DEMONSTRATION OF WEIGH-IN-MOTION SYSTEMS FOR DATA COLLECTION AND ENFORCEMENT

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16. Abstract

In a series of data-taking sessions, over 800 trucks selected from the traffic stream on IH-10 near Seguin, Texas, were weighed in motion by a WIM system at three different speeds and then statically by three different axle-load scales and by three different sets of wheel-load weighers. The accuracy and efficiency with which static weighing of truck wheels, axles and axle-groups could be accomplished was determined by comparing all other weights against weights from a specially-designed AXLE/WHEEL scale. The effect of the height of the portable axle-load scales and the wheel-load weighers on weighing accuracy was analyzed. Tolerances which will allow for the probably weighing error when using the different types of static scales were defined. The importance of on-site calibration of WIM systems was demonstrated. Considerable improvement in WIM system performance was shown when loaded 5-axle, tractor-semitrailer trucks were used as a basis for calibration as compared with multiple runs of a loaded 2-axle, single-unit test truck. The expected range in the variability of WIM system weight estimates from a properly-calibrated system was identified for different speeds. Speed has a systematic, but relatively small, effect on accuracy of the Radian WIM system. The Radian WIM system produces high-quality statistical data that are essential to the transportation industry. The potential usefulness of WIM systems for enforcement was identified. The low-speed weigh-in-motion (LSWIM) performed better on the average and within a narrower range of variation than any of the wheel-load weighers evaluated. It was more consistent throughout the full range of loads than the flush-mounted axle-load scale, but had somewhat more variability.

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Research Project IAC(84-85)-1024

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State Department of Highways and Public Transportation

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable undre the patent laws of the United States of America or any foreign country.

PREFACE

This is the first and final project report on the Texas RTAP WIM Demonstration Project. This project was a cooperative effort among the Federal Highway Administration (FHWA), the State Department of Highways and Public Transportation (SDHPT), the Department of Public Safety (DPS), the Center for Transportation Research (CTR) at The University of Texas at Austin with additional technical support from the Texas Department of Agriculture and the Radian Corporation.

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ABSTRACT

In a series of data-taking sessions, over 800 trucks selected from the traffic stream on IH-10 near Seguin, Texas were weighed in motion by a WIM system at three different speeds and then statically by three different axle-load scales and by three different sets of wheel-load weighers. The accuracy and efficiency with which static weighing of truck wheels, axles and axle-groups could be accomplished was determined by comparing all other weights against weights from a specially-designed AXLE/WHEEL scale. The effect of the height of the portable axle-load scales and the wheel-load weighers on weighing accuracy was analyzed. Tolerances which will allow for the probable weighing error when using the different types of static scales were defined.

The importance of on-site calibration of WIM systems was demonstrated. Considerable improvement in WIM system performance was shown when loaded 5-axle, tractor-semitrailer trucks were used as a basis for calibration as compared with multiple runs of a loaded 2-axle, single-unit test truck. The expected range in the variability of WIM system weight estimates from a properly-calibrated system was identified for different speeds. Speed had a systematic, but relatively small effect on accuracy of the Radian WIM system. The Radian WIM system produces high-quality statistical data that are essential to the transportation industry.

The potential usefulness of WIM systems for enforcement was identified. The low-speed weigh-in-motion (LSWIM) performed better on the average and within a narrower range of variation than any of the wheel-load weighers evaluated. It was better on average, and about the same with respect to variability as the portable axle-load scale. It was more consistent throughout the full range of loads than the flush-mounted axle-load scale, but had somewhat more variability.

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SUMMARY

A unique 4-lane WIM system was developed for use on this project. It was deployed initially as part of an extensive field experimental program to study the effect of speed on in-motion weighing accuracy and later for routine statistical data taking at several sites in Texas. Data from these uses have been analyzed and are presented in this report.

The accuracy of two axle-load scales and three types of wheel-load weighers was defined from weighings on these devices and on an accurate axle/wheel scale that was installed specially for the project. Tolerances for using these devices in enforcement have been suggested.

Calibration procedures for the WIM system using different types of trucks were studied. The importance of on-site calibration for every installation was identified. Accuracy of the ISWIM and HSWIM systems was improved considerably when loaded 5-axle tractor-semitrailer trucks were used as a basis for calibration as compared with multiple passes of a loaded 2-axle, single-unit truck. Adequate calibration of the LSWIM scales was achieved with both dead-load test blocks and low-speed moving test vehicles.

On average, there was a very small effect of speed on the accuracy with which the Radian WIM system estimated static weights. Higher speed increased the range of variability in the estimated weights.

A procedure for predicting traffic loading on multi-lane highways is presented. Timewise changes in the patterns of loading are illustrated for a site on a rural interstate highway.

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IMPLEMENTATION STATEMENT

The advantages and feasibility of using WIM systems for collecting significant amounts of statistical truck weight and classification data have been convincingly demonstrated. The accuracy of the Radian WIM system that was evaluated in this demonstration is entirely adequate for operational data taking when the system is properly calibrated at each site where it is used. A comprehensive, continuing data collection program with the Radian WIM system that was developed under this project should be implemented in Texas and should include instrumentation in all highway lanes at all sampling sites to obtain wheel, axle, axle-group, and gross-vehicle weights along with axle-spacing, speed and classification information at representative locations. Other states should develop statistical data collection programs to utilize multilane WIM systems. Statistical sampling techniques must be used in these programs to assure that timewise variations in traffic loading are properly identified. Means for summarizing, interpreting, and storing the large amounts of statistical data which will be generated by WIM systems are urgently needed to serve the design, management, planning, and financing needs of the State. Appropriate consideration should be given to a network of microcomputers for this purpose. An automated vehicle-classifier system should be developed to complement and extend the coverage of traffic data that can be represented by the detailed truck weight and classification data from each WIM system site.

The statistical data from routine WIM data-taking sessions should be shared with enforcement agencies to help identify locations and times where overloading problems occur. Enforcement agencies should consider using WIM systems as a sorting device to identify suspected overload violators. Further consideration must be given to the possibility of using the low-speed WIM technique directly for enforcement. Appropriate tolerances for static weighing need to be identified for use by enforcement agencies. Results of this study provide valuable information for this purpose.

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CHAPTER 1. INTRODUCTION

During the past half century, highway agencies have been weighing trucks to obtain the pertinent information that is needed for statistical data and for law enforcement. Trucks have also been weighed for commerce. Commercial truck weighing requires that a highly-accurate determination of the gross weight of individual loaded and unloaded vehicles be made. Thus, this weight can be relied upon as the quantitative basis for trading goods without risk of serious injury to either party involved in the transaction. For this exacting purpose, the only acceptable means of weighing is by using a vehicle scale and single-draft weighing whereby all wheels on the vehicle are weighed simultaneously while the vehicle is in static equilibrium.

Statistical data, on the other hand, provide descriptive information upon which decisions regarding the planning, financing, design, operation, maintenance, and management of highway facilities are based. These applications do not require the same degree of attention to the weight of individual vehicles nor to the exact measurement of individual wheel loads as no single person or firm is at risk. Successive weighing of vehicle wheels, axles, or axle groups statically on axle-load scales, wheel-load weighers, or weigh-in-motion (WIM) systems is generally used for acquiring such statistical data. Sampling techniques are usually employed to weigh selected trucks at representative locations on the highway system and to develop representative frequency distributions of weight data. These data, along with representative frequency distributions of vehicle classification data, are utilized to define past and present traffic loads and to forecast future patterns of traffic loading at selected locations with respect to time. Then, based on anticipated future traffic loading, designs are drawn to accommodate efficiently and effectively the motor vehicle traffic that is expected to use the design facilities during some future period of time.

In order to protect the facilities from unexpected loads, legal weight limits which respect engineering principles are established, and enforcement weighing programs are implemented. The enforcement program involves checking wheel, axle, axle-group, and gross-vehicle weights as well as the center-to-center spacings of axles and the overall length of individual vehicles to detect overloaded and/or oversized vehicles and to remove them from the highways. These weight determinations must be made within reasonable tolerances as an individual is at risk when a violation of the established legal limit is detected. Vehicle scales with single or multiple load-receiving platforms, axle-load scales, and wheel load weighers are all used in enforcement weighing programs. Weigh-in-motion (WIM) systems are not used directly for this purpose as the legality of WIM estimates of static weight has not been established. The type of static scale that is used in a specific enforcement program is determined by safety considerations, weigh site availability, equipment capabilities and limitations, type of legal limits to be enforced, time requirements, and costs. Practicable enforcement tolerances which recognize all these factors must be adopted either by law or by a policy of the enforcement agency.

OBJECTIVES OF THE RESEARCH

As a continuing need exists to obtain as accurately and efficiently as possible the essential traffic data that are required for statistical and enforcement purposes, a weigh-in-motion demonstration project was undertaken to address the following overall objectives:

(1) To evaluate the practicability of using state-of-the-art WIM equipment for obtaining statistical truck weight and classification data.

(2) To determine the feasibility of using WIM equipment in truck weight and size enforcement programs.

To attain these general objectives, a series of intermediate objectives were identified as follows:

(1) To define the range of accuracy within which the portable and semi-portable static truck weighing equipment that is currently used in Texas performs in typical enforcement operations.

(2) To define the attainable accuracy of a low-speed weigh-in-motion (LSWIM) system.

(3) To explore the possibility of using LSWIM weighing to obtain truck weight and size information of adequate quality for legal evidence of the violation of weight and size-laws.

(4) To demonstrate the feasibility of using high-speed weigh-in-motion (HSWIM) techniques for simultaneously collecting statistical data and sorting suspected overweight and oversized vehicles from the traffic stream for subsequent static weighing and dimensioning.

(5) To study the effects of permanent weigh station operations on "by-passing" or "waiting-it-out" truck traffic patterns.

(6) To evaluate the practicability of combining enforcement and statistical data collection weighing operations using WIM equipment.

(7) To demonstrate the importance of weighing trucks in all lanes, in both directions, on multilane highways for statistical data sampling purposes.

(8) To study timewise variations in vehicle weights using data collected by the new 4-lane WIM system at a site in Texas.

The unique features of this research project as compared to others of the same type are: (1) development of a 4-lane WIM system that can be deployed efficiently and effectively at various locations, (2) design of a sampling procedure for selecting trucks for weighing statically and in-motion at three different speeds, (3) evaluation of the overall performance capabilities of various types of static axle-load and wheel-load scales, (4) defining the accuracy of WIM scales at three different speeds (low $\leq$ 10 mph, intermediate = approximately 30 mph, and high = approximately 55 mph), (5) study of the effect of operating a fixed weigh station on trucks by-passing on alternate routes or waiting-out the schedule of the station, and (6) development of a practical technique for estimating the pattern of traffic loading in each lane of multilane highways.

STUDY APPROACH

The work reported here is largely an experimental and observational attempt to explore and develop better ways and means of collecting high-quality weight data for the purposes mentioned above. A series of data-taking sessions conducted according to a carefully planned experiment in the summer of 1984 produced extensive data sets upon which to base several of the proposed comparisons and evaluations. Chapter 2 describes the field testing program and in addition includes a discussion of the concepts of static and in-motion weighing techniques. The variability in truck wheel, axle, axle-group, and gross-vehicle weights that were observed when about 800 trucks were weighed on different types of static scales is discussed in Chapter 3. This chapter presents the statistical analysis of the data along with an evaluation of the factors which affected the performance of each scale.

WIM data were collected in the field-testing program for the same trucks operating at three different speeds when weighed in motion. The results are documented in Chapter 4. Comparison of the WIM-estimated weights with the respective static weights from an accurate referee scale served as the basis for evaluating an on-site calibration technique that should be used immediately upon installation of a WIM system at a site and periodically thereafter. The adequacy of using a particular type of truck for on-site calibration was investigated. Chapter 4 also includes an analytical discussion of the difference in load carried on the left and right-side wheels of an axle, axle-group, and truck. Furthermore, the feasibility of using WIM systems for statistical weight-data acquisition and for enforcement purposes is evaluated and described in this chapter, and the relative accuracy of a WIM system is documented.

Chapter 5 presents the concept of weighing tolerances and discusses the techniques used in analyzing the data to develop appropriate tolerance limits for each type of scale that was evaluated. In conjunction with evaluating the performance and accuracy of static and WIM scales, efficiency and effectiveness of each weighing technique is examind in Chapter 6. During the course of the field experiment, size measurements on the trucks which were weighed were also made both manually and by the WIM system at three different speeds. This experience indicated that WIM can simultaneously classify traffic by lane and by direction efficiently and accurately. The efficiency of using static scales in typical weighing operations, in terms of time requirements for weighing and dimensioning, is also evaluated in Chapter 6. Furthermore, the effects of weigh station operations on "by-passing" or "waiting-it-out" truck traffic is described.

Chapter 7 describes a practicable technique for estimating the patterns of traffic loading in each lane of multilane highways. This procedure is outlined and illustrated with four multi-day data sets taken during 1984 and 1985 at a 4-lane WIM site in Texas.

Chapter 8 summarizes the results of the study and presents conclusions drawn from the investigation. Recommendations for possible implementation of the findings and for further research into WIM technology are also presented in this chapter.

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CHAPTER 2. CONCEPTS OF WEIGHING AND EXPERIMENTAL PROGRAM

This chapter presents a discussion of the concepts of static and in-motion weighing techniques followed by a description of the carefully-planned experiment that was conducted. The field-testing program was designed to produce a valid data set that could serve as the basis for defining the range of accuracy and the relative efficiency within which a WIM system, three axle-load scales, and three types of wheel-load weighers can perform in typical weighing operations. The WIM system was used to make dynamic tire-force measurements at three different speeds, and the axle-load scales and wheel-load weighers were used to make static weight measurements on the same trucks that were sampled from the traffic stream at an enforcement station on an interstate highway in a rural area of Texas. The experimental site, the profile of the road surface at the site, the equipment, and the data collection process are described in this chapter. Analysis of the data obtained from the various scales is described in following chapters.

STATIC WEIGHING

Weight is the force with which an object is attracted toward the earth by gravity. It is equal to the product of the mass of the object and the local value of gravitational acceleration. A highway vehicle is made up of several interconnected components, each with its own mass. The connectors, which can be viewed as springs, hinges, and motion dampers, also have mass. A force applied to any vehicle component, such as a wheel assembly, will be transferred to the other components through the connectors.

To weigh a highway vehicle accurately, all tires of the vehicle must be supported simultaneously on force transducers (scales) which are capable of measuring the total upward force required to balance the downward force of gravity when no component of the vehicle is experiencing vertical acceleration. That is, no external force other than gravity, nor any vertical inertial force, can be acting on any vehicle component at the time of weighing. This zero-vertical-acceleration condition is realized in practice only after a vehicle has stopped on a weighing device and sufficient time has been allowed for any kinetic energy stored in the vehicle components to be dissipated. Measurement of the total upward vertical force applied through the tires of the vehicle in this condition of static equilibrium is called static, single-draft weighing and is the most accurate way to determine gross-vehicle weight.

Gross-vehicle weight can also be determined by successively stopping the axles of the vehicle on axle-load scales or wheel-load weighers and measuring the downward force exerted by the tires of the vehicle when all vehicle components are motionless and in exactly the same relative position to each other throughout the entire sequence of the weighing operation. If the vehicle is moved between successive tire-force measurements, such a condition of exact juxtaposition among the components can only be approximated in practice; therefore, some sacrifice in static weighing accuracy must be expected when this technique is used.

Moving a vehicle usually changes the relative positions of its components due to such factors as torque in the drive train, friction in the brake and suspension systems, and unevenness in the road/scale surface. For all practical purposes, gravity applies a constant downward force to each vehicle component regardless of its displacement relative to the other interconnected components; therefore, the sum of these forces -- the gross-vehicle weight -- will not change as the vehicle is moved from place to place. The proportion of the gross-vehicle weight carried by each of the interconnected vehicle components at the time of each weighing is, however, a direct function of the relative position of all components of the vehicle at that time.

A typical spring rate for a rear truck wheel suspension is about 3,500 to 4,000 lb/in of displacement and each tire also has a rate of about 4,000 lb/in. The front suspension generally has a spring rate of about 500 lb/in [Ref 1]. Thus, if one wheel of a vehicle is raised or lowered with respect to the others during the weighing sequence, the wheel weight on the scale or weigher will be considerably different than when the wheel is not displaced. Special attention must be given to this concept when weighing the wheels of tandem or triple axles if reasonable accuracy is to be achieved with wheel load weighers. The same principles also apply to weighing axles and axle groups with a set of wheel load weighers or with axle-load scales. Therefore, the only way to weigh a highway vehicle accurately by successive positioning of wheels on a scale, or a series of scales, is to maintain all wheels of the vehicle on a smooth and level surface and to have no redistribution of weight during the weighing process. This means that the deflection of the scale itself must be considered and that the friction in the vehicle suspension, drive, and braking system must be accounted for. A considerable amount of weight transfer among axles occurs during acceleration and stopping of a vehicle, and the weight distribution at the time of weighing depends on the frictional forces in the suspension system at that time. In practice, efforts must be made to minimize the effects of weight transfer during successive weighings in order to make measurements within acceptable tolerances. The magnitude of these effects is illustrated in Chapter 3 by analyzing data sets taken under carefully-controlled field conditions.

IN-MOTION WEIGHING

The concept of in-motion weighing is that gross-vehicle weight or the portion of this weight carried by a wheel, an axle, or an axle group can be estimated from instantaneous measurements of the vertical component of the dynamic (continually changing) force that is applied to the road surface by the tires of a moving vehicle. The gross weight of the vehicle does not change as it moves over the road, but the dynamic force imposed on the road surface by a rolling tire can vary from more than double its static weight when it mounts a bump, thereby exerting a large unbalanced force on the wheel-assembly mass, to zero when the tire bounces off the road.

The pattern of wheel force for a given highway vehicle traveling over the same roadway surface profile at the same speed is consistent. This is evident from the small scatter in the experimental measures documented in Refs 2 and 3. The forces acting on the vehicle components are the same, and the response of the interconnected masses that make up the vehicle is the same. The mass of the vehicle components affects the magnitude and the frequency of the dynamic wheel forces and their variation from static weight; therefore, different vehicles react differently to the same pattern of road roughness. Observation has shown that the wheels (unsprung masses) oscillate typically in the range

of about 8 to 12 Hz when displaced suddenly, and that oscillations damp rather quickly [Ref 1]. During these veritical oscillations, the dynamic wheel force is sometimes less than static weight, and sometimes greater. An out-of-round or out-of-balance tire or wheel can apply vertical forces to the rotating mass and cause large variations in dynamic wheel force. Another characteristic of truck behavior is that the sprung mass (body and pay load) typically oscillates at about 0.5 to 3 or 4 Hz depending on many factors which include mass [Ref 1]. These oscillations cause variations in the proportion of the sprung mass that is transferred to a tire at any given instant.

Accurate in-motion weighing of highway vehicles is possible only when the vertical acceleration of all vehicle components is zero. The sum of the vertical component of tire forces exerted on a smooth, level surface by the perfectly round and dynamically-balanced, rolling wheels of a vehicle moving at a constant speed in a vacuum is exactly equal to the gross weight of the vehicle. None of the vehicle components will be accelerating vertically under these ideal conditions. Such conditions never exist in practice. No road surface is perfectly smooth and level, no vehicle has perfect components, and the existence of the earth's atmosphere cannot be ignored. The nearer actual conditions approach ideal conditions, the better the estimation of vehicle weight that can be made from samples of the vertical component of tire forces applied to the road surface by a moving vehicle.

In practice, the adverse effects of the roadway factors can be minimized by careful site selection, proper installation, on-site calibration, and maintenance of in-motion weighing equipment. Undesirable environmental effects can be recognized or perhaps avoided by scheduling weighing operations. The vehicle factors, except for possibly speed and acceleration, are largely uncontrollable at a weighing location. Legal and safety regulations restrict the range within which certain other vehicle factors occur, and economic considerations influence the vehicle operating conditios that drivers and owners are willing to tolerate. Perhaps the most significant uncontrollable vehicle factor that affects in-motion weighing is tire condition. Unbalanced or out-of-round tires rotating at high speed can cause large variations in the vertical component of force acting on the wheel mass and can therefore produce vertical acceleration of this mass. Tire inflation pressure also contributes significantly to the dynamic behavior of the tire and wheel mass. Even though the tire-condition variable cannot be controlled in in-motion weighing, observation and experience indicate that the tires on most over-the-road vehicles are maintained in reasonably good condition; therefore, the results of this potentially adverse effect might also fall within tolerable limits for most vehicles and for certain types of in-motion weighing operations.

EXPERIMENTAL PROGRAM

Site Location

One of the early efforts in the experimental program involved the selection of an existing vehicle inspection station where a permanent axle-load scale was in place and where a second axle-load scale (i.e. referee scale) could be installed without major changes to the geometry of the station. Furthermore, the station needed to accommodate the deployment of a portable axle-load scale and a set of wheel-load weighers. It was important that the selected station meet the following conditions:

(1) be adjacent to the lanes of an interstate highway,

(2) have a relatively straight, smooth, and level road surface,

(3) have low radio-frequency noise,

(4) have a convenient source of electric power, and

(5) be reasonably accessible to all the participating parties in the program.

The weigh station adjacent to the eastbound lanes of IH-10 at Milepost 616 east of Seguin, Texas was selected as the experimental site for data collection. The arrangement of scales and the deployment of personnel at this site are shown in Fig 2-1. As indicated in this figure, the weigh strip consisted of a standard tapered exit ramp, a 500-ft straight section 40 feet wide, plus a tapered entrance ramp leading back into the main lanes.
High-speed weigh-in-motion (HSWIM) scales were installed in the right-hand main lanes about 500 ft in advance of the exit ramp gore (see Fig 2-2(a)). A SPEED LIMIT 55 (R2-1) sign was erected 6-ft beyond the right edge of the right-hand shoulder at 6-ft height 300 ft in advance of the HSWIM scales, and a traffic cone was placed on the right-hand edge of the shoulder to aid drivers in identifying the scale location. Speed over these scales actually averaged about 50 mph in the experiment.

Intermediate-speed weigh-in-motion (ISWIM) scales were placed in the straight section of the exit ramp 470 ft in advance of the low-speed weigh-in-motion (LSWIM) scales (see Fig 2-2(b)). A SPEED LIMIT 35 (R2-1) sign was erected on the exit ramp 6-ft beyond the edge of the scale at 6-ft height 200 ft in advance of the ISWIM scales. In addition, traffic cones were placed at the scale to identify its location. The average speed over the ISWIM scales was observed to be 30 mph. A STOP SIGN was erected in the weigh station 3 ft beyond the right-hand edge of the pavement at 7-ft height 20 ft in advance of the LSWIM scales (see Fig 2-2(c)). The roll-over speed on the LSWIM scales was less than about 10 mph. All the WIM scales were supported by an instrument system that was housed in a mobile laboratory trailer located opposite the ISWIM scales. The referee scales were placed 80 ft beyond the LSWIM scales on a straight level (longitudinally) section of the weigh station (see Fig 2-2(c)).

