fluctuate randomly. These characteristics are useful in evaluating the recorded traffic count patterns.

Erroneous data records comprised from 3 to 18 percent of the total records, depending on the site and the month. The WIM system in Laredo began to behave erratically in February 1995 and worsened progressively thereafter. Following three visits to the site, we finally (in October 1995) identified the causes of the intermittent problem: a defective loop detector wire and a broken wire on one weigh pad cable. Both sensors were operating intermittently and generating reliable signals for most of the day but, on occasion, were producing records that were impossible to associate with real vehicles. The worst cases occurred in August 1995 when more than half the data indicated obvious irregularities; these were eliminated from the analysis. Northbound El Paso erroneous truck count data are around 12 percent of the total, with a low of 4 percent (August 1994) and a high of 18 percent (May 1995). At this location, over 80 percent of the erroneous data come from vehicles having zero wheel load for one or more of its axles. As explained before, these are believed to be vehicles running off the scale. Owing to the frequent queues of trucks in southbound traffic at El Paso, automatic, on-site vehicle classification is not feasible. Despite this shortcoming, it was possible to salvage approximately 50 percent of the five-axle truck records, which in turn represents approximately 78 percent of all trucks traveling to Mexico at the Zaragosa International Truck Bridge.

Figures 2.3 to 2.7 were developed in an attempt to describe the general truck flow pattern for the entire analysis period. These figures show the median values of the number of trucks counted per day during each month. El Paso NB represents the northbound traffic; similarly, El Paso SB represents southbound traffic. In Laredo all the trucks are northbound and no distinction is necessary at this site. The Laredo estimates are made for missing data points during the months of March, April, and May 1995. These estimates also include modified values for the months of February, June, July, and August 1995. These modifications to the observed counts were made in order to estimate reasonable values for vehicles not counted (or falsely generated) when the WIM system malfunctioned.

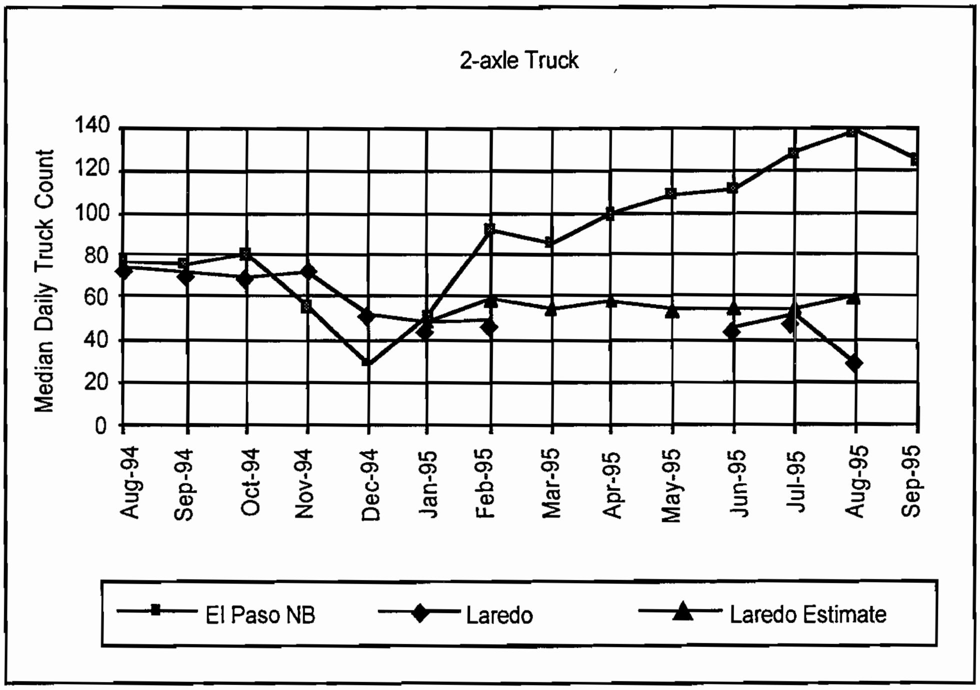


Figure 2.3 Two-axle daily truck count for August 1994 through September 1995

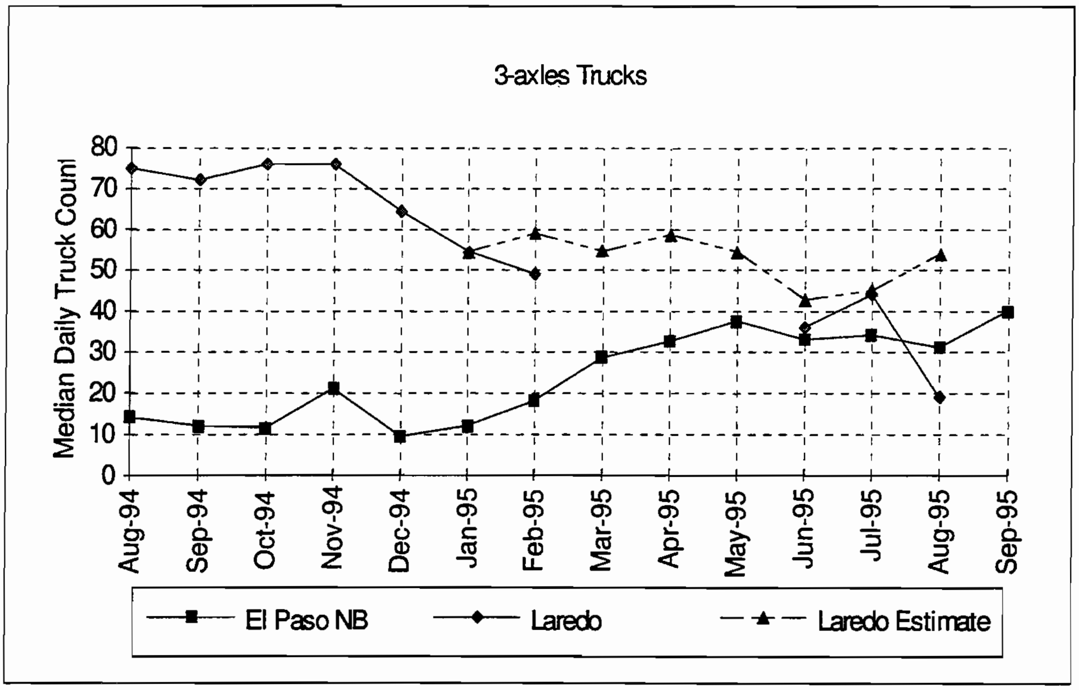


Figure 2.4 Three-axle daily truck count for August 1994 through September 1995

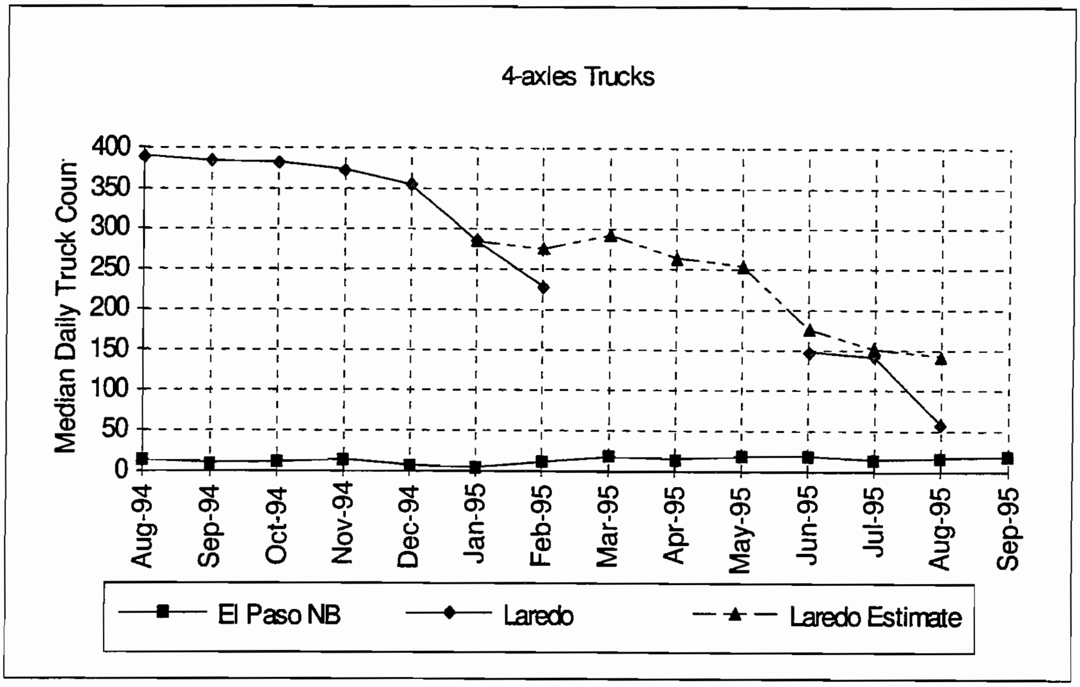
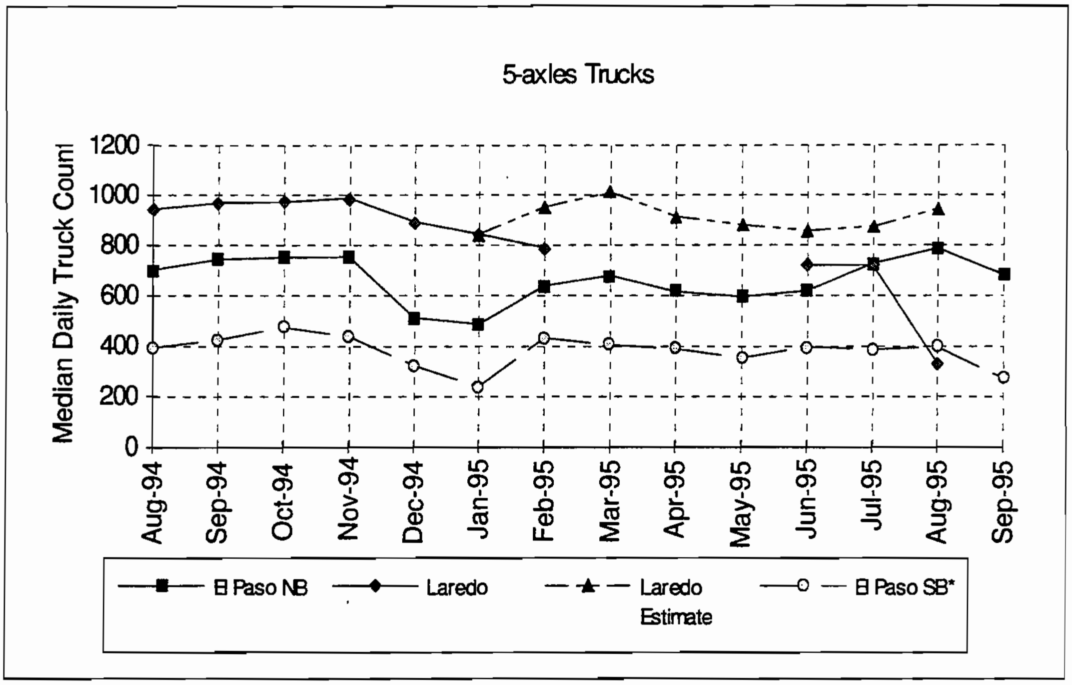


Figure 2.5 Four-axle daily truck count August 1994 through September 1995



*Figures 2.6 Five-axle daily truck count for August 1994 through September 1995 (*The southbound 5-axle trucks in El Paso is significantly larger than the number shown. The estimated count is between 1.4 and 1.6 times larger than this.)*

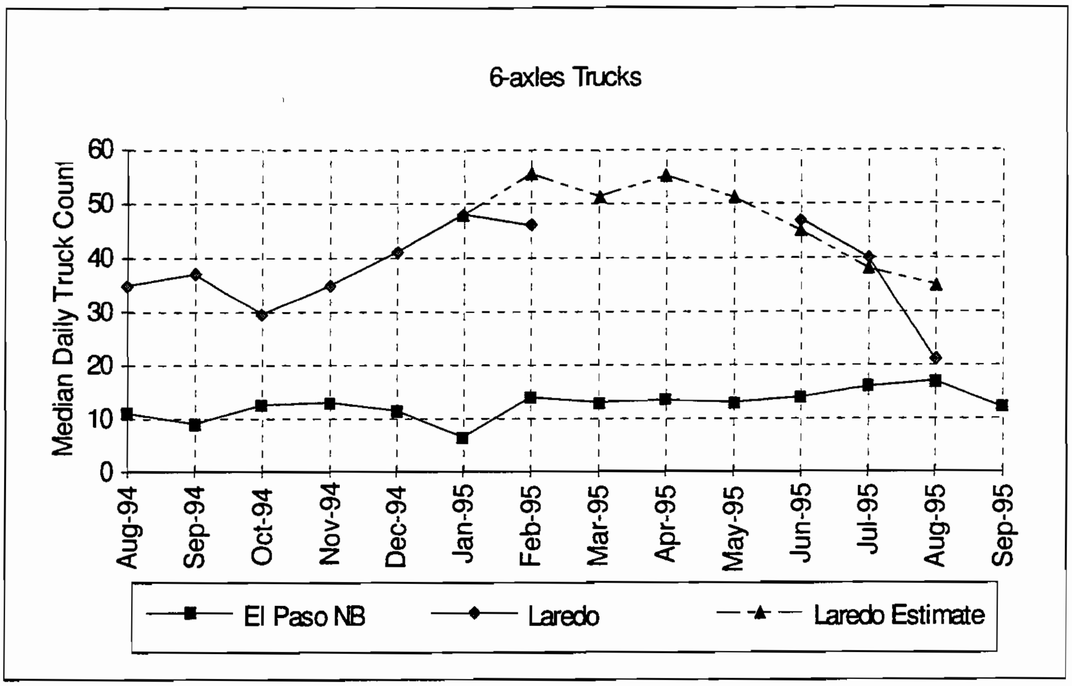


Figure 2.7 Six-axle daily truck count for August 1994 through September 1995

To supply reasonable values for the number of northbound trucks in Laredo for those months during which we experienced equipment problems, the count pattern for each vehicle type was examined. It was determined that six-axle trucks at Laredo have a count pattern similar to that for El Paso northbound six-axle trucks. Both sites have a steady flow from Tuesday to Friday, with peaks on Mondays. Also, we found that six-axle truck traffic at Laredo has the same general flow pattern as two- and three-axle trucks at this site. The five-axle truck count patterns were similar to their counterparts in El Paso. The count patterns of these trucks for August 1994 through January 1995 are in almost the same ratio; therefore, we assumed that the pattern held throughout the analysis period. Four-axle trucks in Laredo follow the characteristic pattern of the five-axle trucks in this location, since a large portion of both truck types are involved in drayage company operations. The tractors are, in most cases, hauling the two-axle trailer of a five-axle rig. Based on the conditions described above, the Laredo estimates were made for the missing months of March, April, and May 1995, with the recorded count data for February, June, July, and August 1995 edited slightly. Edited values proportion the atypical data points to values conforming to regular data points.

2.2. MONTHLY TRUCK COUNT PATTERN

An estimated 1,600[12] northbound trucks cross the WIM device at Laredo daily, while around 1,000 trucks cross the WIM device in the northbound direction at El Paso. It is estimated that the southbound truck traffic at El Paso is approximately the same as that crossing northbound from Mexico. Northbound truck traffic increased at both sites during the last months of 1994. However, in December of that year, a drop from 860 trucks a day in November to 570 was experienced in El Paso. This lower count continued during the month of January 1995. A rapid increase (similar to the reduction) took place in February 1995. Some of the decrease in traffic during the month of December is explained by the holiday season. The traffic reduction is more apparent during the week of December 26 to December 30, 1994 (see Appendix C). However, the holiday season does not account for all the traffic reduction. The fact that this lower traffic count continued during the entire month of January indicates a cause with a greater effect upon the temporal situation, namely, the peso devaluation in Mexico. The devaluation occurred mid-December 1994 and may have caused an initial period of instability in commercial trade. As the economic situation stabilized through time, truck traffic resumed its growth. An LBJ School of Public Affairs study (LBJ 1994b) on U.S.-Mexico transportation practices suggested a similar trend when shipment companies were studied. A change in truck traffic trends during the Mexican peso crisis was also reflected at Laredo, though the impact was less dramatic. Laredo experienced a 17 percent drop (130 vehicles each month for two months) in traffic during the same period; El Paso, 33 percent. Trucks entering Mexico at El Paso were also affected, showing a 25-percent drop for December with respect to the previous month. The LBJ study attributed the effect on trade (both imports and exports) to uncertainty in currency value.

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[12] This value and the El Paso value are estimates from actual count with adjustments for disregarded data from vehicles with errors in axle spacing and wheel load.

Another significant change in truck traffic was observed during the months of July and August 1995. The northbound count increased during these months, adding around 98 trucks per month for an 11-percent increase. A research report published by the Texas Transportation Institute (TTI 1992) found an increase of 100 trucks per month (15 percent increase) in the Brownsville area during the late summer months, a period that coincides with the Mexican harvest season. Agricultural goods rank in the top ten commodity imports from Mexico but are not a major export from the U.S. (LBJ 92b). Figure 2.6 shows a peak in the northbound traffic but not the southbound, which possibly indicates the influx of agricultural goods during the summer. The estimate for Laredo in the summer could be somewhat conservative, since the truck traffic in El Paso is more heavily linked to the maquiladora industry than that in Laredo.

The relationship between northbound and southbound traffic lacks the total count of southbound vehicles to evaluate a traffic balance. Nevertheless, the ratio of northbound to southbound five-axle trucks shown by the data in Figure 2.6 indicates that no change in the north-south relationship was detected after the peso devaluation in December 1994.

2.2.1. Vehicle Types

The vehicles examined in this study are classified primarily by the number of axles. Only trucks having two to six-axles are discussed. Those vehicles account for nearly 100 percent of the trucks moving across the bridge at Laredo and El Paso. It is extremely rare to see a larger vehicle having more than six-axles at these sites.

The number of two-axle trucks was steady at Laredo during the 14 months studied. These trucks represented about 5 percent of the trucks at this location. The share of two-axle trucks in El Paso is larger, representing 11 percent of all northbound trucks. Also, this location had a rate of increase of 12 two-axle trucks per month during January 1995 to August 1995. Two-axle trucks comprised 9 percent of the total prior to this period and 13 percent thereafter. Tables 5.1 to 5.5 detail these and other truck count and load characteristics by month for all vehicle types.

Northbound three-axle trucks in El Paso registered a slight increase in the early months of 1995 and remained steady after May, with 34 units per month. These vehicles accounted for 3 percent of the truck traffic at this location. The single-unit truck is the predominant configuration (94 percent) of the three-axle truck population. Laredo has double the number of three-axle trucks recorded in El Paso. In general, three-axles trucks represent 5 percent of all the trucks in Laredo, with 84 percent of them being single unit vehicles.

El Paso registered 15 northbound four-axle trucks per month, equating to 2 percent of all trucks. The 2S2 vehicle type (two-axle tractor with two-axle semi-trailer) comprises between 35 percent and 55 percent of all four-axle trucks in El Paso. This pattern has remained stable through time. However, Laredo shows a very distinctive pattern of reduction in the count of four-axle trucks. After December 1994, the number of four-axle trucks decreased at a rate of 24 units per month until June 1995, when it reached 176 vehicles. The following two months indicate a similar number of four-axle trucks, which suggests stability in the count of this truck type.

In Laredo, the percentage of four-axle trucks dropped from 26 percent in August 1994 to 13 percent in August 1995 (averaging 20 percent over the entire analysis period). During this period, the 2S2 vehicles dropped from 374 per day (95 percent of all four-axle trucks) to 117 (83 percent of four-axle trucks). This decrease could be indicative of the effect of changes in drayage operations under NAFTA. It is noteworthy that, as the percentage of four-axle trucks was decreasing in Laredo, the percentage of five-axle trucks was *increasing*. The combined proportion of five-axle trucks and four-axle trucks in Laredo, at any point in time during the analysis period, is similar to the percentage of five-axle trucks at northbound El Paso, where four-axle trucks are minimal. In Laredo there seems to be a tendency for drayage companies to use two-axle tractors to haul two-axle semi-trailers across the bridge. El Paso is not affected similarly in this regard, since short-hauler companies are less dominant in the area.

The five-axle semi-trailer (3S2) represents the vast majority of trucks crossing the bridge at Laredo and El Paso. They comprise about 675 vehicles a day (82 percent of all northbound trucks) in El Paso and 925 vehicles (67 percent of all trucks) in Laredo. In both cases, the 3S2 axle arrangement represents over 95 percent of all five-axle trucks. Inasmuch as these vehicles account for most of the international truck traffic, they can be used to describe the general trends discussed in Section 2.2.

The truck type counted least in Laredo and El Paso is the six-axle truck. These vehicles, which are frequently used to transport agricultural products, comprise 3 percent of all trucks in Laredo and 2 percent in El Paso. A daily average of 43 six-axle trucks is seen in Laredo; for El Paso, the figure is 13. In addition, the 3S3 axle arrangement accounts for 84 percent of the six-axle trucks in El Paso and 95 percent in Laredo. Data for six-axle trucks (3S3) in Laredo shows an increase of six such vehicles per month from October 1994 to February 1995, and then a decrease at the rate of five per month, from April 1995 to August 1995. These changes are perhaps indicative of two agricultural phenomena: The increased use of this larger capacity truck might represent an increase in the dollar value of agricultural goods, as it is financially desirable to change destinations of such cargo in order to obtain better value in the U.S. On the other hand, the decrease perhaps represents the seasonal depletion of agricultural products available for the U.S. market.

2.3 1996 TRUCK COUNT PROFILES

Truck count profiles for 1996 were developed after 1994 and 1995 data from Laredo and El Paso had been analyzed. The more recent tendencies in truck traffic at the weigh-in-motion stations in Laredo and El Paso are described here.

In El Paso, the actual number of usable truck records processed by the WIM system decreased, though the total number of trucks passing the site was similar to previously observed truck counts. Faulty records were mostly due to vehicles running off-scale. Recent construction adjacent to the WIM station may have resulted in the increase in this type of error. Nevertheless, a consistent reduction in traffic count was observed in the early months of 1996, with the lowest point occurring in May. June and July exhibited a significant increase compared with March, April, and May. These tendencies are mostly reflected in the five-axle truck category. This truck type represents around 75 percent of all trucks observed during the first seven months of 1996 in El Paso. All other truck types showed a small reduction in the daily truck count, though the general composition of the truck population remained approximately the same. A small increase in the percentage of three-axles and a similar decrease in the five-axle truck category were observed. This might be due to more loaded five-axle trucks (three-axle tractor with two-axle semi-trailer) moving south and then having the tractor return without the semi-trailer. The WIM system recorded the tractor as a single-unit, three-axle truck. Three-axle, single-unit trucks represented more than 95 percent of all observed three-axle trucks. The configuration of four-axle trucks remained about the same as for previous years: about 60 percent 2S2 four-axle trucks and 35 percent 3S1 four-axle trucks.

Truck traffic in Laredo differed from that in El Paso. For one thing, the total number of trucks increased. Also, the increase in traffic during the summer months was more noticeable in Laredo than in El Paso. The number of six-axle trucks counted daily in Laredo remained about the same, although the number of four-axle trucks decreased slightly. This tendency in the four-axle truck count began in October 1994. For example, in August 1994 there were 390 four-axle trucks per day; by June 1995 this number had decreased to 148 trucks daily; during March 1996 only 70 trucks of this class were counted daily. Accordingly, the percentage of trucks in this class decreased from 26 percent in the fall of 1994 to 4 percent in the summer of 1996. Consequently, four-axle trucks in Laredo are no longer the second most common. Two-axle trucks in Laredo, as in El Paso, are now second in percentage count. The number of five-axle trucks counted daily in Laredo increased by about 125 trucks from the summer of 1995 to the same period in 1996. Also, a large increase was observed in the two-axle truck category. The number of these trucks rose from 40 for a summer day in 1995 to 120 in 1996 for the same period. Correspondingly, the percentage of these trucks doubled during the same period. An increasing tendency in the number of three-axle trucks in Laredo was observed; however, the change was not as large as that for two-axle trucks.

On May 20, 1996, truck routing across the downtown international bridges was changed. Truck traffic from International Bridge No. 2 was rerouted to International Bridge No. 1. The most significant effect of this action was reflected in the number of three-axle trucks observed daily. On Friday, May 17, the number of three-axle trucks counted by the WIM system was 170; the next working weekday, Monday, May 20, about 1,110 trucks of this class were counted. Only the number of three-axle trucks was affected in this way; two-axle truck count followed with an increase of about 5 percent. A site visit indicated that most of these trucks were three-axle tractors, presumably used for short-hauling across the international bridges.

CHAPTER 3. TRUCK LOAD PROFILES

The analysis of data presented in this chapter addresses the axle loads associated with the various truck types considered in the previous chapter. The steering (front) axle of these trucks is not discussed, as its load rarely exceeds the allowable single-axle load. Thus, for a two-axle truck, load data for only the second axle are presented. For the same reason, only the tandem axle of a three-axle, single-unit truck is documented. The single-axle loads of a 2S1 (two-axle tractor with a single-axle semi-trailer) unit are not included, since this axle arrangement comprises less than 10 percent of the three-axle truck population. Vehicle types 3S1 and 2S2 are discussed in the four-axle truck category. The single axles of two four-axle vehicle types are included: the single-drive (2S2) and the single-trailer (3S1) axle. Trailer-tandem (2S2) and tractor-drive-tandem (3S1) axles are included as the tandem axle of four-axle trucks. Axles on five-axle trucks (3S2) include tractor-tandem and trailer-tandem axles. Likewise, six-axle trucks (3S3) have a tractor-tandem and a trailer-tridem axle.

Tables 3.1 to 3.5 show the percentage of loaded trucks by month. The gross vehicle weight minimums for loaded trucks were assumed to be the following: 12 kip for two-axle trucks; 18 kip for three-axle trucks; 25 kip for four-axle trucks; 32 kip for five-axle trucks; and 38 kip for six-axle trucks.

The percentage of loaded vehicles crossing into the U.S. increased at both Laredo and El Paso during 1995. For example, the percentage of loaded, northbound five-axle trucks in El Paso increased from 82 percent in August 1994 to 96 percent in August 1995. Similar values were noted for Laredo. January 1995 was the time when these changes became apparent. However, the percentage of loaded, southbound five-axle trucks moving into Mexico seems not to have changed with time. Rather, the loaded five-axle trucks comprise a smaller percentage than before January 1995. Data for November 1994 and March 1995 were selected to represent typical loading patterns for the respective year. It was noted that in November, 38 percent of the southbound five-axle trucks had gross-vehicle weight between 80 and 96 kip. During March 1995 this distribution dropped to half the November value, while the number of trucks with lower weight increased. These observations confirm recent motor carrier companies operation in the early months of 1995, (LBJ 1994b). As the demand for Mexican goods increased due to lower cost, it was necessary to send empty, or partially loaded, trucks into Mexico to meet the north-side demand. Also, northbound trucks with more cargo (heavier trucks) could respond to the need of alleviating the financial burden imposed on carrier operation as a result of unbalanced trade and the hauling of partially-loaded trucks.

3.1. AXLE LOADING ATTRIBUTES

Figures 3.1 through 3.7 show the axle group load by year and location. The number of axles counted for each category is included in the legend of these figures. The single drive axle of 2S2 vehicles is the more heavily loaded single axle observed in Laredo and in El Paso. In Laredo during 1994 (see Fig 3.1), 15 percent of these axles were overweight and the situation worsened during 1995, with 30 percent over the legal limit (20 kip).