The flush axle-load scale (permanent scale at the weigh station) which was already set in a shallow concrete pit with the long axis of the load-receiving elements in the direction of traffic (see Fig 2-2(d)) was 80 ft beyond the referee scale. In addition, a pair of portable axle-load scales was placed on the pavement surface 70 ft beyond the flush-mounted axle-load scales for some of the tests (see Fig 2-2(e)). This scale was operated by ramping each axle or axle group up about 4 inches onto the platforms. Three different types of wheel-load weighers, one on each day of the first three days of data-taking sessions, were also operated 70 ft beyond the ramped, portable axle-load scales (see Fig 2-2(f)).

Profile of the Road Surface

Gross-vehicle weight and axle-group weights can be determined in several ways. The most accurate way requires the use of a multiple-section vehicle scale using single-draft weighing wereby all wheels on the vehicle are weighed simultaneously while the vehicle is in static equilibrium. Because of the expense involved, such a vehicle scale was not made available to determine the gross-vehicle weight and axle-group weights of the trucks that were

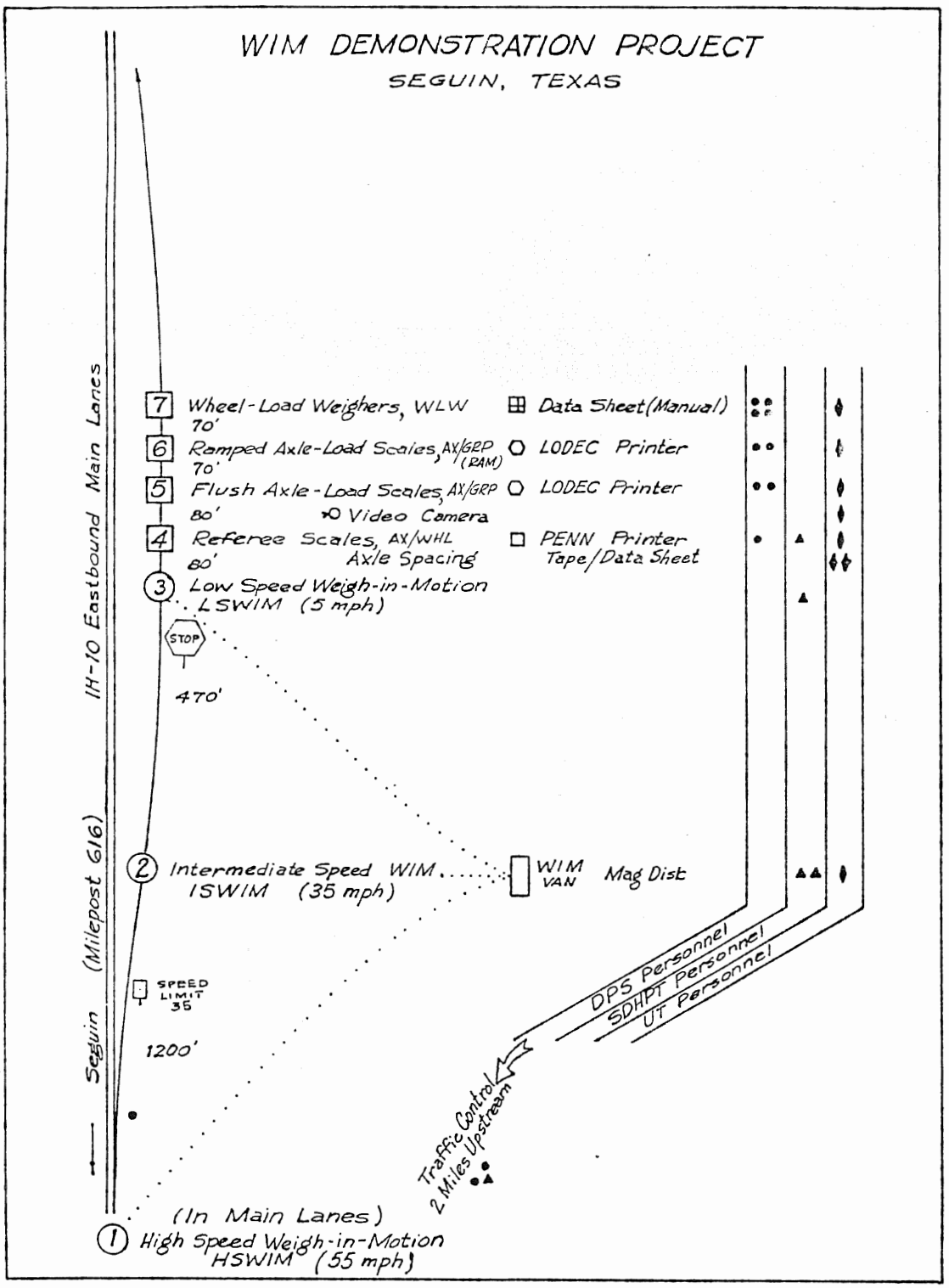
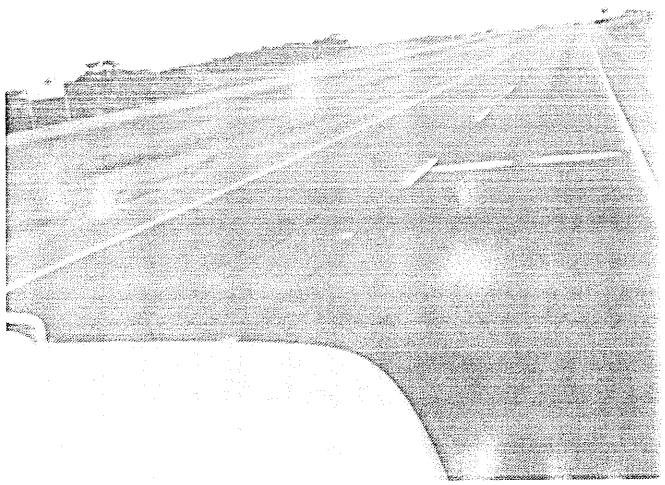
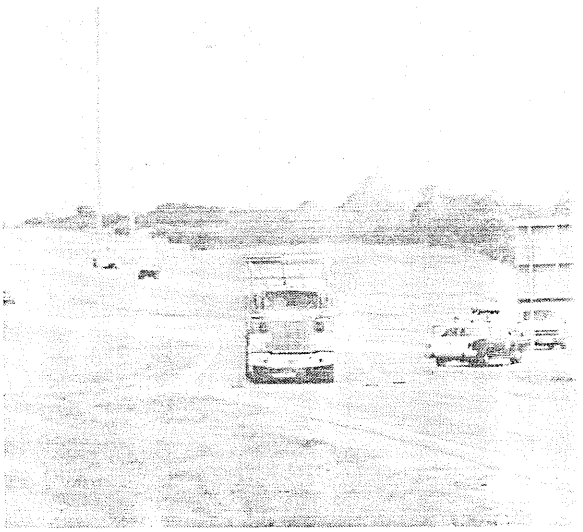


Figure 2-1. Lay-out of the IH-10 weigh station and arrangement of the scales.



(a)



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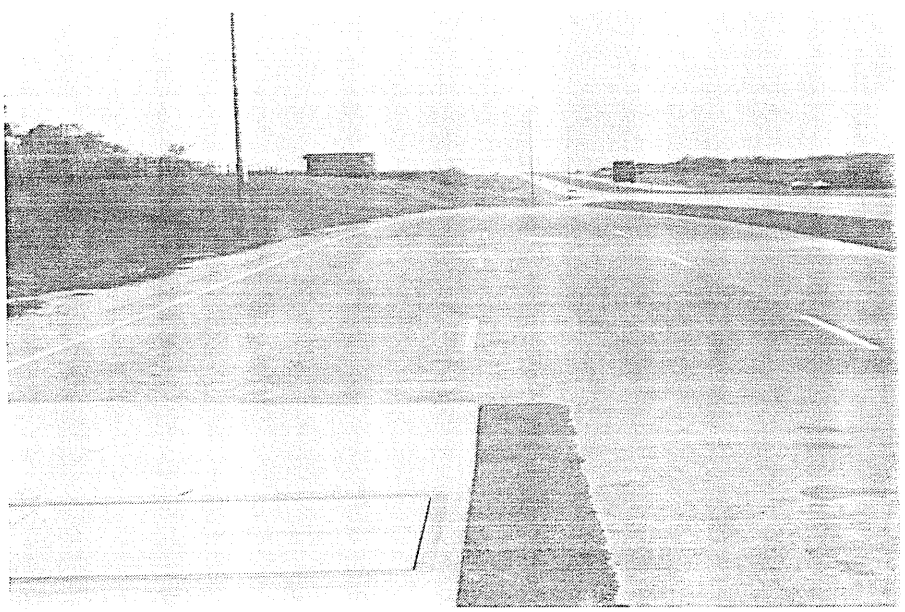


(c)

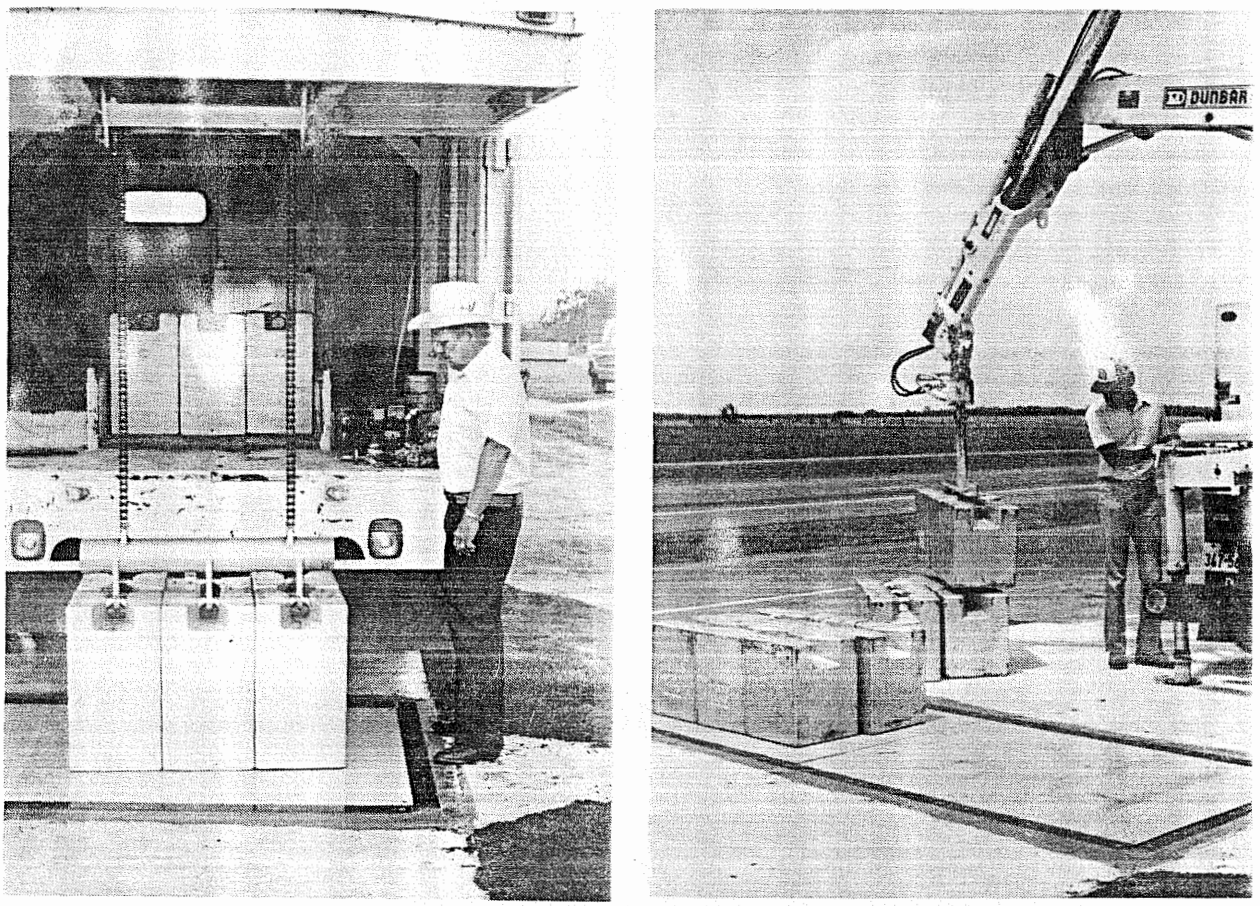
Figure 2-2. (a) HSWIM scales in right-hand main lanes of IH-10, (b) ISWIM scales in exit ramp to weigh station. (c) AX/WHL (referee) scales in foreground, LSWIM in right-hand lane of weigh strip, ISWIM on exit ramp from main lanes in background and instrument trailer on horizon.

(d)

(e)

(f)

Figure 2-2. (continued) (d) AX/GRP scale, (e) AX/GRP (RAM) sacle (portable axle-load scale), (f) WLW/M300 (wheel-load weighers).



(g)

Figure 2-2. (continued) (g) Test weights on AX/WHL scale by Texas Department of Agriculture.

weighed on the axle-load and wheel-load scales used in the study. As mentioned previously, another way to determine gross-vehicle weight and axle-group weights is to successively weigh wheels, axles, or axle groups on axle-load scales or wheel-load weighers with all the vehicle components motionless and in exactly the same relative position to each other at the time of each weighing. Theoretically, this condition of exact positioning can be best achieved on a perfectly smooth and horizontal surface that is free of any unevenness. In reality, however, a road surface of this type is almost impossible to construct and maintain because of economic factors. Displacement of any vehicle component between or during successive weighings due to torque, braking, load shifting, and the associated frictional forces causes redistribution of the gross-vehicle weight among the axles and wheels and therefore results in inaccuracy in the gross-vehicle weight and the axle-group weights calculated by summing the successive measurements.

The existing straight, zero-grade section of the weigh station chosen for use in this study had a three-percent cross slope to the left-hand side in the weighing lane. At the time the site was selected, the permanent axle-load (axle/ group) scale had been installed in a shallow concrete pit with zero cross slope in the immediate vicinity of the scales. The asphalt concrete surface had been warped from the three-percent cross slope before and beyond the shallow pit to transition to the level plane of the scale surface. This warped cross section was not shown on the plans and was not evident until construction of the referee scale pit was begun. Limited funds and time available for the study made it necessary to install the referee (axle/wheel) scale also at zero cross slope and to warp the adjacent surface into the ten-foot long concrete approach aprons that were constructed before and beyond the scales. Figure 2-3 shows the longitudinal profile in each wheel path at the site at the time when data collection began. The longitudinal profile at the center of the vehicle path was excellent, but the warping of the cross slope at the scale pits was a matter of concern as it could possibly affect wheel weights adversely. The effects of the local warping of cross slope were not expected to be as pronounced on axle, axle-group, and gross-vehicle weights, however. The effects of this warped surface are further discussed later in this report.

After the first two days of data taking, the resident engineer for the State Department of Highways and Public Transportation (SDHPT) had the existing asphalt concrete surface on the right-hand side of the weighing lane excavated. Premixed asphalt concrete was then used to build a lane with zero cross slope before, between, and beyond the axle/wheel and the axle/group scales. This level surface held up well under truck traffic for two days of data taking, but rutted considerably in the hot summer weather by the fifth day of data taking.

Later in June 1984, the premixed surface material was removed and replaced with hot-mixed, hot-laid asphalt concrete to form a level lane (longitudinally and transversely) approximately 400 feet long. The LSWIM scales were removed before the leveling and reinstalled afterwards. An additional 100 trucks were weighed on the axle/wheel, axle/group, and LSWIM scales on 6 July 1984 after leveling the surface to within about 0.02 ft for 380 feet surrounding these three scales.

Description and Operational Features of Equipment

The data-collection sessions were conducted over a period of five days in June and on one day in July of 1984. Table 2-1 shows the types of scales operated each day along with the number of trucks weighed by each scale

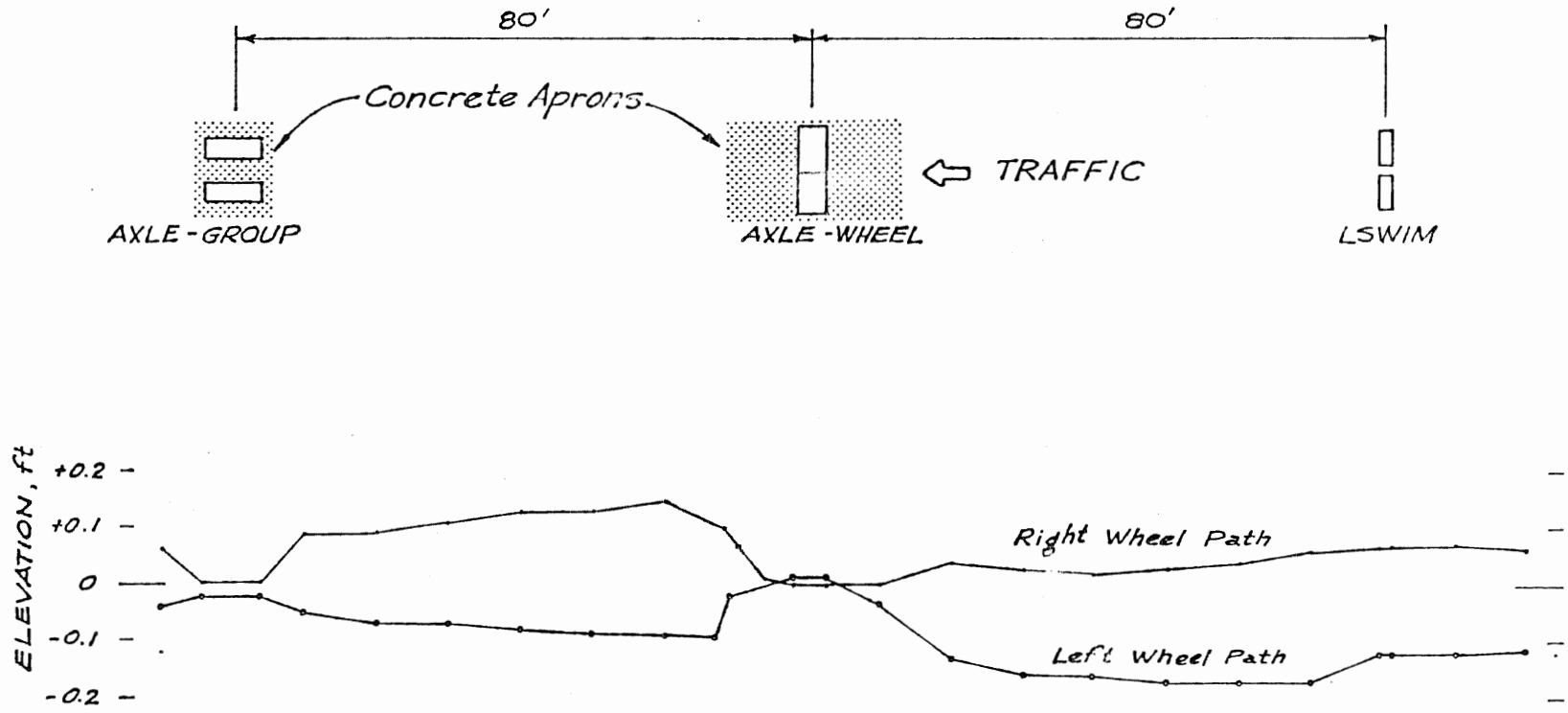


Figure 2-3. Longitudinal profile in each wheel path of the weighing lane at beginning of tests.

TABLE 2-1. TYPES OF SCALES AND THE NUMBER OF TRUCKS WEIGHED ON EACH TYPE

DATE	TYPE OF SCALE								
	AX/WHL	AX/GRP	AX/GRP (RAM)	WLW/M300	WLW/M400	WL/100	HSWIM	ISWIM	LSWIM
June 5, 1984	133	133	133	100	-	-	136	133	133
June 6, 1984	106	106	-	-	-	100	106	106	106
June 11, 1984	150	150	-	-	40	-	152	150	150
June 12, 1984	148	148	-	-	-	-	148	148	148
June 13, 1984	174	174	-	-	-	-	174	174	174
July 6, 1984	101	101	-	-	-	-	-	-	100

type. A complete listing of the weight data collected by the static scales on each day has been printed, but is not published in this report. The nomenclature and operating features of each scale are given below in the order in which each truck passed over them.

HSWIM -- High-Speed Weigh-In-Motion. (Fig 2-2(a))

This scale used two flush-mounted wheel-force transducers, each 53 x 18 inches in plan dimensions, centered transversely in each wheel path such that the tires travelled along the 18-inch dimension. Each transducer was supplied with ± 1 percent maximum tolerances in electrical output signal. The analog signal was digitized and processed by a micro-computer in real time, on site to convert the measured dynamic wheel force to an estimate of static wheel weight. Speed and axle spacing computations were also made by the WIM system from inductance loop type vehicle-presence detector signals. Thus, as a truck passed over the WIM scales time of day, speed, axle spacing, wheelbase, wheel weights, axle weights, axle-group weights, gross-vehicle weights, bridge-formula compliance, and vehicle class were determined automatically, displayed on the video screen, and recorded on magnetic disc in digital format. Instruments for the WIM system were housed in a mobile laboratory trailer (see Fig 2-2(c)).

ISWIM -- Intermediate-Speed Weigh-In-Motion. (Fig 2-2(b))

This scale was the same as HSWIM, but it was used at a slower speed (approximately 30 mph).

LSWIM -- Low-Speed Weigh-In-Motion. (center Fig 2-2(c))

This scale also was the same as HSWIM but each truck rolled over it at a speed less than about 10 mph. Furthermore, on the last day (July 6) of data taking, this scale system was calibrated in place with ten 1,000-lbs test blocks furnished by the Texas Department of Agriculture, Weights and Measures Section. The LSWIM scales performed within ±1 percent overall system tolerances under dead-weight loading.

AX/WHL -- Axle and Wheel Scale. (foreground Fig 2-2(c))

This scale consisted of two scale platforms, each 4 x 6 feet in plan dimensions, arranged side-by-side and mounted flush with the road surface so that wheels rolled along the four-foot dimension; thus, each wheel on an axle could be weighed separately when the axle was positioned on the pair of scales. The design of the scale utilizes all flexure-type devices to transfer forces to the levers and finally to a single strain-gage load cell. The load-receiving surface is supported by a tabular metal frame which deflects very little under load. The manufacturer states that one part in 5,000 (0.02 percent) tolerances are attainable with the scale. Under dead-weight testing using a series of 1,000-lbs test blocks (see Fig 2-2(g)), the scale always indicated correctly within the 20-pound increment that was selected for use in the study. Time of day, wheel weights, axle weights, axle-group weights, and gross-vehicle weights from these scales were printed on a hard copy tape by a microcomputer.

AX/GRP -- Axle-Group Scale. (Fig 2-2(d))

This scale had two load-receiving elements, each approximately 30 inches x 8 feet in plan dimensions, mounted flush with the road surface and arranged in shallow pits in the wheelpaths of the lane in such a way that the wheels rolled along the eight-foot dimension. The signals from all strain-gage load cells in the scale were summed electrically to give only the total weight on both platforms; thus, the weight of either a single axle or a group of axles was measured, displayed, and printed. The scales performed within the minimum 20-pound increments that were displayed on an indicator under dead-load testing using a series of 1,000-lbs test blocks. The aluminum load-receiving elements of these scales deflected noticeably under heavy axle-group loads.

AX/GRP (RAM) -- Axle-Group Scale (Ramped). (Fig 2-2(e))

This scale had the same basic design and operational features as the AX/GRP scale, but it was longer, had more load cells, and was placed on the road surface in each wheel path in such a way that the wheels rolled up the ramps of both platforms and then rolled along the 11-foot dimension. The height of the weighing surface was approximately four inches above the road. Weight measurements were displayed and printed on a hard copy tape. The printer was housed in a DPS van.

WLW/M300 -- Wheel-Load Weigher Model 300. (Fig 2-2(f))

This scale was a hydraulic rollover-type portable wheel-load weigher approximately 20 x 10 inches in plan dimensions and 3 1/4 inches in height. Depending on the number of wheels in each axle group, two, four, or six weighers were positioned, one in front of each wheel in such a manner that wheels drove along the 20-inch dimension. Dual-tire wheels were lifted somewhat less than three inches as all load on the wheel was transferred to a single tire. The truck was not required to stop with each wheel on a weigher as a feature of this model attempts to hold the maximum force reading as the tire moves slowly over the weigher. Data were read and recorded manually on a data sheet.

WLW/M400 -- Wheel-Load Weigher Model 400.

This device was very similar to the Model 300 except that a single hydraulic piston is used and no load-holding feature is provided in the hydraulic system. The wheels had to be stopped on the 10-inch wide by 11-inch long weighing surface while the weight indication was read by the operator and recorded manually on a data sheet.

WL/100 -- Wheel-Load Scale WL100.

This scale was a low-height hydraulic wheel-load weigher which consists of a platform for weight registration and of a laterally-affixed dial-type indicator. The platform is approximately 18 x 27 inches in plan dimensions and 0.79 inch in height. Both tires of a dual-tire wheel must be approximately centered on the scale during static weighing. A firm, smooth surface is needed to support this thin device. Weight readings were recorded manually on a data sheet.

Traffic Control and Data Collection

Traffic through the weigh station was controlled by uniformed officers of the Department of Public Safety (DPS). One DPS officer and one State Department of Highways and Public Transportation (SDHPT) person were stationed approximately two miles upstream of the weigh station. Selected trucks were directed to stop on the shoulder by the officer; all other traffic was allowed to continue on the main lanes. A serialized identification number was attached to the front windshield of each selected truck by the SDHPT person. The trooper instructed each driver how to proceed through the weigh station and released a truck only when it could be processed at the weigh station without having to stop before crossing the LSWIM scale. The release time was coordinated via radio contact with the weigh station.

When released by the trooper, each truck traveled in the right-hand lane of IH-10, passed over the HSWIM scale at about 55 mph, exited, and passed over the ISWIM scale at approximately 30 mph. Each truck was then stopped approximately 20 feet in advance of the LSWIM scale and the driver was instructed to roll slowly over the LSWIM scale and stop with the front axle on the AX/WHL scale. Another trooper instructed the driver to release the brakes after stopping each axle on the AX/WHL scale and wait for weighing. A weight reading was taken only after

no appreciable change in the indicated weight was observed. Meanwhile, two CTR personnel measured the center-to-center axle spacings of each truck at this site with a steel tape and another person recorded images of each vehicle and its suspension system on video tape. Tire inflation pressures and temperatures were measured on selected trucks by personnel from the Texas Transportation Institute, Texas A&M University while the trucks were stopped here for weighing. The same successive-weighing procedure was followed when each single axle or axle group was stopped on the AX/GRP scale located 80 feet beyond. Tandem axles that were more than about six feet apart, center-to-center, were weighed separately on the eight-foot long AX/GRP scale, and axle groups were split into two weighings when necessary due to the limited length of the scales. Finally, the driver of each truck was asked to stop approximately 80 feet beyond the AX/GRP scale. Here, the troopers placed either two wheel-load weighers, one in front of each wheel of a single axle, or four wheel-load weighers, one in front of each wheel of a tandem axle and instructed the driver to drive up onto or to roll over the scales depending on the type of weigher in use. Six wheel-load weighers were used to weigh triple axles. The identification number affixed to each truck was removed while the truck was being weighed on the wheel-load weighers.

REFERENCE SCALE

In analyzing the field data for defining accuracy, developing calibration factors, and consequently arriving at use tolerances for WIM systems, it was necessary to choose one scale as a control or reference scale. The AX/WHL scale as described in the preceding section was selected to serve as the referee scale. The manufacturer of this scale claims that it can perform within 0.02 percent tolerance. In the field when each platform of the scale was subjected to dead-weight testing with up to fifteen 1000-lb test blocks, the scale always gave a correct indication of the applied static load within the 20-lb increment that was selected for use in the data collection.

To further validate the reliability of this scale, a 2-axle, single-unit, loaded dump truck furnished by the SDHPT was weighed repeatedly throughout the six days of data collection. Table 2-2 gives wheel, axle, and gross-vehicle weight readings as well as the right and left side weights for seven successive weighings of the test truck on the AX/WHL scale on 5 June 1984. Given also in this table are the corresponding averages and standard deviations. As can be seen in the table, the weight readings do not differ more than 40 lbs.

The AX/WHL scale proved to be accurate under dead weight testing, reliable in repeated weighings of a test truck, and capable of weighing both wheel loads and axle loads without excessive deflection of the load-receiving platforms. Therefore, it was used as the reference scale in the analysis of the data sets throughout the project.

TABLE 2-2. WEIGHTS (LBS) FOR A 2-AXLE, SINGLE-UNIT TEST TRUCK WEIGHED ON THE AX/WHL (REFEREE) SCALE

Run Number	Front			Rear			Side		Gross
	Left Wheel	Right Wheel	Axle	Left Wheel	Right Wheel	Axle	Left	Right	
1	3400	2980	6380	8320	8240	16560	11720	11220	22940
2	3400	3000	6400	8340	8220	16560	11740	11220	22960
3	3400	2980	6380	8360	8200	16560	11760	11180	22940
4	3360	3020	6380	8340	8220	16560	11700	11240	22940
5	3400	2980	6380	8320	8200	16520	11720	11180	22900
6	3400	3000	6400	8340	8200	16540	11740	11200	22940
7	3380	2980	6360	8360	8200	16560	11740	11180	22920
Mean	3391	2291	6383	8340	8211	16551	11731	11203	22934
Standard Dev.	16	16	14	16	16	16	20	24	19

(5 June 1984)

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CHAPTER 3. COMPARISON OF WHEEL-LOAD WEIGHERS AND AXLE-LOAD SCALES

PURPOSE

To enhance safety and to protect the roads and bridges in the State of Texas from unexpected vehicle loads, maximum load limits and maximum vehicle sizes have been established by state law. Enforcement of these weight and size regulations is performed by the Texas Department of Public Safety (DPS). Implementation of the weight enforcement program involves weighing wheel loads, axle loads, axle-group loads (tandems, triples, etc), and gross-vehicle weights as well as measuring the spacing between adjacent axles and the overall length of individual truck units. Each of these determinations must be made within reasonable tolerances as an individual is at risk when a violation of the legal limit is charged by an enforcement officer.

All weight enforcement presently is based on legally-recognized static weights obtained with one or more of the following types of weighing devices: (1) vehicle scales with single or multiple load-receiving platforms, (2) axle-load scales, and (3) wheel-load weighers. The type of device that is used in a specific enforcement program is determined by safety considerations, weigh site availability, equipment capabilities and limitations, type of legal limits to be enforced, time requirements, and costs. Practicable enforcement tolerances which recognize all these factors must be adopted either by law or by a policy of the enforcement agency.

The purpose of this chapter is to discuss the variability in truck wheel loads, axle loads, axle-group loads, and gross-vehicle weights that were observed when about 800 trucks were weighed in a field testing program on three different static axle-load scales and on three different types of wheel-load weighers during a five-day period in June and one day in July 1984. A brief description of the field testing program is given in Chapter 2. Presentation and analysis of the data sets that were collected are discussed in this chapter. Analysis and interpretation of the data provide a valuable resource for consideration when selecting suitable weighing equipment and when defining appropriate tolerances for truck weight enforcement operations or for other purposes. Practicable enforcement tolerances for using the various types of weighing devices are developed and suggested in Chapter 5.

ANALYSIS OF DATA

In analyzing the field data, a comparison is made of the wheel, axle, axle-group, and gross-vehicle weights that were obtained for trucks which were weighed on several different scales as described in the preceding chapter. The flush-mounted AX/GRP scale was configured to indicate only the total weight of all wheels on one axle (single), or on two axles (tandem), that were spaced less than about six feet apart center-to-center since the length of the scale platforms was approximately eight feet. Axles in a group with greater extreme spacing were therefore

weighed separately, and the weights were summed. Axle groups with an overall spacing between extreme axles in the group greater than this were weighed in pairs and separately in successive stops of the truck on the scale before summing. The platforms of the surface-mounted AX/GRP (RAM) scale were approximately 11 feet long; therefore, any axle group with center-to-center spacing of the extreme axles less than about 9 feet could be weighed in a single stop. No axle group with greater spacing than this was encountered in the data set. All the other scales indicated the weight of each wheel. Axle weight and axle-group weight has been taken as the sum of all wheel weights for the particular axle or axle group under consideration, and gross-vehicle weight has been computed as the sum of all axle and axle-group weights on a truck or truck-trailer combination. Comparisons are arranged in the following order.

First, axle-group and gross-vehicle weights determined from the AX/GRP scale are compared against those from the AX/WHL scale as the reference scale. Both of these scales were flush-mounted, certified axle-load scales spaced 80 feet apart. Two data sets, one taken on June 5 and 6 and the other taken on July 6, are presented in order that the possible effects of the distorted cross-slope pattern described previously can be evaluated. Then, the AX/GRP (RAM) scale data are compared against those from each of the flush-mounted axle-load scales as a reference scale. Finally, weights from each type of wheel-load weigher - the WHL/M300, WL/100, and WLW/M400 - are compared first against the AX/WHL scale weights and then against the AX/GRP scale weights as a reference.

Results of all comparisons are presented in two different ways: (1) graphical representation of the data, and (2) statistical inference values drawn from the data. In the graphical approach, the weight data for the same truck or truck-trailer combination measured by the reference scale (scale with which other scales are compared) are plotted on the x-axis (horizontal) and the respective values from the scale being compared are plotted on the y-axis (vertical). If there were perfect agreement between the measurements, all the plotted points would lie exactly on a 45-degree sloping line (equality line) which passes through the origin. Lines which represent plus and minus ten percent deviation from the equality line are shown in the graphs to indicate visually the extent of the variation present in the data. Dot-dash lines indicate the legal weight limits: single-axle, 20,000 lbs; tandem-axle, 34,000 lbs; and gross-vehicle, 80,000 lbs.

Another form of graphical presentation of data uses the relative difference in the weight data for each truck which was weighed on the reference scale and on the scale being compared. This relative difference is calculated and expressed as a percentage of the weight measured by the reference scale. That is,

$$D_i = 100[(C_i - R_i)/R_i] \qquad 1 \leq i \leq k \qquad (3\text{-}1)$$

where D_i = difference in the weight determined by the Compared scale expressed as a percentage of the weight determined by the Reference scale for observation i.

C_i = weight determined by the Compared scale for observation i.

R_i = weight determined by the Reference scale for observation i.

k = total number of observations.

If the relative differences in weights are normally distributed, statistically-based inferences can be drawn concerning the probability of weight differences exceeding certain magnitudes. For example, if in a normally-distributed population past experience is repeated, at least 95 out of 100 observations of weight differences should be within plus and minus two standard deviations from the mean weight difference previously observed. That is, only five percent of the observations are expected to exceed these magnitudes due to chance alone. The assumption concerning the normally-distributed population of the relative differences in weights is discussed in the next section.

Percentagewise deviations of each weight from each scale are also plotted against the corresponding weights from the reference scales. In addition, to show graphically the 95 percent confidence limits for the relative differences in the weight data, dashed horizontal lines which represent plus and minus two standard deviations from the mean difference (shown by a solid horizontal line) are drawn on each plot. A vertical dot-dash line indicates the applicable legal weight limit.

DISTRIBUTION OF RELATIVE DIFFERENCES IN WEIGHTS

The procedures used here for drawing statistical inferences from the relative differences in weights which are computed from the sampled weight data are based on the assumption that the population of the differences is normally distributed, or at least approximately so. Two indicators of a normal distribution are appropriate for consideration:

(1) the central limit effect, which shows a tendency for the frequency distribution of relative differences to be a "bell-shaped curve", and

(2) the robustness or insensitivity of many commonly-used statistical tests to deviations from theoretical Gaussian or normal distribution.

A number of procedures are described in the literature to test the normality assumption. Three of these are summarized here for possible applicability.

Empirical Rule

The characteristic properties of a normal distribution can be used to make an informal check on the normality assumption. A normal distribution can be defined by two parameters: population mean, μ, and population standard deviation, σ. The population mean, μ, is a measure of central tendency which locates the population distribution, and the population standard deviation, σ, is a measure of the dispersion of the population about the mean. The properties of the normal distribution curve have been carefully defined, and tables of values of the area under the curve for increments of σ are readily available. If the mean of the sample observations, $\overline{D}$, is taken as a measure of central tendency for the sample and the standard deviation, σ, of these observations about the sample mean is calculated, a comparision can be made against the location and shape of the normal distribution curve in accordance with an empirical rule. For the assumption of normality to be valid under one such rule, the following inequalities must be met [Ref 4].

(1) $|$ (No. in $\bar{D}$ - s, $\bar{D}$ + s) - 0.683n $|$ < 1.41 $\sqrt{n}$,

(2) $|$ (No. in $\bar{D}$ - 2s, $\bar{D}$ + 2s) - 0.955n $|$ < 0.654 $\sqrt{n}$, or

(3) $|$ (No. in $\bar{D}$ - 3s, $\bar{D}$ + 3s) - 0.997n $|$ < 0.164 $\sqrt{n}$

where n is the number of observations in the sample, $\bar{D}$ is the sample mean, and s is the sample standard deviation.

Normal Probability Plot

A graphical check on the normality assumption can be provided by plotting the sample data levels versus the expected normal values of observations at each level on normal probability paper. A sample drawn from a normally-distributed population should roughly resemble a straight-line plot on this specially constructed paper.

Goodness-of-Fit Tests

These statistical tests are based on the comparison of the observed sample distribution (empirical) with the theoretical distribution to see if the hypothesized distribution function "fits" the sampled observations. The most commonly used tests of this kind are the Chi-Squared test (χ^2 test), the Kolmogorov-Smirnov test (D test), and the Shapiro-Wilk test (W test).

The Chi-Squared test is the oldest and best-known goodness-of-fit test, first introduced by Pearson [Ref 5]. It is applicable to enumeration (counted) data which are grouped in discrete increments, and such a grouping of data is usually arbitrary; therefore, the distribution of the test statistics is known only approximately. The test is usually not very powerful.

The Kolmogorov-Smirnov test is usually preferred for measurement-type data, in particular if the sample size is small. The test is exact even for small samples. There is controversy over which test is more powerful, but the general feeling seems to be that the Kolmogorovo-Smirnov test is probably more powerful than the Chi-Squared in most applications. For details see a paper by Slakter [Ref 6].

Tests of normality were given new insights with the introduction of the so called analysis of variance test by Shapiro and Wilk [Ref 7]. The test statistic W is constructed by evaluating the regression of ordered sample data on corresponding expected normal order statistics, which for a sample from a normally distributed population is linear. Extensive empirical comparisons of the Shapiro-Wilk test with other tests of normality using computer-generated random numbers indicated that the W test was generally superior in detecting non-normality when evaluated on various symmetric, asymmetric, short and long-tailed alternatives over sample sizes ranging from 10 to 50 [Ref 8]. Using IMSL library subroutines [Ref 9] and Statistical Algorithms [Refs 10-13], a Fortran computer program is written to perform the Shapiro-Wilk test for samples of size up to 2000 [Ref 14] (see Appendix A).

APPLICATION OF NORMALITY TEST TO OBSERVED RELATIVE WEIGHT DIFFERENCES

Variability in truck weight measurements on axle-load scales can be attributed to: (1) random error, (2) equipment and operator error, and (3) inherent variability in tire forces due to displacement of any vehicle component

between or during successive weighings - such displacement is caused by torque, braking, load shifting, and the associated frictional forces. Mistakes due to faulty scales or human errors cannot be considered in normality tests. The variability due only to chance errors (i.e. random errors), is considered in the population distribution.

Some of the aforementioned tests for normality made on relative differences computed from the sampled weight data, indicated that the differences are normally distributed. To illustrate the applications of these tests for normality, the relative differences in gross-vehicle weights which were sampled by the AX/GRP scale and by the AX/WHL (reference) scale on 5-6 June 1984 were used. The test results are described in the following tables and paragraphs.

Table 3-1 indicates the results of applying the empirical rule described above to the data set. From Table 3-1, it is clear to see that all the inequalities are satisfied; therefore, an assumption of normality is plausible. As illustrated in Fig 3-1, the plot of the sampled differences on specially-constructed normality axes is approximately a straight line; therefore, the sample can be assumed to be drawn from a normally-distributed population.

A goodness-of-fit test for normality (i.e., the Shapiro-Wilk test), was also applied to the example data set. The results are presented in Table 3-2. As with the aforementioned tests, the two-tailed probability associated with the Shapiro-Wilk W statistic fails to reject the null hypothesis. Therefore, it is reasonable to assume that the distribution of the population of the relative differences in gross-vehicle weights is normal. The frequency distribution of the relative differences appears in Fig 3-2.

It may be concluded that (1) the normality assumption for the relative differences in weights appears reasonable, and (2) the relative differences computed for sample data from each compared scale should be treated separately as the samples may be drawn from normally-distributed populations with different means and/or variances.

COMPARISON OF AX/GRP SCALE AGAINST AX/WHL SCALE

All Truck Types

The 662 axle-group weights that were obtained for 237 trucks which were weighed on these two certified scales on June 5 and 6 (before resurfacing of the existing straight section of the weigh station) are presented graphically in Fig 3-3(a). Inspection of this figure indicates that there is not perfect agreement between the weights, but that virtually all axle-group weights measured by the two scales differ by less than ten percent. The AX/GRP scale weights are generally lower than the AX/WHL scale weights for the lighter axle groups and higher for the heavier ones.

For further comparison, differences in the weight of each of the 662 axle groups which were weighed on the two scales were computed and expressed as a percentage of the axle-group weights measured by the AX/WHL scale. Figure 3-3(b) depicts these differences. A solid horizontal line is drawn at the mean of the differences (+1.8 percent), and dashed lines indicate the range included within two standard deviations about the mean. A statistical interpretation of the information shown in this figure indicates that only 5 times in 100, will the differences in axle-group weights measured by these scales be expected to fall outside the -4.1 percent and +7.6 percent levels.

TABLE 3-1. RESULTS OF NORMALITY TEST BY EMPIRICAL RULE

Statistic	Sample Size $n = 237$	Mean, % $\bar{D} = 2.1085$	Standard Deviation $S = 1.6645$	Number of Observations In the Interval
Intervals	$(\bar{D} - S, \bar{D} + S) = (0.4440, 3.7730)$			173
	$(\bar{D} - 2S, \bar{D} + 2S) = (-1.2205, 5.4375)$			225
	$(\bar{D} - 3S, \bar{D} + 3S) = (-2.8850, 7.102)$			237
Inequalities	$\lvert 173 - .68(237) \rvert < 1.41\sqrt{237}$?			Yes
	$\lvert 225 - 0.954(237) \rvert < 0.654\sqrt{237}$?			Yes
	$\lvert 237 - 0.997(237) \rvert < 0.164\sqrt{237}$?			Yes
Decision Rule	Since all of the inequalities are satisfied, an assumption of normality is presumably correct			

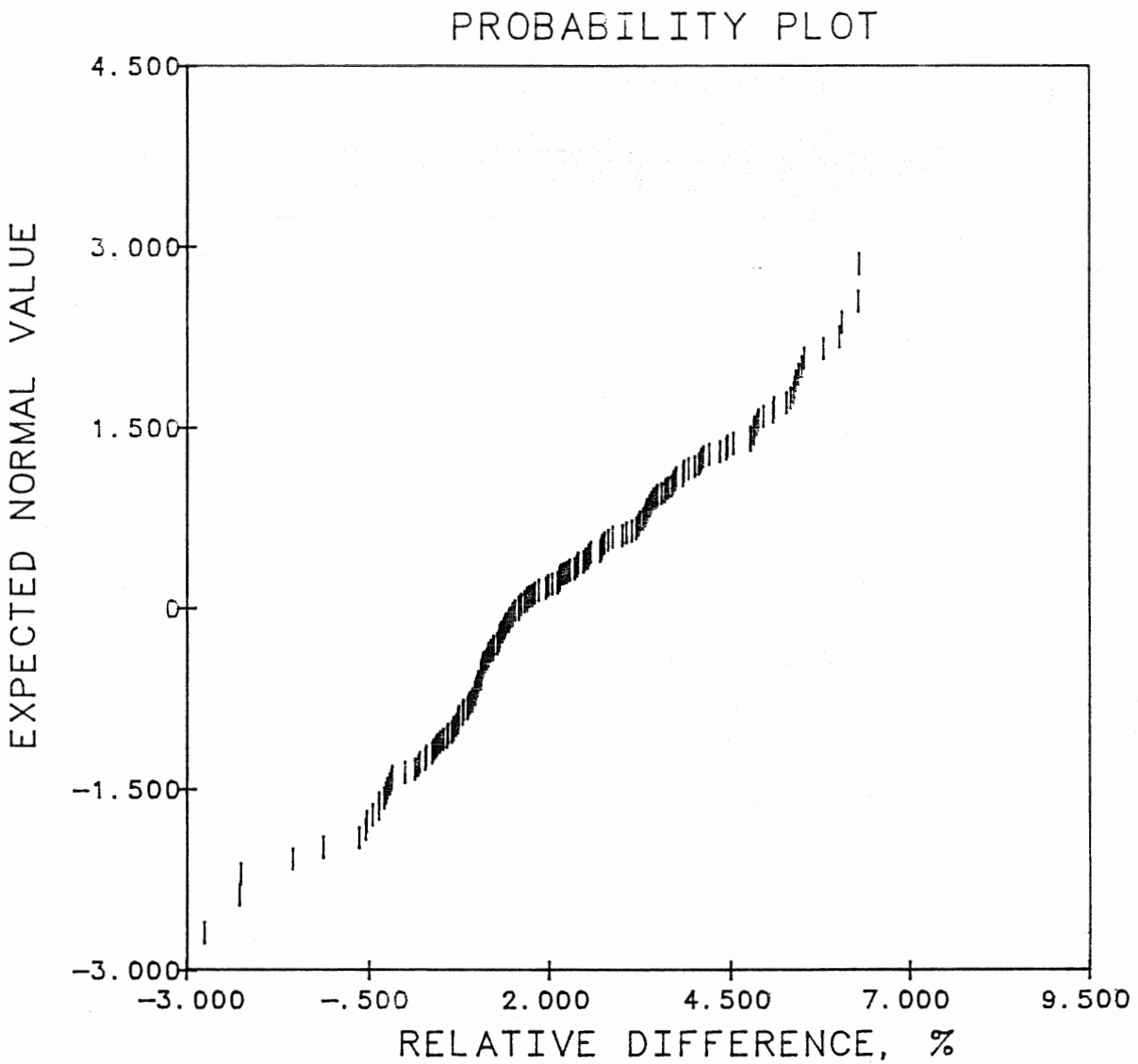


Figure 3-1. Plot of relative weight differences on normal probability axes.