Table 3.1 Summary of two-axle truck characteristics

2-Axles Trucks					Loaded* 2-Axles Trucks		
Month/Year	Site	Daily Volume	% in Class	Daily ESAL's	% of Loaded Vehicles	ESAL Factor	% of All ESAL's
Aug-94	El Paso	77	9.3	6.99	68.5	0.13	1.7
	Laredo	75	5.0	14.33	74.5	0.27	1.2
Sep-94	El Paso	76	8.7	6.61	70.2	0.13	1.7
	Laredo	73	4.7	17.57	74.0	0.31	1.3
Oct-94	El Paso	80	9.2	7.90	66.8	0.15	1.8
	Laredo	69	4.5	14.32	80.0	0.34	1.6
Nov-94	El Paso	56	9.3	3.65	63.8	0.12	1.6
	Laredo	72	4.7	21.17	77.6	0.38	1.8
Dec-94	El Paso	30	6.1	3.64	65.7	0.16	1.4
	Laredo	53	4.0	14.22	76.8	0.38	1.5
Jan-95	El Paso	51	9.4	4.80	70.7	0.19	2.0
	Laredo	49	3.7	10.26	74.2	0.31	0.9
Feb-95	El Paso	92	11.7	13.44	63.3	0.25	1.5
	Laredo	49	4.3	15.77	73.7	0.48	1.4
Mar-95	El Paso	86	11.2	11.84	53.9	0.25	1.1
Apr-95	El Paso	99	13.1	12.41	54.2	0.28	1.4
May-95	El Paso	108	13.8	16.66	56.7	0.34	2.0
Jun-95	El Paso	111	14.1	15.44	57.6	0.26	1.6
	Laredo	46	4.5	19.16	62.0	0.77	1.4
Jul-95	El Paso	127	13.8	16.19	60.8	0.28	1.8
	Laredo	53	5.3	25.96	66.7	0.70	1.6
Aug-95	El Paso	137	14.0	18.93	62.3	0.29	2.1
	Laredo	29	6.0	8.62	48.5	0.52	0.9
Sep-95	El Paso	124	14.0	17.93	59.8	0.26	1.6

* Gross Vehicle Weight > 12,000 lbs.

Table 3.2 Summary of three-axle truck characteristics

3-Axles Trucks					Loaded* 3-Axles Trucks		
Month/Year	Site	Daily Volume	% in Class	Daily ESAL's	% of Loaded Vehicles	ESAL Factor	% of All ESAL's
Aug-94	El Paso	14	1.7	5.92	59.2	0.66	1.3
	Laredo	75	5.0	25.79	80.6	0.43	2.1
Sep-94	El Paso	12	1.6	3.72	52.5	0.53	0.9
	Laredo	72	4.7	25.72	81.3	0.43	2.0
Oct-94	El Paso	12	1.4	3.68	62.5	0.66	1.1
	Laredo	76	5.0	23.78	79.8	0.40	2.0
Nov-94	El Paso	21	2.6	2.19	48.0	0.20	0.6
	Laredo	76	5.0	23.23	79.3	0.42	2.2
Dec-94	El Paso	10	1.6	0.54	52.6	0.25	0.5
	Laredo	65	4.5	16.36	75.8	0.36	1.6
Jan-95	El Paso	12	2.1	1.70	79.4	0.28	0.8
	Laredo	55	4.2	19.07	82.0	0.46	1.6
Feb-95	El Paso	18	2.3	4.05	91.6	0.33	0.6
	Laredo	49	4.2	17.43	80.9	0.51	1.6
Mar-95	El Paso	29	3.7	14.44	82.6	0.63	1.4
Apr-95	El Paso	33	4.3	7.17	84.6	0.54	1.4
May-95	El Paso	38	5.2	17.87	86.5	0.63	2.2
Jun-95	El Paso	33	4.2	15.71	87.3	0.77	2.1
	Laredo	36	4.2	31.21	89.8	0.90	2.1
Jul-95	El Paso	34	3.6	23.09	90.5	0.71	1.7
	Laredo	44	4.6	30.42	88.2	0.80	2.2
Aug-95	El Paso	31	3.4	17.29	89.0	0.64	1.6
	Laredo	19	4.3	11.20	89.1	0.67	1.6
Sep-95	El Paso	40	4.8	14.94	89.3	0.46	1.5

* Gross Vehicle Weight > 18,000 lbs.

Table 3.3 Summary of four-axle truck characteristics

4-Axles Trucks					Loaded* 4-Axles Trucks		
Month/Year	Site	Daily Volume	% in Class	Daily ESAL's	% of Loaded Vehicles	ESAL Factor	% of All ESAL's
Aug-94	El Paso	13	1.5	11.33	91.9	0.87	2.3
	Laredo	390	26.1	310.30	85.6	0.92	24.8
Sep-94	El Paso	10	1.2	9.89	89.3	1.25	2.8
	Laredo	384	24.9	306.52	85.5	0.90	23.2
Oct-94	El Paso	11	1.3	9.85	90.6	1.16	2.7
	Laredo	382	25.2	267.41	85.0	0.85	23.3
Nov-94	El Paso	14	1.6	16.55	84.2	1.14	3.5
	Laredo	373	24.7	244.63	82.5	0.77	21.0
Dec-94	El Paso	7	1.3	6.03	84.2	1.00	2.5
	Laredo	355	25.1	222.89	79.0	0.81	20.6
Jan-95	El Paso	5	1.1	4.66	83.2	2.05	3.1
	Laredo	284	22.1	235.84	84.2	1.04	19.8
Feb-95	El Paso	11	1.7	22.17	83.6	1.90	2.2
	Laredo	228	19.4	199.12	86.5	1.13	17.2
Mar-95	El Paso	18	2.1	30.28	86.2	2.16	2.8
Apr-95	El Paso	15	2.1	18.95	87.7	1.72	2.2
May-95	El Paso	18	2.4	19.43	87.8	1.45	2.3
Jun-95	El Paso	19	2.4	27.07	89.3	1.85	3.0
	Laredo	148	14.3	265.38	97.5	1.89	16.9
Jul-95	El Paso	14	1.8	29.69	94.4	2.01	2.5
	Laredo	141	13.4	270.47	96.1	2.05	17.5
Aug-95	El Paso	16	1.7	30.56	90.5	2.29	2.9
	Laredo	58	12.9	126.42	94.7	1.94	14.8
Sep-95	El Paso	18	2.2	23.19	86.1	1.79	2.6

* Gross Vehicle Weight > 25,000 lbs.

Table 3.4 Summary of five-axle truck characteristics

5-Axles Trucks					Loaded* 5-Axles Trucks		
Month/Year	Site	Daily Volume**	% in Class	Daily ESAL's	% of Loaded Vehicles	ESAL Factor	% of All ESAL's
Aug-94	El Paso NB	701	86.0	373.58	82.2	0.63	86.8
	El Paso SB	(395)	-	(534.38)	96.9	1.39	-
	Laredo	944	61.6	764.91	79.7	1.02	60.8
Sep-94	El Paso NB	744	87.4	374.65	80.8	0.60	89.5
	El Paso SB	(426)	-	(574.53)	96.8	1.34	-
	Laredo	965	63.3	796.19	81.9	1.00	62.6
Oct-94	El Paso NB	751	86.4	382.65	84.3	0.62	87.3
	El Paso SB	(476)	-	(564.42)	97.3	1.29	-
	Laredo	971	63.3	757.48	80.3	0.97	63.2
Nov-94	El Paso NB	753	84.6	341.67	82.2	0.57	86.8
	El Paso SB	(438)	-	(542.03)	95.8	1.39	-
	Laredo	985	63.3	731.57	77.3	0.97	63.3
Dec-94	El Paso NB	513	89.0	216.57	73.0	0.59	85.6
	El Paso SB	(323)	-	(543.45)	96.7	1.62	-
	Laredo	891	63.4	684.78	75.0	1.00	61.0
Jan-95	El Paso NB	488	86.0	250.67	90.7	0.71	89.2
	El Paso SB	(238)	-	(180.88)	95.6	1.38	-
	Laredo	843	66.2	764.35	81.4	1.09	59.9
Feb-95	El Paso NB	638	82.2	814.13	97.1	1.38	89.3
	El Paso SB	(433)	-	(571.80)	95.3	1.53	-
	Laredo	789	67.8	853.93	86.3	1.14	60.8
Mar-95	El Paso NB	679	81.3	1014.69	95.5	1.55	88.9
	El Paso SB	(405)	-	(571.72)	95.5	1.60	-
Apr-95	El Paso NB	617	78.7	984.52	95.7	1.66	87.6
	El Paso SB	(389)	-	(469.22)	95.4	1.51	-
May-95	El Paso NB	595	76.7	872.98	96.2	1.55	85.9
	El Paso SB	(353)	-	(475.69)	92.7	1.42	-
Jun-95	El Paso NB	619	77.5	893.92	96.4	1.52	85.5
	El Paso SB	(396)	-	(614.11)	95.6	1.59	-
	Laredo	720	72.5	974.36	97.6	1.39	63.0
Jul-95	El Paso NB	725	79.1	927.58	96.8	1.48	86.1
	El Paso SB	(386)	-	(564.64)	95.2	1.61	-
	Laredo	721	72.7	1006.46	96.9	1.36	63.5
Aug-95	El Paso NB	787	79.2	1069.62	95.7	1.40	86.4
	El Paso SB	(397)	-	(596.13)	95.3	1.67	-
	Laredo	331	72.8	466.13	96.0	1.58	68.3
Sep-95	El Paso NB	681	77.5	1014.34	96.5	1.55	88.0
	El Paso SB	(272)	-	(450.33)	95.6	1.58	-

* Gross Vehicle Weight > 32,000 lbs.

**Figures in parenthesis represent between 40% to 60% the true value

Table 3.5 Summary of six-axle truck characteristics

6-Axles Trucks					Loaded* 6-Axles Trucks		
Month/Year	Site	Daily Volume	% in Class	Daily ESAL's	% of Loaded Vehicles	ESAL Factor	% of All ESAL's
Aug-94	El Paso	11	1.5	36.61	98.5	2.82	7.8
	Laredo	35	2.4	131.62	89.4	4.30	11.1
Sep-94	El Paso	9	1.1	20.50	98.6	2.18	5.1
	Laredo	37	2.4	115.19	87.3	4.40	11.0
Oct-94	El Paso	13	1.7	26.02	89.9	2.48	7.1
	Laredo	30	2.0	120.69	85.4	4.56	9.9
Nov-94	El Paso	13	1.8	19.84	77.7	2.49	7.6
	Laredo	35	2.2	129.91	88.1	4.31	11.3
Dec-94	El Paso	12	2.1	32.14	91.4	2.37	10.0
	Laredo	41	2.9	163.98	87.3	4.69	15.4
Jan-95	El Paso	7	1.3	21.62	100.0	3.84	8.2
	Laredo	48	3.8	230.87	92.2	4.98	17.8
Feb-95	El Paso	14	2.1	54.62	98.7	3.88	6.5
	Laredo	46	4.2	239.76	95.6	5.19	19.1
Mar-95	El Paso	13	1.7	50.38	100.0	4.57	5.8
Apr-95	El Paso	14	1.9	69.42	100.0	5.70	7.5
May-95	El Paso	13	1.9	69.34	98.3	5.49	7.7
Jun-95	El Paso	14	1.8	76.78	99.7	5.83	7.8
	Laredo	47	4.5	273.70	98.0	5.89	16.6
Jul-95	El Paso	16	1.8	75.36	99.1	5.67	7.9
	Laredo	40	4.1	224.13	98.1	5.71	15.2
Aug-95	El Paso	17	1.7	75.01	100.0	5.07	7.1
	Laredo	21	4.0	117.82	98.7	5.82	14.4
Sep-95	El Paso	12	1.5	52.57	98.8	5.46	6.3

* Gross Vehicle Weight > 38,000 lbs.

El Paso data (see Fig 3.2) show that the single-drive axle of four-axle trucks was even heavier than in Laredo. In El Paso, however, these vehicle types are represented by only a few trucks per day. Laredo data indicate that about 10 percent of the drive axles of two-axle trucks were overweight. At this location, 61,674 single axles were weighed during the analysis period, 12 percent of which were loaded in excess of 22 kip, or 110 percent of the permissible load. El Paso had only 4 percent of the 21,208 single axles over the 22 kip load.

Tandem axles comprise about 90 percent of all axles recorded at the two WIM sites. The tandem axles on the tractor and the trailer of 3S2 vehicles were loaded similarly (see Figs 3.3 and 3.4). For instance, in Laredo during 1994, 77 percent of both the tractor tandem and the trailer tandem axle load of 3S2 type trucks were within the legal limit. In El Paso during the same period, this value was 89 percent. During 1995 (see Fig 3.5 and Fig 3.6) these figures were 65 percent for Laredo and 75 percent for El Paso. In 1995 at Laredo, 7,360 of the 96,800 tandem axles (7.6 percent) were loaded between 38 kip and 42 kip (112 percent to 124 percent of the legal load). The corresponding ratio of 3S2 northbound tandem axle loads within this range in El Paso was 6 percent for the same year. The tandem axle on three-axle SU trucks also exceeded considerably the permissible load. This type of unit violated the limits in larger proportion in Laredo. It is noted that 85 percent of the SU and the 3S2 tandem axle loads were between 34 kip and 38 kip for all northbound trucks at both WIM sites during the analysis period.

Analysis of the load data sample for southbound five-axle trucks originating in the U.S. indicated that a larger percentage of these trucks was overloaded, even more than such trucks of Mexican origin. During 1994, 4,050 out of 18,600 (22 percent) tractor tandem axles and 2,240 out of 17,500 (13 percent) trailer tandem axles of southbound 3S2 vehicles at El Paso were loaded between 38 kip and 42 kip — that is, up to 8,000 lb over the legal U.S. tandem axle load (34 kip). In 1995, the proportion of overloaded tandem axles of 3S2 units fell to 36 percent. However, 24 percent of the 95,000 tandem axles on southbound 3S2 vehicles that were recorded exceeded the 38-kip load. The 85 percentile value mentioned previously for the entire analysis period was between 38 kip and 42 kip. The overloading of those five-axle trucks moving from the U.S. toward Mexico most likely reflects the higher axle loads allowed under Mexican laws. American truckers knowing the higher Mexican limits (and the reputed lack of enforcement) perhaps take advantage of this when loading on the north side of the border.

The tractor tandem axle on six-axle trucks (3S3) was most frequently overloaded at both WIM locations. In 1995, a stunning 81 percent of all recorded six-axle tractor tandems were above the legal limit. Twelve percent of the six-axle tractor tandems were loaded to between 54 kip and 58 kip. This represents axle loads of 160 percent to 170 percent of the U.S. legal load (34 kip). The characteristic overweight of the tandem drive axle on six-axle trucks was consistently observed in Laredo and El Paso.

The triple-axle group on the semi-trailer of 3S3 vehicles was flagrantly overweight. The percentage of tridem axles exceeding the legal limit (42 kip) varied from 62 percent to 87 percent. Laredo vehicles represent the worst case for both years. In 1994, 987 (31 percent) of the 3,227 triple axles recorded were more than 20 kip over the legal load. The following year, 44 percent had this characteristic. In El Paso, the excessive loads on these axles were between 46 and 68 kip. The tridem axles within these limits include 65 percent of all triple axles. Although these loads are alarming, six-axle trucks represent only 43 vehicles per day in Laredo (3 percent) and 13 in El Paso (2 percent).