TABLE 3-2. SHAPIRO-WILK NORMALITY TEST ON SAMPLE RELATIVE DIFFERENCES

Hypothesis	1. Null Hypothesis, H_0: The sampled relative differences come from a normally distributed population. 2. Alternative Hypothesis, H_1: The distribution of the differences is not normal.
Test Statistic	$W = \left[\sum_{1}^{n} a_i D_{(i)}\right]^2 \Big/ \sum_{1}^{n} (D_i - \bar{D})^2$ where $D_{(i)}$ is the ith order statistic with its corresponding coefficient a_i. From the data set W is found to be .94.
Criterion	Reject H_0 at the level of significance α if w is less than α quantile as given by standard tables, $W_\alpha = .98$
Decision	Since $(W = .94) < (W_\alpha = .98)$ do not reject H_0. In other words, the assumption of normality is plausible.

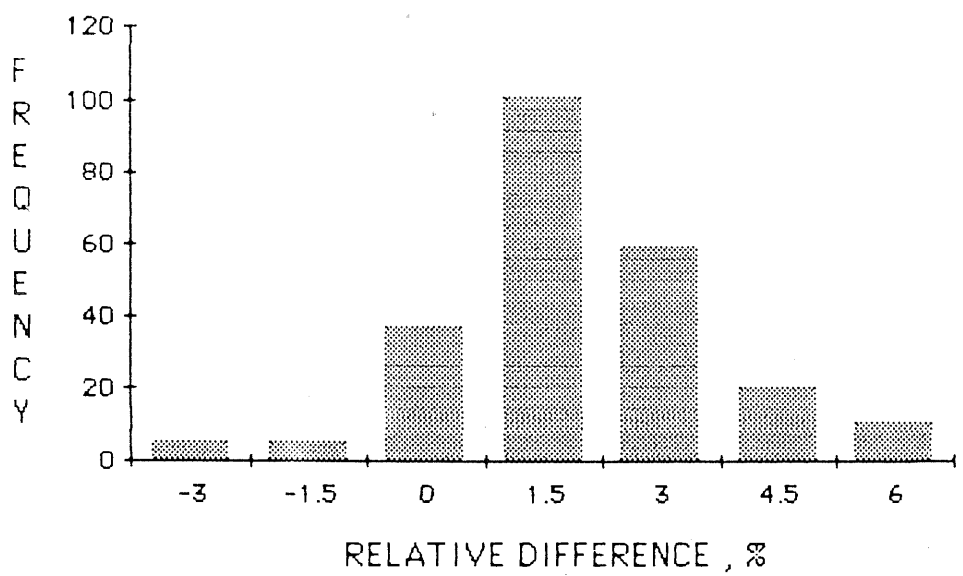
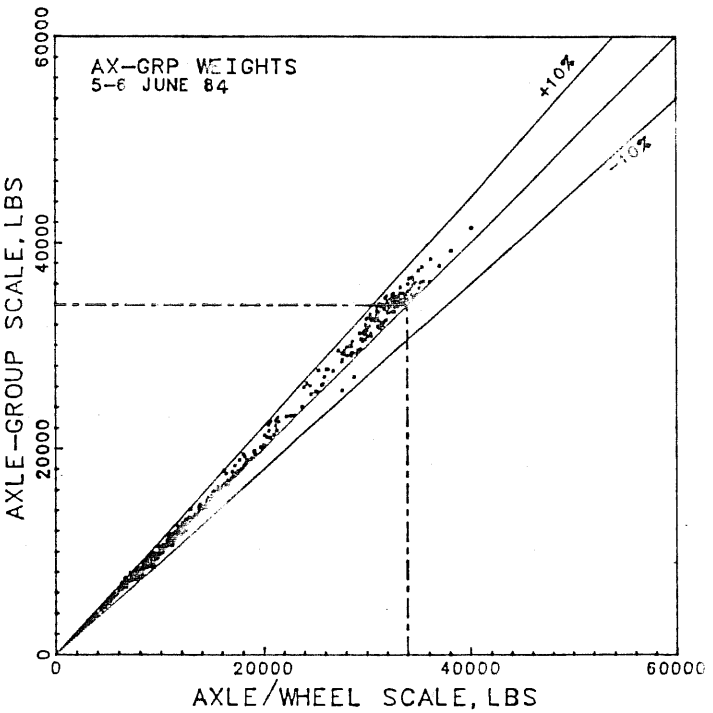
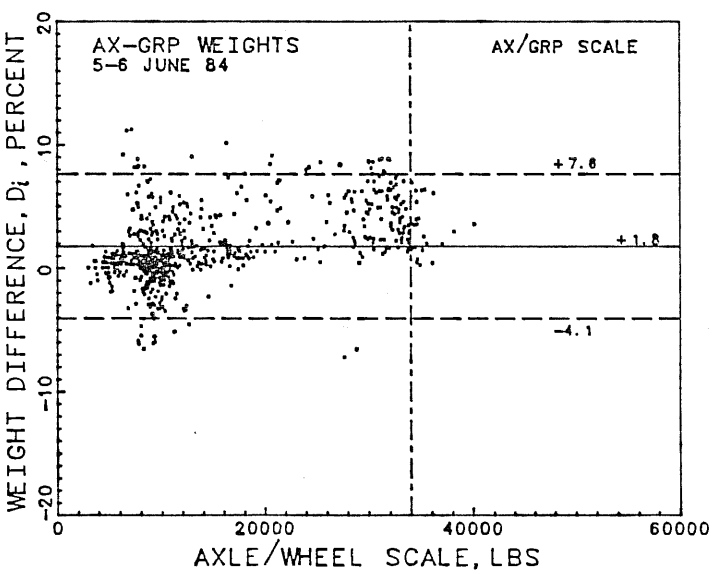


Figure 3-2. Frequency distribution of the relative differences in gross-vehicle weights from the AX/GRP and AX/WHL scales, June 5-6, 1984.



(a)



(b)

Figure 3-3. (a) Weights of 662 axle groups measured directly by the AX/GRP scale vs weights obtained by summing individual axle weights from the AX/WHL scale, (b) percentage difference in axle group weights for the AX/GRP vs the AX/WHL scale weights.

The gross-vehicle weights of these trucks which were calculated by summing the wheel weights and the axle-group weights from the AX/WHL and the AX/GRP scales, respectively, are shown in Fig 3-4(a). The corresponding percentage differences are shown in Fig 3-4(b). Inspection of these figures indicates that there is not perfect agreement between the measurements, but that they differ by not more than about seven percent. Again, except for the lighter trucks, the AX/GRP scale weights are shown to be generally higher, particularly for the trucks with gross-vehicle weights above about 50,000 lbs.

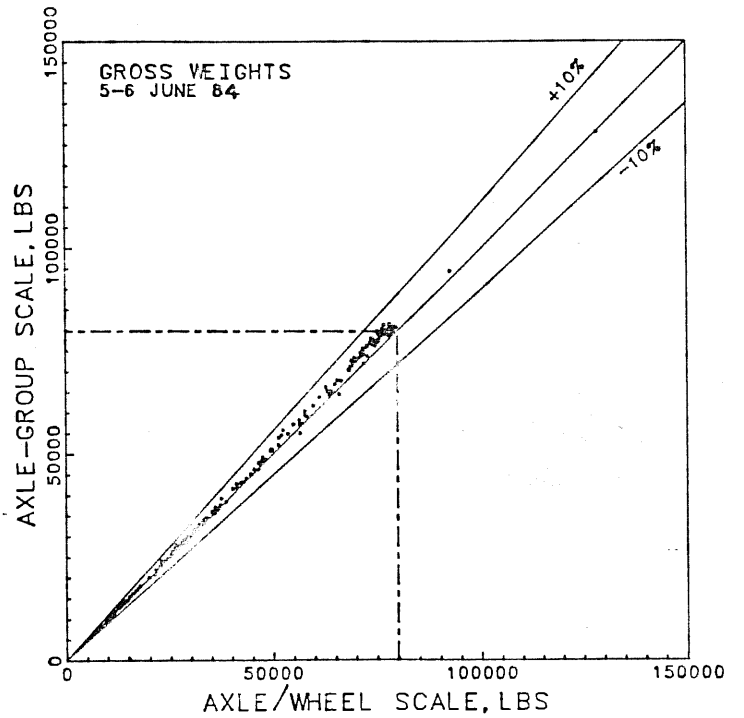
Deflection of the scale platforms under heavy loads will pitch weight toward the lower axles and tend to cause discrepancies of this kind. The tractor drive-tandem axle groups and the trailer-tandem groups were each weighed in a separate stop on the AX/GRP scale; therefore, the AX/GRP scale platform received all the load on each tandem axle set. Each axle was weighed one at a time on the AX/WHL scales which deflected only negligibly. Visual inspection of Fig 3-4(b), and statistical analysis of the differences in gross-vehicle weight, indicates that gross-vehicle weight differences were between -1.2 percent and +5.4 percent 95 times in 100, with mean and standard deviation of +2.1 percent and 1.6 percent, respectively.

The observed differences in gross-vehicle weight as determined by the AX/GRP and AX/WHL scales, each capable of measuring loads to within 0.2 percent of an applied test load (see Chapter 2), can also be attributed to the transfer of weight among the various axles as the truck moved into positions for successive weighing of the axles or group of axles. However, there is no way to quantify, from the data obtained in the field, the amount of weight transfer that occurred. Therefore, the magnitude of this effect as well as deflection of the scales and the possible effects of transversely non-level scale approaches (including warped-surface condition) on the calculated axle-group and gross-vehicle weights are indicative of the type of variability which can occur in practice. These effects should, then, be considered in setting tolerance limits for enforcement weighing and for interpreting statistical data when axle-load scales and wheel-load weighers are used. The magnitude of these effects for the other types of scales is illustrated in the subsequent sections of this chapter, and tolerances are suggested in Chapter 5 based on the available data.

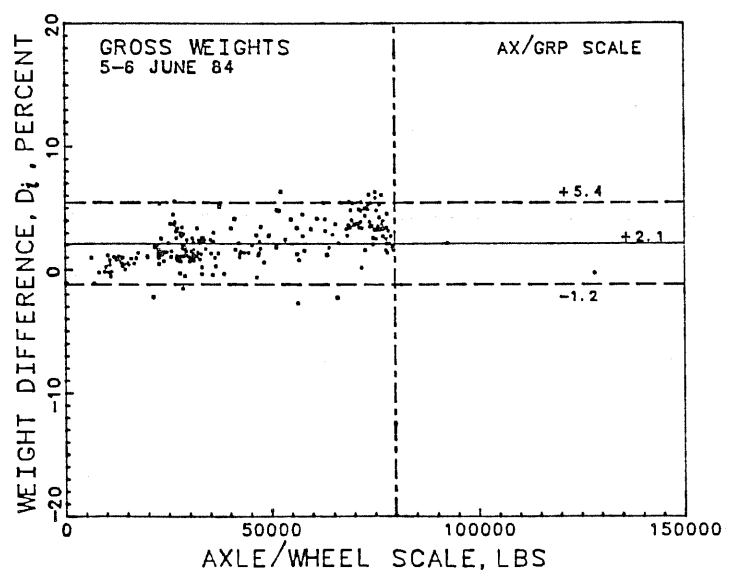
Effect of Transversely-Warped Surface Around the Scales

On July 6, 1984, another 101 trucks were weighed on the AX/GRP and the AX/WHL scales after the adverse cross slope in the weighing lane (see Chapter 2) had been removed. Hot-mixed, hot-laid asphalt concrete was used to make a level surface throughout the scale area. Comparison of the weights obtained after the road and scale surfaces had been leveled with the weights obtained when the scales were in the previously-described warped-surface condition might give an indication of the possible effects of transversely non-level scale approaches on axle-group and gross-vehicle weights.

Axle-group weight data for the 285 axle groups on 101 trucks after leveling the surface are shown in Fig 3-5. These data are roughly comparable with the data shown in Fig 3-3 for the warped surface condition. Direct comparison would require that exactly the same trucks be weighed in both cases. The similarity in the pattern of weights and weight differences shown in these two figures is readily apparent even though the number of observations is different. Axle-group weights from the AX/GRP scale are generally lower than those from the



(a)



(b)

Figure 3-4. (a) Gross-vehicle weights of 237 trucks weighed on the AX/GRP and AX/WHL scales, (b) percentage difference in weights for the AX/GRP vs the AX/WHL scale weights.

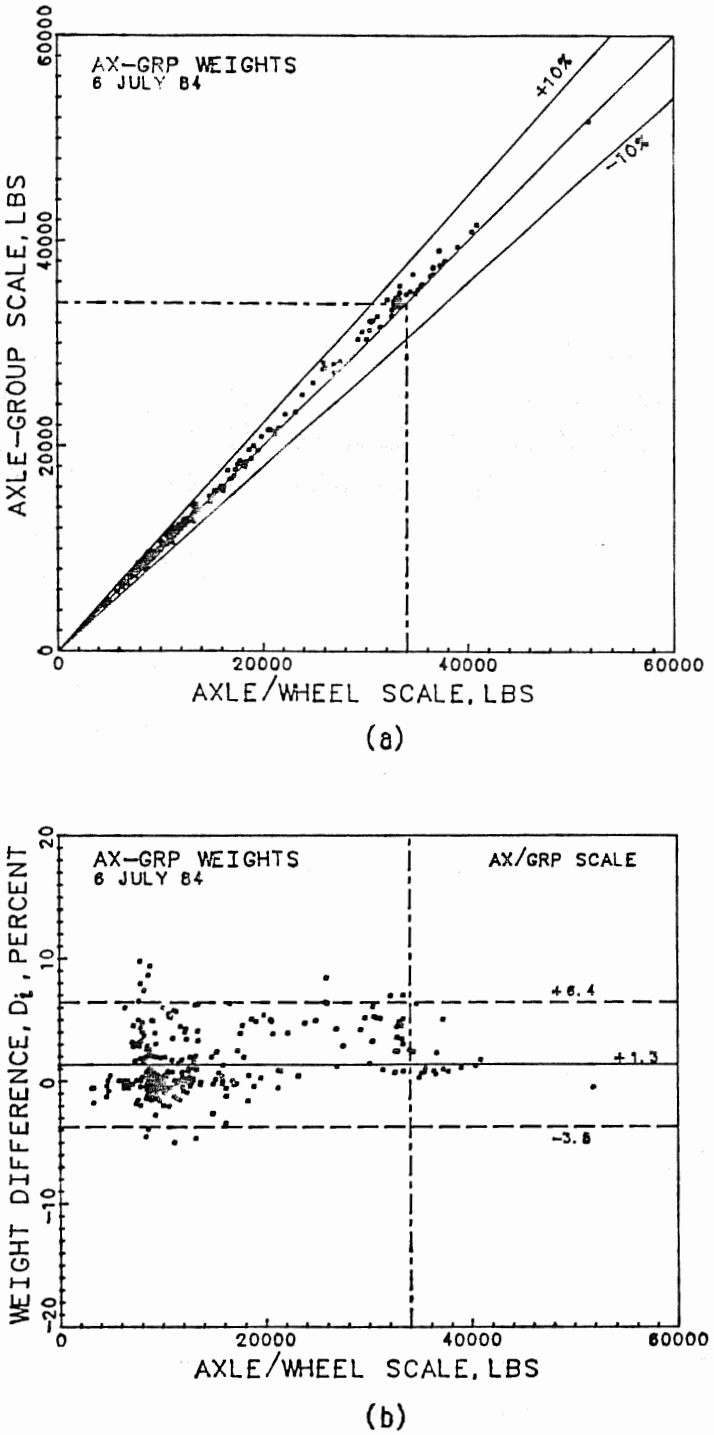


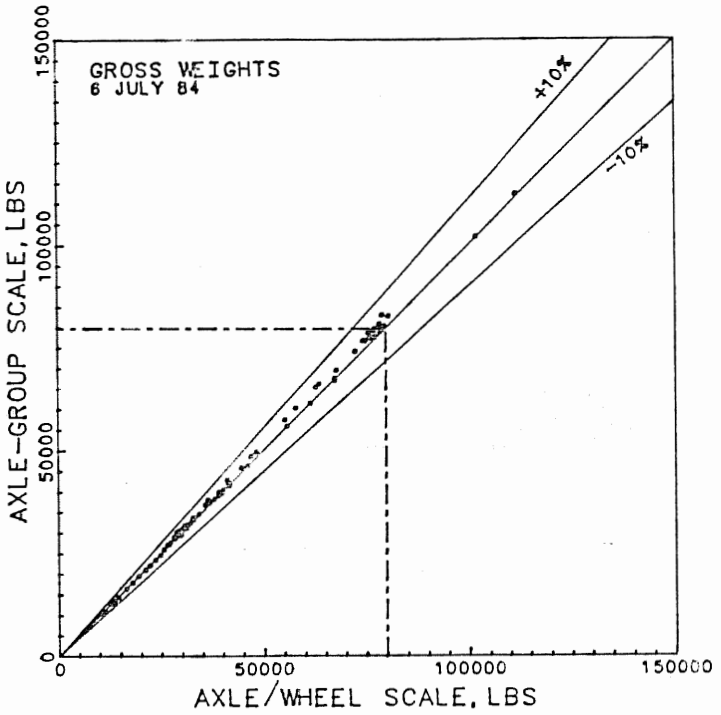
Figure 3-5. (a) Weights of 285 axle groups weighed on the AX/GRP and AX/WHL scales after removing cross slope from weighing lane, (b) percentage difference in weights from the AX/GRP scale compared to the AX/WHL scale weights.

AX/WHL scale for lighter loads and higher for the heavier loads as noticed previously. The mean weight difference of +1.3 percent after leveling is 0.5 percent less than the +1.8 percent mean difference for the before-leveling condition. The scatter in the weight differences, as indicated by the magnitude of the standard deviation about the mean, is also nearly the same (two standard deviations = 5.8 before and 5.1 after). In addition, the results of a two-sided (pooled standard deviation) t-test (or a one-way analysis of variance), at level of significance a = 0.1, (t = 2.2) failed to prove that the difference in the two means is statistically significant. Thus, when the magnitude of the observed variations in axle-group weight differences from the two scales is considered, it is not appropriate to attribute the cause of the difference in mean values for the two data sets to the warped and unwarped surface condition alone; part of this difference was due to the random fluctuation in the weight measurements made on the two scales and to variations in the behavior of each individual truck that was weighed.

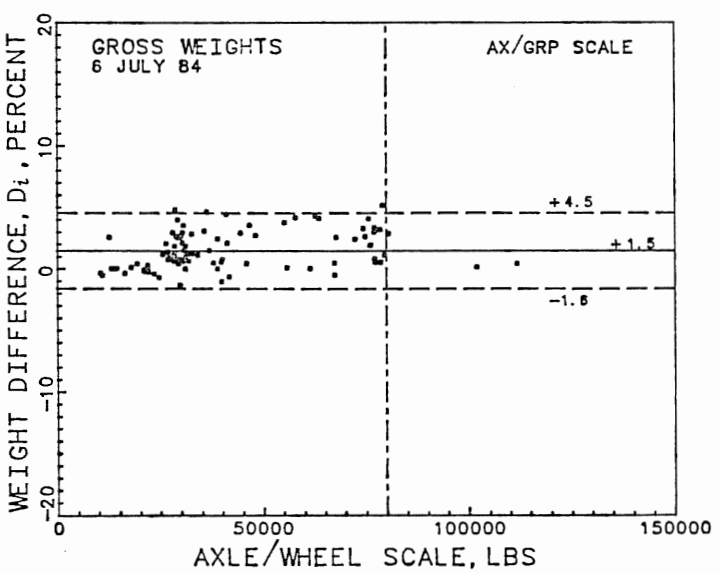
Gross-vehicle weights for 101 trucks were obtained by summing the appropriate axle-group weights from the two scales after the surface around both scales had been made level. These gross-vehicle weights are shown graphically in Fig 3-6(a). The pattern of gross-vehicle weights after surface leveling is quite similar to that for the before-leveling conditions as shown in Fig 3-4(a). All the variations are less than seven percent. Differences in gross-vehicle weight for the 101 trucks weighed on July 6, 1984 on the two scales with leveled surfaces are shown in Fig 3-6(b). Again, the pattern of scatter is quite similar to that in Fig 3-4(b) and the magnitude of the statistical inference values are very much alike. The magnitude of the mean and two standard deviations of the weight differences is +2.1 and +3.3 percent, respectively, for the before-leveling condition compared with +1.5 and +3.1 percent for the after-leveling condition. The results of a two-tailed t-test using a pooled estimate of the standard deviation, indicates that the test statistic is significant at the .01 level (t = 3.3). That is, differences in the mean value of gross-vehicle weights equal to or greater than those observed in the two data sets would be expected to occur due to chance alone with a probability of only 1 in 100. Surface warping around the scales - a known change in the conditions under which observations were made - could, therefore, be said to affect the mean value of the gross-vehicle weights measured by the two scales, based on this statistical test. The actual difference in the two mean values was, however, only 0.6 percent (2.1 warped minus 1.5 level = 0.6). Strict interpretation of the statistical test results in this case of marginal significance is of doubtful validity. Judgment says that differences of this magnitude in gross-vehicle weight as measured by two different axle-load scales should be attributed to several factors including, but not limited to, surface warping. It is well recognized by experts in the field that a plane surface around axle-load scales is necessary for accurate weighing. Performance of the AX/WHL (referee) scale was improved somewhat after the undesirable transverse surface warping was removed in late June 1984.

Tractor Semi-Trailer Trucks (3-S2)

Since about 70 percent of the trucks on IH-10 at the experimental site were the tractor semi-trailer type (3-S2) and a proportional sample was attempted, 66 trucks of this type were weighed on the leveled roadway surface on July 6, 1984. This portion of the data set is analyzed separately in order to study the variability in axle-group and gross-vehicle weights among trucks of the 3-S2 type. Axle-group weights for 66 tractor-semi trailer trucks of the 3-S2 type that were weighed on the two static scales are plotted in Fig 3-7. A graphical check of the data shown in

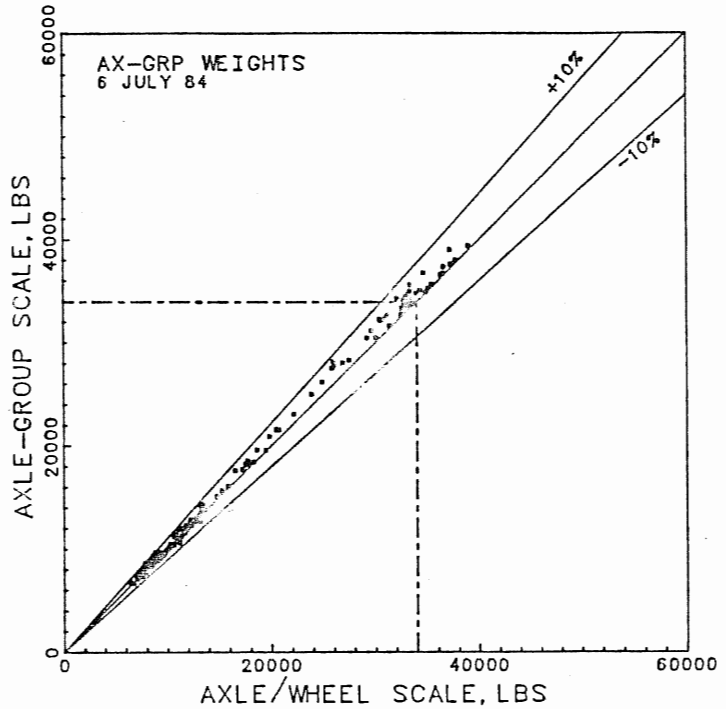


(a)

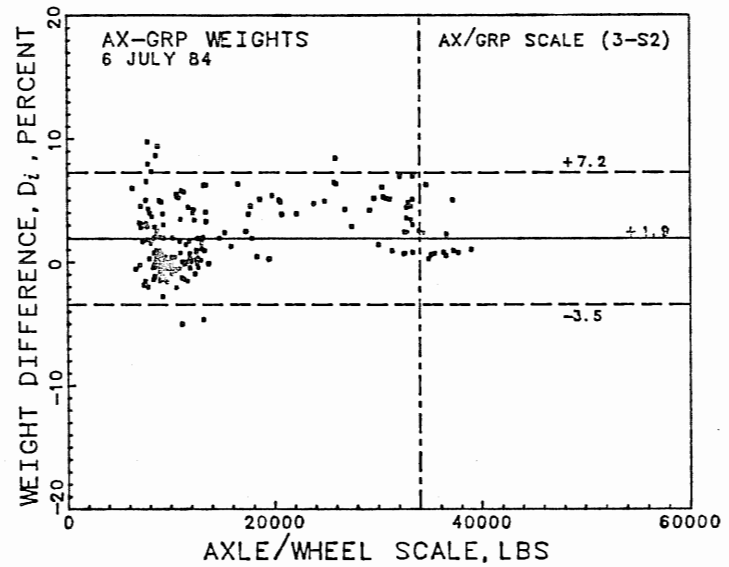


(b)

Figure 3-6. (a) Gross-vehicle weights of 101 trucks weighed on the AX/GRP and AX/WHL scales after cross slope was removed from the weighing lane, (b) percentage difference in weights from the AX/GRP scale compared to the AX/WHL scale weights.



(a)



(b)

Figure 3-7. (a) Weights of 198 axle groups on 66 3-S2 trucks measured on the AX/GRP and AX/WHL scales; (b) percentage difference in the AX/GRP vs the AX/WHL scale weights.

Fig 3-7(b) or a statistical analysis of this data set shows that the difference in the axle-group weights had a mean value of +1.9 percent and ranged between -3.5 percent and +7.2 percent in 95 percent of the cases. This difference is slightly larger than that for the axle-group weights on all truck types (see Fig 3-5(b)).

Gross-vehicle weights of the 3-S2 trucks from these two static scales are shown in Fig 3-8(a). Figure 3-8(b) depicts the observed differences in gross-vehicle weights of 3-S2 type trucks as determined by weighing on the two axle-load scales. Statistical analysis of these data indicates that the difference in gross-vehicle weight would lie between -0.6 percent and +4.9 percent when weighing a 3-S2 truck on the two scales 95 times out of 100. All 3-S2 type trucks with gross-vehicle weights above 40,000 lbs weighed heavier on the AX/GRP scale than on the AX/WHL scale. Note that the gross-vehicle weights calculated by summing the applicable axle-group weights have less percentagewise variation than the individual axle-group weight observations.

COMPARISON OF AX/GRP (RAM) SCALE AGAINST AX/WHL AND AX/GRP SCALES

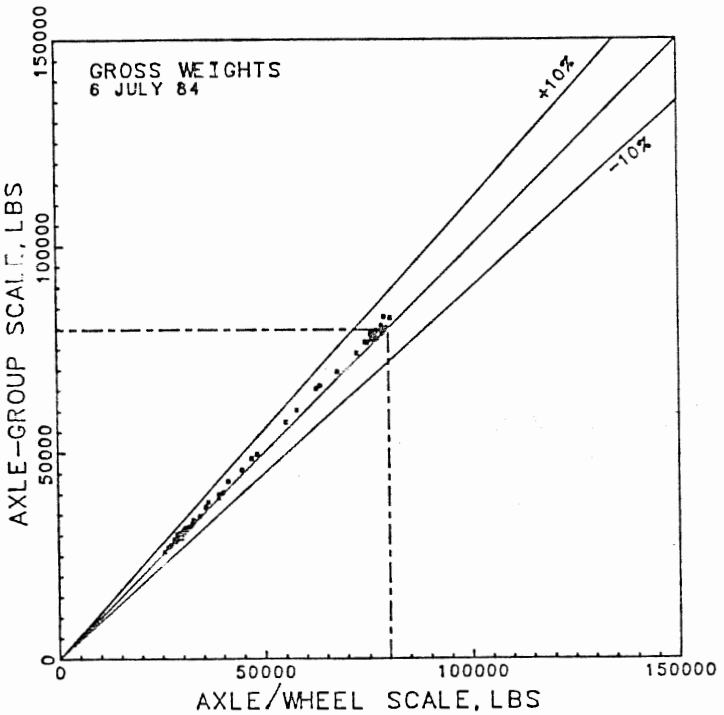
Axle-Group Weights for All Truck Types

The axle-group weights and the percent differences in the 355 weights that were obtained for 131 trucks which were weighed on the AX/GRP (RAM) and AX/WHL scales on June 5 are presented graphically in Fig 3-9. These data indicate that there is not perfect agreement between the weights, but that most of the axle-group weights measured by the two scales differ less than ten percent. In general, the AX/GRP (RAM) scale weights are higher than the AX/WHL scale weights, especially for the trucks with axle-group weights above about 18,000 lbs. In fact, all these heavier axle-group weights are within the positive ten-percent deviation range. As shown in Fig 3-9(b) the deviations range from -6.6 to +15.1 percent with 95 percent of the observed differences lying between -3.4 and +10.2 percent (standard deviation = 3.4 percent) with a mean difference of +3.4 percent.

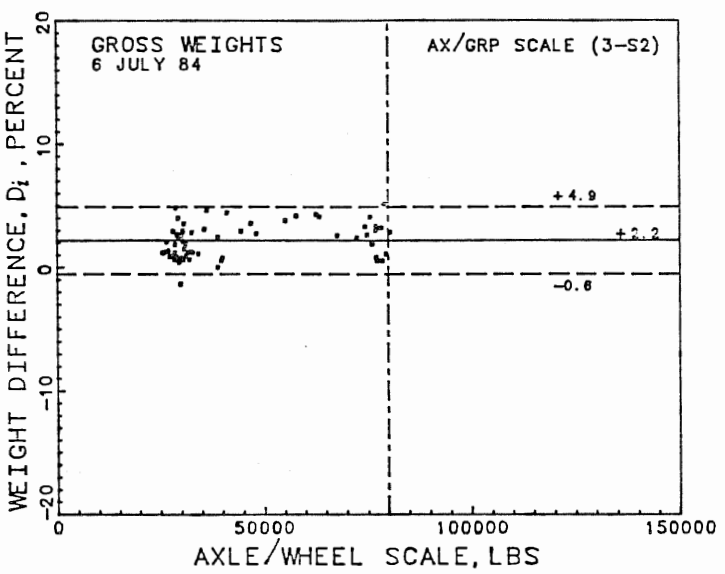
The 355 axle-group weights of the 131 trucks each weighed by the AX/GRP (RAM) scale are plotted versus comparable weights from the AX/GRP scale in Fig 3-10(a). The corresponding percentage differences in the axle-group weights are shown in Fig 3-10(b). Weights from the AX/GRP (RAM) scale were slightly higher than those from the AX/GRP scale particularly for the lighter axle groups (mean value = 1.5 percent). From statistical analysis of these data one can conclude that the differences in indicated weights range between -5.6 percent to +8.6 percent 95 percent of the time with a standard deviation of 3.7 percent. Note the cluster of heavier weights from the AX/GRP (RAM) scale between 7,000 and 12,000 pounds. This is the weight range within which many front (steering) axles fall.

Axle-Group Weights for 3-S2 Trucks

The AX/GRP (RAM) scale was about three feet longer than the AX/GRP scale and its weighing surface was approximately 4 inches above the road surface. Elevating the axle or the axle group that is being weighed causes a redistribution of the gross-vehicle weight among axles and thus affects the actual force on the scales at the time of weighing. The location of the center of mass of the various truck components is affected by the pitching of the

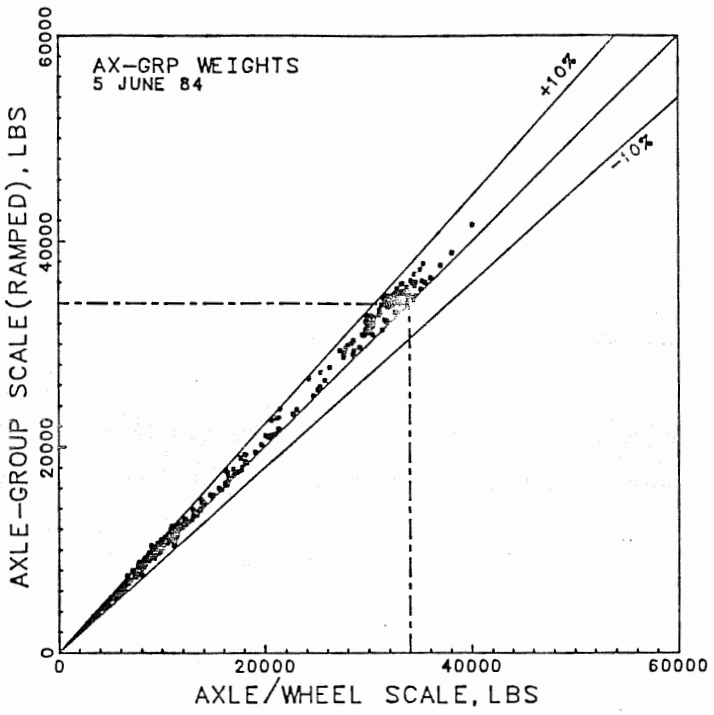


(a)

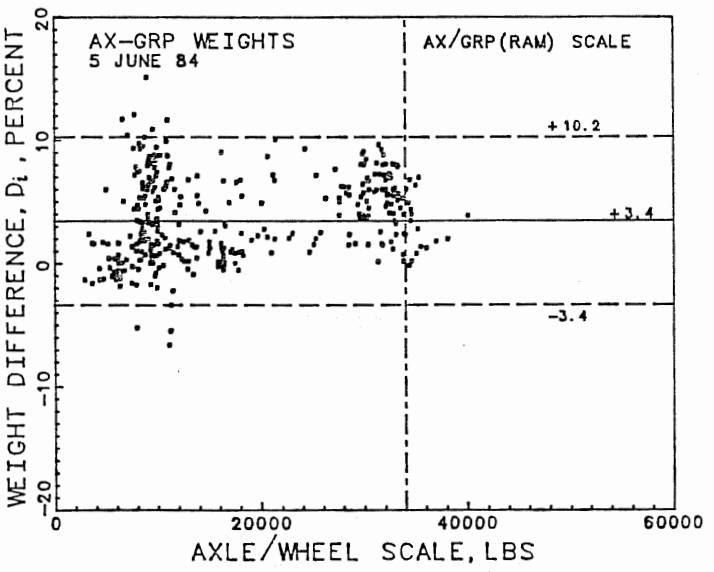


(b)

Figure 3-8. (a) Gross-vehicle weights of 66 3-S2 trucks weighed on the AX/GRP and AX/WHL scales, (b) percentage difference in gross-vehicle weights by the AX/GRP scale vs the AX/WHL scale weights.



(a)



(b)

Figure 3-9. (a) Weights of 355 axle groups measured directly by the AX/GRP (RAM) scale vs those summed from the AX/WHL scale, (b) percentage difference in weights for the AX/GRP (RAM) vs the AX/WHL scale weights.

vehicle frame and by deflection of the supporting springs. Friction in the various suspension components also influences the force at the time of weighing.

As mentioned previously, the lighter axle groups weighed heavier on the AX/GRP (RAM) scale than on the AX/GRP scale (see Fig 3-10). It appears that most of these axle groups are the front steering axles. This will be examined further by analyzing the axle-group weights, obtained from both scales, individually on the basis of type and location of axles on 3-S2 trucks. Since the 3-S2 tractor semi-trailer trucks comprised approximately 65 percent of the trucks weighed on both scales, the axle-group weight data from 81 trucks of this kind is used in this analysis. Thus, the front, drive-tandem, and rear-tandem axle weights from both axle-group scales are considered separately and plotted in Figs 3-11, 3-12, 3-13, respectively.

As Fig 3-11(a) indicates almost all the front axle weights lie above the equality line; in fact most of the points are within the positive ten percent deviation range and several points are above the positive ten percent. The corresponding differences in front axle weights from the AX/GRP (RAM) scale, expressed as a percentage of the front axle weights measured from the AX/GRP scale, are illustrated in Fig 3-11(b). Statistical analysis of these data shows that 95 percent of the differences in front axle weights lie between the limits -2.7 and +14.6 percent. The mean and the standard deviation for the normally-distributed differences are +5.9 and 4.3 percent, respectively.

The information contained in Fig 3-12 indicates that the drive-tandem axle weights from the AX/GRP (RAM) scale are slightly higher (mean value = +1.4 percent) than those measured by the flush-mounted AX/GRP scale. On the other hand, both scales gave virtually the same readings on rear-tandem axles (see Fig 3-13), the mean difference is -0.1 percent. It should be noted that both axle-group scales, AX/GRP and AX/GRP (RAM), gave heavier weight indications for heavy axle groups (tandems) than the AX/WHL scale.

Gross-Vehicle Weights for All Truck Types

Gross-vehicle weights and the percentage relative difference in these weights that were computed for the same 131 trucks of various types which were weighed on 5 June 1984 on the AX/GRP (RAM) and the AX/WHL scales are presented graphically in Fig 3-14. Inspection of these figures indicates that all the gross-vehicle weights measured by the two scales differ less than ten percent but that almost every truck with a gross-vehicle weight above 30,000 lbs was weighed heavier by the AX/GRP (RAM) scale. Statistically, the analysis showed that the difference in gross-vehicle weight for any truck measured by the two scales would be expected to range from -2.4 percent to +8.6 percent 95 times in 100. These differences have a mean of +3.1 percent and a standard deviation of 2.7 percent, respectively.

Gross-vehicle weights of 131 trucks of various types weighed on the AX/GRP (RAM) scale are plotted against those from the AX/GRP scale in Fig 3-15(a). The corresponding percentage differences in gross-vehicle weights are shown in Fig 3-15(b). Statistical analysis of this data set indicates that the differences range from -2.6 percent to +4.0 percent 95 percent of the time, with a mean difference of +0.7 percent and a standard deviation of 1.6 percent. This is generally consistent with the fact that the AX/GRP scale gave gross-vehicle weight readings that were on average 1.5 percent heavier than those from the AX/WHL scale (see Fig 3-6(b)).

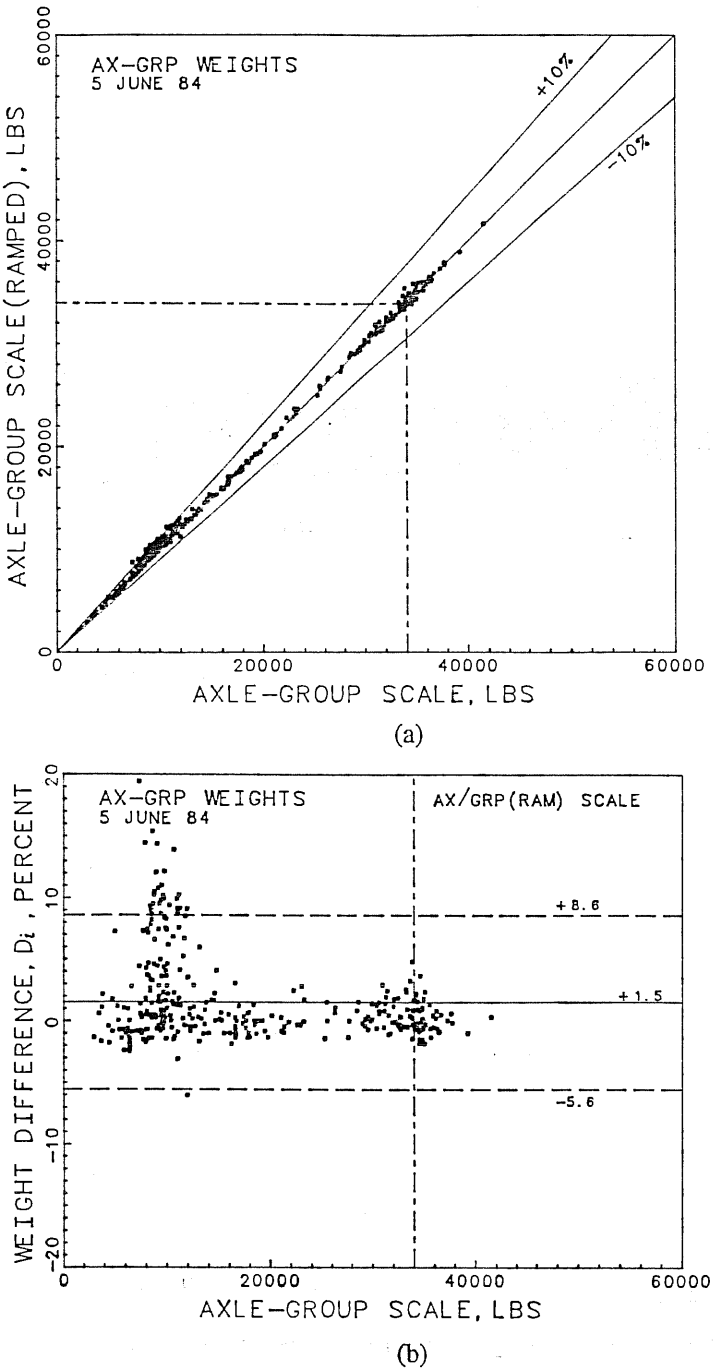
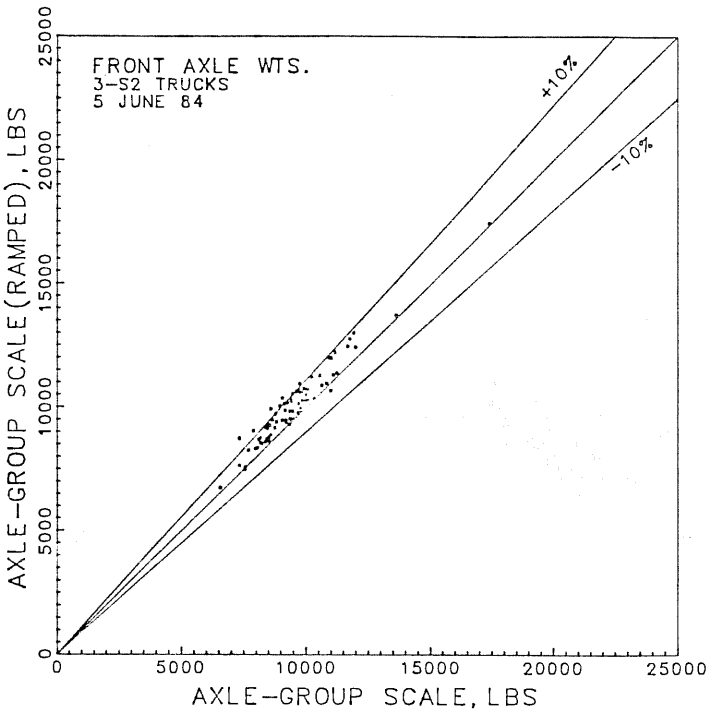
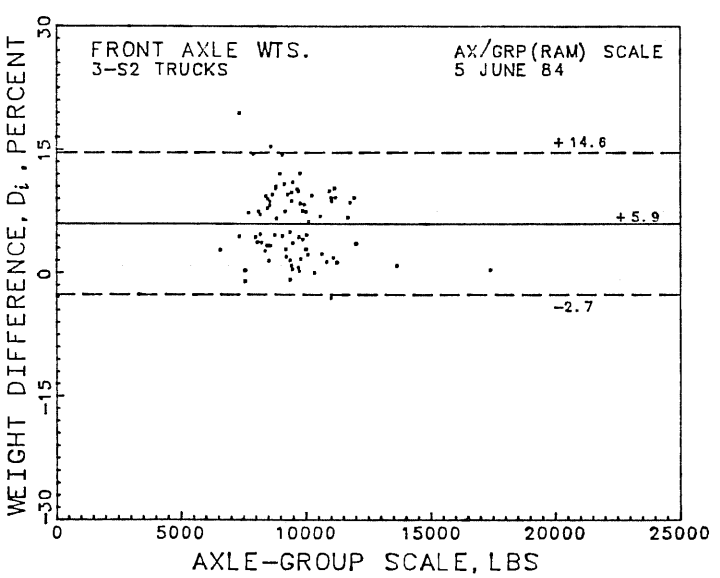


Figure 3-10. (a) Weights of 355 axle groups weighed directly on the AX/GRP (RAM) and AX/GRP scales, (b) percentage difference weights for the AX/GRP (RAM) scale vs the AX/GRP scale weights.