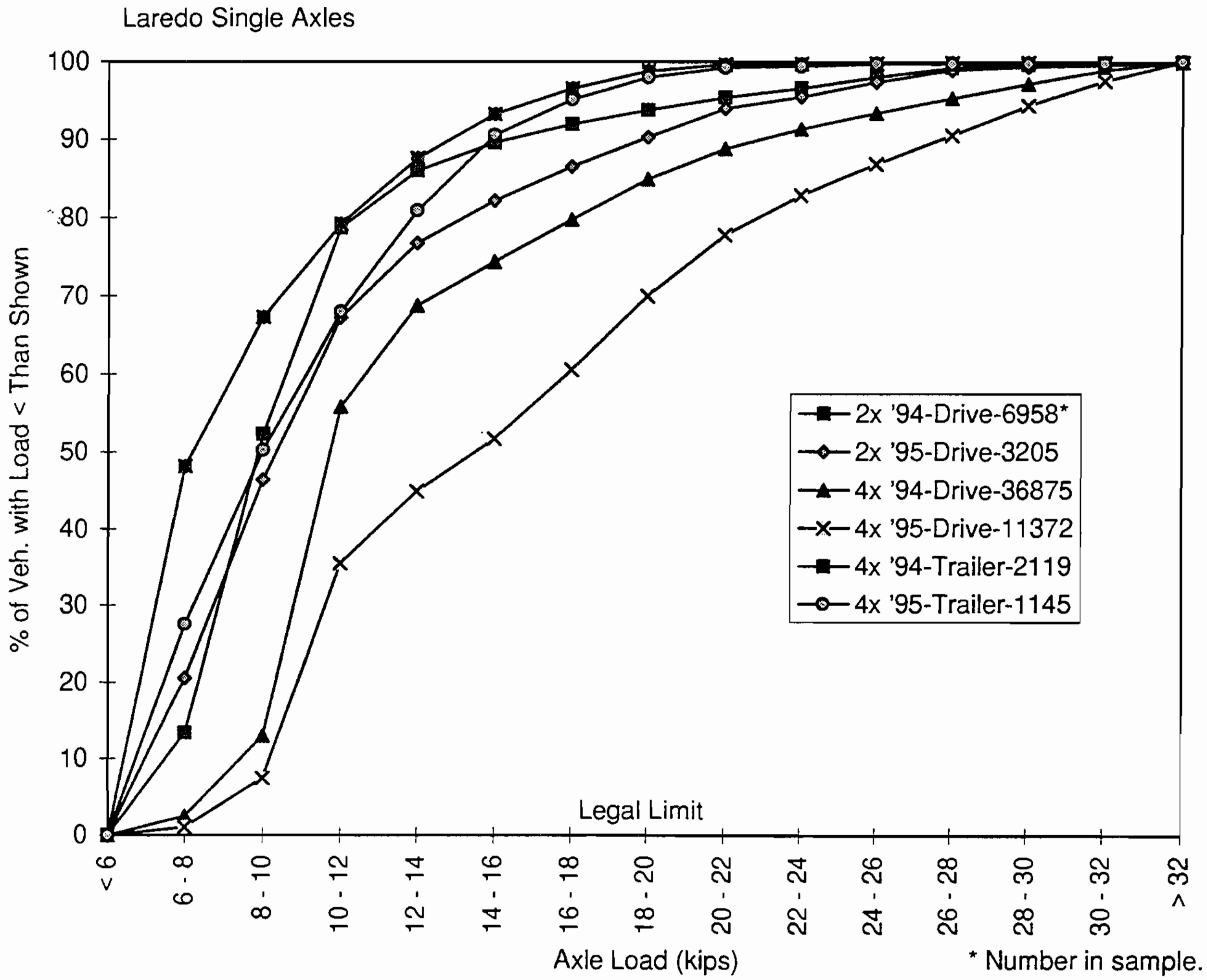

Figure 3.1 Single-axle loads at Laredo

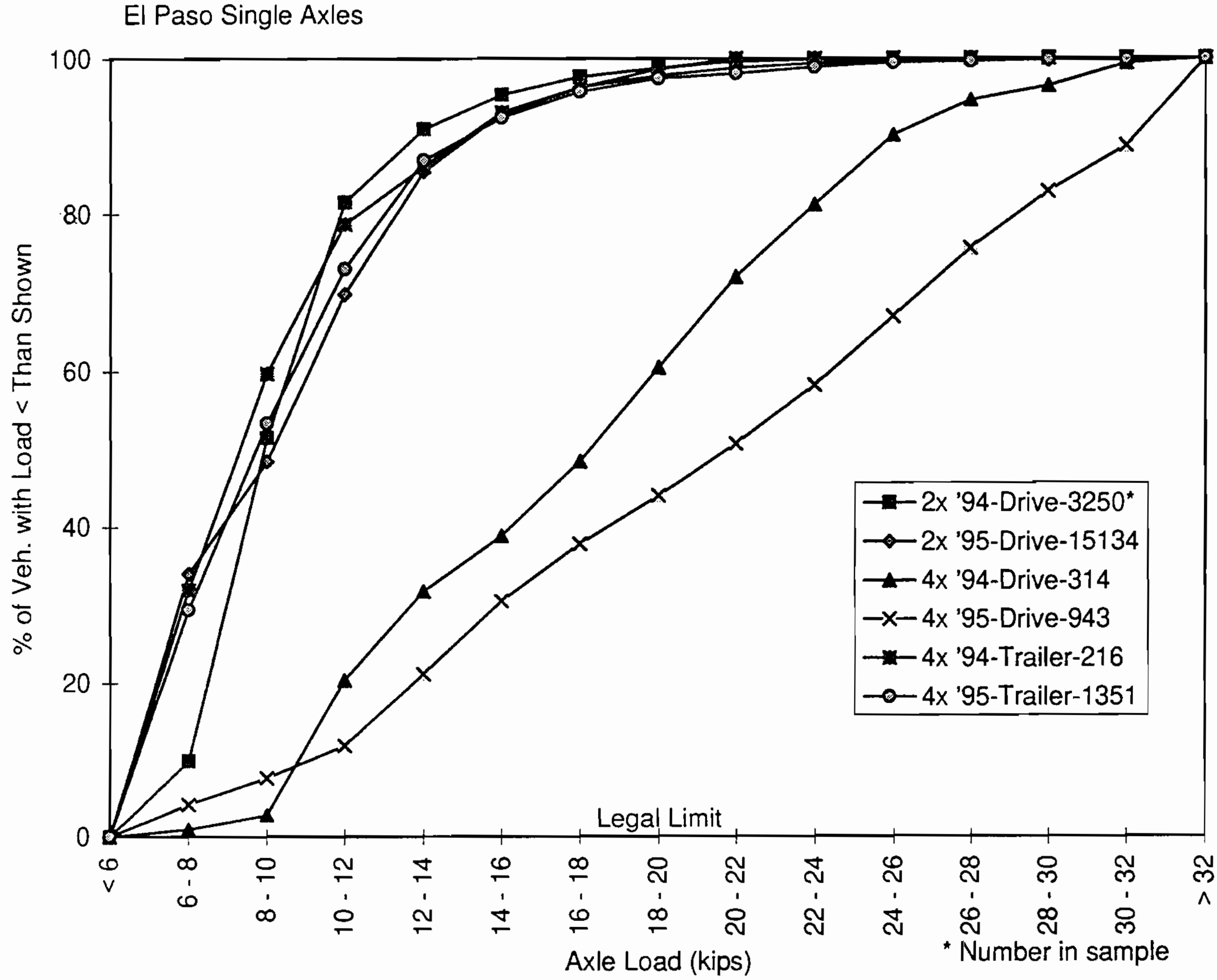

Figure 3.2 Single-axle loads at El Paso

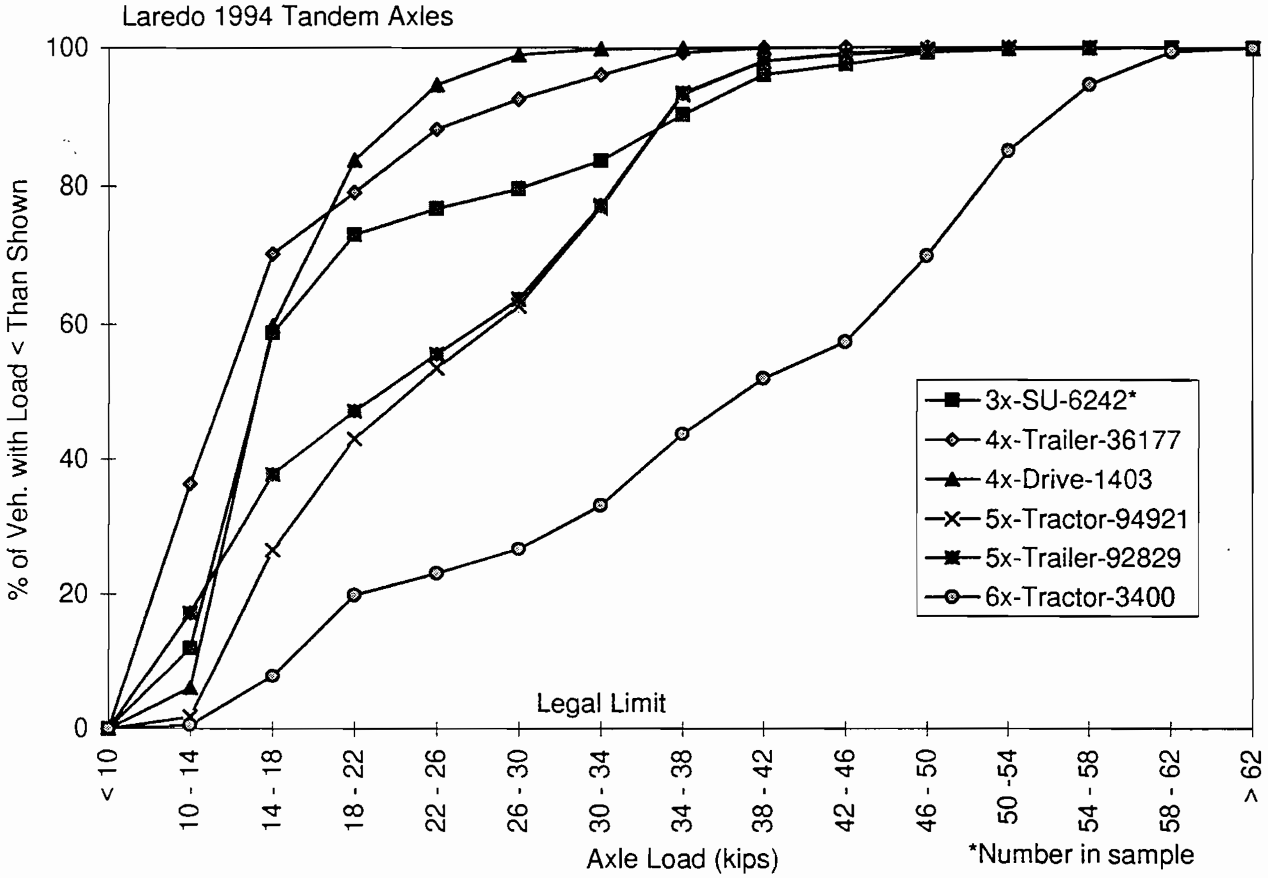

Figure 3.3 Tandem axles at Laredo during 1994

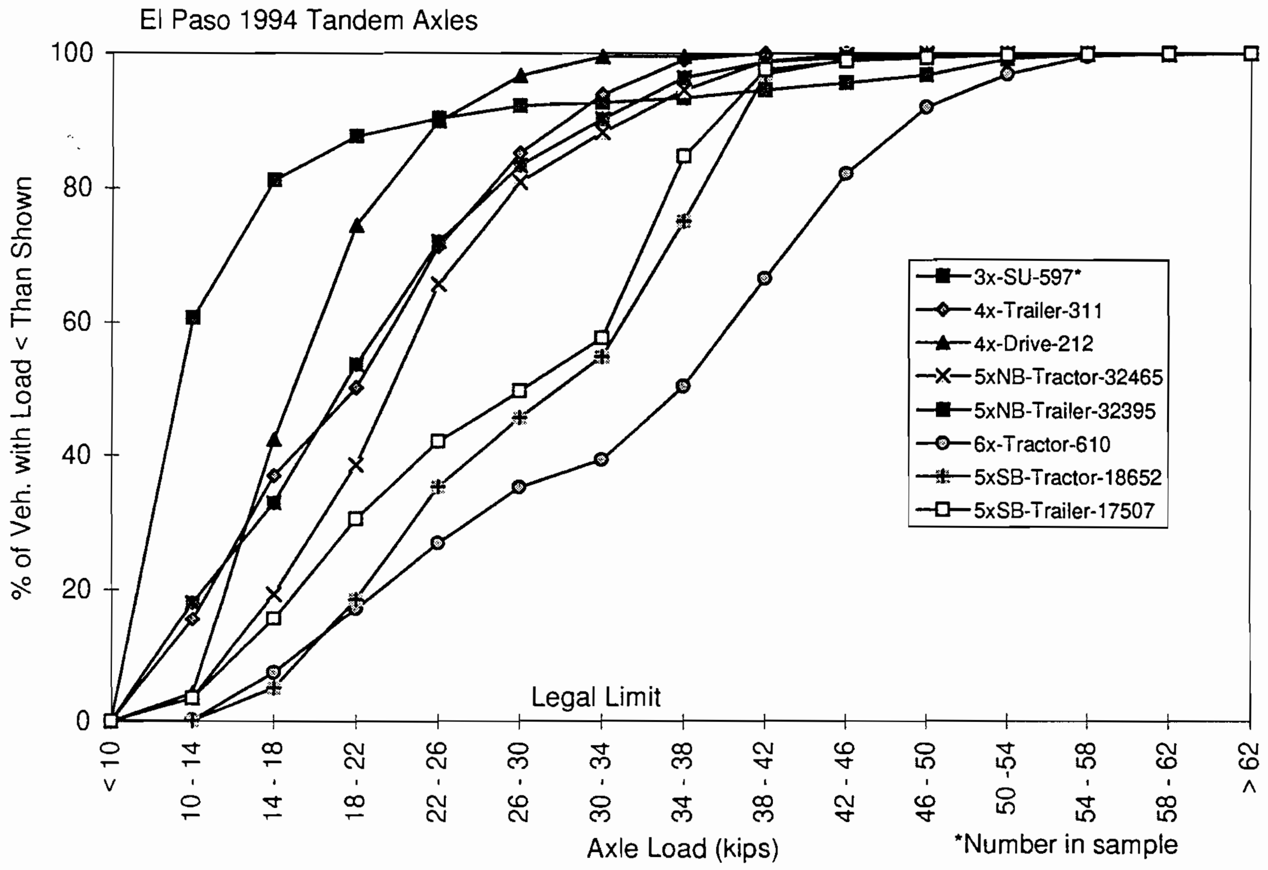

Figure 3.4 Tandem axles at El Paso during 1994

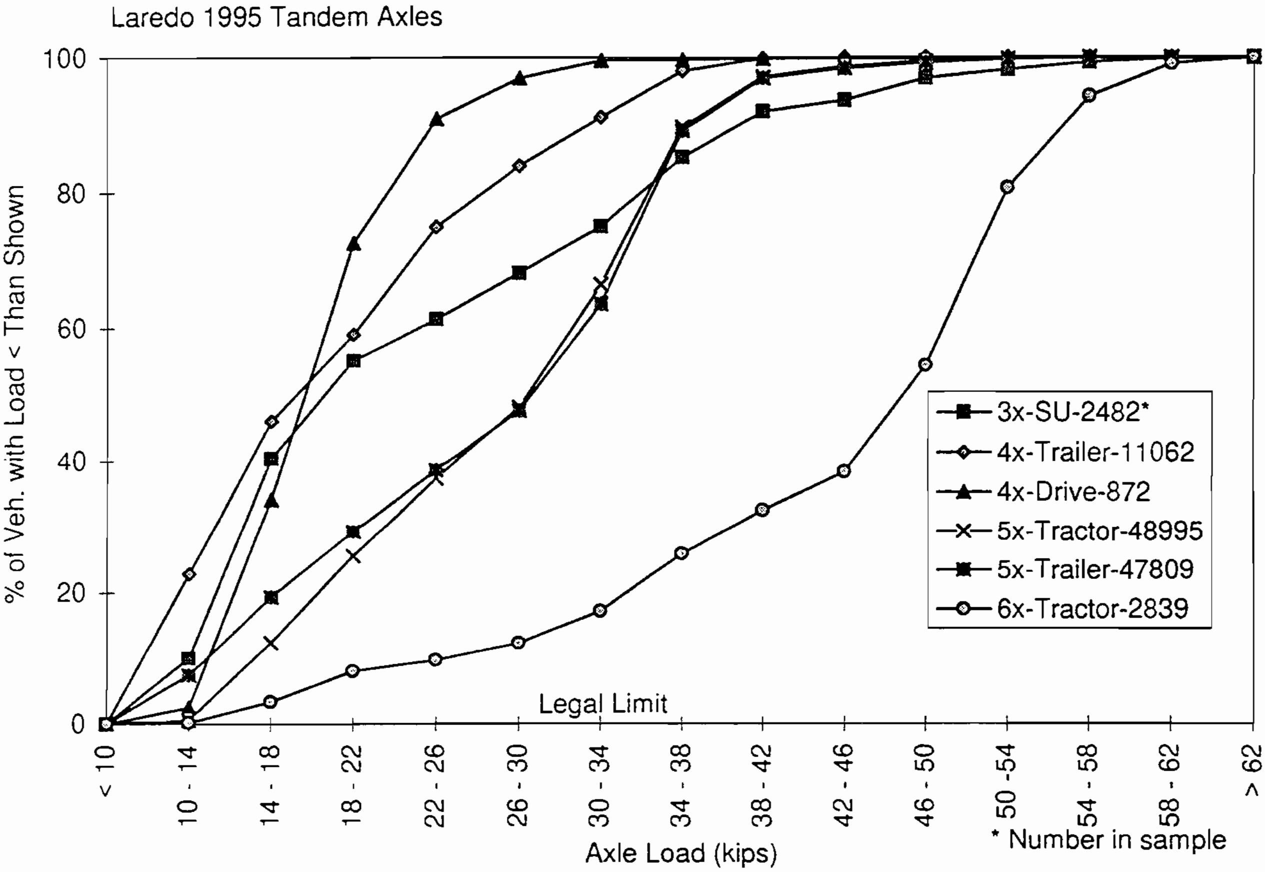

Figure 3.5 Tandem axles at Laredo during 1995

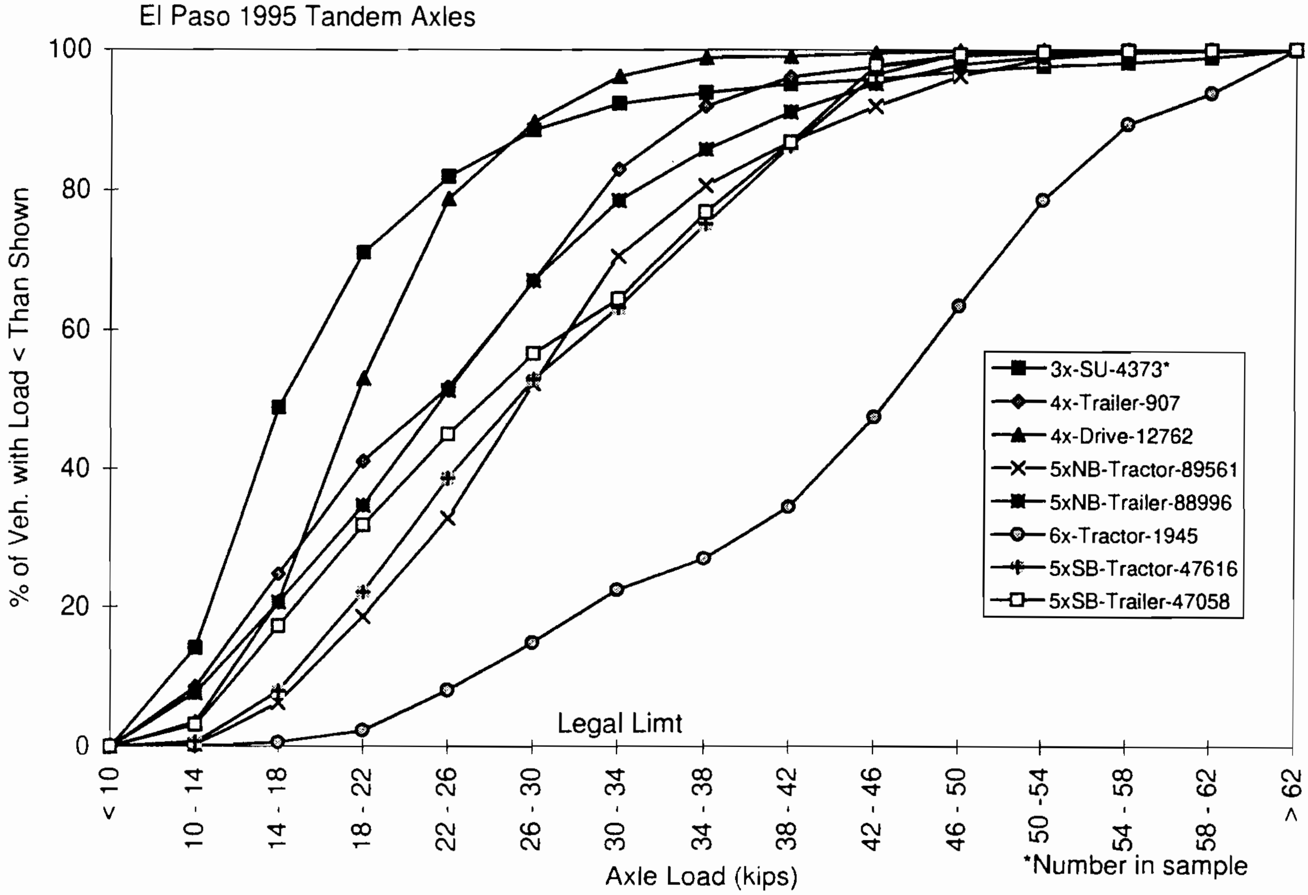

Figure 3.6 Tandem axles at El Paso during 1995

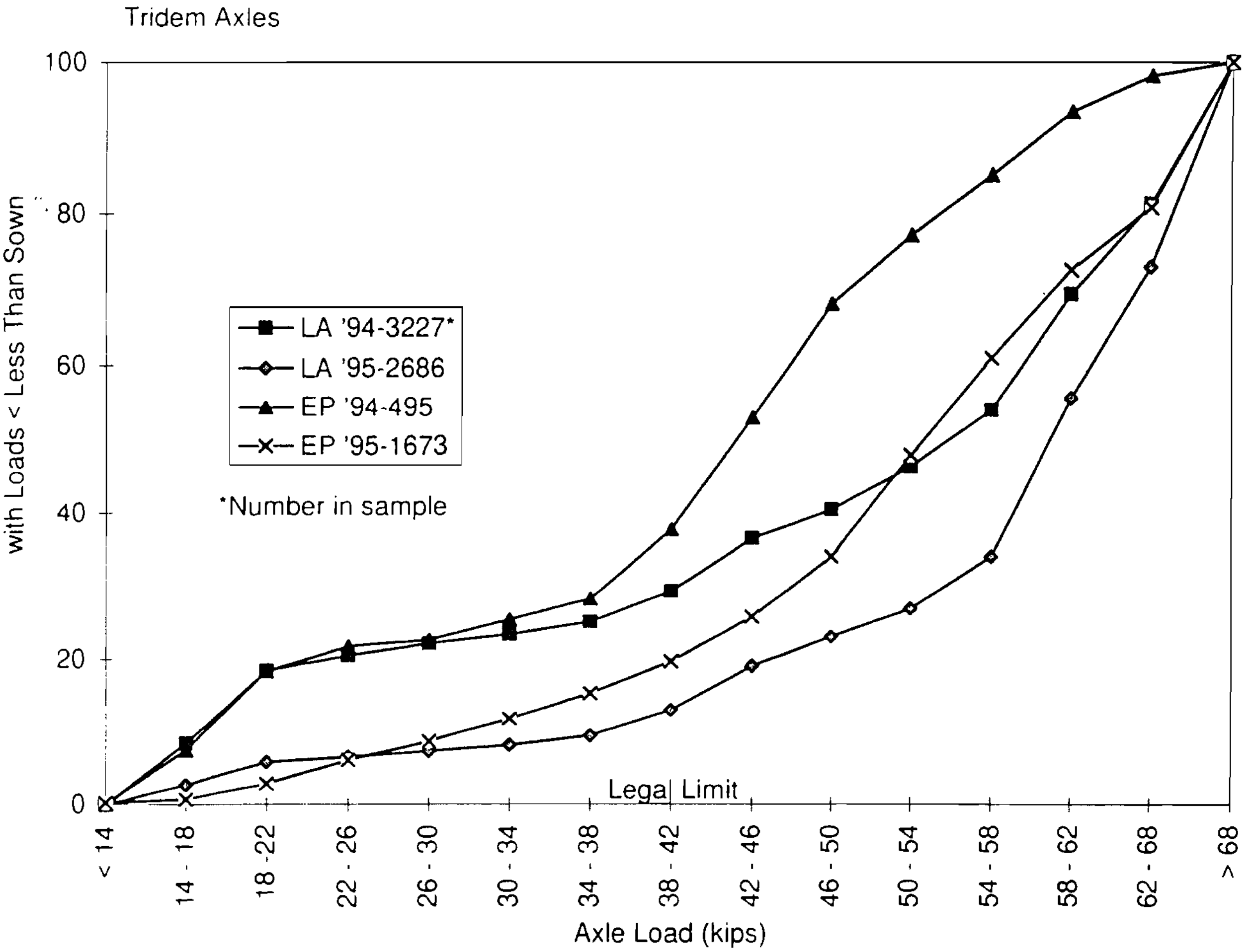

Figure 3.7 Tridem axles in Laredo and El Paso during 1994 and 1995

3.2. RELATIVE HIGHWAY DAMAGE BY LOADED TRUCKS

The pavement damage caused by various axle loads is estimated by applying an equivalent single axle load (ESAL)[13] factor. An equivalent single axle load (ESAL) factor is defined as the number of passes of a standard (usually 18-kip single) axle needed to equal the damage to a particular pavement structure caused by one pass of a given axle type (e.g., single, tandem, tridem, or steering) when it applies its observed (or assumed) load to the pavement. Thus, an average ESAL factor may be developed for a vehicle type (or axle arrangement) by summing the ESALs for all axles on all observed vehicles of that type and dividing by the number of observed vehicles. The average ESAL factor for selected truck types presented herein is assumed to be the number of ESALs generated by observed loaded[14] trucks divided by the number of such loaded trucks. Equivalent single axle loads were calculated assuming a flexible pavement with a characteristic structural number (SN) of 5.0 and a terminal serviceability index P_t of 2.5.

Figures 3.8 through 3.12 show plots of the average monthly ESAL factor for five vehicle types. These graphs generally show an increase in the relative damage after January 1995. This indicates an increase in the axle loads observed at the Laredo and El Paso ports of entry. The increment of change in Laredo was not as large as that in El Paso, as the trucks in Laredo were already carrying heavier loads.

As mentioned before, 10 percent of the two-axle trucks observed at Laredo had overloaded drive axles; half of these axles were loaded to around 22 kip. A single axle loaded to 22 kip (10 percent overload) increases the ESAL factor by 50 percent in reference to the legal limit of 20 kip. It was observed that the average ESAL factor for loaded two-axle trucks in Laredo rose from 0.33 in 1994 to 0.62 in 1995. El Paso experienced a proportional increase to 0.28. The magnitude of the ESAL factor for El Paso was expected, as only 2 percent of the two-axle trucks that crossed the WIM system were overweight. The three-axle trucks in Laredo produced about 1.7 times more damage in 1995 than in 1994, and generally about 1.2 times the damage caused by this truck type in El Paso. In both locations, the two- and three-axle trucks generated approximately 2 percent of all ESALs. An increase in ESAL factor magnitude between 1.5 and 2 times was observed for the four-axle trucks at El Paso (see Fig 3.10). This site generated 10 percent more ESALs for this truck type than Laredo. However, the ESALs generated by the four-axle trucks in Laredo account for 20 percent of all ESALs, while in El Paso they represent only 2 percent.

As shown in Figure 3.11, potential highway damage caused by northbound five-axle trucks increased dramatically during the first few months in 1995. There is a distinct shift in the pattern of loads after January 1995. A similar increase was noted in Laredo (northbound), although not in the same proportion as that of northbound El Paso. This indicates heavier loads on this predominant truck type. Five-axle trucks in El Paso accounted for about 88 percent of all ESALs generated by northbound trucks. In Laredo, on the other hand, five-axle truck ESALs represent about 63 percent of all ESALs. The loads of southbound five-axle trucks did not change

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[13] ESAL determination is discussed in Section 1.4.2.

[14] The criteria for <u>loaded</u> trucks are given in the second paragraph of Chapter 3.

significantly during the time frame presented. The southbound and northbound trucks have similar ESAL values: 1.56 for southbound and 1.51 for northbound. The northbound five-axle-truck ESAL value for Laredo during 1995 was 1.37, approximately 10 percent less than that for El Paso.

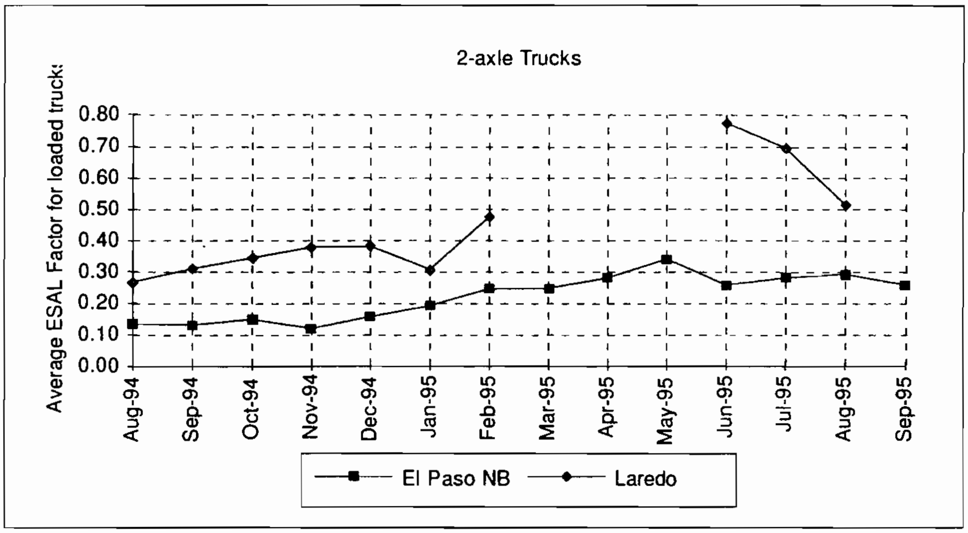

Figure 3.8 Average ESAL factor for two-axle loaded trucks

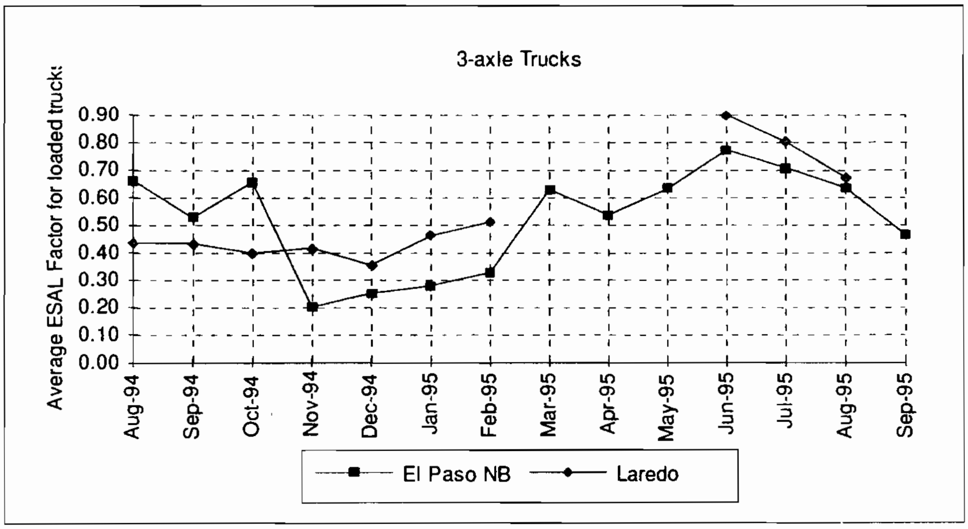

Figure 3.9 Average ESAL factor for three-axle loaded trucks

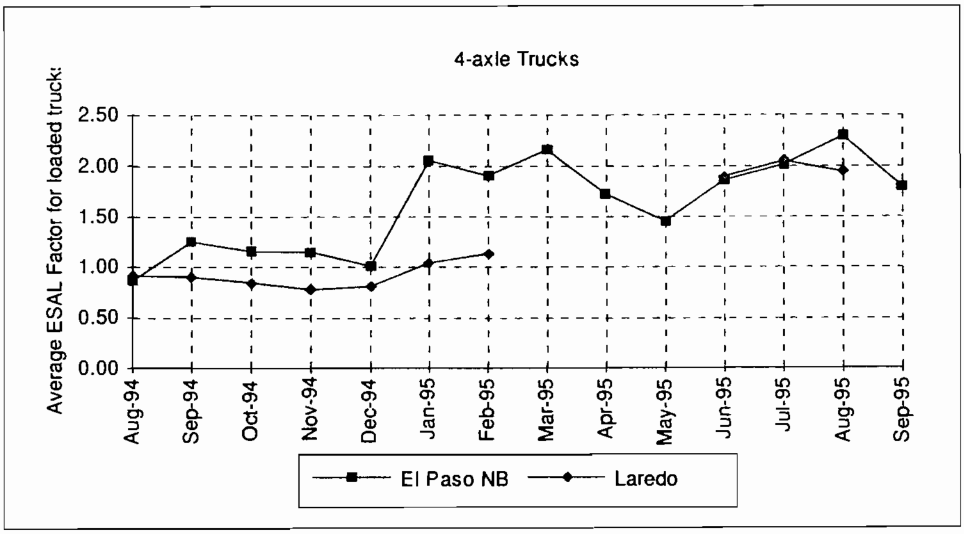

Figure 3.10 Average ESAL factor for four-axle loaded trucks

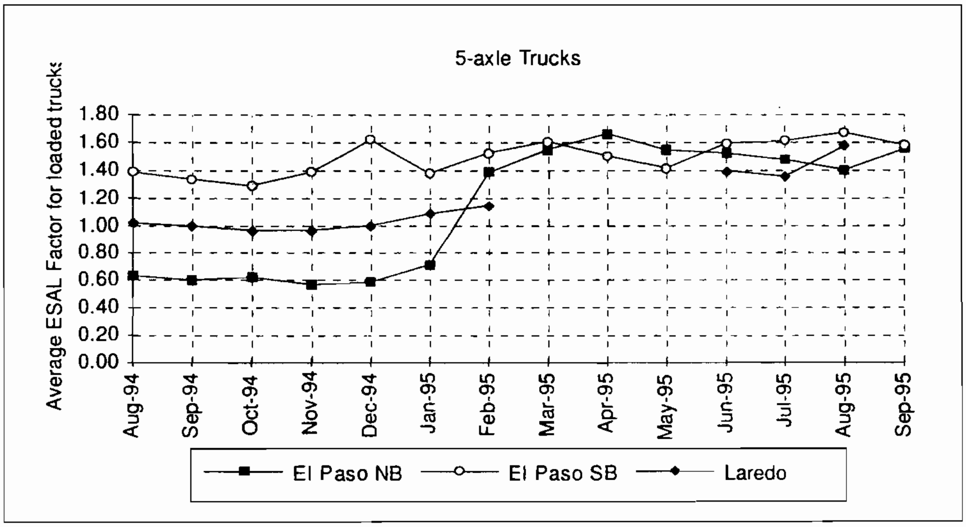

Figure 3.11 Average ESAL factor for five-axle loaded trucks

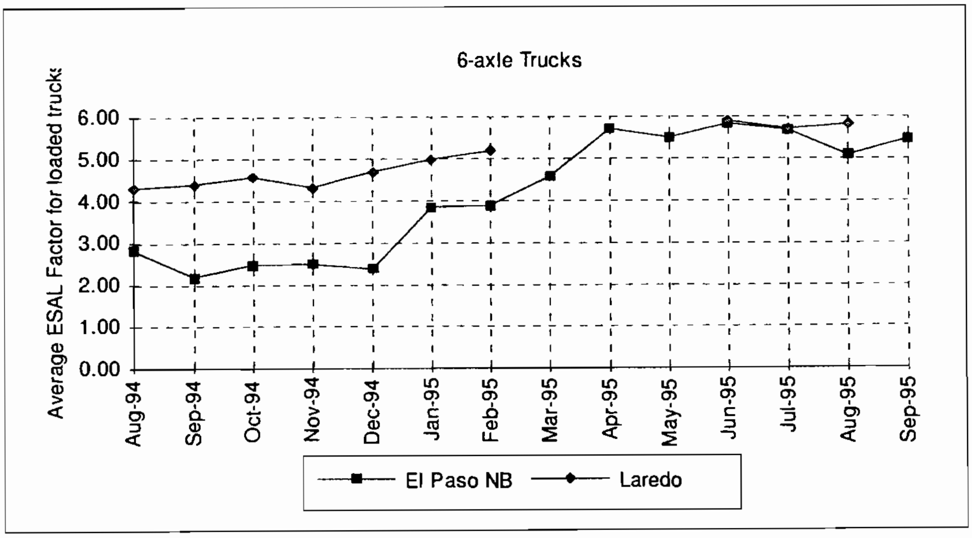

Figure 3.12 Average ESAL factor for six-axle loaded trucks

The ESAL factor at EL Paso for six-axle trucks increased steadily for the first three months of 1995 (see Fig 3.11). Afterwards, the factor reached a consistent level of around 5.54 — 2.2 times larger than in 1994. The change in Laredo was about 20 percent (4.7 to 5.65 ESALs); yet these six-axle trucks cause only 8 percent more damage to the road than those observed in El Paso. Six-axle trucks account for 7 percent of the total ESALs in El Paso — a disproportional amount, considering they represent only 2 percent of the vehicle count. In Laredo, six-axle trucks comprised only 3 percent of the truck count, though they produced 14 percent of the ESALs.

A 3S2 vehicle loaded to the legal limits can carry 34 kip on each tandem axle and 12 kip on the front axle (80 kip gross vehicle weight). This five-axle truck will generate 2.18 ESALs for pavement conditions of 2.5 terminal serviceability index and a structural number of 5. It will take 2.5 legally-loaded five-axle trucks to cause the same damage that a single pass of a typically-loaded six-axle truck will cause. Likewise, a typically-loaded six-axle truck observed during 1995 in Laredo caused the same damage as 4.1 typically-loaded five-axle rigs in that location. This ratio for El Paso is 1 to 3.5.

3.3. 1996 TRUCK LOAD PROFILES

Truck load profiles were developed for 1996 following the analysis of data obtained from Laredo and El Paso during 1994 and 1995. Truck loading characteristics observed at the weigh-in-motion stations in Laredo and El Paso in 1996 are described here.