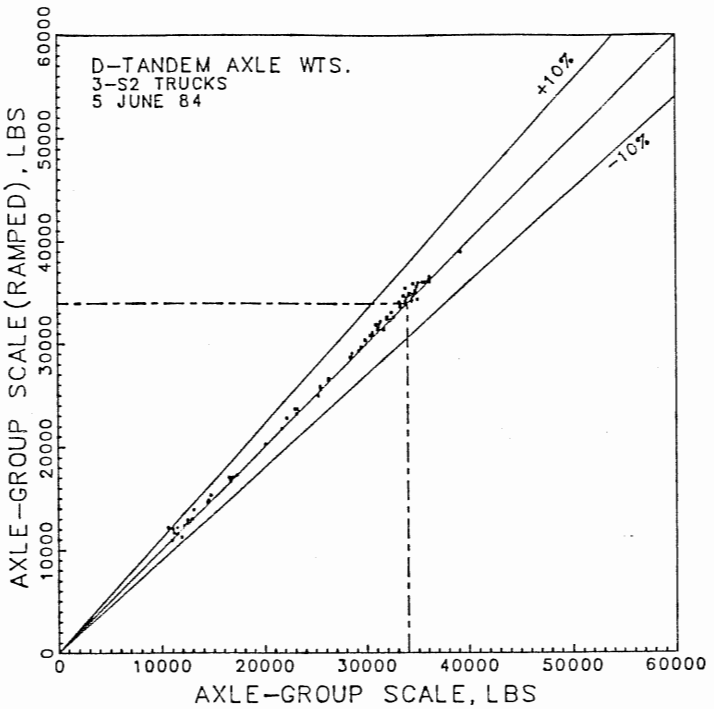


(a)

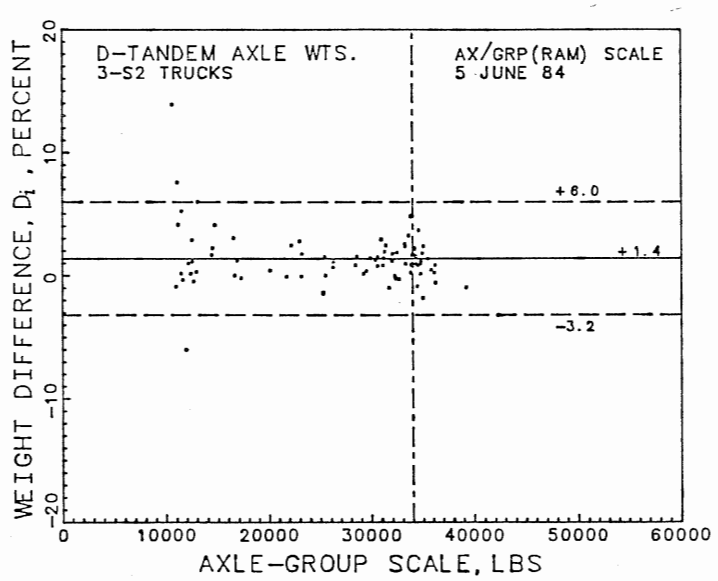


(b)

Figure 3-11. (a) Front axle weights of 81 3-S2 trucks weighed on the two axle-group scales, (b) percentage difference in front axle weights by the AX/WHL (RAM) scale vs the AX/WHL scale weights.

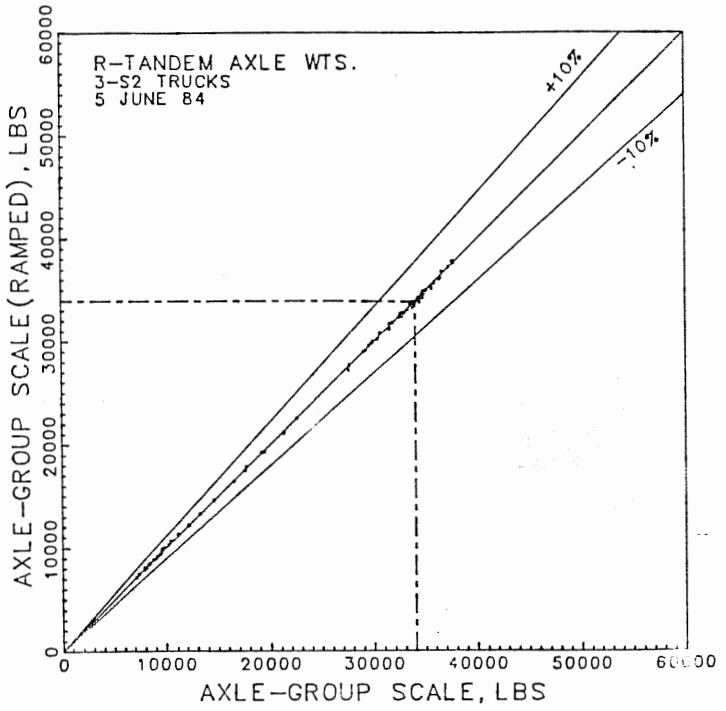


(a)

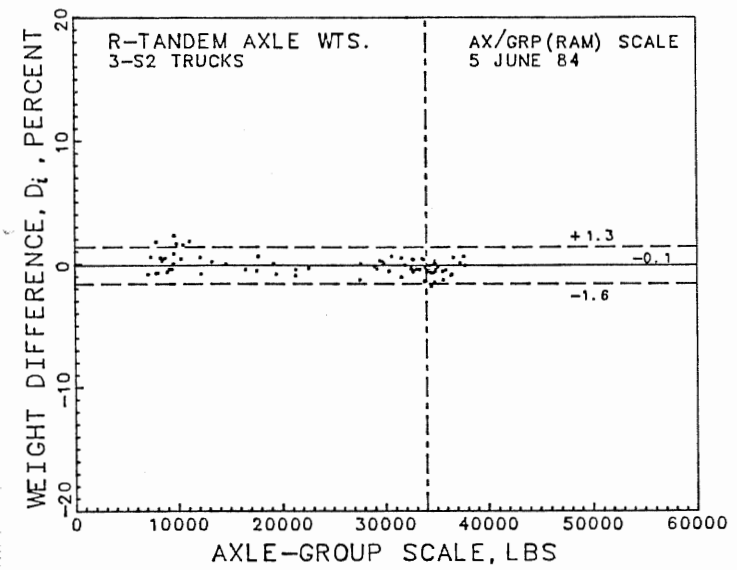


(b)

Figure 3-12. (a) Weights of 81 drive-tandem axles on 81 3-S2 trucks from two axle-group scales, (b) percentage difference in the AX/GRP (RAM) vs the AX/GRP scale weights for drive-tandem axles.

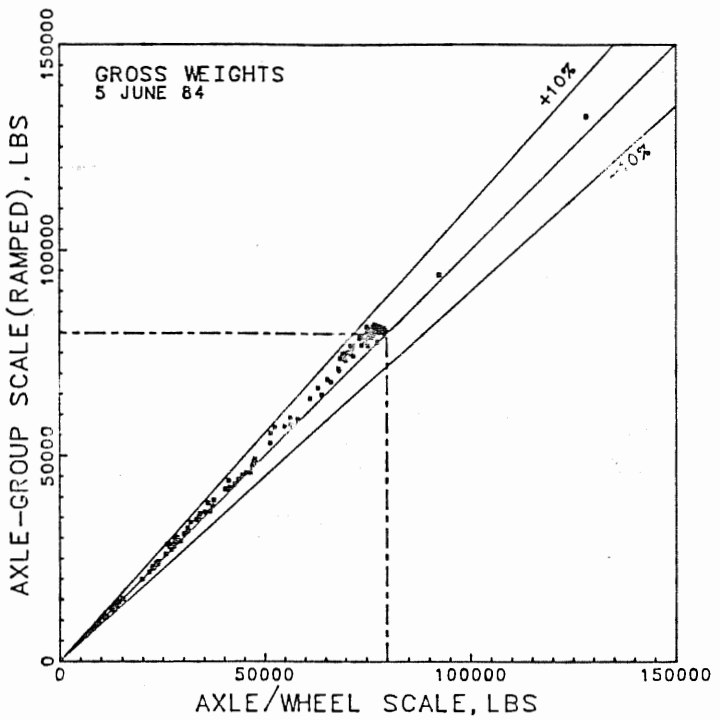


(a)

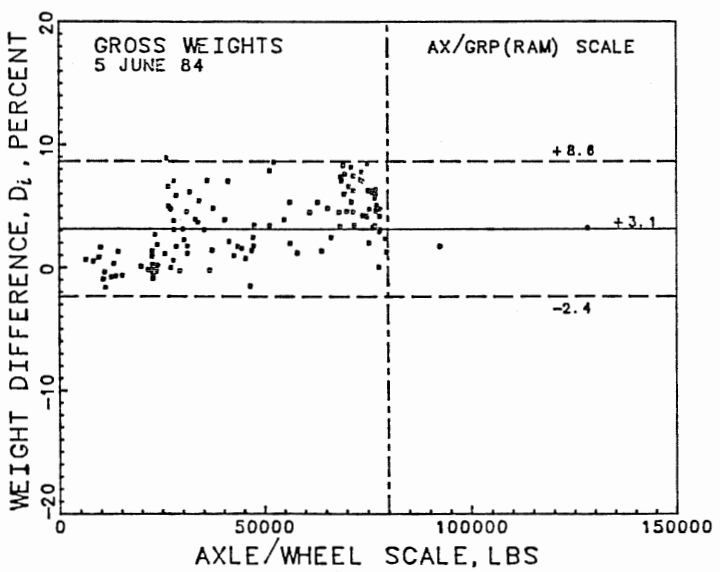


(b)

Figure 3-13. (a) Weights of 81 rear-tandem axles weighed on the AX/GRP (RAM) and AX/GRP scales, (b) percentage difference in weights by the AX/GRP (RAM) scale vs the AX/GRP scale weights.

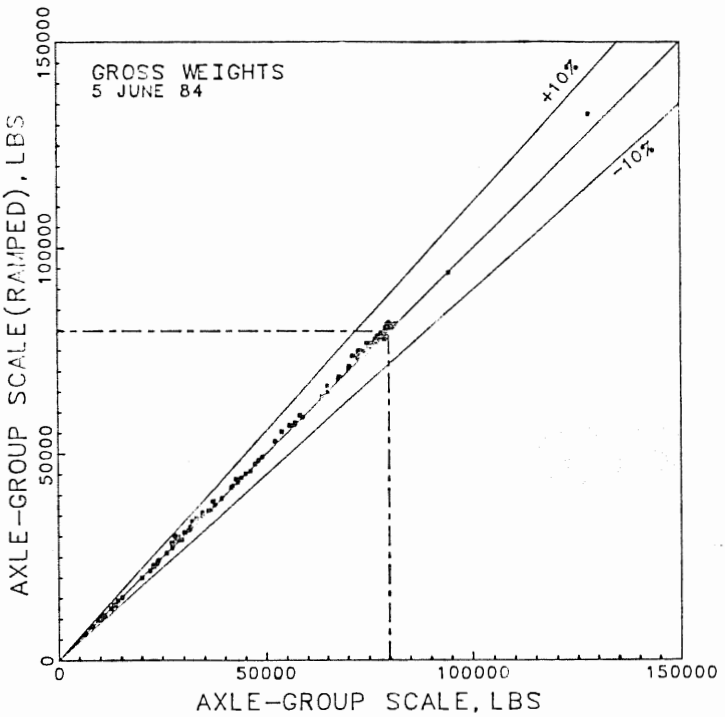


(a)

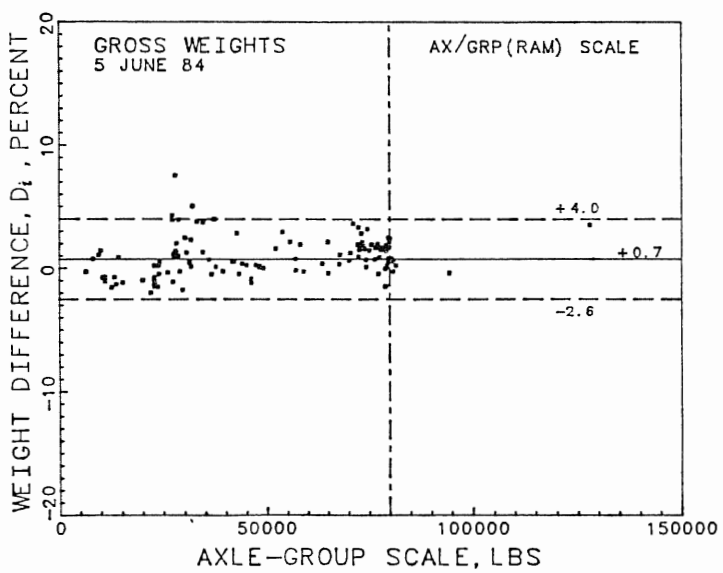


(b)

Figure 3-14. (a) Gross-vehicle weights of 131 trucks from the AX/GRP (RAM) vs those of AX/WHL scale weights, (b) percentage difference in weights for the AX/GRP (RAM) scale vs the AX/WHL scale weights.



(a)



(b)

Figure 3-15. (a) Gross-vehicle weights of the same 131 trucks weighed on the AX/GRP (RAM) and AX/GRP scales, (b) percentage difference in weights for the AX/GRP (RAM) scale vs AX/GRP scale weights.

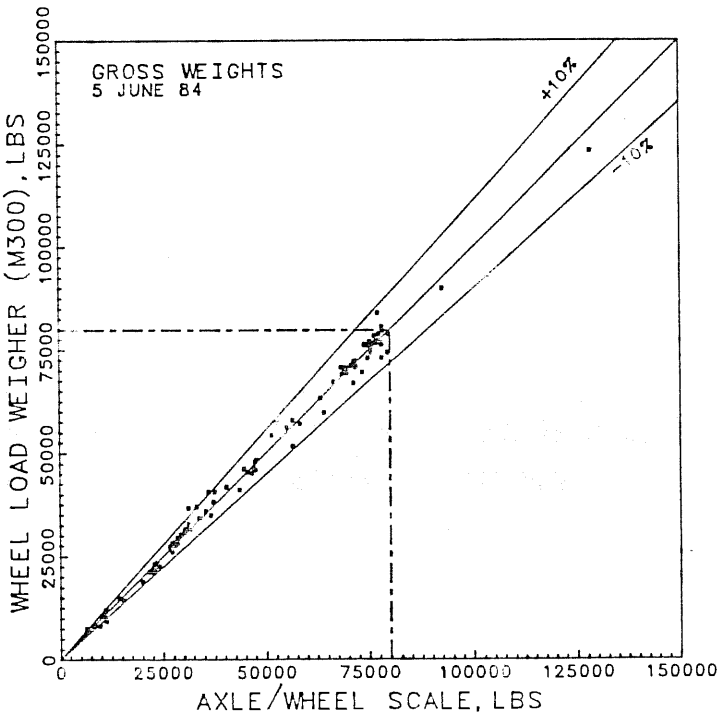
COMPARISON OF WLW/M300 AGAINST AX/WHL AND AX/GRP SCALES

The gross -vehicle weights and percentage relative difference in these weights that were obtained for 93 trucks which were weighed on WLW/M300 and AX/WHL scales are presented graphically in Fig 3-16. Inspection of these figures shows that a few of the gross-vehicle weights measured by the two types of scales differ by slightly more than ten percent. Out of 93 gross-vehicle weights three of the observations for very light trucks and those for three other trucks lie slightly outside the minus and plus ten percent deviation lines, respectively. Figure 3-16(b) depicts differences in the gross-vehicle weight of each of the 93 trucks along with lines indicating two standard deviations from the mean difference. Statistical analysis of these data indicate that the differences range from -9.9 percent to +11.2 percent 95 times out of 100, with average and standard deviation of +0.7 percent and 5.3 percent, respectively. Also notice that the differences are evenly scattered around the mean difference line throughout the range of gross-vehicle weights observed. This indicates that both scales performed similarly throughout their weighing range from light to heavy loads. There was no pronounced tendency for the WLW/M300 to overweigh or underweigh within any load range.

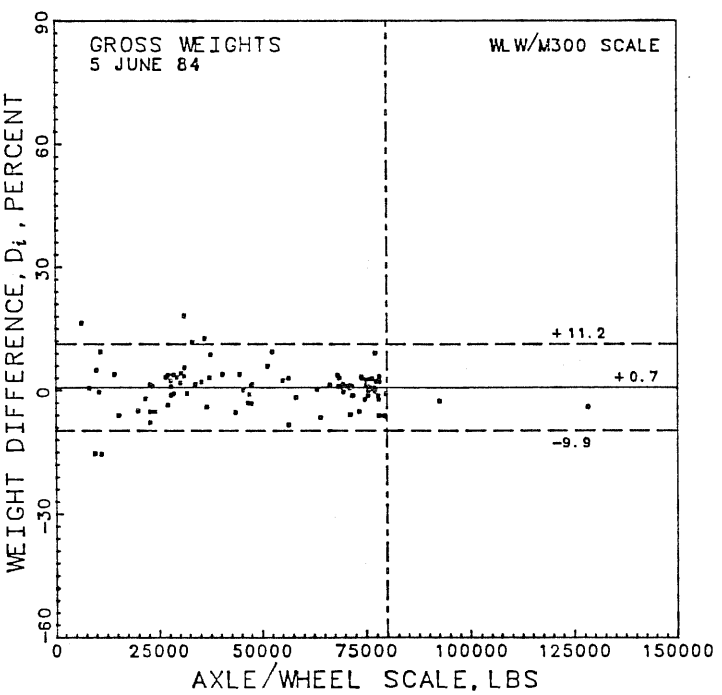
Gross-vehicle weights of 93 trucks weighed on the WLW/M300 scales are plotted versus comparable weights from the AX/GRP scale in Fig 3-17(a). The corresponding percentage differences in gross-vehicle weights are illustrated in Fig 3-17(b). Weights from the AX/GRP scale were in general slightly higher than those from the WLW/M300 scale particularly for the heavier trucks. This is consistent with the previously mentioned tendency of the AX/GRP scale to indicate higher weights for the heavier loads when compared with the AX/WHL scale (see Figs 3-4 and 3-6). The extreme differences are somewhat more than ten percent in a few cases. Statistical analysis of these differences or visual inspection of Fig 3-17(b) indicates that they lie between -11.9 percent and +8.7 percent 95 times in 100, with mean and standard deviation of -1.6 percent and 5.1 percent, respectively. Gross-vehicle weight differences from the WLW/M300 on average agree more closely with those from the AX/WHL scale than with those from the AX/GRP scale. Variability about the mean is virtually the same with respect to both reference scales.

Illustrated in Fig 3-18 are 260 computed axle-group weights from the AX/WHL and WLW/M300 scales and their corresponding percentage differences. Even though, there is scatter in the axle-group weights from the two scales, they are evenly distributed around the mean difference which is virtually zero (i.e., +0.3). The extreme difference ranges from -36.4 to +37.3 percent with 95 percent of the observed differences lying between -15.9 percent and +16.5 percent as shown in Fig 3-18(b). The standard deviation is 8.1 percent.

The observed and calculated weights from AX/GRP and WLW/M300 scales, respectively, for 260 axle groups weighed by these scales, are plotted in Fig 3-19. The WLW/M300 scale weights are generally somewhat lower (mean value = -1.5 percent) than the AX/GRP scale weights, especially for the heavier axle groups. As shown in Fig 3-19(b), the deviations range from -36.4 to +36.4 percent (standard deviation = 7.9 percent) with 5 percent of the observed differences lying outside the interval -17.2 and +14.3 percent . It is interesting to note that the gross-vehicle weights computed by summing the applicable axle-group weights (see Fig 3-17(b)) have less percentage deviation than the individual axle-group weight observations (see Fig 3-19(b)). Moreover, as this scale was a rollover type, its height did not affect the front axle weights of 3S-2 type trucks whereas the ramped axle-load scale (AX/GRP (RAM)) scale indicated otherwise.

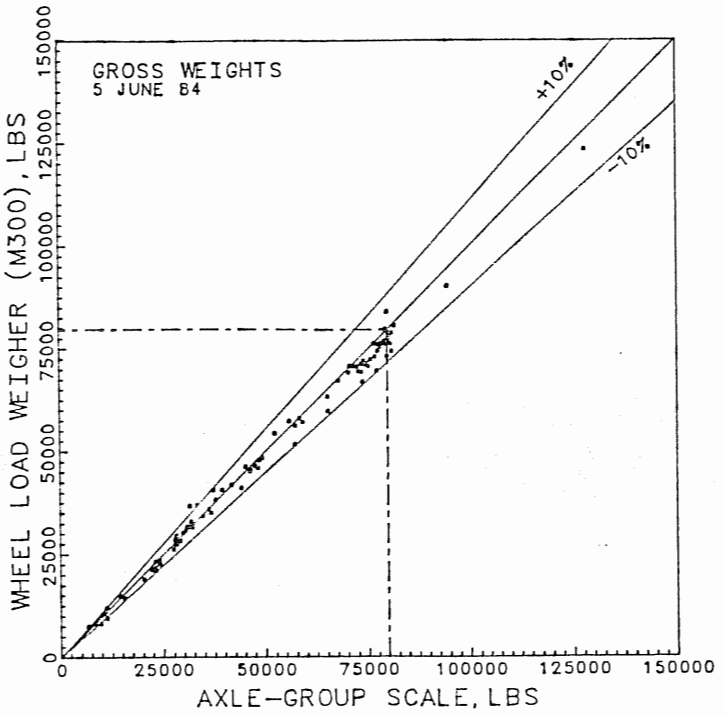


(a)

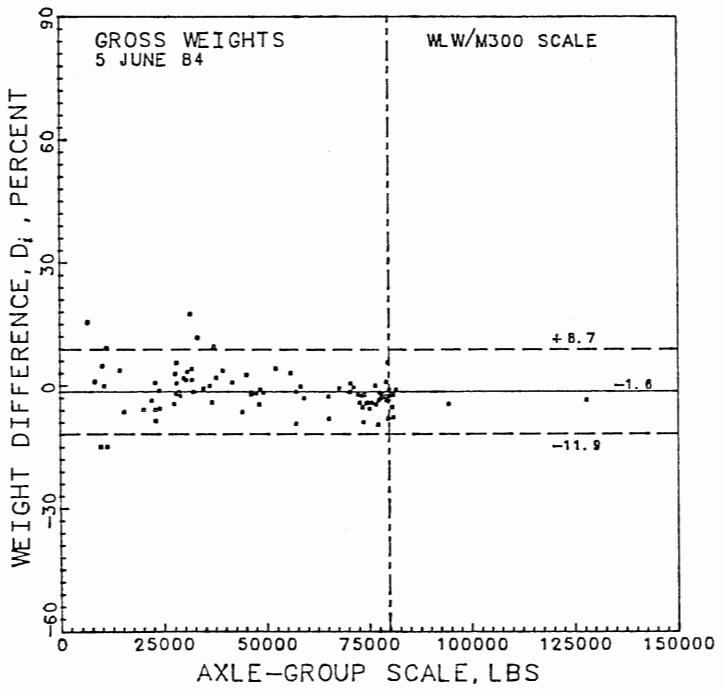


(b)

Figure 3-16. (a) Gross-vehicle weights of 93 trucks weighed on the WLW/M300 and AX/WHL scales, 5 June 1984, (b) percentage difference in weights for the WLW/M300 vs the AX/WHL scale weights.