The percentage of loaded (as contrasted to empty) trucks crossing the WIM system has remained about the same as that in 1995 with two exceptions. There were more empty two-axle trucks in El Paso and slightly more loaded four-axle trucks in Laredo. In terms of actual loads, almost all the single drive axles of two-axle trucks were within the legal limit at both Laredo and El Paso. This contrasts with the findings of the previous year in Laredo, where approximately 10 percent of the same axle group of this truck type was overloaded.

The tandem drive axle loading pattern of three-axle trucks in Laredo and El Paso did not change during 1996 as compared with 1995; it was around 10 to 15 percent overloaded axles. After the change in truck routing that occurred in Laredo on May 20, 1996 (all truck traffic uses International Bridge No. 1, resulting in more than a 600-percent increase in the number of single-unit three-axle trucks), the number of overloaded tandem axles on three-axle single-unit trucks decreased considerably. This can be attributed to the large number of three-axle tractors without a semi-trailer.

The single-drive axle of four-axle trucks (2S2 class) continued to be the dominant overloaded axle within this vehicle type. However, in this instance, we were less concerned, as the number of trucks within this truck class decreased significantly in 1996. This axle type is more heavily loaded in El Paso than in Laredo. About 45 percent of these axles were overloaded in El Paso (where the actual number of 2S2 trucks is quite small) and 14 percent in Laredo. Nearly all other axles on four-axle trucks were within the legal limit.

The number of overloaded tractor tandem drive axles on five-axle trucks in Laredo and El Paso was reduced by half during the first six months of 1996 as compared with 1995. Also, in Laredo the number of overloaded semi-trailer tandem axles on five-axle trucks was less than half that observed in previous years. In El Paso there was no significant change in the number of overloaded trailer tandem axles; about 15 percent of them were over the legal limit in 1996.

While there was some move towards load limit compliance on the tractor tandem drive axle on six-axle trucks (3S3 class), some 40 percent of these axles were still overloaded in Laredo; this figure for El Paso was 45 percent. This is the first period in which six-axle trucks in El Paso were heavier than those observed in Laredo. This change was also seen in the semi-trailer tridem axle of six-axle trucks. During the first six months of 1996 in Laredo, 28 percent of these axles were overloaded. Compared with the previous year, this represents a significant improvement. In 1995 in Laredo, 85 percent of such tridem axles were overloaded. In El Paso, the percentage of overloaded tridem axles in 1996 was 46 percent; while this is a significantly higher percentage than that in Laredo, it is lower than that in 1995 when 82 percent of the tridem axles observed in El Paso were overloaded. It is important to note that these percentages relate to a relatively small number of six-axle trucks counted at both WIM sites. The daily six-axle trucks counted in Laredo was about 50; in El Paso, the count was about 15.

A general tendency toward better compliance with legal load limits was seen in 1996 as compared to 1995, although the smaller trucks (two-, three-, and four-axle trucks) had loading characteristics similar to those surveyed in 1994. The improvement is noted mainly in two truck classes: five-axle trucks and six-axle trucks. This is important, given that five-axle trucks are the most common truck class used for international commerce, and six-axle trucks generally have the heaviest axle loads.

In terms of highway damage, the two- and three-axle trucks observed during 1996 generated approximately the same ESALs per truck as they did the year before at both WIM locations. The same applies to the four-axle trucks in El Paso. In Laredo, however, the ESAL factor for four-axle trucks diminished from 1.95 in the summer of 1995 to 0.85 in 1996 during the same period. Correspondingly, the percentage of all ESALs generated by the four-axle trucks in Laredo fell from 16 percent to 4 percent during the corresponding periods. The five-axle trucks in El Paso generated about the same ESALs per truck as they did the year before, namely, 1.51. In Laredo, the ESAL factor changed from 1.50 in the summer of 1995 to 1.20 in 1996. An even larger reduction was seen for six-axle trucks. In Laredo, the ESAL factor changed from 5.80 in the summer of 1995 to 2.32 for the same period in 1996. A comparable change in ESAL factor was also observed in El Paso for this truck type.

The restrictions imposed on Mexican trucks entering the U.S. may have had the effect of improving safety and load limit compliance. In addition, the large reduction in the number of overloaded six-axle trucks (and the subsequent reduction in ESAL generation), as well as the better compliance with load limits in 1996 by five-axle trucks in Laredo, may have come in response to a weight enforcement program deployed at the U.S. Custom yard in Laredo for a short period of time. This program targeted the larger trucks.

CHAPTER 4. CONCLUSION

For this study, weigh-in-motion (WIM) devices were used to count, classify (by number and arrangement of axles), and measure the axle loads of 449,886 trucks at two major land ports of entry for international commerce moving between Texas and Mexico. These devices were located near the exit gates of the U.S. Customs check points at International Bridge No. 1 in Laredo and at the Zaragosa International Truck Bridge in El Paso. In Laredo, only northbound trucks with Mexican origin passed over the WIM sensors, while in El Paso, southbound trucks of U.S. origin and northbound trucks of Mexican origin were processed.

Various circumstances, such as equipment malfunction, traffic routing, and vehicle queuing over the WIM sensors, precluded continuous data collection. However, the very large, representative sample of unique data collected during the approximately 1-year period from 1994 to 1995 was analyzed to define daily and monthly patterns of truck count and axle loads, and to identify changes in these patterns with respect to time.

Only weekday traffic was included in the analysis, as weekend traffic comprises only a small fraction of the total flow. In operation, northbound trucks at both sites are released in single file from the Customs yard before they pass over the WIM sensors, generally at a speed between 15 and 25 m/h. Axle-load, speed, and vehicle class measurements for these trucks are handled accurately and reliably by the WIM systems when all wheels cross over the sensors. However, when southbound trucks at El Paso form a queue in advance of the toll gate (stopping intermittently over the WIM sensors as they await processing by Mexican authorities), it is not possible for the system software to calculate axle spacing from the available sensor outputs. Thus, while automatic classification is not accomplished, wheel loads are measured and recorded, along with the time of the load determination. Manual data analysis makes it feasible, subsequently, to group axles and classify vehicles reasonably according to axle configuration and load. This technique was used on selected samples of data to develop characteristic count and axle-load profiles for southbound trucks at El Paso.

With respect to the various truck axle arrangements, the composition of truck traffic in Laredo differs from that in El Paso. At both locations, five-axle trucks constitute a major portion of all vehicles observed. In El Paso, five-axle rigs accounted for 82 percent of all trucks, while in Laredo, they comprised about 62 percent. These percentages translate to some 675 five-axle trucks per weekday in El Paso and about 925 in Laredo. The second most common truck type observed in Laredo was the four-axle configuration. Here, this type made up approximately 20 percent of the total number of trucks that passed over the WIM system. In El Paso, the second most-frequently-occurring truck type was the two-axle truck; it accounted for 11 percent of all trucks observed.

The predominance of four-axle trucks in Laredo, as compared with El Paso, might be associated with the popular drayage[15] (haul across the bridge) operation in Laredo. In Laredo, about 95 percent of all four-axle trucks that were recorded by the WIM system were the 2S2 type

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[15] Processing of international freight across the Texas-Mexico border is discussed extensively in Leidy (1995).

(two-axle tractor pulling a two-axle semi-trailer), while this type comprised some 45 percent of all four-axle trucks measured in El Paso. A two-axle semi-trailer can be towed by either a two-axle tractor or a three-axle tractor. It appears that the drayage operators frequently choose to use the more-economical two-axle tractor (single-drive axle) for moving loaded two-axle semi-trailers across the bridge. It is noteworthy that the loads of the single-drive axle on the tractor of 2S2 type trucks in Laredo exceeded the legal limit (20 kip) more frequently than any other single axle observed. Also, four-axle trucks in Laredo cause approximately 20 percent of the total estimated truck-induced pavement damage, while in El Paso they account for only about 2 percent.

Six-axle trucks — for example, the 3S3 type (three-axle tractor pulling a three-axle semi-trailer) — cause a significant amount of the traffic-induced pavement damage in the Texas-Mexico border area. Although these trucks constituted only about 3 percent of the total number of trucks observed, their loads are estimated to account for some 14 percent of the total traffic-induced pavement damage in Laredo and 7 percent in El Paso. Nearly 80 percent of the six-axle trucks observed in 1994 and 1995 were overweight. Axle loads on these trucks ranged up to 150 percent of the legal limit.

The relative amount of pavement damage caused by different axle types (steering, single, tandem, and triple), each carrying various loads, is usually estimated in terms of equivalent single axle loads (ESALs). An ESAL is the number of passes of a single axle carrying a standard load (usually 18 kip) needed to cause equal damage to a given pavement structure as one pass of the axle type under consideration when this axle applies its observed, or assumed, load to the pavement. Five-axle trucks, which include the 3S2 axle arrangement, accounted for 88 percent of all ESALs generated in El Paso and 63 percent of all ESALs generated in Laredo during the study analysis period. The number of overloaded tandem axles on 3S2 trucks increased in El Paso and Laredo during the first few months of 1995. In El Paso, the portion of overloaded tandem axles on this type truck changed from 11 percent in 1994 to 25 percent in 1995. The portion of overloaded tandems on 3S2 trucks observed in Laredo went from 23 percent in 1994 to 35 percent in 1995. Most of these overloaded axles had loads ranging between 34 and 38 kip (up to 12 percent above the legal limit). The ESAL factor for five-axle trucks in El Paso showed a dramatic increase in February 1995. Pavement damage caused by northbound and by southbound five-axle trucks in El Paso was approximately equal in terms of ESALs.

The portion of overloaded tandem axles on southbound five-axle trucks in El Paso fell from 44 percent in 1994 to 36 percent in 1995. WIM data at the Zaragosa International Truck Bridge indicated that southbound five-axle trucks were somewhat heavier than northbound trucks.

The truck count pattern — stable within the day-to-day operation — did not show significant changes on a monthly basis during the analysis period, though small variations were observed seasonally. In the summer of 1995, an 11 percent increase in the truck count was observed. The southbound truck count in El Paso did not indicate any significant fluctuation in the truck count during this period. An increase in truck count may be related to an influx of agricultural goods from Mexico. Given that summer is the Mexican harvest season and that the U.S. is not a major exporter of agricultural products to Mexico, the observed increase in the northbound truck count pattern for the summer months might be related to the movement of agricultural goods into the U.S. In addition, an increase in small units was observed in the northbound truck count in El Paso. During December 1994 and January 1995, we observed a nearly 30-percent drop in traffic in Laredo and El Paso. The decrease in traffic was perhaps a consequence of the Mexican peso devaluation, which took place in December 1994. In February 1995, the truck count rose to a value similar to that observed before the devaluation — a phenomenon that may indicate the stabilization of the currency. Data continue to be collected at the Laredo and El Paso WIM systems to gain further insights in the international truck crossing characteristics along the Texas-Mexico border.

Following the initial data analysis period (1994–1995), we incorporated additional data obtained for the January to July 1996 period. These data show that Laredo truck traffic has increased while El Paso truck traffic has remained stable. In Laredo, the number of 2S2 four-axles trucks have decreased significantly and are no longer the second most predominant truck in the area. Two-axle trucks in Laredo have increased in number and are now the second most predominant. In Laredo and El Paso, five-axle trucks predominate and account for about 75 percent of all truck traffic in the area. Drivers of the five-axle trucks and the six-axle trucks in Laredo and El Paso are showing better compliance with load limits. With respect to the six-axle trucks in Laredo, the instances of compliance with the legal limit has more than doubled over the previous year. However this figure still represents between 30 to 40 percent of the overloaded trucks. This loading tendency may be a reflection of a weight enforcement activity established at the U.S. Custom yards in Laredo. This program targeted large vehicles, including six-axle trucks and five-axle trucks.

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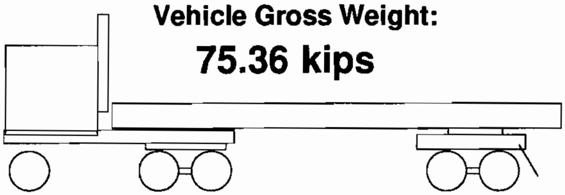
APPENDIX A

WIM CALIBRATION DATA

Project 1319 - Laredo
6/28/95 WIM Calibration

Calibration Truck: TxDOT Lic. Plate 969 - 180
Reference Weight:



Vehicle Gross Weight:
75.36 kips

Steering Axle	**Drive Axle Group**	**Tandem Axle**
10.9 kips	32.9 kips	31.56 kips

Spacing: 12.3 ft 4.5 ft 32.7 ft 4.0 ft

Calibration Settings Before Changes	
Sensitivity Leading Weigh Pad:	1500
Sensitivity Trailing Weigh Pad:	1500
Sensitivity:	**1400**
Corr.-Fact. 1:	1020
Corr.-Fact. 2:	**1070**
Corr.-Fact. 3:	1000
Speed Point 1:	1500
Speed Point 2:	2500
Speed Point 3:	3500
Peak Limit:	7

Trial 1 Sensitivity

Run / Record Number	Attempted Speed	Measured Speed	Measured Load			
			Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1 824	15	16	74.4	9.9	33.7	30.8
2 830	15	16	72	10	32.2	29.7
3 833	15	16	72.2	10.1	31.8	30.1
4 845	15	17	73.1	9.3	34.1	29.4
5 853	15	16	76.7	9.8	35.1	31.7
		Average	73.68	9.82	33.38	30.34
		Difference from Known Weight:	-2.23%	-9.91%	1.46%	-3.87%

Trial 2

Run / Record Number		Attempted Speed	Measured Speed	Measured Load Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1	943	15	16	80.7	10.5	36.9	33
2	964	15	16	79.3	10.4	36	32.7
3	979	15	16	74.8	10.8	33.7	30.2
4	987	15	16	79.6	10.4	35.6	33.4
5	1007	15	16	79	10.7	35.2	33
			Average	78.68	10.56	35.48	32.46
		Difference from Known Weight:		4.41%	-3.12%	7.84%	2.85%

Eliminating Run 3

Deviation from Average of Runs

New Sensitivity Factor:

Interpolating between (1400, 72.93) and (1445, 79.63)

Sensitivity: 1416 Time: 1610

Trial 3

Run / Record Number		Attempted Speed	Measured Speed	Measured Load Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1	1090	15	15	73.5	10.7	32.6	30.1
2	1113	15	16	79.3	10.5	35	33.6
			Average	76.4	10.6	33.8	31.85
		Difference from Known Weight:		1.38%	-2.75%	2.74%	0.92%

New Sensitivity Factor:

Interpolating between (1400, 72.93) and (1416, 76.4)

Calculated Sensitivity: 1411

IMPUT VALUE:1422 Time: 1626

Trial 4 Verification

Run / Record Number		Attempted Speed	Measured Speed	Measured Load Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1	1090	15	15	73.5	10.4	31.6	31.4
			Average	73.5	10.4	31.6	31.4
		Difference from Known Weight:		-2.47%	-4.59%	-3.95%	-0.51%

Trial 1B Correction Factor 2 - Speed Point 2500

Run / Record Number	Attempted Speed	Measured Speed	Measured Load			
			Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1 1132	25	23	76.7	10.6	33.9	32
2 1137	25	24	77.6	10.6	34.6	32.1
		Average	77.15	10.6	34.25	32.05
Difference from Known Weight:			2.38%	-2.75%	4.10%	1.55%

New Correction Factor 2: 1045 $= \frac{1070*75.36}{77.15}$

Time:1640

Trial 1B Correction Factor 2 Verification

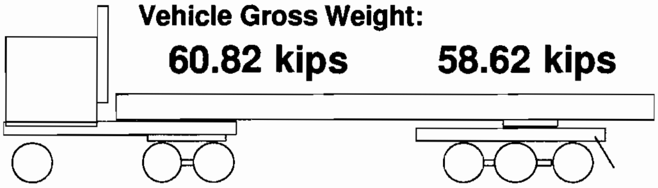
Run / Record Number	Attempted Speed	Measured Speed	Measured Load			
			Gross Weight	Steering Axle	Drive Axle Group	Tandem Axle Group
1 1149	25	23	74.7	10.4	32.8	31.3
2 1171	25	24	75.5	10	34	31.3
		Average	75.1	10.2	33.4	31.3
Difference from Known Weight:			-0.35%	-6.42%	1.52%	-0.82%

Current Calibration Settings	
Sensitivity Leading Weigh Pad:	1500
Sensitivity Trailing Weigh Pad:	1500
Sensitivity:	**1422**
Corr.-Fact. 1:	1020
Corr.-Fact. 2:	**1045**
Corr.-Fact. 3:	1000
Speed Point 1:	1500
Speed Point 2:	2500
Speed Point 3:	3500
Peak Limit:	7

Project 1319 - El Paso
6/1/94 WIM Calibration

Calibration Truck: TxDOT Six-AxleTruck. Lic. Plate 951-166

Reference Weight: *First Calibration* *Second Calibration*



Vehicle Gross Weight:

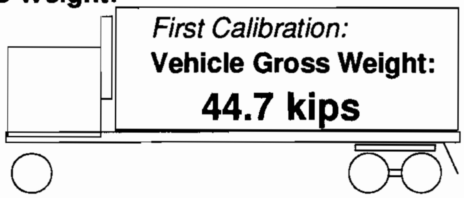
60.82 kips **58.62 kips**

First Calibration:

Steering Axle	**Drive Axle Group**	**Tandem Axle**
10.24 kips	24.48 kips	26.1 kips
Second Calibration:		
96.4 kips	24.98 kips	24 kips

Calibration Truck: TxDOT Three-Axle Dump Truck. Lic. Plate 300-923

Reference Weight:



First Calibration:
Vehicle Gross Weight:
44.7 kips

Second Calibration:
59.12 kips

First Calibration:

Steering Axle	**Drive Axle Group**
13.9 kips	30.8 kips
Second Calibration:	
16.04 kips	43.26 kips

Second Calibration: 8/12/94-8/13/94

Trial 1

Three axle-truck

Lane 1				Lane 2			
Speed	GVW	Right Side Load	Left Side Load	Speed	GVW	Right Side Load	Left Side Load
6	56.01	24.67	31.34	6	54.96	24.48	30.48
5	55.16	24.63	30.53	7	55.07	24.88	30.19
7	56.90	24.44	32.46	6	54.03	24.13	29.90
6	55.20	24.14	31.06	6	55.24	24.89	30.85
6	55.43	24.29	31.14	7	55.08	24.93	30.15
8	54.93			7	54.64	25.09	29.55
6	55.15	24.03	31.12	7	54.59	23.97	30.62
7	56.93	25.07	31.86	6	55.59	24.39	31.20
6	55.55	24.37	31.18	10	55.91	24.57	31.34
11	53.91	23.53	30.38	10	57.33	25.35	31.98
11	55.03			10	56.43	24.60	31.81
11	56.40	25.65	30.75	15	59.34	25.85	33.49
15	59.54	26.46	33.08	15	59.79	25.96	33.83
15	58.23	25.51	32.72	15	59.16	25.76	33.40
15	60.78	27.31	33.47	20	54.89	23.81	31.08
20	55.02	24.63	30.39	19	56.08	24.71	31.37
20	54.38	23.85	30.53	19	55.48	24.18	31.30
20	55.57	24.55	31.02	24	54.48	23.14	31.34
22	54.75	25.13	29.62	19	53.26	23.52	29.74
19	57.84	25.97	31.87	26	56.60		
25	50.33	20.99	29.34	28	52.36	23.14	29.22
20	55.18	24.55	30.63	25	54.33	24.01	30.32
21	55.89	25.01	30.88	25	54.00	23.12	30.88
20	54.92			28	51.99	22.95	32.90
20	55.50			29	51.89	22.81	20.08
21	53.83			28	50.44		
				26	50.24		
				29	53.32		
				28	52.08		

Six-Axle Truck	(Trial 1, continuation)						
Lane 1				Lane 2			
Speed	GVW	Right Side Load	Left Side Load	Speed	GVW	Right Side Load	Left Side Load
8	56.79	25.89	30.90	10	58.42	27.71	30.71
9	58.65	27.07	31.58	9	58.14	26.71	31.43
11	58.09	27.15	30.94	9	61.38	28.61	32.77
11	60.74	28.46	32.28	9	56.74	26.38	30.36
11	59.66	27.79	31.87	11	58.77	28.13	30.64
15	59.92	28.19	31.73	16	61.64	29.06	32.58
15	61.95	29.44	32.51	15	62.55	29.65	32.90
15	60.94	28.50	32.44	20	53.58	24.52	29.06
20	56.94	26.50	30.44	21	52.32		
20	56.98	26.84	30.14	28	54.28		
20	56.46			26	56.58		
20	56.09			28	55.32		
20	56.80			15	64.73	31.04	33.69
				20	52.85		

Trial 2							
Three axle-truck				Six-Axle Truck			
Lane 1		Lane 2		Lane 1		Lane 2	
Speed	GVW	Speed	GVW	Speed	GVW	Speed	GVW
20	58.09	21	59.62	11	59.55	16	61.63
20	58.46	6	60.26	11	63.22	15	61.90
22	58.86	10	60.06	20	55.75	20	63.07
6	59.89	26	60.59	15	59.45	20	59.99
26	60.59	28	59.78	19	60.53	27	60.56
14	60.02	12	60.56	19	58.42	19	58.89
20	58.04	14	63.31	15	60.66	20	57.69
8	58.47			20	58.94	20	59.43
20	58.31			19	58.29	27	59.54
19	56.99			15	60.97		
				15	59.62		
				20	59.64		

Trial 3

Three axle-truck				Six-Axle Truck			
Lane 1		Lane 2		Lane 1		Lane 2	
Speed	GVW	Speed	GVW	Speed	GVW	Speed	GVW
12	58.97	11	59.18	11	61.17	11	63.31
12	62.76	11	57.63	11	62.85	8	60.65
15	60.39	18	57.19	11	60.96	11	60.27
10	59.64	11	57.88	10	61.46	16	57.05
16	57.05	23	55.93	15	59.61	16	61.47
16	58.24	20	56.66	15	60.31	15	60.65
19	57.75	18	57.00	15	61.38	20	56.26
17	54.85	24	56.91	15	60.90	20	57.19
19	56.52	21	55.83	15	61.16	15	61.33
19	56.01	20	56.82	15	61.81	20	57.17
19	56.18	20	55.72	15	60.91	20	57.97
19	55.88	22	56.62	15	60.26	20	58.10
19	57.42	22	55.11	15	62.53	20	57.83
19	55.61	22	54.34	15	61.85	15	60.30
19	57.34	26	55.57	15	61.38	20	56.82
15	58.37	17	58.58	11	61.90	15	61.04
17	56.28	26	55.97	11	62.07	20	56.22
20	56.64	26	54.14	11	59.88	9	60.79
19	57.29	28	55.63	11	61.98	8	61.22
20	56.01	28	55.35	15	62.65	19	60.71
19	57.64	19	57.53	19	56.41	15	61.17
18	51.77	26	56.61	15	61.01	15	60.48
18	55.84	26	54.77	11	61.13	11	60.07
19	56.63	28	55.69	11	62.21	11	60.26
13	61.50	26	57.37	15	61.83	15	60.10
19	57.01	27	56.16	15	61.85	15	60.52
19	57.85	17	57.04	15	60.76	22	54.00
20	57.69	26	55.03	15	61.79		
18	55.68	25	55.24	15	59.86		

"Stop and Go" Test on Lane 2
Three--axle truck

time over weight pad (sec.)	GVW
10	60.96
30	61.58
60	59.95
120	61.89
300	61.36

Lane 1: Northbound

Current Calibration Settings	
Sensitivity Leading Weigh Pad:	1470
Sensitivity Trailing Weigh Pad:	1330
Sensitivity:	1475
Corr.-Fact. 1:	1050
Corr.-Fact. 2:	965
Corr.-Fact. 3:	1065
Speed Point 1:	1000
Speed Point 2:	1700
Speed Point 3:	2500
Peak Limit:	10

Lane 2: Southbound

Current Calibration Settings	
Sensitivity Leading Weigh Pad:	1470
Sensitivity Trailing Weigh Pad:	1330
Sensitivity:	1440
Corr.-Fact. 1:	1015
Corr.-Fact. 2:	1050
Corr.-Fact. 3:	1100
Speed Point 1:	1000
Speed Point 2:	2000
Speed Point 3:	3000
Peak Limit:	15

APPENDIX B

IMAGES OF WEIGH-IN-MOTION SYSTEMS

Figure B.1: Pavement surface recondition for WIM installation.

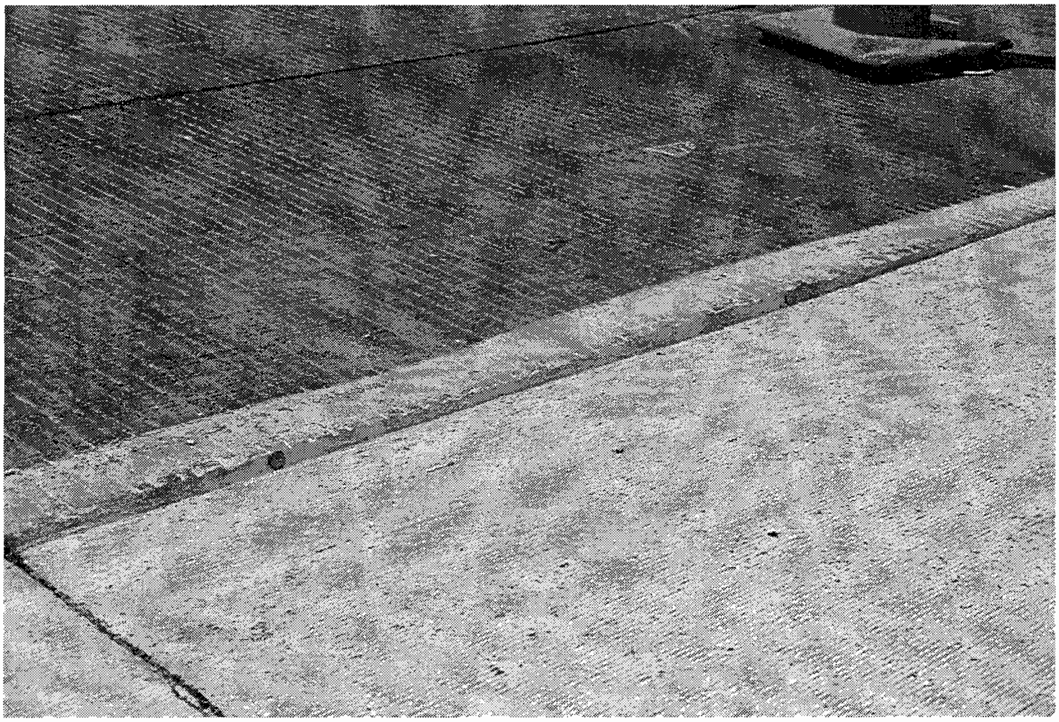


Figure B.2: Surface profile before and after grinding. Note U.S. pennies (1.9 cm diameter at deepest cuts).

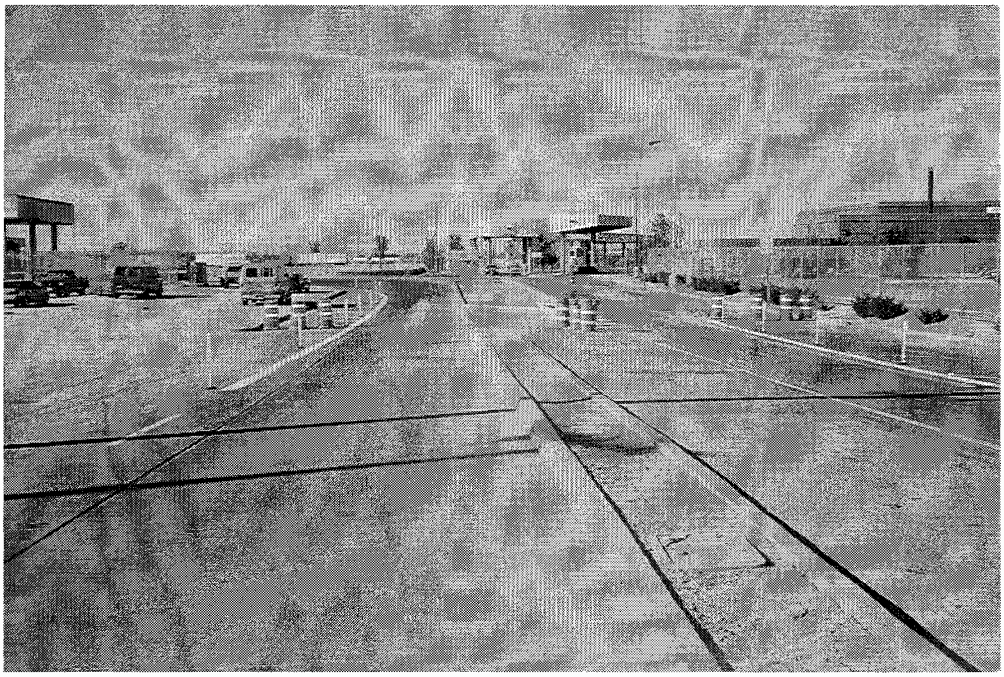


Figure B.3: El Paso WIM lanes and US Customs gates. Left lane is for trucks entering the US, right lane is for trucks entering Mexico.

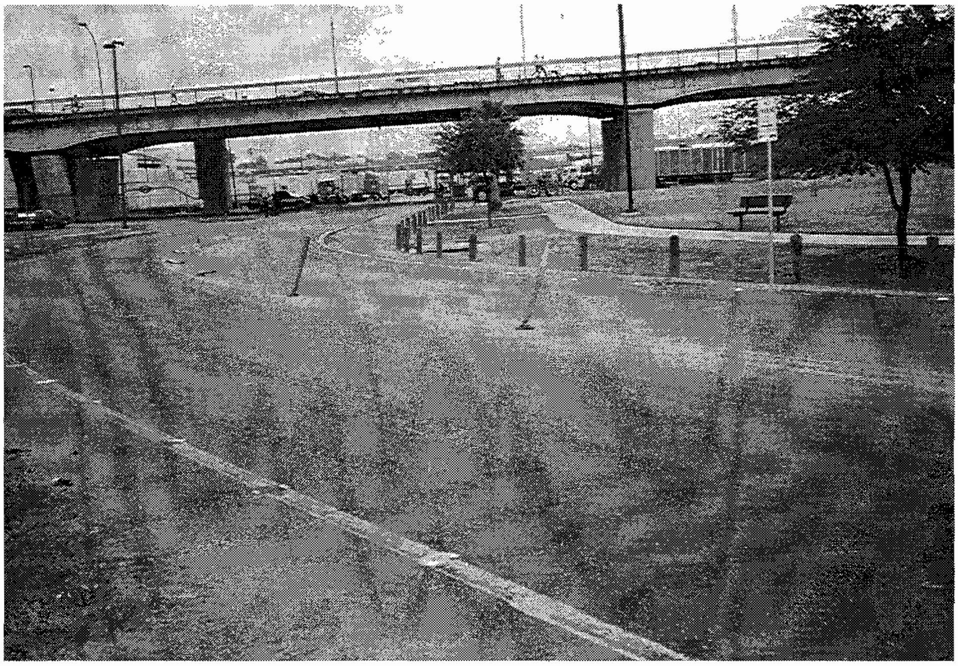


Figure B.4: Laredo WIM lane and US Customs gates. Left lane (in photo) is for trucks entering the U.S.

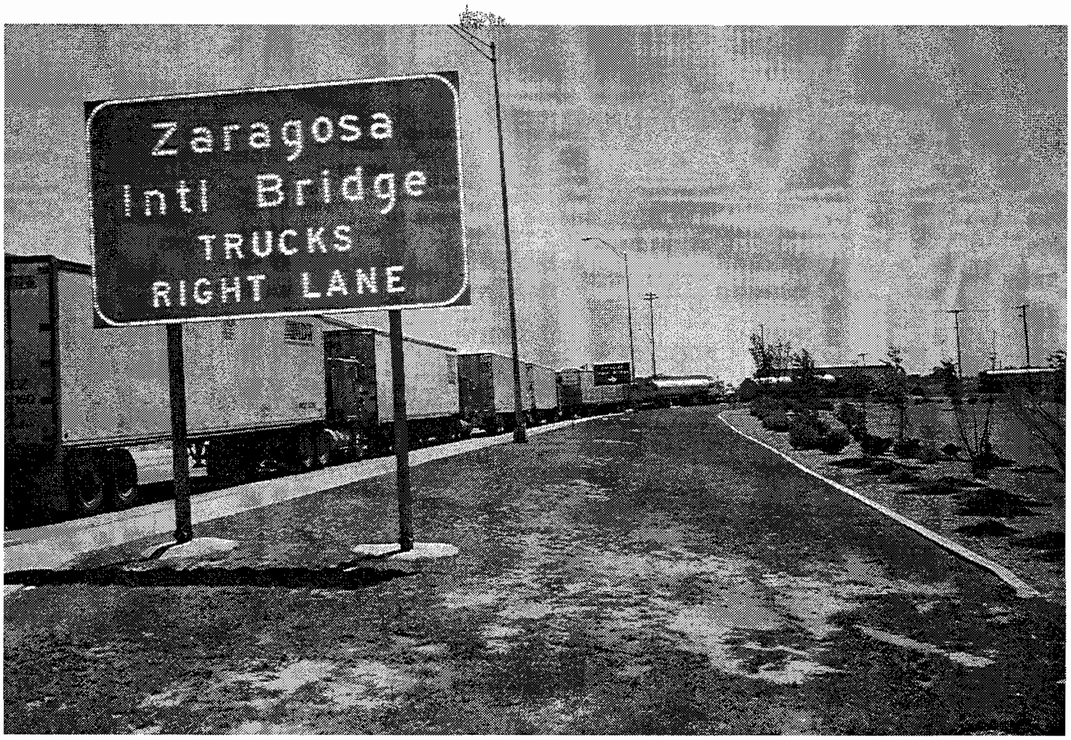


Figure B.5: Traffic congestion in southbound access in El Paso.

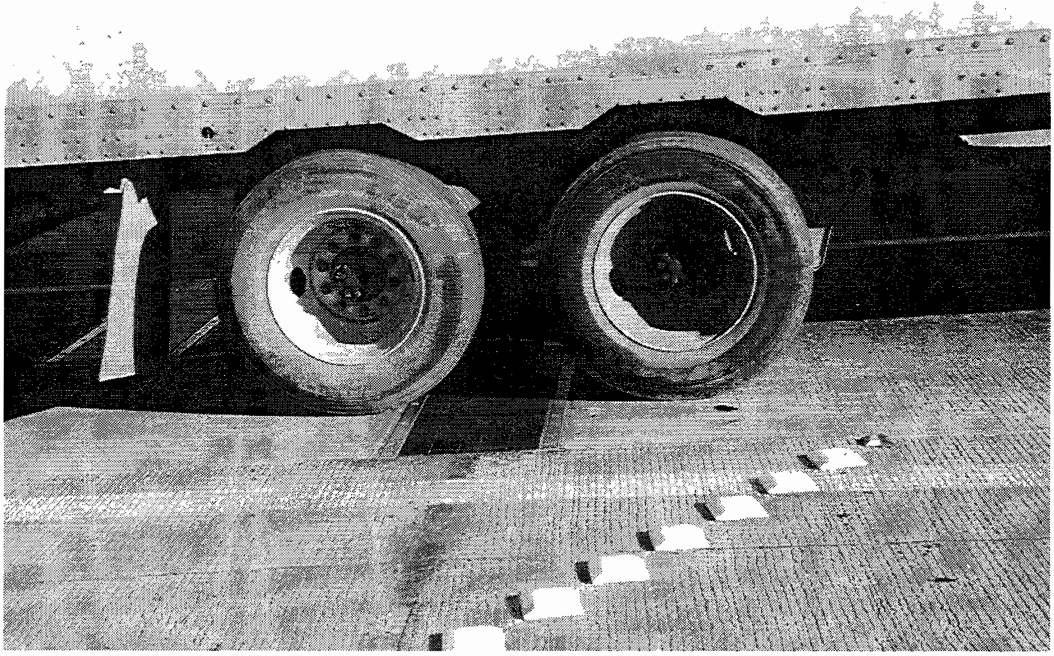


Figure B.6: Truck moving over WIM weigh pad.

APPENDIX C

DAILY TRUCK COUNT BY MONTH

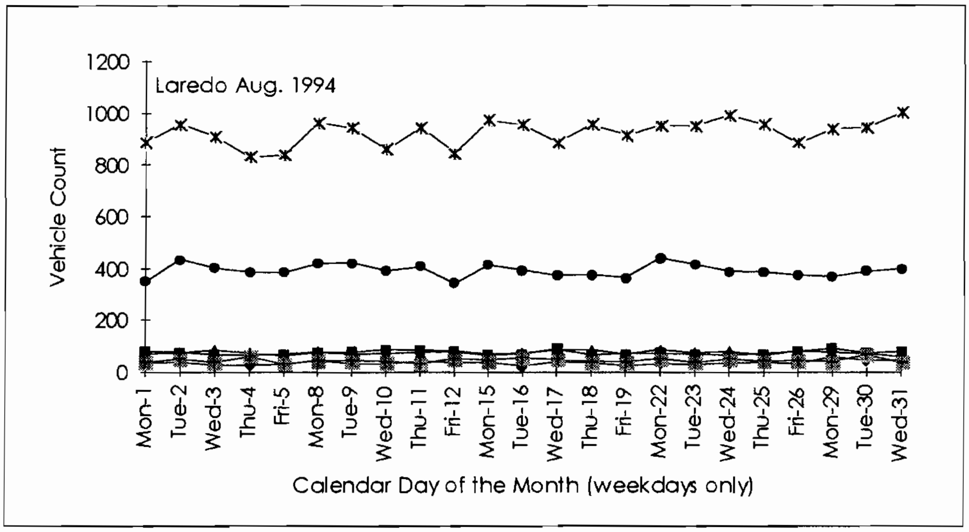


Figure C.1: Laredo daily truck count for August 1994.

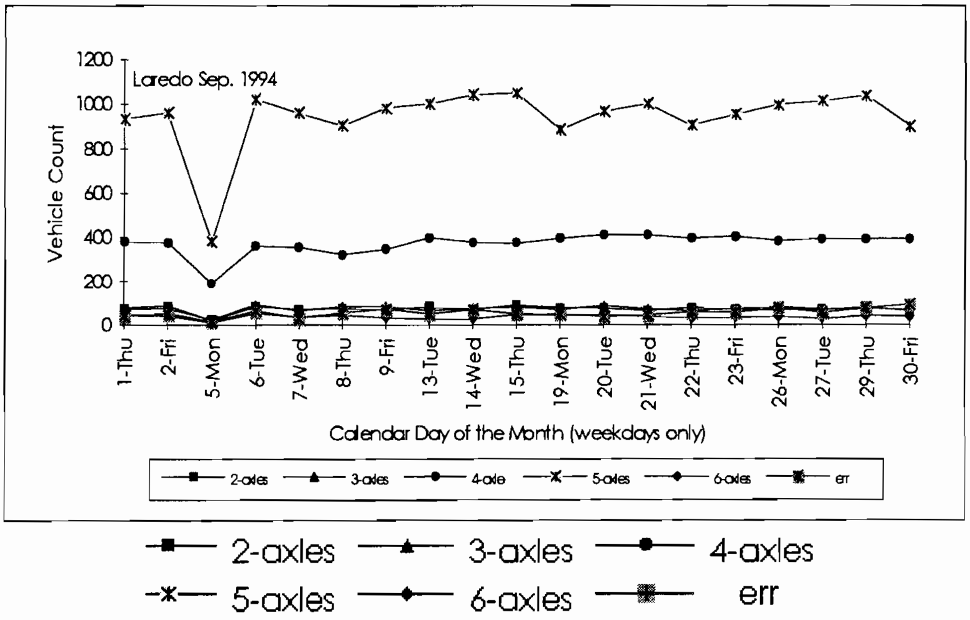


Figure C.2: Laredo daily truck count for September 1994.

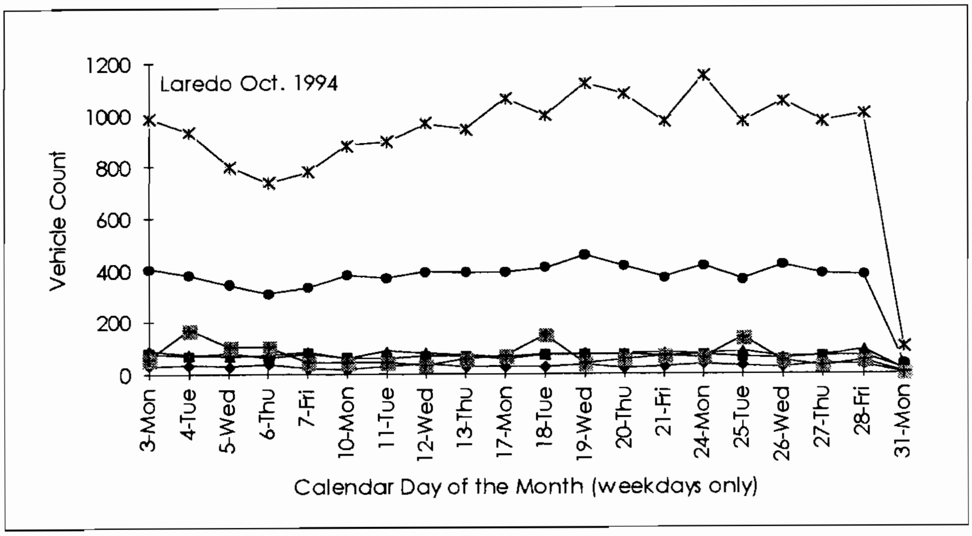


Figure C.3: Laredo daily truck count for October 1994.

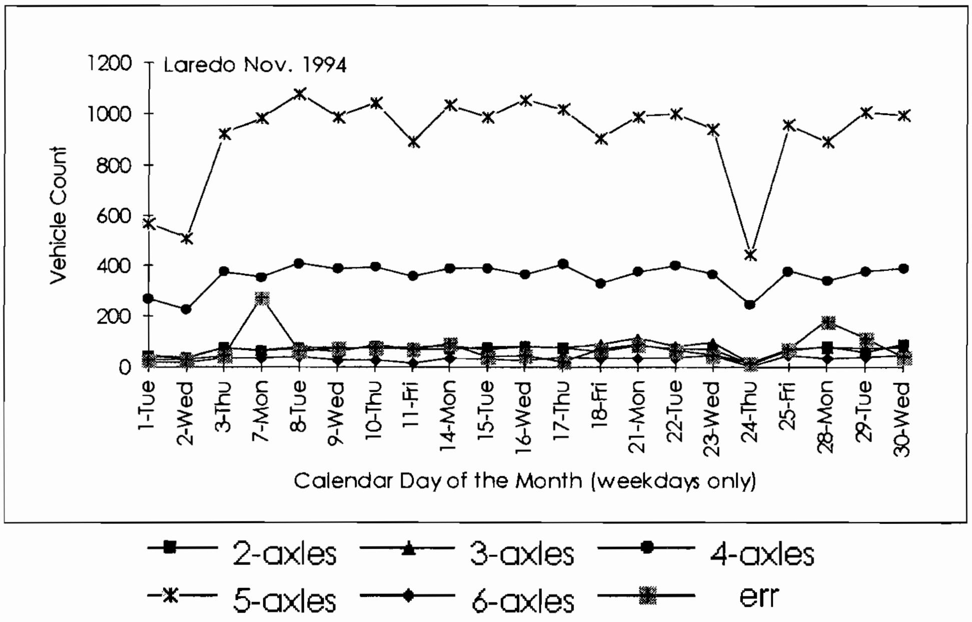


Figure C.4: Laredo daily truck count for November 1994.

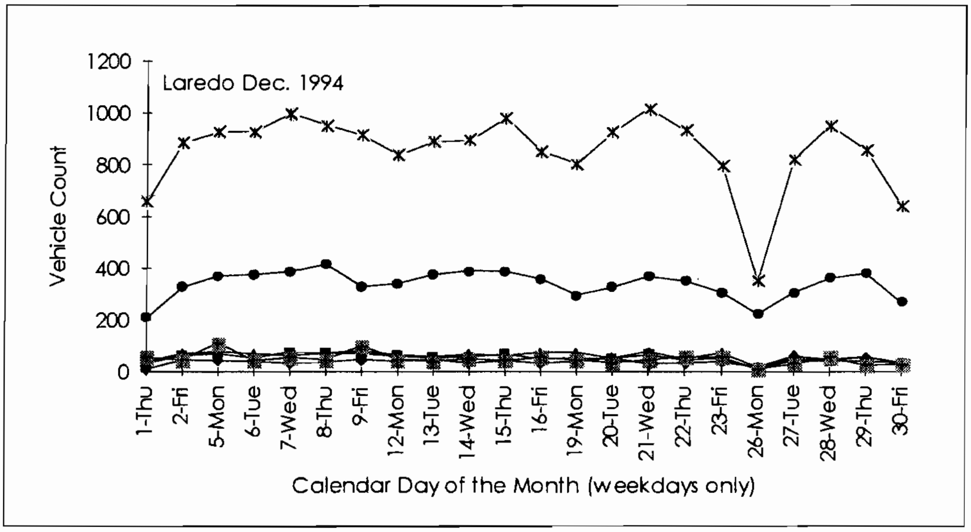


Figure C.5: Laredo daily truck count for December 1994.

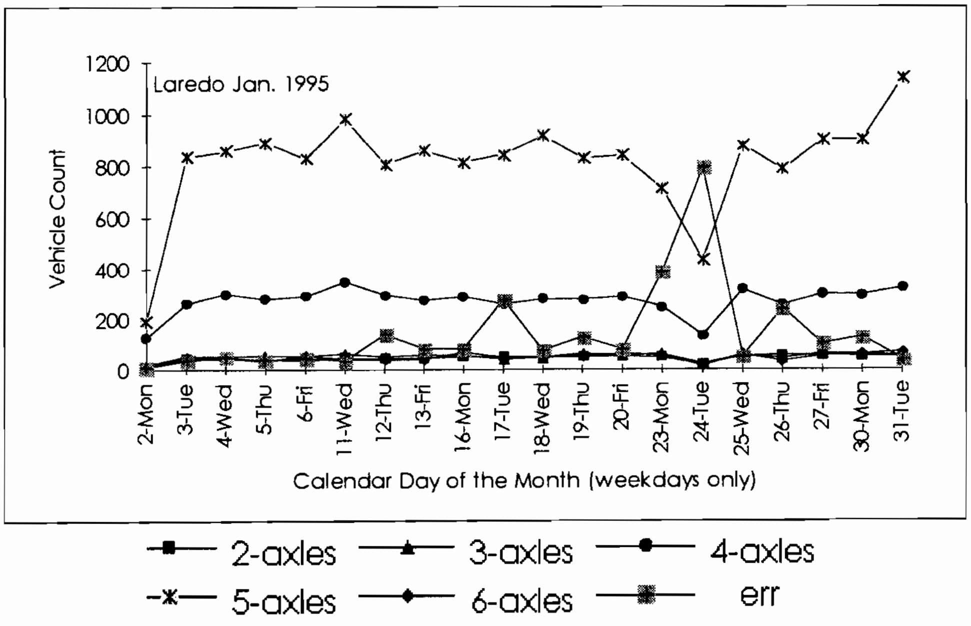


Figure C.6: Laredo daily truck count for January 1995.

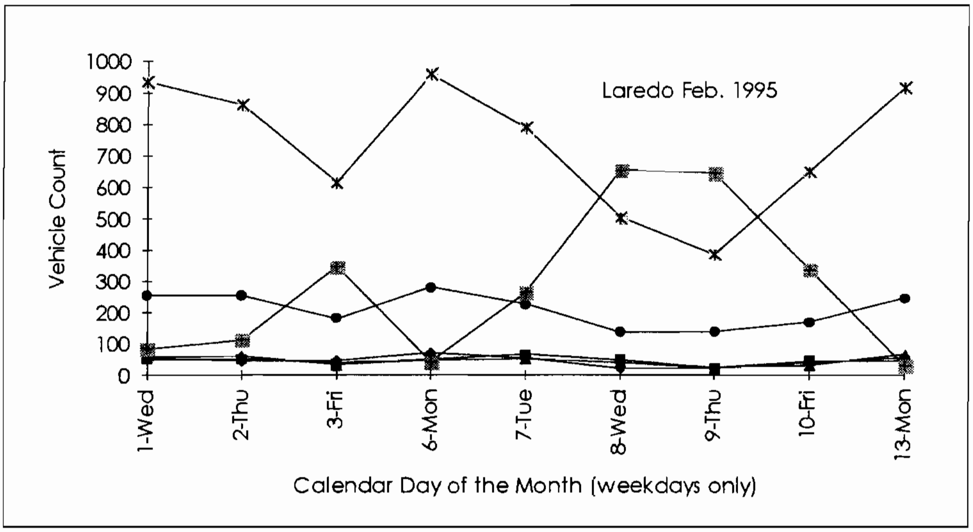


Figure C.7: Laredo daily truck count for February 1995.

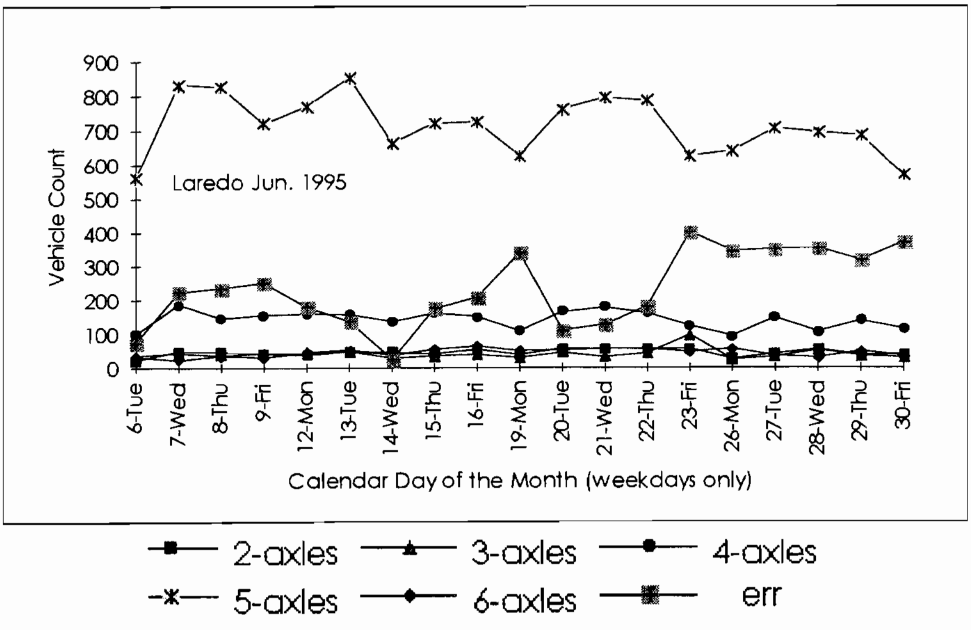


Figure C.8: Laredo daily truck count for June 1995.

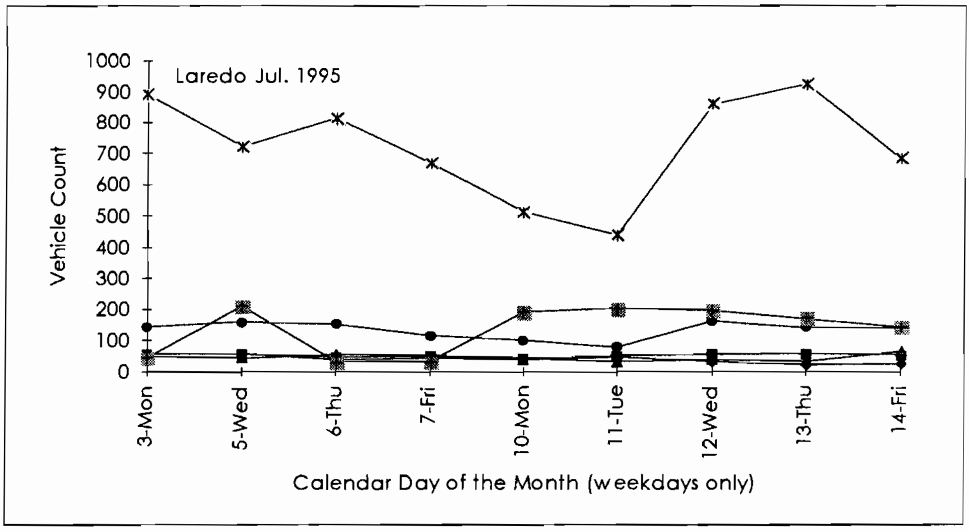


Figure C.9: Laredo daily truck count for July 1995.

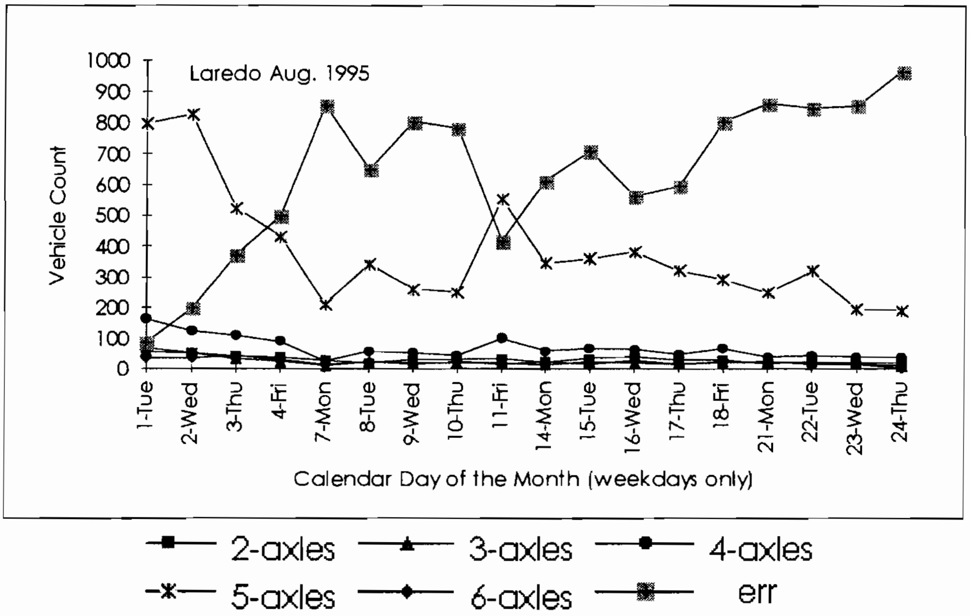


Figure C.10: Laredo daily truck count for August 1995.