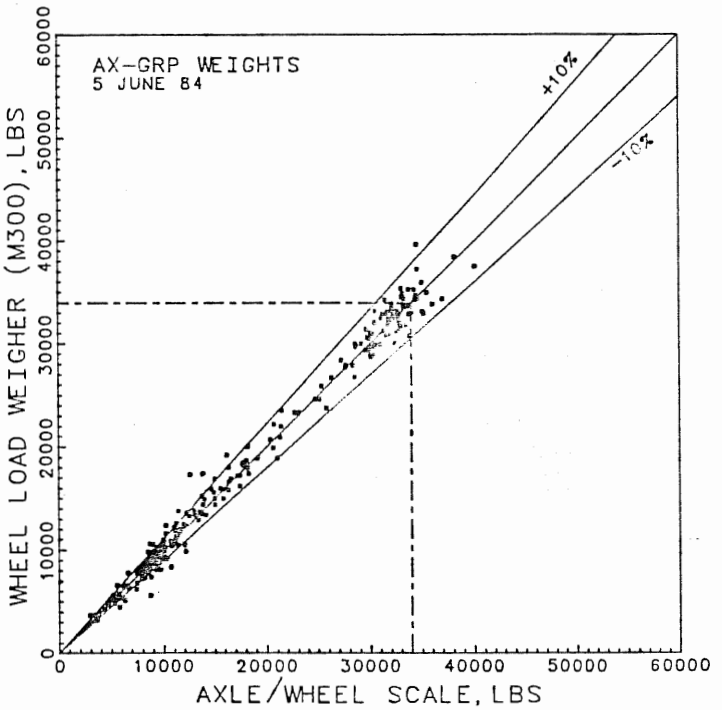


(a)

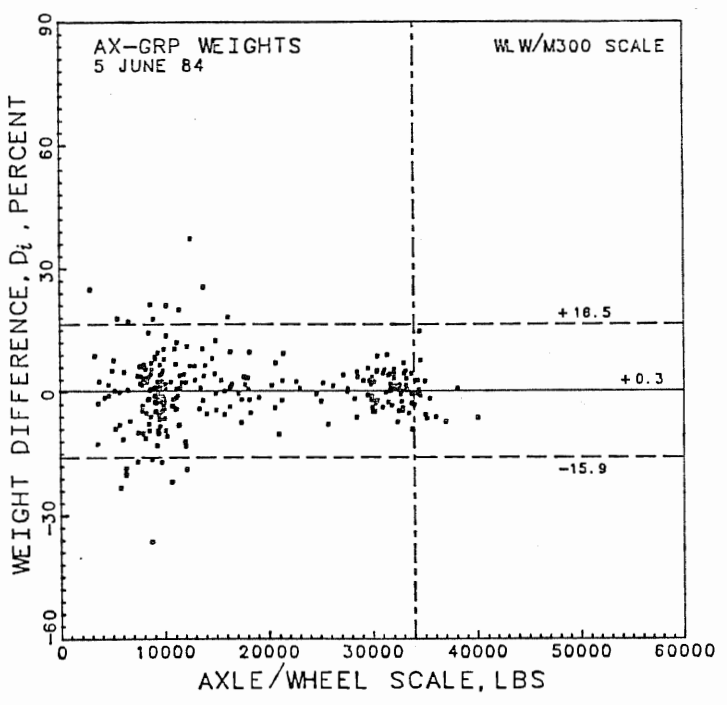


(b)

Figure 3-17. (a) Gross-vehicle weights of 93 trucks weighed on the WLW/M300 and AX/GRP scales, (b) percentage difference in weights for the WLW/M300 vs the AX/GRP scale weights.

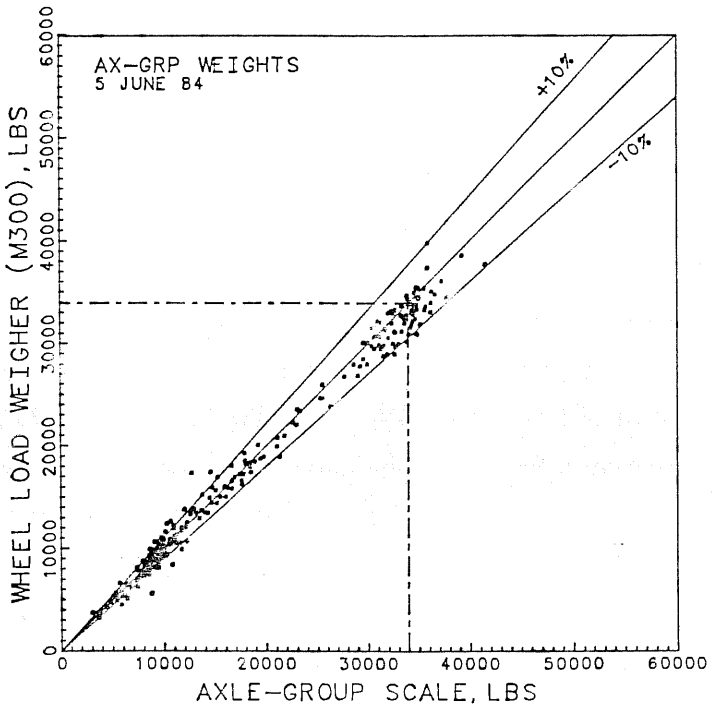


(a)

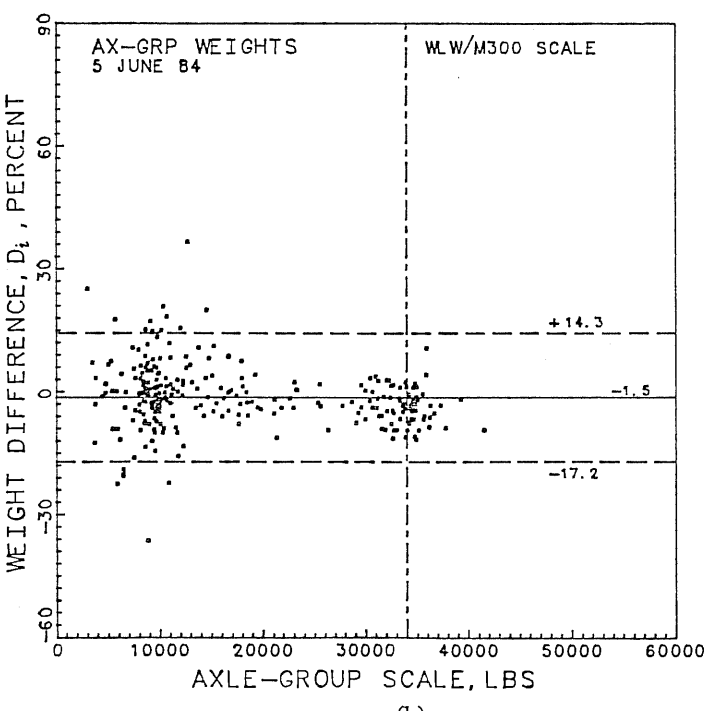


(b)

Figure 3-18. (a) Weights of 260 axle groups calculated from the WLW/M300 and AX/WHL scales, (b) percentage difference in weights for the WLW/M300 vs the AX/WHL scale weights.



(a)



(b)

Figure 3-19. (a) Weights of 260 axle groups computed from the WLW/M300 vs those observed from the AX/GRP scale.

Values for the 398 individual-axle weights that were determined on both the AX/WHL and the WLW/M300 scales are shown in Fig 3-20. About 36 percent of the data points lie outside the ten-percent deviation lines, particularly for lighter axle weights. The WLW/M300 scale weights are generally somewhat higher (mean value = 1.3 percent) than those determined by the AX/WHL scale. The scatter of these differences is shown in Fig 3-20(b). Statistical analysis of these differences show that they occur in the range of -25.2 percent to +28.1 percent if 95 percent of all possible comparisons are considered. Again, the scale performed rather consistently throughout the range of axle weights measured by the two scales, sometimes high and sometimes low.

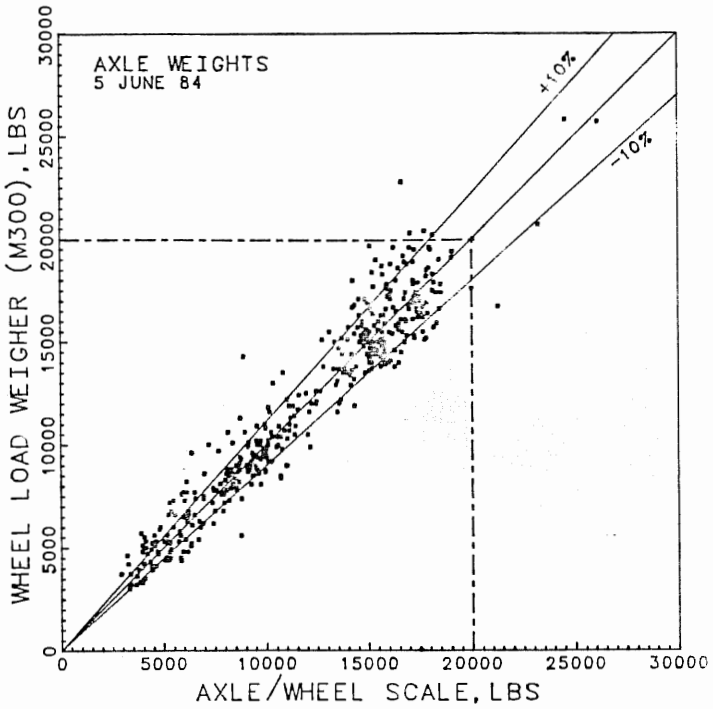
The 796 wheel weights that were summed to compute the respective axle weights shown in Fig 3-20 are depicted individually for the AX/WHL and the WLW/M300 scales in Fig 3-21(a). About 48 percent of the wheel weights lie outside the ten-percent deviation lines, particularly for the lighter wheel weights. Again, the WLW/M300 scale in general weighs heavier than the AX/WHL scale (mean value = 2.4 percent). Statistically, the implications of these data are that when a wheel is weighed on both scales, differences in wheel weights lying somewhere between -33.8 percent and +38.5 percent can be expected 95 percent of the time; larger differences are expected five percent of the time. Figure 3-21(b) shows the scatter of these differences with a standard deviation of 18.1 percent. The 95 percent confidence limits are shown at two standard deviations about the mean. It should be noted that the surface around the AX/WHL scale was warped transversely about 3 percent beyond the 10-ft long level aprons on each side and that the WLW/M300 scales were used on a 2 percent uniform cross slope. Some unknown amount of the variability in wheel weights can be attributed to these factors.

COMPARISON OF WL/100 AGAINST AX/WHL AND AX/GRP SCALES

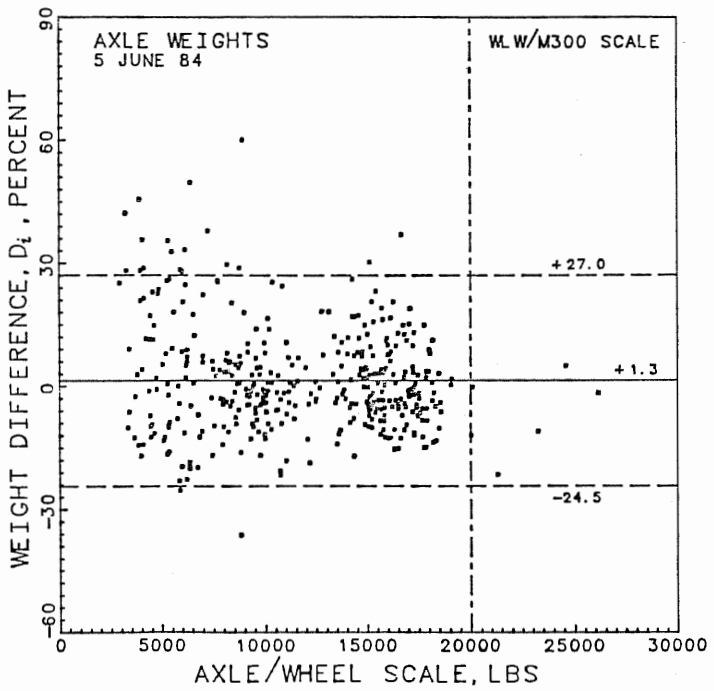
Figure 3-22 depicts the gross-vehicle weights and their relative differences, when 94 trucks were weighed on the WL/100 and the AX/WHL scales. Inspection of these figures indicates that there is not perfect agreement between the weights but that all gross-vehicle weights differ less than ten percent. There is approximately an even distribution of the weights about the line of equality. As shown in Fig 3-22(b), statistical analysis of the differences in gross-vehicle weight indicates that they range between -4.9 percent to +7.6 percent 95 times in 100, with mean and standard deviation of +1.4 percent and 3.1 percent, respectively.

Gross-vehicle weights of the same 94 trucks each weighed by the WL/100 scale are plotted against those from the AX/GRP scale in Fig 3-23(a). Their respective percentage differences are shown in Fig 3-23(b). Statistical analysis of these data indicate that the differences range from -6.4 percent to +5.4 percent 95 percent of the time, with mean of -0.5 percent and standard deviation of 2.9 percent. It has been noted previously that the AX/GRP scale generally weighs heavier than the AX/WHL scale.

The calculated weights for 278 axle-groups from the WL/100 and AX/WHL scales and their corresponding relative differences are illustrated in Fig 3-24. The WLW/100 scale weights are generally somewhat higher (mean difference = +1.3) than the weights from the AX/WHL scale. Statistically, axle-group weights calculated from the WL/100 are estimated to differ from those from the AX/WHL scale by some amount between -8.5 percent and +11.1 percent with 95 percent confidence. It can be seen from Fig 3-24(b) that the deviations from the reference scale

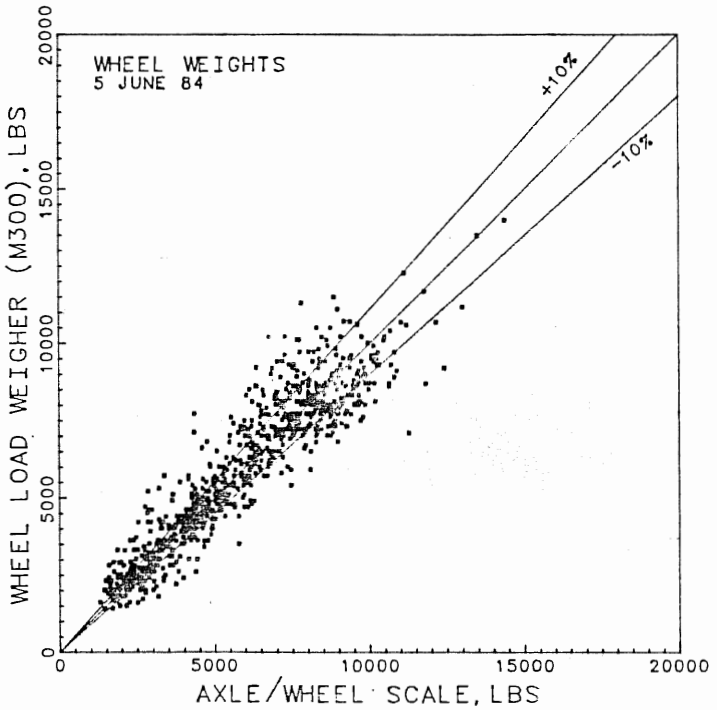


(a)

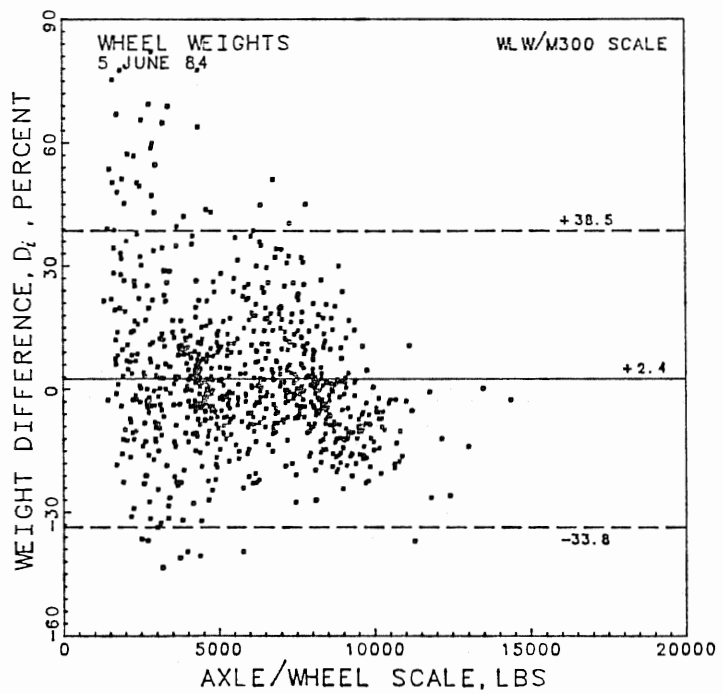


(b)

Figure 3-20. (a) Weights of 398 individual axles calculated by the WLW/M300 and AX/WHL scales, (b) percentage difference in weights for the WLW/M300 vs those by the AX/WHL scale.

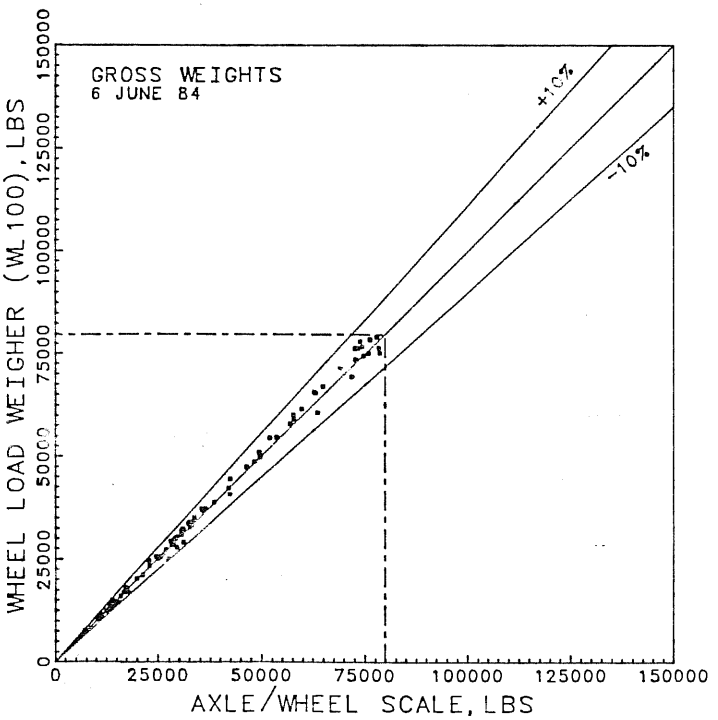


(a)

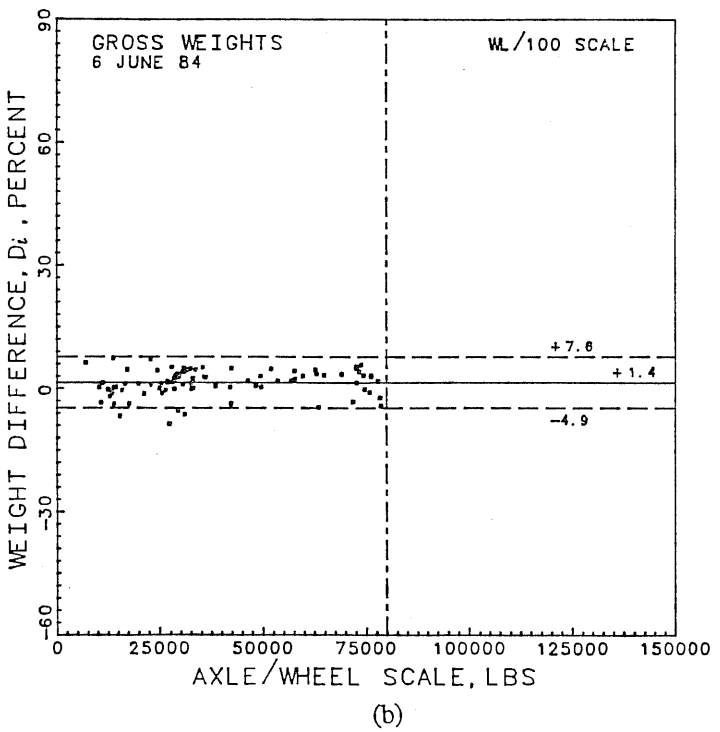


(b)

Figure 3-21. (a) Weight of 796 wheel weights measured by the WLW/M300 and AX/WHL scales, (b) percentage difference in weights for the WL/100 vs the AX/WHL scale weights.

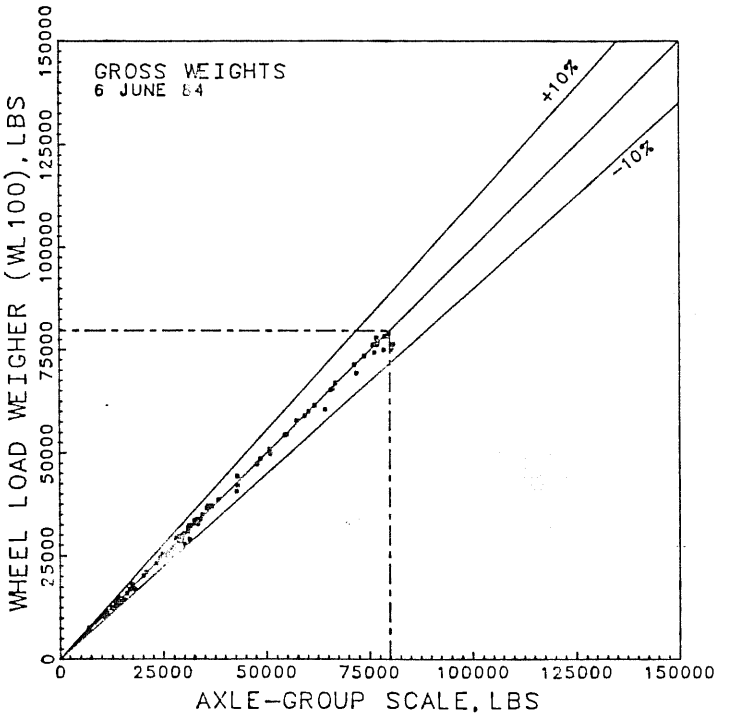


(a)

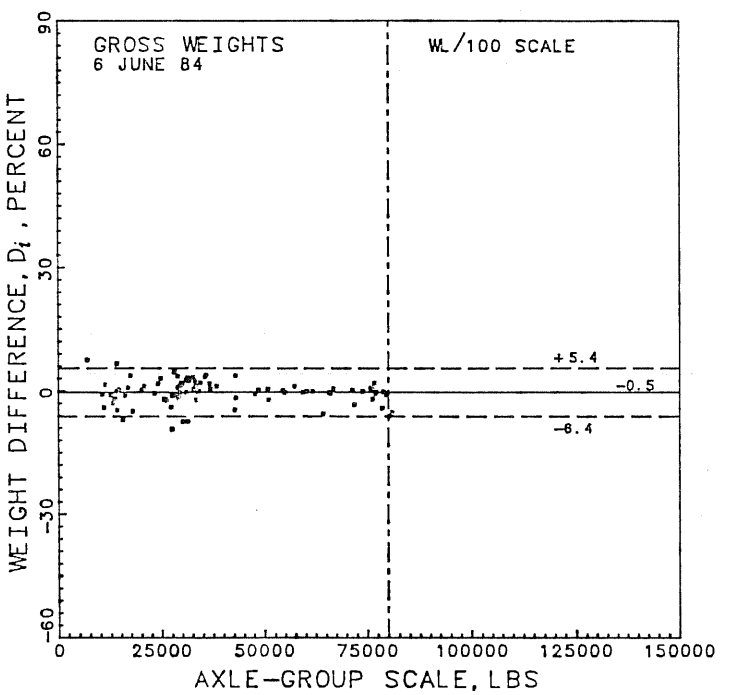


(b)

Figure 3-22. (a) Gross-vehicle weights of 94 trucks weighed on the WL/100 and AX/WHL scales, 6 June 1984, (b) percentage difference in weights for the WL/100 vs the AX/WHL scale weights.