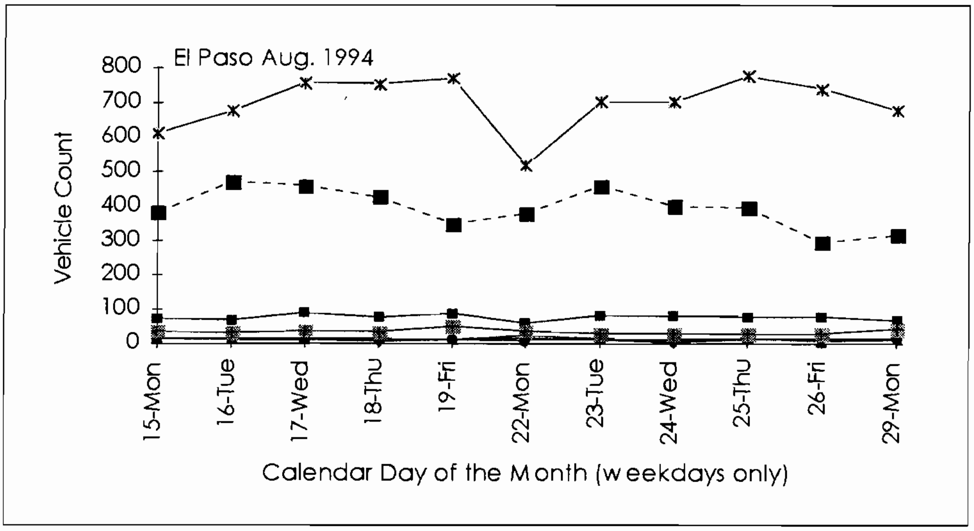


Figure C.11: El Paso daily truck count for August 1994.

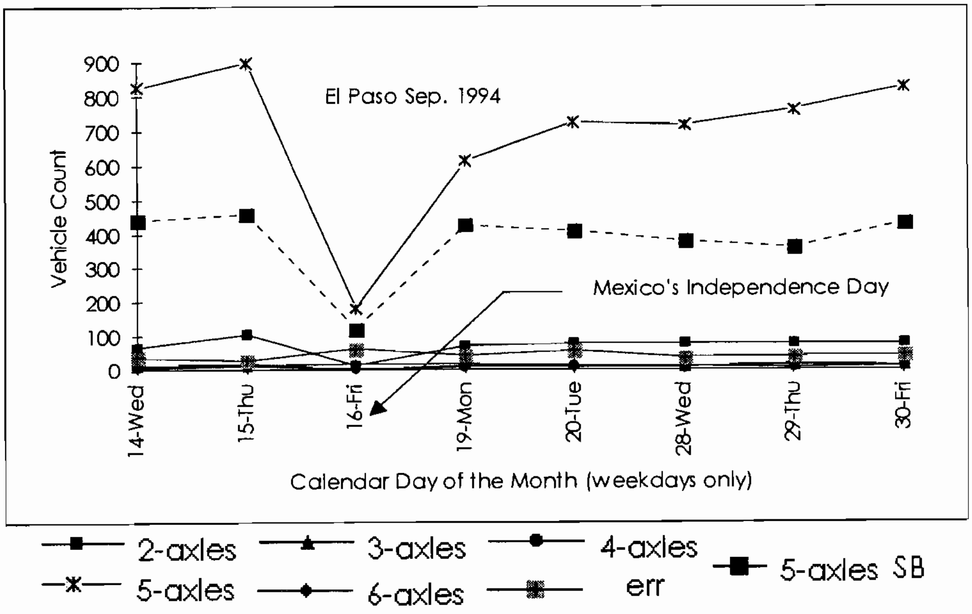


Figure C.12: El Paso daily truck count for September 1994.

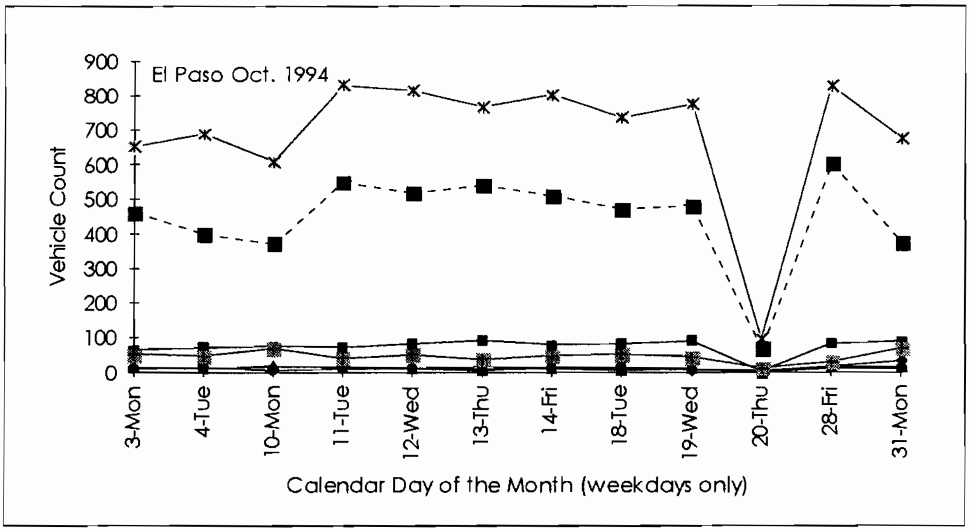


Figure C.13: El Paso daily truck count for October 1994.

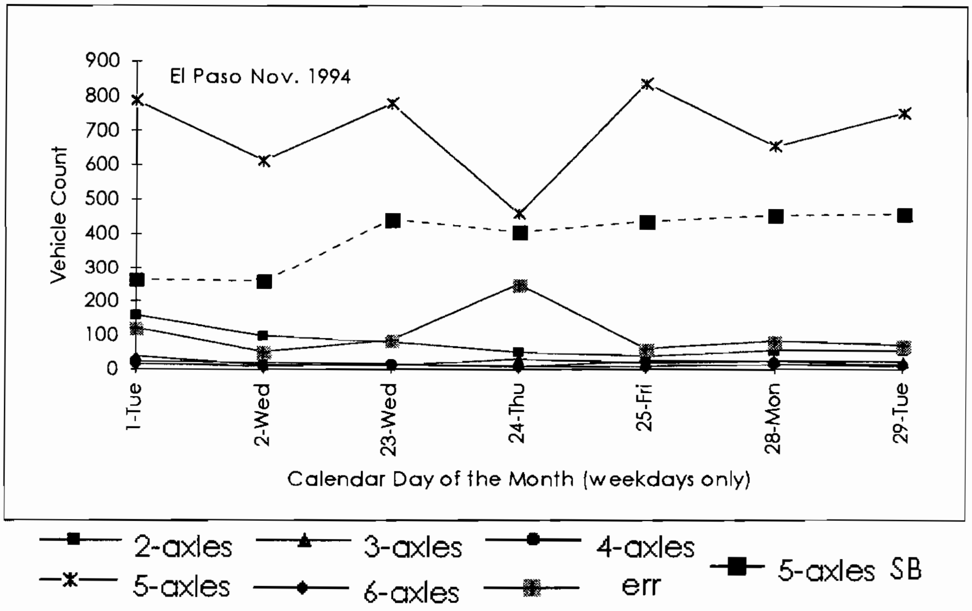


Figure C.14: El Paso daily truck count for November 1994.

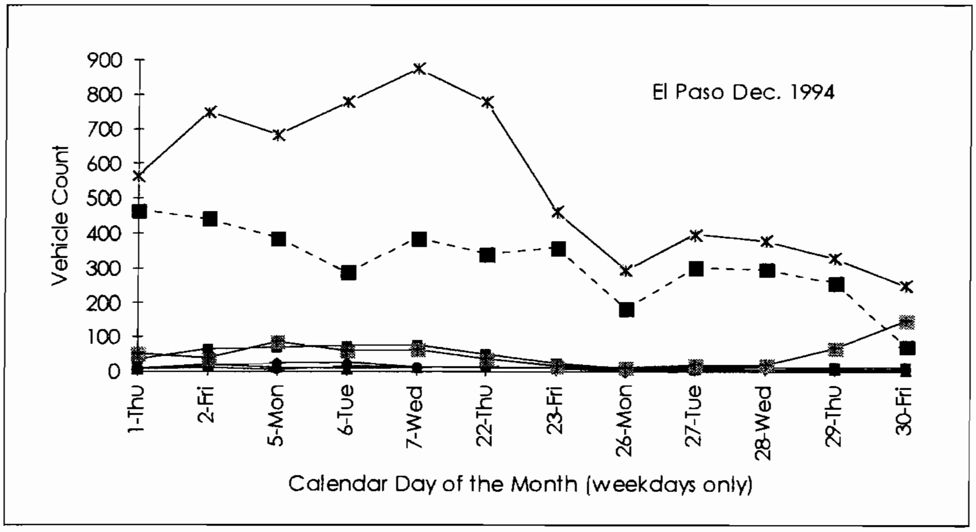


Figure C.15: El Paso daily truck count for December 1994.

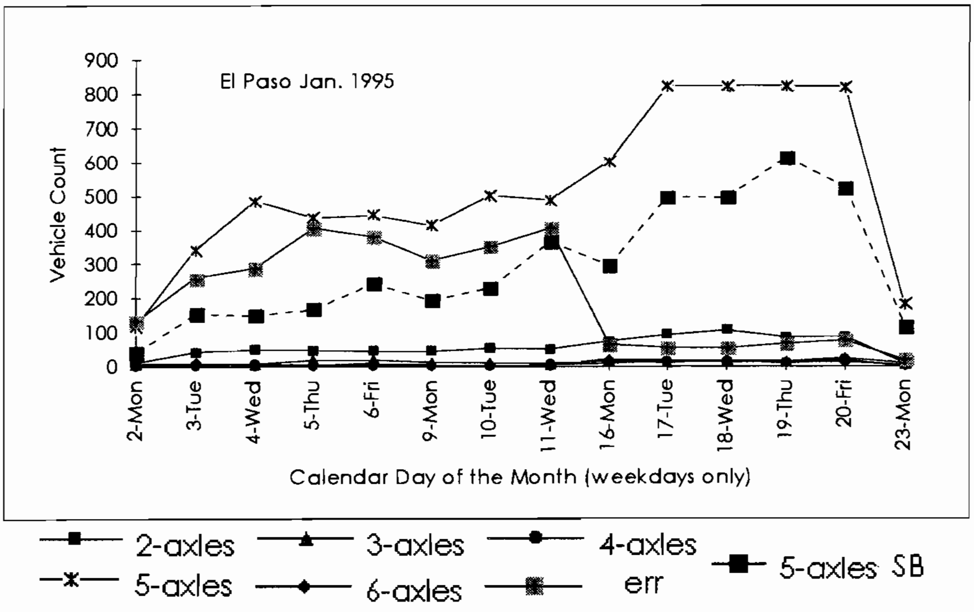


Figure C.16: Laredo daily truck count for January 1995.

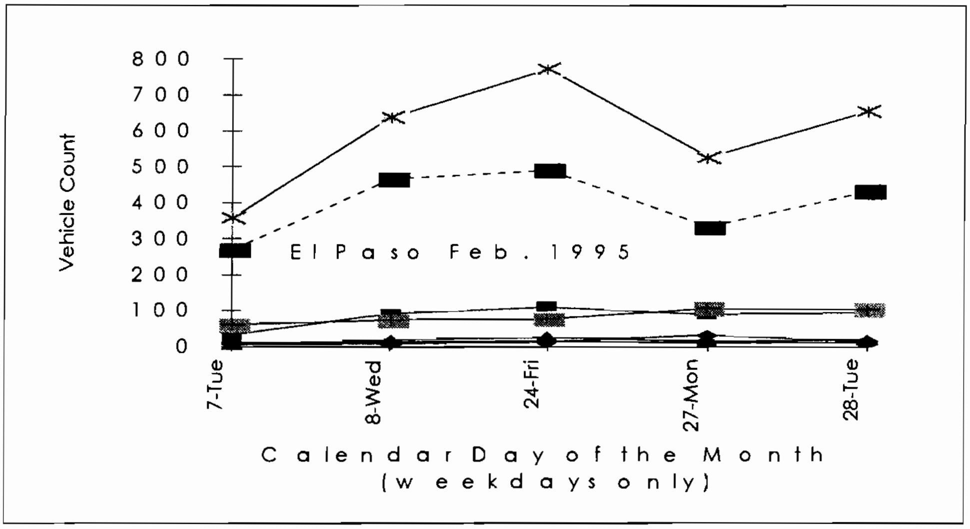


Figure C.17: El Paso daily truck count for February 1995.

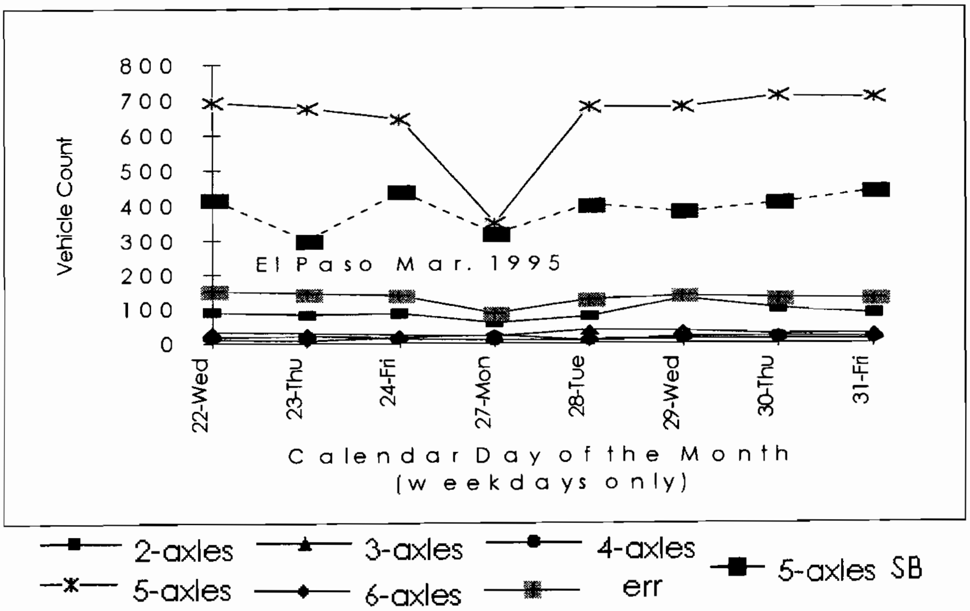


Figure C.18: El Paso daily truck count for March 1995.

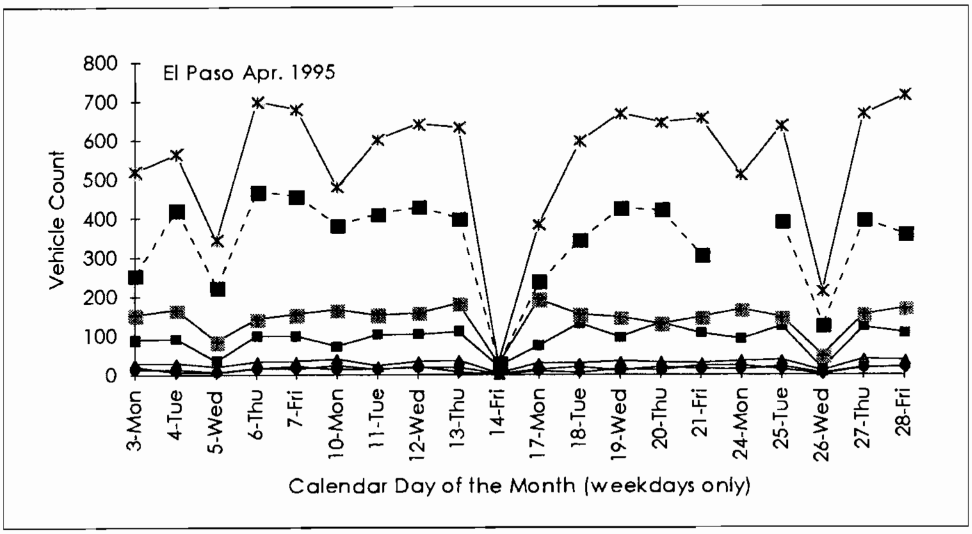


Figure C.19: El Paso daily truck count for April 1995.

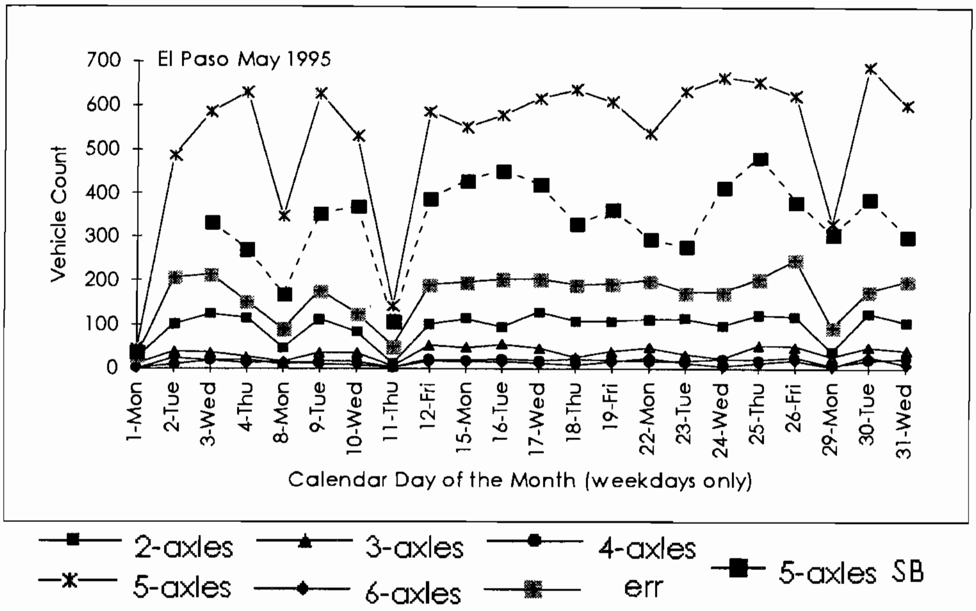


Figure C.20: El Paso daily truck count for May 1995.

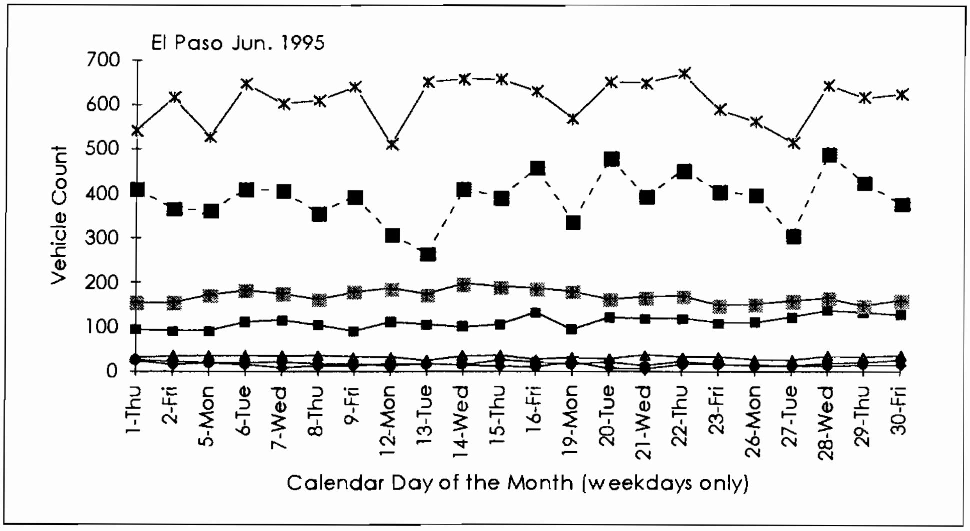


Figure C.21: El Paso daily truck count for June 1995.

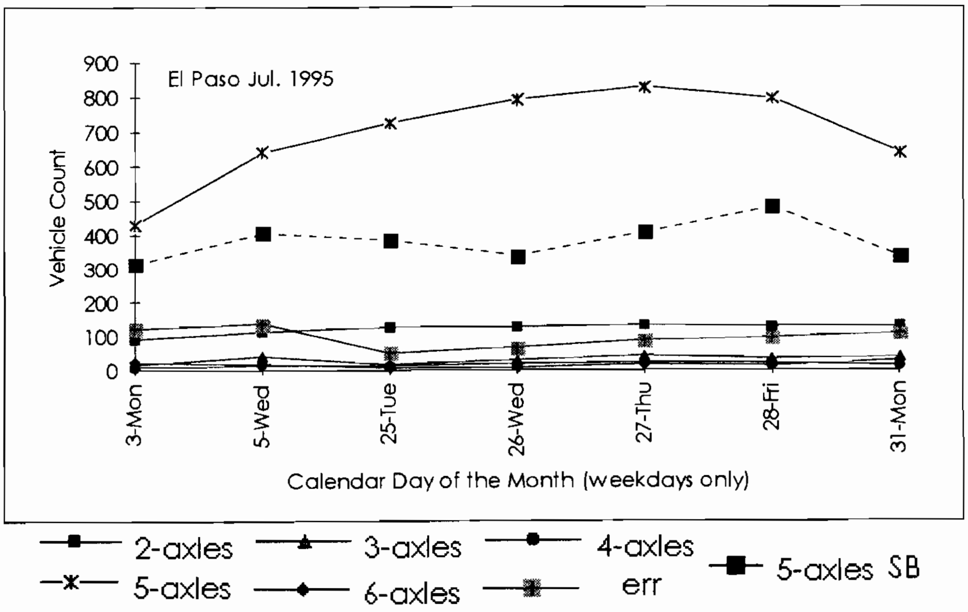


Figure C.22: El Paso daily truck count for July 1995.

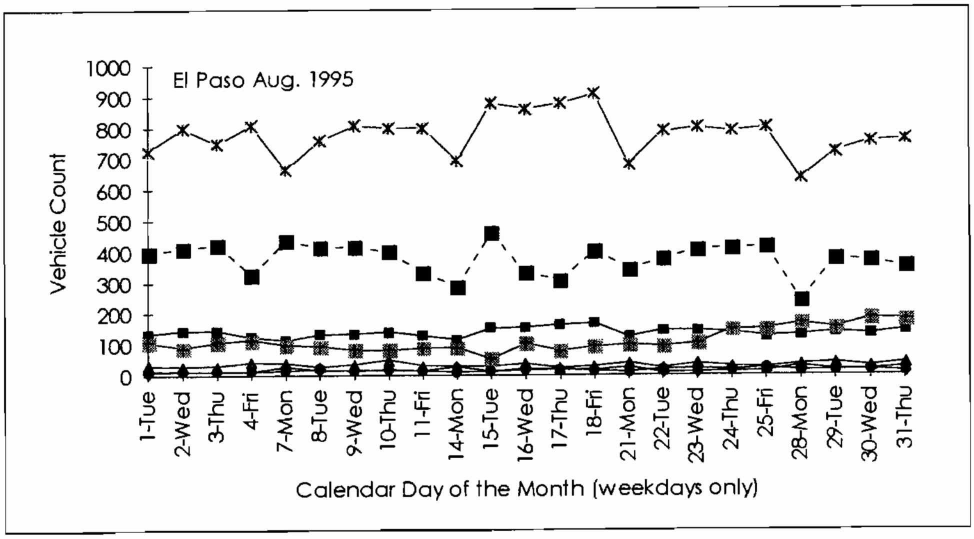


Figure C.23: El Paso daily truck count for August 1995.

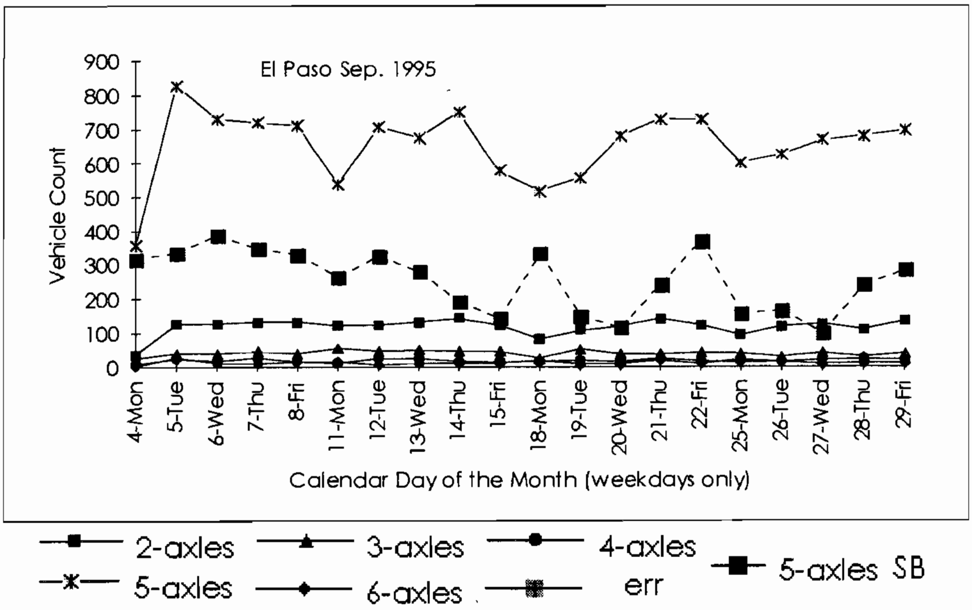


Figure C.24: Laredo daily truck count for September 1995.

APPENDIX D

ASTM E 1318-94:

STANDARD SPECIFICATION FOR HIGHWAY WEIGH-IN-MOTION (WIM) SYSTEMS WITH USER REQUIREMENTS AND TEST METHOD

From: *1996 Annual Book of Standards,* Section 4, Construction, Vol. 04.03 Road and Paving Materials; Pavement Management Technologies, ASTM, 100 Bar Harbor Drive, West Conshohoken, PA, 19428.

Designation: E 1318 – 94

Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Method[1]

This standard is issued under the fixed designation E 1318; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification describes Weigh-in-Motion (WIM), the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle. Gross-vehicle weight (mass) of a highway vehicle is made up of the mass of several contiguous vehicle components, and is distributed among the tires of the vehicle through connectors such as springs, motion dampers, and hinges. Highway WIM systems are capable of estimating the gross weight of a vehicle as well as the portion of this weight that is carried by each wheel assembly (half-axle with one or more tires), axle (with two or more wheel assemblies lying approximately on a common axis oriented transversely to the nominal direction of motion of the vehicle), and axle group on the vehicle.

1.2 Ancillary information concerning the speed, lane of operation, date and time of passage, number and spacing of axles, and classification (according to axle arrangement) of each vehicle that is weighed in motion is desired for certain purposes. It is feasible for a WIM system to measure or calculate these traffic parameters and to process, summarize, store, display, record, hard-copy, and transmit the resulting data. Furthermore, differences in measured or calculated parameters as compared with selected control criteria can be detected and indicated. In addition to tire-load information, a WIM system is capable of producing all, or specified portions of, this information.

1.3 Highway WIM systems generally have three applications: (1) collecting statistical traffic data, (2) aiding enforcement, and (3) enforcement. This specification classifies WIM systems according to their application and gives the related performance requirements and user requirements for each type of system.

1.4 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are for informational purposes only. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other.

1.5 The following safety hazards caveat applies only to the test method portion, Section 7, of this specification. *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Document

2.1 *ASTM Standard:*

E 1155 Test Method for Determining Floor Flatness and Levelness Using the F-Number System (Inch-Pound Units)[2]

3. Terminology

3.1 *Descriptions of Terms Specific to this Standard:*

3.1.1 *accuracy*—the closeness or degree of agreement (within a stated tolerance and probability of conformity) between a quantity measured or estimated by a WIM system and an accepted reference value. Precision and bias of the test method used to determine WIM-system accuracy are discussed in Section 7.

3.1.2 *axle-group load*—the sum of all tire loads on a group of adjacent axles.

3.1.3 *axle load*—the sum of all tire loads on an axle. An axle is comprised of two or more wheel assemblies lying approximately on a common axis oriented transversely to the nominal direction of motion of the vehicle.

3.1.4 *gross-vehicle weight*—the total mass of the vehicle or the vehicle combination including all connected components.

3.1.5 *tire load*—the portion of the gross-vehicle weight imposed upon the static tire at the time of weighing, expressed in units of mass, pounds (kilograms), due only to the vertically-downward force of gravity acting on the mass of the static vehicle.

3.1.6 *tolerance*—the defined limit of allowable departure from the true value of a quantity measured or estimated by a WIM system.

3.1.7 *weigh*—to measure the tire load on one or more tires by using a vehicle scale, an axle-load scale, a portable axle-load weigher, or a wheel-load weigher (see Sec. 2.20, of the National Institute of Standards and Technology Handbook 44).[3] These devices are usually subjected to field standard test weights at each locality of use and are adjusted to indicate units of mass (see 3.2, Appendix B, NIST Handbook 44).

3.1.8 *Weigh-in-Motion* (WIM), *n*—the process of estimating a moving vehicle's gross weight and the portion of

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[1] This specification is under the jurisdiction of ASTM Committee E-17 on Vehicle-Pavement Systems and is the direct responsibility of Subcommittee E17.52 on Traffic Monitoring Device Interconnect.

Current edition approved April 15, 1994. Published June 1994. Originally published as E 1318 – 90. Last previous edition E 1318 – 92.

[2] *Annual Book of ASTM Standards*, Vol 04.07.

[3] "Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices," *National Institute of Standards and Technology Handbook 44*, U.S. Department of Commerce, Washington, DC 20234.

that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces.

3.1.9 *weight*—synonymous with mass. The mass of a body is a measure of its inertia, or resistance to change in motion.

3.1.10 *wheel load*—the sum of the tire loads on all tires included in the wheel assembly which comprises a half-axle.

3.1.11 *WIM System*—a set of sensors and supporting instruments which measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates tire loads, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information. This specification applies only to highway vehicles.

4. Classification

4.1 WIM systems shall be specified to meet the needs of the user for intended applications in accordance with the following types. Exceptions and options may be specified. All systems shall be designed to operate on 110V, a-c, 60-Hz power, and lightening protection for affected system components shall be provided by the vendor. The user may specify as options a completely battery-powered system or battery-backup power in case of failure of normal power.

4.1.1 *Type I:* This type of WIM system shall be designed for installation in up to four lanes at a traffic data-collection site and shall be capable of accommodating highway vehicles moving at speeds from 10 to 70 mph (16 to 113 km/h), inclusive. For each vehicle processed, the system shall produce all data items shown in Table 1. A user-controlled feature of the system shall allow tire-force information from the wheel(s) on only one half of an axle to be used to estimate axle load. Provisions shall be made for entering selected limits for wheel, axle, axle-group (including bridge-formula grouping[4]) loads, and gross-vehicle weights as well as speed and for detecting and indicating suspected violation of any of these limits by a particular vehicle. A feature shall be provided so that the user can determine whether or not the WIM system will prepare selected data items for display and recording. Use of this feature shall not inhibit the system from receiving and processing data. Data shall be processed on-site in such a way that all data items shown in Table 1 can be displayed in alphanumeric form for immediate review. Means for recording data items 1, 5, 6, 7, 8, 9, 10, and 11 for permanent record shall be provided. On-site presentation of a hard-copy of all data items produced by the system shall be an optional feature (Option 1) of the system. Option 2 for this type of WIM system shall additionally provide means for counting and for recording hourly the lanewise count of all vehicles traveling in all lanes, up to a maximum of ten lanes, at a data-collection site, including lanes without WIM sensors. Option 3 shall provide for counting, classifying (via axle arrangement), measuring the speed of, and recording the hourly totals concerning all such vehicles by class and by lane of travel.

TABLE 1 Data Items Produced by WIM System

1.	Wheel Load
2.	Axle Load
3.	Axle-Group Load
4.	Gross-Vehicle Weight
5.	Speed
6.	Center-to-Center Spacing Between Axles
7.	Vehicle Class (via axle arrangement)
8.	Site Identification Code
9.	Lane and Direction of Travel
10.	Date and Time of Passage
11.	Sequential Vehicle Record Number
12.	Wheelbase (frontmost to rearmost axle)
13.	Equivalent Single-Axle Load (ESAL)
14.	Violation Code

4.1.2 *Type II:* This type of WIM system shall be designed for installation at traffic data-collection sites and should be capable of accommodating highway vehicles moving at speeds from 10 to 70 mph (16 to 113 km/h), inclusive. For each vehicle processed, all data items shown in Table 1 except Item 1 shall be produced by the system. All other features and options of the Type II WIM system shall be identical to those described in 4.1.1 for the Type I WIM system.

4.1.3 *Type III:* This type of WIM system shall be designed for installation in one or two lanes at weight-enforcement stations to identify vehicles operating at speeds from 15 to 50 mph (24 to 80 km/h), inclusive, that are suspected of weight-limit or load-limit violation. For each vehicle processed, the system shall produce all data items shown in Table 1 except 7, 12, and 13 and shall also estimate acceleration (while the vehicle is over the WIM-system sensors). Provisions shall be made for entering selected limits for wheel, axle, axle-group (including bridge-formula grouping[4]) loads, and gross-vehicle weight as well as speed and acceleration and for detecting and indicating suspected violation of any of these limits by a particular vehicle. Means shall be provided for automatically controlling official traffic-control devices which will direct each suspect vehicle to a scale for confirmation weighing and guide all non-suspect vehicles past the scale without stopping. Manual operation of these official traffic-control devices shall be provided as an optional feature (Option 1) of the Type III WIM system. Information used in determining a suspected violation shall be displayed in alphanumeric form for immediate review and recorded permanently. Option 2 shall provide means for presenting this information in hard-copy form if requested by the system operator. Option 3 may be specified to exempt the Type III WIM system from producing wheel-load information (Item 1 in Table 1) if this data item is not of interest for enforcement. Option 4 for this type of WIM system shall provide for recording the following data items shown in Table 1 for every vehicle processed by the system: 1 (2 in lieu of 1 when Option 3 is specified), 5, 6, 8, 9, 10, and 11. These items allow subsequent computation of statistical traffic data.

4.1.4 *Type IV:* This type of WIM system shall be designed for use at weight-enforcement stations to detect weight-limit or load-limit violations. Speeds from 0 to 10 mph (0 to 16 km/h), inclusive, shall be accommodated. For each vehicle

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[4] *Traffic Monitoring Guide, June 1985*, U.S. Department of Transportation, Federal Highway Administration, Office of Highway Planning, Washington, DC 20590.

TABLE 2 Functional Performance Requirements for WIM Systems

Function	Tolerance for 95 % Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				Value ≥ lb (kg)[A]	±lb (kg)
Wheel Load	±25 %		±20 %	5 000 (2 300)	250 (100)
Axle Load	±20 %	±30 %	±15 %	12 000 (5 400)	500 (200)
Axle-Group Load	±15 %	±20 %	±10 %	25 000 (11 300)	1 200 (500)
Gross-Vehicle Weight	±10 %	±15 %	±6 %	60 000 (27 200)	2 500 (1 100)
Speed	±1 mph (2 km/h)				
Axle-Spacing	±0.5 ft (150 mm)				

[A] Lower values are not usually a concern in enforcement.

that is processed, the system shall produce all data items shown in Table 1 except 7, 9, 12, and 13 and shall also estimate acceleration (while the vehicle is over the WIM-system sensors). Provisions shall be made for entering and displaying selected limits for wheel, axle, axle-group (including bridge-formula grouping,[4]) loads, and gross-vehicle weights as well as speed and acceleration and for detecting and indicating violation of any of these limits by a particular vehicle. Information used in determining a violation shall be displayed in alphanumeric form for immediate review and recorded permanently. Option 1 shall provide means for presenting this information in hard-copy form if requested by the system operator. Option 2 may be specified to exempt the Type IV WIM system from producing wheel-load information (Item 1 in Table 1) if this data item is not of interest for enforcement.

5. Performance Requirements

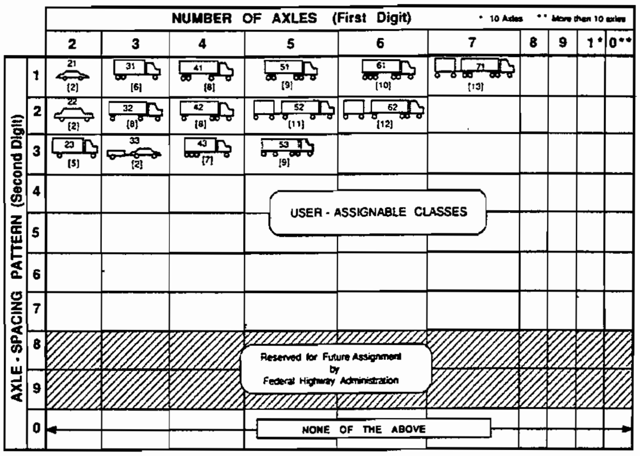
5.1 Each type of WIM system shall be capable of performing the indicated functions within the accuracy shown in Table 2. A test method for determining compliance with these requirements is given in Section 7. After computation of the data items shown in Table 2, no digit which indicates less than 10 lb (5 kg) (load or weight), 1 mph (2 km/h) (speed), or 0.1 ft (30 mm) (axle spacing) shall be retained.

5.2 Vehicle classification according to axle arrangement shall be accomplished by Type I and Type II WIM systems. The vendor shall incorporate software within each Type I and Type II WIM system for using the available WIM-system axle-count and axle-spacing information for estimating the Federal Highway Administration (FHWA) Vehicle Types described briefly in Table 3. See U.S. Department of Transportation Traffic Monitoring Guide[4] for the complete description of FHWA Vehicle Types. The FHWA Vehicle Type shall be indicated by the 2-Digit Code shown in Table 3. A vehicle type code 00 shall be applied to any vehicle which the software fails to assign to one of the types shown.

TABLE 3 FHWA Vehicle Types

2-Digit Code	Brief Description
01	Motorcycles
02	Passenger Cars
03	Other Two-Axle, Four-Tire Single-Unit Vehicles
04	Buses
05	Two-Axle, Six-Tire, Single-Unit Trucks
06	Three-Axle, Single-Unit Trucks
07	Four-or-More Axle Single-Unit Trucks
08	Four-or-Less Axle Single-Trailer Trucks
09	Five-Axle Single-Trailer Trucks
10	Six-or-More Axle Single-Trailer Trucks
11	Five-or-Less Axle Multi-Trailer Trucks
12	Six-Axle Multi-Trailer Trucks
13	Seven-or-More Axle Multi-Trailer Trucks

5.2.1 As an option to the FHWA vehicle classes indicated by the 2-digit code, the user may specify the 3-Digit Vehicle



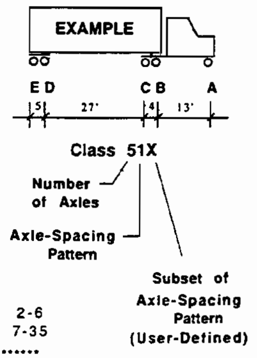
Note—Corresponding Federal Highway Administration (FHWA) Vehicle Types are shown as [ ]. e.g., Class 51 shown above is FHWA [9].

Third Digit allows the user to describe a subset(s) of the axle-spacing pattern defined by the second digit.

FIG. 1 Graphical Representation of 3-Digit Vehicle Classes

TABLE 4 Axle-Spacing Patterns for 3-Digit Vehicle Classes

CLASS	RANGE OF SPACING BETWEEN PAIRS OF AXLES (FT)					
	A,B	B,C	C,D	D,E	E,F	etc.
21	6-9					
22	9-11	-				
23	11-25					
20	"OTHER"					
31	8-26	2-6				
32	8-20	11-45				
33	6-10	6-22				
30	* OTHER 3-AXLE *					
41	8-20	11-45	2-6			
42	8-20	2-6	11-45			
43	8-25	2-6	2-6			
40	****** OTHER 4-AXLE ******					
51	8-25	2-6	11-55	2-6		
52	8-20	11-36	6-20	7-35		
50	********** OTHER 5-AXLE **********					
61	8-20	2-6	11-42	2-6	2-6	
62	8-20	2-6	11-30	7-15	11-25	
60	**************** OTHER 6-AXLE **************					



Classes shown graphically in Fig. 1 and numerically in Table 4. In the 3-digit code, the first digit indicates the total number of axles on the vehicle or the combination, the second digit indicates the axle-spacing pattern, and the third digit indicates a user-assigned subset of the axle-spacing pattern. Provisions shall be made for the user to enter additional axle-spacing criteria for the user-assignable classes shown in Fig. 1 as well as for the user-assignable subsets of the axle-spacing patterns which are to be designated by a selected third digit.

5.3 Provisions shall be made in Type I, Type II, Type III, and Type IV WIM systems for entering, displaying, and recording a 10-character alphanumeric Site Identification Code for each data-taking session. This code can be used to incorporate information required for FHWA Truck Weight Data Collection.[4]

5.4 A lane and direction-of-travel code for each vehicle processed by Type I, Type II, and Type III WIM systems shall consist of a number beginning with 1 for the right-hand northbound or eastbound traffic lane and continuing until all the lanes in that direction of travel have been numbered; the next sequential number shall be assigned to the lanes in the opposite direction of travel beginning with the left-hand lane and continuing until all lanes have been numbered. Provision shall be made for 12 numbers in the code. This code may be used to incorporate information required for FHWA Truck Weight Data Collection.[4]

5.5 Date of passage shall be indicated numerically for each vehicle processed by Type I, Type II, Type III, and Type IV WIM systems in the following format: MM/DD/YY, where M is the month, D is the day, and Y is the year.

5.6 Time of passage shall be indicated numerically for each vehicle processed by Type I, Type II, Type III, and Type IV WIM systems in the following format: hhmm:ss, where h is the hour beginning with 00 at midnight and continuing through 23, m is the minute, and s is the second.

5.7 Type I, Type II, Type III, and Type IV WIM systems shall provide sequential-numbering (user-resettable) for each recorded vehicular data set.

5.8 Type I and Type II WIM systems shall compute wheelbase as the sum of all axle spacings between the front most and the rearmost axles on the vehicle or combination that have tires in contact with the road surface at the time of weighing. This value shall be rounded to an integer value (in ft) (or to the nearest 0.1 m) before display or recording.

5.9 Type I and Type II WIM systems shall compute Equivalent Single-Axle Load (ESAL) as described in the Annex to this standard. The WIM system shall be capable of computing ESALs for single and tandem axles for both flexible and rigid pavements, and provision shall be made for the user to select one of these pavement types for application during any given data-collection session. The system shall compute the total ESALs for each vehicle or vehicle combination and prepare these data for display as part of each vehicle record. When displayed, this value shall be truncated to 2 digits following the decimal and presented in the following format: FESAL = for flexible pavements, and RESAL = for rigid pavements. The parameter for serviceability at the end of time t, P_t, shall be adjustable by the user, but 2.5 shall be programmed as a default value. Similarly, the value for structural number, $\overline{SN}$, used for computing flexible pavement equivalency factors shall be user adjustable, but shall be defaulted to 3.0. The value for thickness of rigid pavement slab, D, used in computing rigid pavement equivalency factors shall be user adjustable, and shall be defaulted to 8.0 in. (203 mm) in the WIM-system program. Provision shall be made in the program to list on demand all parameters actually utilized in the ESAL computation during any given data-collection session.

5.10 Violations of all user-set parameters shall be determined by Type I, Type II, Type III, and Type IV WIM systems. A 2-character violation code, such as shown in Table 5, shall be used for each detected violation and shall be included in the displayed data. Provision shall be made for the user to define up to 15 violation codes. An additional optional feature that calls attention to any data items which are in violation of user-set limits may be specified by the user, for example, flashing, underlining, bold-facing, or audio tones.

5.11 Type III and Type IV WIM systems shall measure vehicle acceleration, which is a change in velocity. Negative acceleration is also called deceleration. The forces acting on a vehicle to produce acceleration can effect significant change in the distribution of the gross-vehicle weight among the axles and wheels of the vehicle as compared to the distribution when the vehicle is static. Therefore, any severe acceleration while the vehicle is passing over the WIM-system sensors can invalidate wheel and axle loads estimated by the system. Average acceleration of 2 ft/s^2 (0.6 m/s^2) or greater during the time that the wheelbase (see 5.8) of the vehicle is passing over the tire-force sensors should be considered as a violation. This value shall be user-adjustable, but the vendor shall program 2 ft/s^2 (0.6 m/s^2) as the default value in these WIM systems.

5.12 For Type I, Type II, Type III, and Type IV WIM systems, provision shall be made to allow manual entry of a user-assignable 3-digit code into any vehicular data set prior to recording.

6. User Requirements

6.1 In order for any WIM system to perform properly, the user must provide and maintain an adequate operating environment. Construction or selection of each WIM site as well as continuing maintenance of the site and the sensors are extremely important considerations. The following site conditions, or better, shall be provided by the user.

6.1.1 The horizontal curvature of the roadway lane for 150 ft (45 m) in advance of and beyond the WIM-system sensors shall have a radius not less than 5700 ft (1.7 km) measured along the centerline of the lane for all types of WIM systems.

TABLE 5 Violation Code

Violation	Code
Wheel Load	WL
Axle Load	AL
Axle—Group Load	AG
Gross-Vehicle Weight	GV
Bridge—Formula Load	BF
Over Speed	OS
Under Speed	US
Acceleration	AC
Deceleration	DE

6.1.2 The longitudinal gradient of the road surface for 150 ft (45 m) in advance of and beyond the WIM system sensors shall not exceed 2 % for Type I, Type II, and Type III WIM-system installations, and shall not exceed 1 % for Type IV installations.

6.1.3 The cross-slope (lateral slope) of the road surface for 150 ft (45 m) in advance of and beyond the WIM-system sensors shall not exceed 2 % for Type I, Type II, and Type III WIM system installations, and shall not exceed 1 % for Type IV installations.

6.1.4 The width of the paved roadway lane for 150 ft (45 m) in advance of and beyond the WIM-system sensors shall be between 10 and 12 ft (3.0 and 3.7 m), inclusive. For Type III and Type IV WIM systems, the edges of the lane throughout this distance shall be marked with solid white longitudinal pavement marking lines 4 to 6 in. (100 to 150 mm) wide, and at least 3 ft (1 m) of additional clear space for wide loads shall be provided on each side of the WIM-system lane.

6.1.5 The surface of the paved roadway 150 ft (45 m) in advance of and beyond the WIM-system sensors shall be maintained in a condition such that a 6-in. (150-mm) diameter circular plate 0.125-in. (3 mm) thick cannot be passed beneath a 20-ft (6-m) long straightedge when the straightedge is positioned and maneuvered in the following manner:

6.1.5.1 Beginning at the longitudinal center of the WIM-system sensors, place the straightedge along each respective lane edge with the outer end at the distances from the longitudinal center of the sensors as indicated below, pivot the straightedge about this end, and sweep the inner end between the lane edges while checking clearance beneath the straightedge with the circular plate. Equivalent flatness may be determined by an alternative means such as is described in Test Method E 1155.

Lane Edge	Longitudinal distance from Center of Sensors, ft (m)
Right	20, 30, 44, 60, 76, 92, 108, 124, 140, and 156 (6, 9, 13, 18, 23, 28, 33, 38, 43, and 48)
Left	20, 36, 52, 68, 84, 100, 116, 132, 148, and 164 (6, 11, 16, 21, 26, 30, 35, 40, 45, and 50)

6.1.6 The user shall provide and maintain a foundation to accommodate the WIM-system sensors and shall install and maintain the sensors in accordance with the recommendations of the system vendor.

6.1.7 The user shall provide and maintain a climatic environment for the WIM-system instruments in accordance with those specified by the user and agreed upon by the system vendor.

6.1.8 The user shall provide an adequate 110V, ac, 60-Hz electrical power supply at each WIM site and/or specify an optional battery-powered system as suggested in 4.1.

6.2 Any desired optional features described in Section 4 and Section 5, any exceptions, and any additional features of the WIM system shall be specified by the user. The user shall also specify the data items to be included in the display, the number of vehicle records to be displayed simultaneously, and whether the ability to hold a selected record(s) on display without interference with continuous data taking by the system is required. The user should note that the number of data items selected will affect the number of vehicle records that can be displayed simultaneously.

6.3 The user shall recalibrate every WIM system following any maintenance or relocation, and at a minimum annually. Recalibration of system Types I, II, and III shall be performed in accordance with the method presented in 7.5, and system Type IV shall be recalibrated in accordance with the method presented in 7.4.5.

7. Test Method for WIM System Performance

7.1 A test method for evaluating the performance of each type of WIM system is presented in this section. Procedures are given for (1) acceptance testing of any new type WIM system, and (2) on-site calibration (to remove as much bias as practicable from the weight estimates) at the time of system installation or when site conditions have changed.

7.1.1 *Apparatus for Weighing Static Vehicles*—When wheel-load data are required from the WIM system, the corresponding reference tire-load values for Type I, Type III, and Type IV WIM systems shall be determined with wheel-load weighers which meet the respective tolerance specification of the current edition of NIST Handbook 44.[3] The minimum number of wheel-load weighers required is 2 and the preferred number is 6. When wheel-load data are not required, axle-load scales, multi-platform vehicle scales, portable axle-load weighers, or a pair of wheel-load weighers which meet the respective tolerance specification of the current edition of NIST Handbook 44, shall be used for obtaining reference tire-load values for Type II and Type III WIM systems. Either an axle-load scale or a multi-platform vehicle scale, along with wheel-load weighers if required, shall be used for measuring reference tire-load values for Type III and Type IV WIM systems.

7.1.2 *Use of Apparatus for Weighing Static Vehicles*—The tire-pavement contact surfaces of all tires on the vehicle being weighed shall be within 0.25 in. (6 mm) of a plane passing through the load-receiving surface(s) of the multi-platform vehicle scale, wheel-load weighers, portable axle-load weighers, or axle-load scales whenever any tire-load measurement is made. The maximum slope of this plane from horizontal shall be 2 %. Suitable blocking or mats may be utilized, or the weighing device(s) may be recessed into the pavement surface to provide the required vertical orientation of the tire-pavement contact surfaces. When wheel-load information is required, wheel and axle load shall be measured simultaneously using a pair of wheel-load weighers. When wheel-load information is not required, axle-load shall be determined by positioning each axle to be weighed either simultaneously or successively on an axle-load scale(s), a multi-platform vehicle scale, a portable axle-load weigher(s), or a pair(s) of wheel-load weighers. Axle-group load shall be determined either by positioning all axles in the group simultaneously on the required number of weighing devices (preferred) or by successively positioning each axle in the group on a pair of wheel-load weighers or on an axle-load weighing device. The number of movements of the vehicle to accomplish the successive tire-load measurements shall be minimized. A tire-load measurement shall be made only when the brakes of the vehicle being weighed are fully released and all tires are properly positioned on the load-receiving surface(s) of the weighing device(s). Suitable means (for example, chocks) shall be used to keep the tires properly positioned while the brakes are released. Gross-vehicle weight shall be the sum of all wheel loads or axle loads for the vehicle. No tire-load measurement shall be taken until inertially-induced oscillations (for example, via a load of liquid) of the vehicle have subsided to a point that indicated tire load is changing less than three scale divisions in 3s.

7.2 *Acceptance Test for Type I and Type II WIM Systems:*

7.2.1 *Scope*—An acceptance test is described for evaluating the performance capabilities of a new WIM system under excellent conditions and under traffic loading that is representative of that which will be of interest where Type I and Type II WIM systems will be applied. Performance requirements for each type of WIM system are given in Section 5 of this standard, and associated user requirements are given in Section 6. The WIM system being evaluated in the acceptance test shall be subjected to a loading test unit consisting of (a) two test vehicles loaded with a non-shifting load, plus (b) 51 additional vehicles selected from the traffic stream at the acceptance-test site. Other types of vehicles may be added to the loading test unit at sites where large numbers of vehicles of classes not already included are operating. The two test vehicles, which will make multiple passes over the WIM-system sensors at the minimum and at the maximum speed specified by the user between 10 and 70 mph (16 to 113 km/h) and at an intermediate speed, serve two functions. First, they provide a basis for evaluating the performance of the WIM system over the full, specified range of speeds, and second, they provide a means (via repeated measurements on the same static vehicle) for ensuring that reference-value tire-load measurement procedures yield reproducible values. The additional vehicles included in the loading test unit serve the function of subjecting the WIM system to loading by a representative variety of vehicle classes. All vehicles comprising the loading test unit shall be weighed statically on certified weighing devices as described in 7.1.1 and 7.1.2 at a suitable site within reasonable proximity to the acceptance-test site.

7.2.2 *Significance and Use*—Interpretation of the results from the acceptance test will allow the user to determine whether the tested Type I or Type II WIM system is capable of meeting or exceeding the performance requirements stated in Section 5. This can also indicate the potential upper limit of performance which can be achieved by the particular type of system as the road surface conditions, which potentially affect the location and magnitude of dynamic tire forces significantly, shall be the best available for conducting the acceptance test and shall, as a minimum, satisfy the user requirements shown in Section 6. Once a specimen WIM system has passed this rigorous acceptance test, it should not be necessary for each subsequent user to repeat the test for every system of the same type from the same vendor.

7.2.3 *Site for Acceptance Test*—Both the user (or a recognized representative of user's interests) and the vendor shall approve the acceptance test site as well as the WIM-system installation prior to conducting the acceptance test. The actual road-surface and WIM-system sensor conditions which prevail during acceptance testing shall be documented in terms of surface conditions measured in a way that verifies compliance with the user requirements given in Section 6. This documentation, along with all acceptance test results, shall be reported to ASTM Committee E-17 on Pavement Management Technologies so that statements about bias and precision of the test can be formulated as experience is accumulated.

TABLE 6 Composition of Test Unit for Acceptance-Test Loading of WIM Systems

Vehicle Class	Number of Selected Vehicles
23	5
31	5
32	4
41	4
42	4
51	20
52	3
62	3
71	3

7.2.4 *Test Unit for Acceptance Test Loading*—The test unit for loading the WIM system being evaluated in the acceptance test shall be comprised of two loaded test vehicles which will make multiple runs over the WIM-system sensors at prescribed speeds along with other vehicles selected from the traffic stream at the acceptance test site. One of the loaded test vehicles shall be Class 23 and the other Class 51 (see Fig. 1 and Table 4). These test vehicles shall be loaded to within 90 to 110 % of their respective registered gross-vehicle weight with a non-shifting load and shall be in excellent mechanical condition. Special care shall be exercised to ensure that the tires on the test vehicles are in excellent condition (preferably dynamically balanced) and inflated to recommended pressures. The number of vehicles in each Vehicle Class (see 5.2) to be selected in random order from the traffic stream for inclusion in the test unit is shown in Table 6 (see Fig. 1 and Table 4). If a significant number of vehicles of another class(s) is operating at the site, define the class(s), and add three selected vehicles of each such class to the test unit.

7.2.5 *Calibration and Certification*—Within 48 h prior to beginning the acceptance test, the WIM system shall be calibrated in accordance with the method presented in 7.5. The radar speed meter shall be calibrated by the method recommended by its vendor within 30 days prior to the acceptance test. All weighing apparatus used in the acceptance test shall be certified as meeting the applicable maintenance tolerance specified in National Institute of Standards and Technology Handbook 44 within 30 days prior to beginning the acceptance test.

7.2.6 *Procedure*—The following steps shall be performed in conducting the acceptance test.

7.2.6.1 As a joint effort between the user (or a recognized representative of user's interests) and the vendor, select the best available WIM-system site which, as a minimum, meets the applicable requirements stated in Section 6.

7.2.6.2 Ensure that a suitable site for weighing vehicles statically is available within a reasonable distance of the WIM site, that traffic can be controlled safely at this location, and that test vehicles can turn around safely and conveniently for multiple passes. Obtain approval from the public authority having jurisdiction over the site for the traffic control procedures that will be used during testing.

7.2.6.3 Install the WIM system in accordance with the vendor's recommendations and calibrate as required in 7.2.5.

7.2.6.4 Measure and record surface conditions as described in 7.2.3.

7.2.6.5 Using traffic control procedures approved by the appropriate public authority and other reasonable safety precautions, have each loaded test vehicle (see 7.2.4) make a series of three runs over the WIM-system sensors at the minimum and at the maximum speed specified by the user between 10 and 70 mph (16 and 113 km/h), record all data, and note the vehicle record number for each run of each test vehicle.

7.2.6.6 For reference values, measure the speed of the test vehicle each time it passes over the WIM-system sensors with a calibrated radar speed meter or by some other means (such as wheelbase/time) acceptable to both the user (or a recognized representative of user's interests) and the vendor, and record the observed speed.

7.2.6.7 At the site where the vehicle is weighed statically, measure the center-to-center spacing between axles on each test vehicle and record these data to the nearest 0.1 ft (30 mm) as reference values.

7.2.6.8 Weigh the test vehicle statically as described in 7.1.1 and 7.1.2 for every run to determine reference-value tire loads. Sum the applicable tire loads to determine reference-value wheel, axle, and axle-group loads as well as gross-vehicle weight.

7.2.6.9 Confirm that the procedure used for determining reference-value tire loads yields acceptable results by making the calculations shown in 7.2.7.1 before continuing the test.

7.2.6.10 If all the measured or calculated loads and weights of the two static test vehicles fall within the specified ranges, run each test vehicle over the WIM-system sensors three more times at a speed which is representative of truck traffic speed at the site, make reference-value determinations of load, weight, speed, and axle spacing for each of these runs, record all data, and proceed to 7.2.6.14.

7.2.6.11 If any of the measured or calculated load or weight values exceeds the specified range, correct deficiencies in the reference-value weighing process and weigh each test vehicle three more times.

7.2.6.12 Repeat 7.2.6.11 until the weighing process yields reference-value loads and weights which are within the specified range.

7.2.6.13 After the observed values for load and weight of the two static test vehicles have been found to be within the specified ranges, run each of the loaded test vehicles over the WIM-system sensors three more times at each of the following attempted speeds: the minimum and the maximum specified by the user between 10 and 70 mph (16 and 113 km/h) and at a speed which is representative of truck-traffic speed at the site. Make reference-value determinations of load and weight (verify that all these values satisfy the ranges specified in 7.2.7.1), speed, and axle spacing for every run of the test vehicles, and record all data.

7.2.6.14 Make the calculations shown in 7.2.7.2 for 18 runs (three runs at three speeds by two vehicles) of the loaded test vehicles and compare the performance of the WIM system with all specification requirements stated in Section 5.

7.2.6.15 If any WIM-system data item resulting from the test-vehicle runs fails to satisfy the standard, have the user (or a recognized representative of user's interests) decide whether to continue the test or declare that the system has failed to meet specification requirements.

7.2.6.16 If continuation is approved, select vehicles from the traffic stream to complete the makeup of the test unit for acceptance-test loading as specified in 7.2.4.

7.2.6.17 Allow each of the selected vehicles to pass over the WIM-system sensors at normal speed and require each vehicle to stop for weighing and for measurement of axle spacing.

7.2.6.18 Make the calculations shown in 7.2.7.2 and compare the performance of the WIM system with the specification requirements stated in Section 5 for the remainder of the vehicles in the test unit.

7.2.6.19 Interpret and report the results as described in 7.2.8.

7.2.7 *Calculation*—Calculation is needed for evaluating (*a*) variability in the reference-value loads and weights of the static test vehicles, and (*b*) conformity of data items produced by the WIM-system to specification requirements.

7.2.7.1 *Procedure for Calculating Reference-Value Loads and Weights*—Only certified weighing devices shall be utilized for determining reference-value tire loads. Reference-value loads and weights are calculated by summing tire loads. For WIM systems which produce estimates of wheel loads, calculate reference-value axle load by summing two wheel loads, axle-group load by summing four wheel loads for the wheels in each tandem-axle group, and gross-vehicle weight by summing all wheel loads separately for each of the two loaded test vehicles specified in 7.2.4. For WIM systems which do not produce estimates of wheel loads, sum the appropriate axle loads to calculate axle-group loads and gross-vehicle weight, if wheel-load weighers are not used. If wheel-load weighers are used, use the procedure stated above for summing tire loads. Calculate the arithmetic mean for each set of values for wheel load, axle load, axle-group load, and gross-vehicle weight; also calculate the difference, in percent, from this mean of each individual value used in calculating the respective mean. Compare these differences to the following specified range for each applicable load or weight: Gross-Vehicle Weight = ±2 %, Axle-Group Load = ±3 %, Axle Load = ±4 %, and Wheel Load = ±5 %. These limits define a practicable range into which an individual observation must fall in order to demonstrate that the static weighing process is producing acceptable results. When multiple weighings are made, always use the mean as the reference-value for load or weight.

7.2.7.2 *Procedure for Calculating Percent of Non-Conforming Data Items*—For each data item that is produced by the WIM system and shown in Table 2, calculate the difference in the value and the corresponding reference value by the following relationship:

$$d = 100[(C - R)/R]$$

where:

d = difference in the value of the data item produced by the WIM system and the corresponding reference value expressed as a percent of the reference value, %,

C = value of the data item produced by the WIM system, and

R = corresponding reference value for the data item.

Determine the number of calculated differences that exceeded the tolerance shown in Table 2 for each data item and express this number as a percent of the total number of observed values of this item by the following relationship:

$$P_{de} = 100[n/N]$$

where:

P_{de} = percent of calculated differences that exceeded the specified tolerance value,

n = number of calculated differences that exceeded the specified tolerance value, and

N = total number of observed values of the data item.

7.2.8 *Interpretation of Test Results and Report*—If more than 5 % of the calculated differences for any applicable data item (specified in Section 4) resulting from all passes of the two loaded test vehicles (each vehicle made three passes at three difference speeds) and from the single pass of each selected vehicle over the sensors at normal speed exceed the specified tolerance (specified in Section 5) for that item, declare the WIM system inaccurate and report that it failed the acceptance test. Regardless of whether the system fails or passes the acceptance test, tabulate all data used in making the determination, including the surface conditions, and send the results to ASTM Committee E-17 on Pavement Management Technologies within 90 days after completion of on-site data collection so that statements about bias and precision of the test can be formulated as experience is accumulated.

7.2.9 *Precision and Bias*—A statement about precision and bias of a test method should allow potential users of the test to assess in general terms its usefulness for a particular purpose. It is intended to provide guidance as to the amount of variation that can be expected in test results when the test is conducted in one or more comparable laboratories or situations. This is a new test method which produces pass-or-fail results. The precision and bias of the procedure and calculations in this acceptance test for Type I and Type II WIM systems are being determined.

7.3 *Acceptance Test for Type III WIM Systems:*

7.3.1 *Scope*—A procedure is given for conducting an acceptance test of a Type III WIM system. This type of system is designed for installation at weight-enforcement stations to identify vehicles operating within a user-specified range of speeds between 15 and 50 mph (24 and 80 km/h), inclusive, that are suspected of weight-limit or load-limit violation. The system must also control official traffic-control devices which direct suspect vehicles to a scale for confirmation weighing and measurement and direct non-suspect vehicles past the scales without stopping. The acceptance test shall be conducted under excellent site conditions and under traffic that includes vehicles which are representative of the vehicle classes of interest where Type III WIM systems will be installed. Performance requirements for this type system are presented in Section 5, and user requirements are given in Section 6. Tolerances for Type III WIM systems are somewhat smaller than for Types I and II because speeds are lower and, with the required reference-value weighing devices continually available, on-site calibration is practicable at any chosen time. Test loading for the acceptance test is designed to allow evaluation of the variability in measured or calculated loads and weights of static vehicles as well as the accuracy of WIM-system estimates of the various data items produced by the system. Capability of the system to detect excessive acceleration of a vehicle while it is over the WIM-system sensors is also evaluated. All vehicles used for test loading the Type III WIM system shall be weighed statically as described in 7.1.1 and 7.1.2 using the certified scales installed at the weight-enforcement site where the acceptance test is conducted.

7.3.2 *Significance and Use*—Interpretation of the results from the acceptance test will allow the user to determine whether the test Type III WIM system is capable of meeting or exceeding the performance requirements stated in Section 5. This can also indicate the potential upper limit of performance that can be achieved by the particular type of system as the road surface conditions, which potentially affect the location and magnitude of dynamic tire forces significantly, shall be the best available for conducting the acceptance test and shall, as a minimum, satisfy the user requirements shown in Section 6. Once a specimen WIM system has passed this rigorous acceptance test, it should not be necessary for each subsequent user to repeat the test for every system of the same type from the same vendor.

7.3.3 *Site for Acceptance Test*—See 7.2.3.

7.3.4 *Test Unit for Acceptance Test Loading*—The test unit for loading the WIM system being evaluated in the acceptance test shall be the same as specified in 7.2.4, except that each vehicle selected from the traffic stream for inclusion in the loading test unit shall have one or more of the following loads or weights that is 80 % or more of the applicable legal limit: gross-vehicle weight, axle-group load, axle load, or wheel load.

7.3.5 *Calibration and Certification*—See 7.2.5.

7.3.6 *Procedure*—The procedure for conducting the acceptance test for Type III WIM systems shall be the same as described in 7.2.6 with the following exceptions:

7.3.6.1 In 7.2.6.5 and 7.2.6.13, the speeds of the loaded test vehicles shall be at the minimum and at the maximum speed specified by the user between 15 and 50 mph (24 and 80 km/h), and

7.3.6.2 After 7.2.6.15, if continuation is approved, verify the ability of the WIM system to detect excessive acceleration by having the driver of each loaded test vehicle approach the WIM-system sensors at a speed between 30 and 40 mph (50 and 60 km/h) and apply heavy braking for approximately one second while the vehicle is passing over the sensor array. Excessive negative acceleration (deceleration) should be indicated by the Violation Code DE (see Table 5). Compare the WIM-system estimates of weights for these runs with those for steady-speed runs and include these comparisons in the data reported to ASTM Committee E-17 on Pavement Management Technologies. Proceed with 7.2.6.16.

7.3.7 *Calculation*—See 7.2.7.

7.3.8 *Interpretation of Test Results and Report*—See 7.2.8.

7.3.9 *Precision and Bias*—The precision and bias of the procedure and calculations in this acceptance test for the Type III WIM system are being determined.

7.4 *Acceptance Test for Type IV WIM Systems:*

7.4.1 *Scope*—The Type IV WIM system is designed to detect weight-limit or load-limit violations by highway vehicles for enforcement purposes. A procedure for acceptance testing of this type system to determine conformity with the performance requirements specified in Section 5 is presented. The procedure includes data collection needed for evaluating the variability in reference-value tire loads measured by certified wheel-load weighers, axle-load scales, a multi-platform vehicle scale, or a combination thereof, as well as the performance of the WIM-system in either measuring the tire loads of a vehicle stopped on the WIM-system sensors or estimating the tire loads and dimensions of a static vehicle from measurements made with the vehicle moving at a steady speed of 10 mph (16 km/h) or less. Reference-value tire loads shall be measured by a multi-platform vehicle scale or an axle-load scale (see 7.1.1) when Option 2 (see 4.1.4) has been specified for the Type IV WIM system under test. When this option has not been specified, reference-value tire loads shall be measured by placing wheel-load weighers directly on the load-receiving surface of the multi-platform vehicle scale or the axle-load scale and raising all tire-pavement contact surfaces approximately into the same plane as described in 7.1.2. The sum of the tire-load values from the wheel-load weighers should compare, within applicable tolerances, with the corresponding value from the scale upon which they are placed; then, the wheel-load-weigher indications should be used only to apportion the axle load(s) indicated by the scale between/among the wheels on the axle(s).

7.4.2 *Significance and Use*—Interpretation of the results from the acceptance test will allow the user to determine whether the tested Type IV WIM system is capable of meeting or exceeding the performance requirements stated in Section 5. This can also indicate the potential upper limit of performance which can be achieved by the particular type of system as the test conditions at the weight-enforcement site shall be the best available for conducting the acceptance test and shall, as a minimum, satisfy the user requirements shown in Section 6. Once a specimen WIM system has passed this rigorous acceptance test, it should not be necessary for each subsequent user to repeat the test for every system of the same type from the same vendor.

7.4.3 *Site for Acceptance Test*—Either an axle-load scale or a multi-platform vehicle scale is required at the site. Other site requirements are the same as 7.2.3.

7.4.4 *Test Unit for Acceptance-Test Loading*—See 7.3.4.

7.4.5 *Calibration and Certification*—Within seven days prior to beginning the acceptance-test, the Type IV WIM system shall, when subjected to field standard test weights, be adjusted to meet the acceptance tolerance for wheel-load weighers or for portable axle-load weighers as stated in NIST Handbook 44, depending upon whether wheel-load data or only axle-load data (4.1.4, Option 2) are of interest. All weighing apparatus used in the acceptance test for determining reference-value tire loads shall be certified as meeting the applicable maintenance tolerance specified in NIST Handbook 44 within 30 days prior to beginning the acceptance test.

7.4.6 *Procedure*—The procedure for conducting the acceptance test for Type IV WIM systems shall be the same as described in 7.2.6 with the following exceptions:

7.4.6.1 In 7.2.6.2, also ensure that an axle-load scale or a multi-platform vehicle scale is available at or near the site,

7.4.6.2 In 7.2.6.5 and 7.2.6.13, the speeds of the loaded test vehicles shall be 0 and 10 mph (0 and 15 km/h),

7.4.6.3 In 7.2.6.9, calculate the difference in each load or weight from the arithmetic mean, in pounds (kilograms), and compare the difference to one-half the applicable tolerance for a Type IV WIM system shown in Table 2. Also, verify that the sum of the tire loads from the wheel-load weighers agrees with the corresponding value from the scale upon which they are placed within applicable tolerances if wheel-load weighers are used. Then, use the wheel-load-weigher indications only to apportion the axle load(s) indicated by the scale between/among the wheels on the axle(s).

7.4.6.4 After 7.2.6.15, if continuation is approved, verify the ability of the WIM system to detect excessive acceleration by having the driver of each loaded test vehicle approach the WIM-system sensors at a speed between 8 and 10 mph (12 and 16 km/h) and apply heavy braking for approximately 1 s while the vehicle is passing over the sensor array. Excessive negative acceleration (deceleration) should be indicated by the Violation Code DE (see Table 5). Compare the WIM-system estimates of loads and weights for these runs with those for steady-speed runs and include these comparisons in the data reported to ASTM Committee E-17 on Pavement Management Technologies. Proceed with 7.2.6.16.

7.4.6.5 In 7.2.6.18, calculate differences in weight and express the differences in pounds (kilograms).

7.4.7 *Calculation*—See 7.2.7 except as described in 7.4.6.

7.4.8 *Interpretation of Test Results and Report*—See 7.2.8.

7.4.9 *Precision and Bias*—The precision and bias of the procedure and calculations in this acceptance test for the Type IV WIM system are being determined.

7.5 *On-Site Calibration Procedure for Type I, Type II, and Type III WIM Systems:*

7.5.1 *Scope*—A procedure is given for on-site calibration of Type I, Type II, and Type III WIM systems. This procedure requires that vehicles selected from the traffic stream at the WIM site pass over the WIM-system sensors and stop for reference-value weighing and measurement.

7.5.2 *Significance and Use*—The dynamic tire force which is measured by the WIM system results from a complex interaction among the vehicle components, the WIM-system sensors, and the road surface surrounding the sensors. Road-surface profiles and sensor installation are different at every WIM site, and every vehicle has unique tire, suspension, mass, and speed characteristics. Therefore, it is necessary to recognize the effects of these site-specific and vehicle-specific factors on WIM-system performance and attempt to compensate for them as much as is practicable via calibration. The calibration procedure shall be applied immediately after the initial installation of a Type I or Type II WIM system at any site. It should be applied again when a system is reinstalled or when site conditions have changed.

7.5.3 *Site for Weighing Static Vehicles*—The calibration procedure requires that vehicles processed over the WIM system stop for reference-value weighing and measurement. Apparatus for weighing static vehicles and their use are described in 7.1.1 and 7.1.2. A suitable site for making these

TABLE 7 Composition of Test Unit for Calibration Loading of WIM Systems

Vehicle Class	Number of Selected Vehicles
23	2
31	3
51	5
71	3

static measurements must be available within a reasonable distance from the WIM site so that specific vehicles can be identified at both locations. Appropriate safety and traffic control measures shall be considered in selecting and operating the static-measurement site. In all cases, traffic control procedures shall be approved in advance by the public authority which has jurisdiction over the site. For Type I and Type II WIM systems, a paved shoulder or a barricaded traffic lane may be considered if a more suitable area is not available. For Type III WIM systems, weighing apparatus will be in place at the weight-enforcement station.

7.5.4 *Test Unit for Calibration Loading*—The test unit for calibration loading shall consist of vehicles selected in random order from the traffic stream at the WIM site and shall, as a minimum, include the numbers and classes of vehicles shown in Table 7. Additional vehicles may be included in the test unit for calibration loading; this is particularly appropriate if a significant number of vehicles of a class(s) not represented in Table 7 are operating at the WIM site.

7.5.5 *Procedure*—The following steps are involved in the on-site calibration process:

7.5.5.1 Adjust all WIM-system settings to vendor's recommendations or to a best estimate of the proper setting based upon previous experience.

7.5.5.2 Select the required number of vehicles that have passed over the WIM-system sensors, or will later pass over them, from the traffic stream in random order and stop these vehicles for static weighing and measuring at the nearby site, using approved traffic-control measures (preferably including a uniformed law-enforcement officer). With a calibrated radar speed meter or by some other means (such as wheelbase/time) that is acceptable to both the user (or a recognized representative of user's interests) and the vendor, measure the speed of each selected vehicle as it passes over the WIM-system sensors.

7.5.5.3 Measure tire loads of the static vehicles as described in 7.1.1 and 7.1.2. Also, measure axle spacings of the static vehicles and record all data for reference values.

7.5.5.4 Calculate the difference in the WIM-system estimate and the respective reference value for each speed, wheel-load, axle-load, axle-group-load, gross-vehicle-weight, and axle-spacing measurement, express the difference in percent (see 7.2.7.2), and find a mean value for the differences for each set of measurements.

7.5.5.5 Make the necessary adjustments to the WIM-system settings which will make the mean of the respective differences for each basic measurement equal zero. For WIM systems which estimate wheel load, the adjustment will be to wheel-load estimates on each side of the vehicles, separately. For the systems which estimate axle loads only, the adjustment will be for axle loads. Some WIM systems allow calibration factors to be entered for selected wheels, axles, or axle groups with respect to their respective location on the vehicle or combination. Adjustment to the speed setting will probably affect axle-spacing estimates.

7.5.6 *Calculation*—In addition to the calculations described in 7.5.5.4 and 7.5.5.5, calculations should be made to determine whether the calibrated WIM system can be expected to perform within specification tolerances at this site. Adjust each calculated difference, as described in 7.5.5.4, by an amount equal to the amount that the mean of the differences varied from zero. Then calculate the percent of these adjusted differences that exceeded the tolerance shown in Table 2 by the method described in 7.2.7.2.

7.5.7 *Interpretation of Results*—If a large number of the adjusted differences for any applicable data item exceeded the specified tolerance shown in Table 2, the WIM system will probably not perform within tolerances at this site.

7.5.8 *Precision and Bias*—No justifiable statement concerning precision and bias of this procedure can be made at this time because there is no experience yet.

8. Keywords

8.1 loading; pavement and bridge; traffic; vehicle; weighing in highways; weigh-in-motion; WIM

ANNEX

(Mandatory Information)

A1. COMPUTATION OF EQUIVALENT SINGLE-AXLE LOADS (ESALs) BY WIM SYSTEMS

A1.1 Equivalency Factors

A1.1.1 Most pavement design procedures which are now in general use are based on theoretical considerations of materials behavior coupled with a complementary evaluation of the cumulative effects of traffic loading. Many of these procedures define the design thickness of a pavement in terms of the number of applications of a standard single-axle load. To use this concept, the damaging effect of each axle load in a mixed traffic stream must be expressed in terms of the equivalent number of repetitions of a selected standard single-axle load. The numerical factors that define the number of passes of a standard single-axle load which would cause pavement damage equivalent to that caused by one pass of a given axle load are called equivalent single-axle load (ESAL) factors.

A1.1.2 The equivalency factors that were derived from the AASHO Road Test[5] are perhaps the most commonly used equivalency factors for pavement design and analysis. These were derived from a statistical analysis of the AASHO (now AASHTO) Road Test data.[6] The standard axle load used by AASHO is an 18 000-lb (8.2-Mg) single-axle load. Analysis of the AASHO Road Test design equations[7] permits the determination of equivalency factors for both flexible and rigid pavements. These factors can be computed with the following equations.

A1.2 Flexible Pavement Equivalency Factors

A1.2.1 The design equations for flexible pavements presented in the AASHTO Interim Guide[7] are:

$$\log W_t = 5.93 + 9.36 \log(\overline{SN} + 1) - 4.79 \log(L_1 + L_2) + 4.33 \log L_2 + \frac{G_t}{\beta} \tag{A1.1}$$

and

$$\beta = 0.40 + \frac{0.081(L_1 + L_2)^{3.23}}{(\overline{SN} + 1)^{5.19}\, L_2^{3.23}} \tag{A1.2}$$

where:

W_t = number of axle load applications at the end of time t for axle sets with dual tires,

$\overline{SN}$ = structural number, an index number derived from an analysis of traffic, roadbed soil conditions, and regional factor which may be converted to a thickness of flexible pavement layers through the use of suitable layer coefficients that are related to the type of material being used in each layer of the pavement structure,

L_1 = load on one single axle, or on one tandem-axle set for dual tires, kips [1 kip = 1000 lb (1 kip = 4.536×10^{-1} Mg)],

L_2 = axle code (one for single axle, and two for tandem axle sets),

P_t = serviceability at the end of time t (Serviceability is the ability of a pavement at the time of observation to serve high-speed, high-volume automobile and truck traffic.),

G_t = a function (the logarithm) of the ratio of loss in serviceability at time t to the potential loss taken to a point where $P_t = 1.5$, or

$G_t = \log \left[\frac{4.2 - P_t}{4.2 - 1.5}\right]$, and

β = a function of design and load variables that influences the shape of the P-versus-W serviceability curve.

A1.2.2 As indicated above, for this design method the number of axle load repetitions to failure is expressed in terms of a pavement stiffness or rigidity value which is represented by Structural Number, $\overline{SN}$, load characteristics denoted by L_1 and L_2, and the terminal level of serviceability selected as the pavement failure point, P_t. Values commonly used to define terminal serviceability, P_t, are 2.0 and 2.5.

A1.2.3 The relationship between the number of applications, $W_{t_{18}}$, of an 18 000-lb (8.2-Mg) single-axle load and the number of applications, W_{t_i}, of any other single or tandem axle load, L_i, to cause the same potential damage to a flexible pavement can be found from the following equation:

$$E_i = \frac{W_{t_{18}}}{W_{t_i}} = \left[\frac{(L_i + L_2)^{4.79}}{(18 + 1)^{4.79}}\right] \left[\frac{10^{G_t/\beta_{18}}}{(10^{G_t/\beta_i}) L_2{}^{4.331}}\right] \tag{A1.3}$$

A1.2.4 The ratio shown in Eq A1.3 is defined as an equivalence factor, and is evaluated by solving the equation with any given axle load L_i. This factor defines the number of 18 000-lb (8.2-Mg) single-axle load applications that would be needed to cause damage to the pavement structure equivalent to one application of the given axle load. Because the term β is a function of $\overline{SN}$ as well as L_i, the equivalence factor varies with $\overline{SN}$.

A1.3 Rigid Pavement Equivalency Factors

A1.3.1 The basic equations for rigid pavements developed from the AASHO Road Test are:

$$\log W_t = 5.85 + 7.35 \log(D + 1) - 4.62 \log(L_1 + L_2) + 3.28 \log L_2 + \frac{G_t}{\beta} \tag{A1.4}$$

and

$$\beta = 1.0 + \frac{3.63(L_1 + L_2)^{5.20}}{(D + 1)^{8.46}\, L_2^{3.52}} \tag{A1.5}$$

where:

D = thickness of rigid pavement slab, in. (mm), and

$G_t = \log \left[\frac{(4.5 - P_t)}{(4.5 - 1.5)}\right]$.

A1.3.2 As can be seen from analyzing Eqs A1.4 and A1.5, the pavement rigidity or stiffness value is expressed in terms of the pavement thickness, D.

A1.3.3 The relationship between the number of applications, $W_{t_{18}}$, of an 18 000-lb (8.2-Mg) single-axle load and the number of applications, W_{t_i}, of any other single or tandem axle load, L_i, to cause the same potential damage to a rigid pavement can be found from the following equation:

$$E_i = \frac{W_{t_{18}}}{W_{t_i}} = \left[\frac{(L_i + L_2)^{4.62}}{(18 + 1)^{4.62}}\right] \left[\frac{10^{G_t/\beta_{18}}}{(10^{G_t/\beta_i})\, (L_2{}^{3.28})}\right] \tag{A1.6}$$

A1.3.4 The ratio is defined as an equivalency factor, and is evaluated by solving Eq A1.6 with any given axle load, L_i. This factor gives the number of 18 000-lb (8.2-Mg) single-axle load applications that would be needed to cause damage to the pavement structure equivalent to one application of the given axle load. Because the term β is a function of D as well as L_i, the equivalency factor varies with D.

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[5] Highway Research Board, "The AASHO Road Test," Report 5, Pavement Research, *Highway Research Board Special Report 61E*, 1962.

[6] Highway Research Board, "The AASHTO Road Test," Proceedings of a conference held May 16–18, 1962, St. Louis, Missouri, *Special Report 73*, Washington, DC 1962.

[7] "AASHTO Interim Guide for Design of Pavement Structure—1972," American Association of State Highway and Transportation Officials, Washington, DC 1974.

A1.1 CONVERSION FACTORS

To Convert From	To	Multiply By
pound (lb avoirdupois)	kilogram (kg)	4.536×10^{-1}
pound (lb avoirdupois)	megagram (Mg)	4.536×10^{-4}
kip (1000 lb avoirdupois)	megagram (Mg)	4.536×10^{-1}
inch	millimetres (mm)	25.4