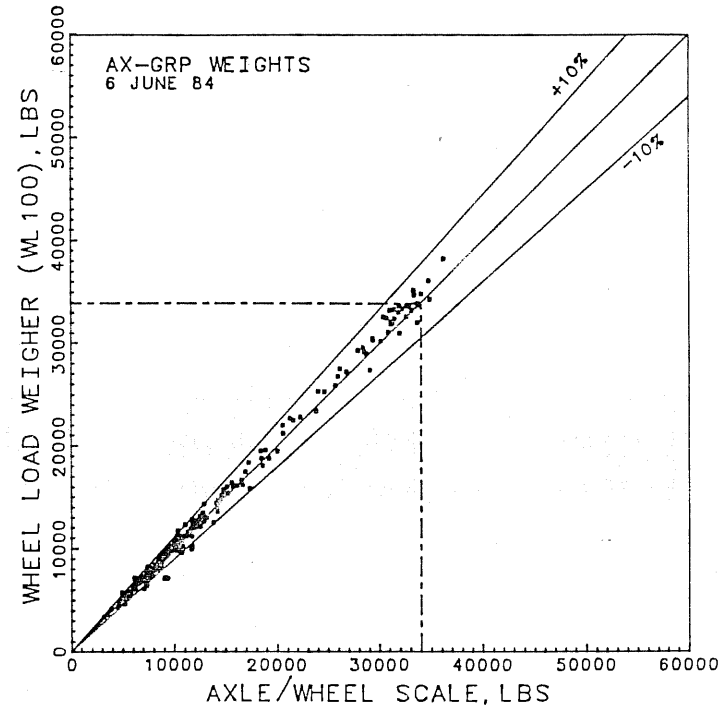


(a)

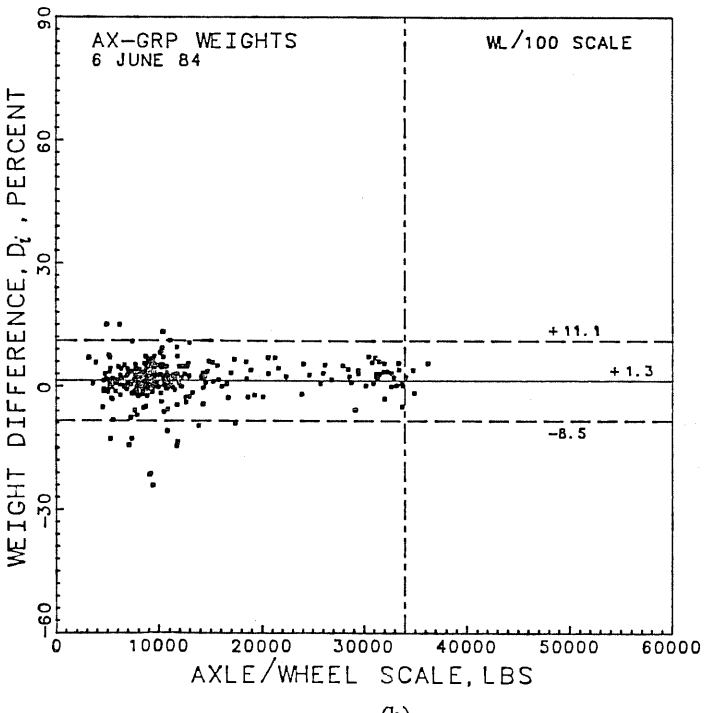


(b)

Figure 3-23. (a) Gross-vehicle weights of 94 trucks weighed on the WL/100 and AX/GRP scales, (b) percentage difference in weights for the WL/100 scale vs those from the AX/GRP scale.



(a)



(b)

Figure 3-24. (a) Weights of 278 axle groups determined from the WL/100 and AX/WHL scales, (b) percentage difference in weights for the WL/100 vs the AX/WHL scale weights.

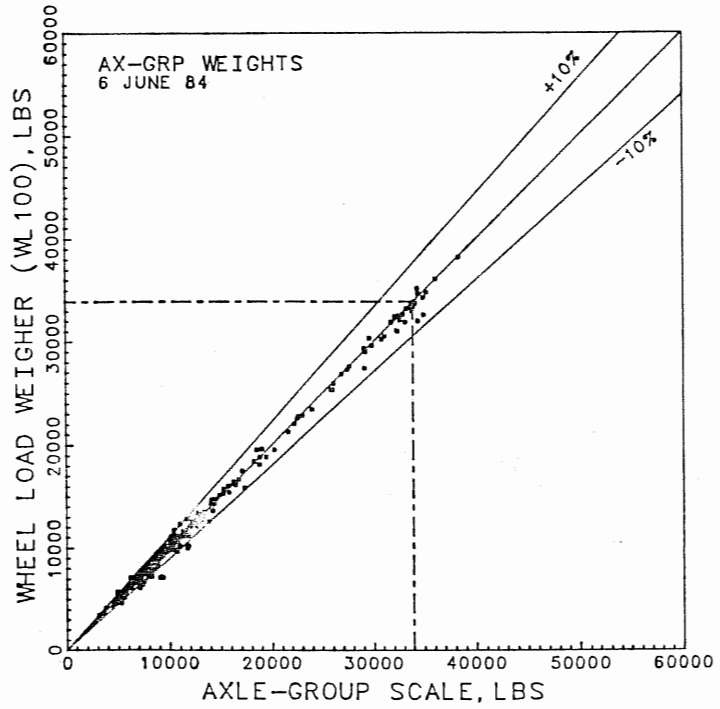
weights by the WL/100 scale weights are generally scattered evenly around the mean difference (standard deviation = 4.9 percent)with a slight tendency for the WL/100 to weigh axle groups heavier than the AX/WHL scale.

The observed and calculated weights from AX/GRP and WL/100 scales respectively for all axle groups are shown in Fig 3-25. The WL/100 scale weights are, on the average, only slightly lower (mean value = -0.4 percent) than the AX/GRP scale weights, mainly for heavier axle groups, and are somewhat higher for most of the lighter ones. As shown in Fig 3-25(b), the differences fall between -10.1 percent and +9.5 percent 95 times in 100. This reflects to some extent the tendency of the AX/GRP scale to overweigh heavy axle groups.

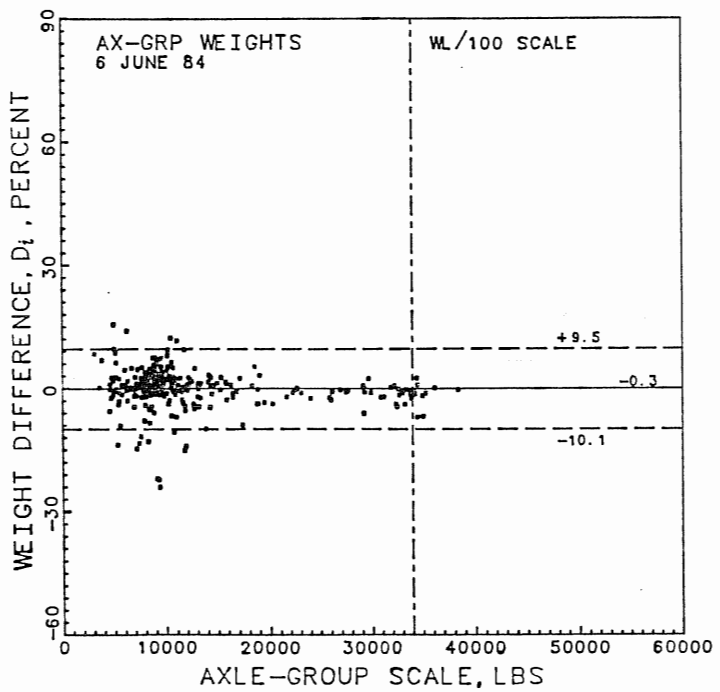
For further analysis, the axle-group weight data for trucks of the 3-S2 type were separated into front, drive-tandem, and rear-tandem axle weights. Plots of the data are not shown, but the following conclusions can be drawn from this analysis. First, when the front axles were weighed on the 0.79 inch high WL/100 scale they were weighed somewhat heavier than on the AX/GRP scale, with the average deviation being +1.7 percent. The AX/GRP scale tended to overweigh axles in the 7,000 to 12,000 pound range as compared to the AX/WHL (referee) scale (see Fig 3-7(b)). The fact that the mean of the differences for the front axles of 3-S2 trucks weighed on the WL/100 scale compared to the same axles weighed on the AX/GRP scale was +1.7 percent indicates that the WL/100 scales will tend to weigh the front axles of 3-S2 trucks heavier than the AX/WHL (referee) scale by an even larger percentage. This is consistent with the fact that the AX/GRP (RAM) scale, which is about 4 inches high, overweighed 3-S2 front axles on the average by 5.9 percent (see Fig 3-11(b)). This is not necessarily a fault in the scales, but an effect of the height of the scales in the mode of use on the road surface. Second, the drive-tandem and rear-tandem axle weights from the WL/100 scale were slightly lower than those from the AX/GRP scale. As a matter of fact the mean difference in drive-tandem axle weights was close to zero and that of rear-tandem axle weights was -1.5 percent. The AX/GRP scale tended to overweigh heavy axle groups as compared to the AX/WHL scale.

Values for 406 individual-axle weights that were determined on both the AX/WHL and the WL/100 scales are plotted in Fig 3-26. About 16 percent of the data points, compared to 36 percent for the WLW/M300 scale, lie outside the ten-percent deviation lines. The WL/100 scale weights are on average somewhat higher (mean value = +1.8 percent) than those determined by the AX/WHL scale. The scatter of these differences is shown in Fig 3-26(b). Analysis of these differences indicates that they occur in the range of -13.2 percent to +16.9 percent when 95 percent of all possible comparisons are made.

The 812 wheel weights that were summed to calculate the respective axle weights shown in Fig 3-26(a) are plotted individually for the AX/WHL and WL/100 scales in Fig 3-27(a). About 41 percent of the wheel weights lie outside the ten percent deviation lines, particularly for lighter wheels. On average, the WL/100 scales weigh heavier than the AX/WHL scale (mean value = +3.2 percent). Statistically, weights determined from the WL/100 will be expected to differ from those measured by the AX/WHL scale by some amount between -25.4 percent and +31.8 percent 95 percent of the time (see Fig 3-27(b). The transversely warped surfaces surrounding the AX/WHL scale and the 2 percent cross slope on which the WL/100 scales were used contributed to the observed differences in wheel weights in an undefinable way.

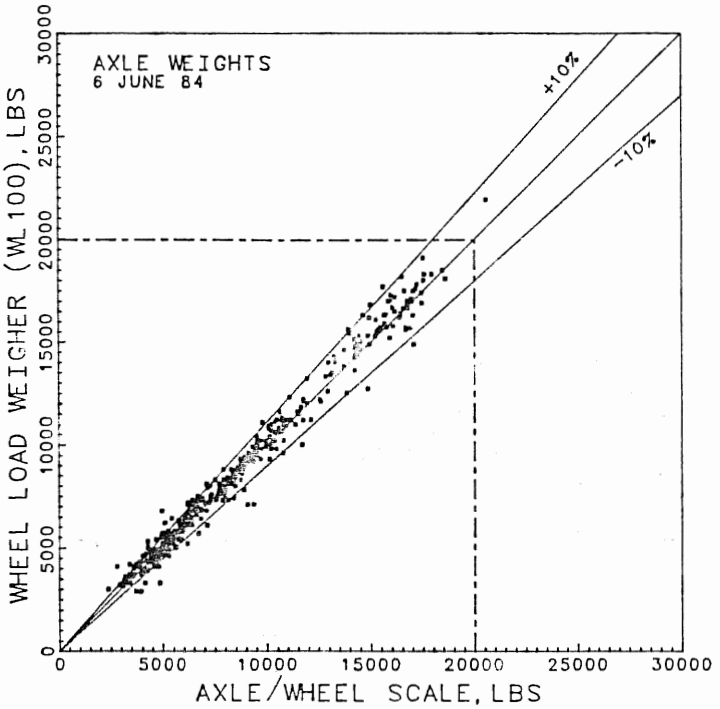


(a)

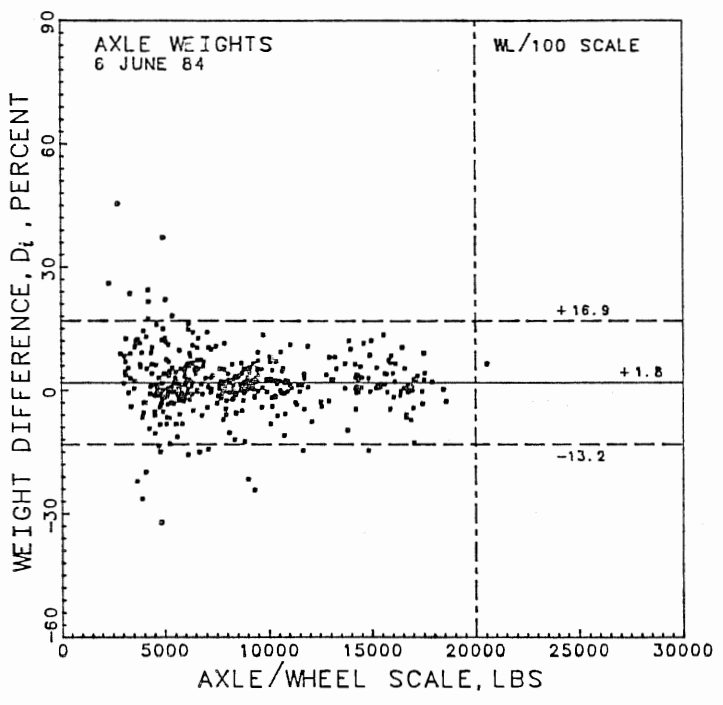


(b)

Figure 3-25. (a) Weights of 278 axle groups calculated from the WL/100 scales vs those measured by the AX/GRP scale, (b) percentage difference in weights for the WL/100 vs the AX/GRP scale weights.

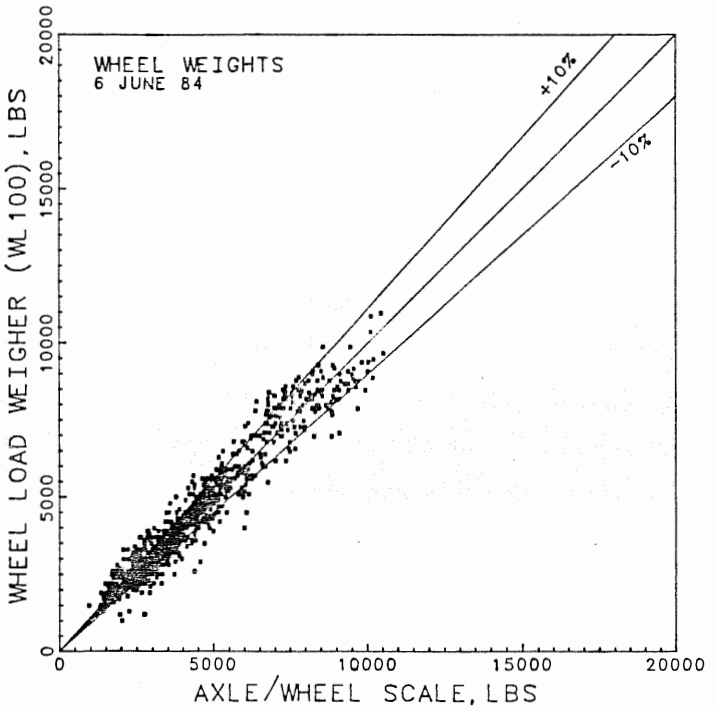


(a)

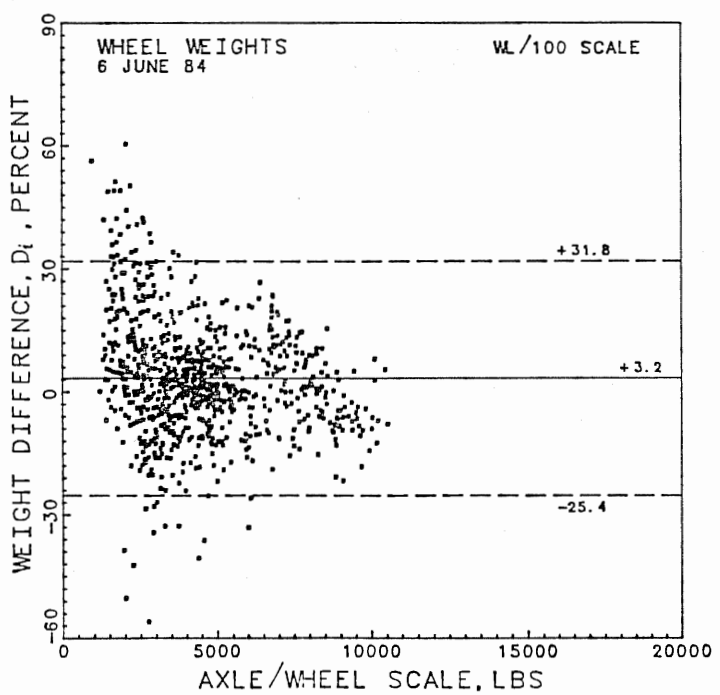


(b)

Figure 3-26. (a) Weights of 406 individual axles calculated from the WL/100 weights and measured by the AX/WHL scale, (b) percentage difference in weights for the WL/100 vs the AX/WHL scale weights.



(a)



(b)

Figure 3-27. (a) Weights of 812 wheels from the WL/100 scale vs those of AX/WHL scale, (b) percentage difference in weights for the WL/100 vs the AX/WHL scale weights.

COMPARISON OF WLW/M400 AGAINST THE AX/WHL AND AX/GRP SCALES

The gross-vehicle weights of 38 trucks weighed on the WLW/400 and the AX/WHL scales on the morning of 11 June 1984 are plotted in Fig 3-28. The lane surface before, between and beyond the AX/WHL and the AX/GRP scales was leveled before these trucks were weighed. The graph in Fig 3-28(a) indicates that only one of the gross-vehicle weights determined by the two types of scales differ more than ten percent. This number of observations is a relatively small sample, and if a larger number of trucks were to be weighed, the same relationship between the respective weights might not hold. Differences in gross-vehicle weights from the WLW/M400 scale expressed as a percentage of the gross-vehicle weight for the same trucks weighed by the AX/WHL scale are shown in Fig 3-28(b). Statistical analysis of these data indicate that differences in indicated gross-vehicle weight range between -3.2 percent and +11.1 percent at 95 percent confidence, with mean and standard deviation of +4.0 percent and 3.6 percent, respectively. This means that on average, the gross-vehicle weights from the WLW/M400 were four percent higher than those from the AX/WHL scale.

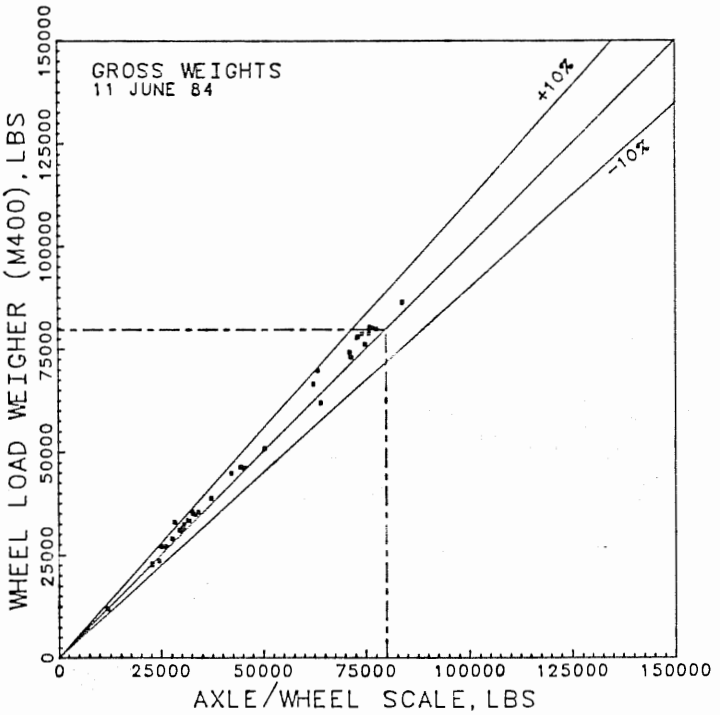
Gross-vehicle weights of the same 38 trucks weighed on the WLW/M400 scales are also plotted versus comparable weights from the AX/GRP scale in Fig 3-29(a). The corresponding percentage differences in gross-vehicle weights are shown in Fig 3-29(b). As shown in this graph, the standard statistical analysis of these differences indicates that they occur in the range of -4.9 percent to -6.9 percent if 95 percent of all possible comparison are considered with a mean difference of +1.0 percent.

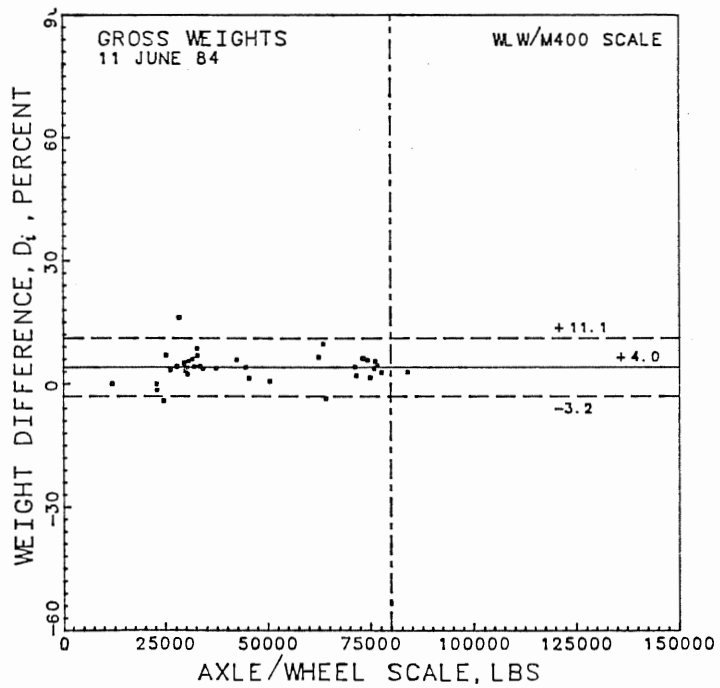
Axle-group weights summed from the WLW/M400 and AX/WHL scale weights are illustrated in Fig 3-30(a); the respective relative differences for the 111 axle groups are given in Fig 3-30(b). From these figures it can be seen that the WLW/M400 weights are systematically heavier than those of the AX/WHL scale, particularly for lighter axle groups (mean value = +4.4 percent). Statistically, it is concluded that the difference in axle-group weights determined from the WLW/M400 with reference to the AX/WHL measurements varies from -5.9 percent to 14.7 percent at the 95 percent confidence level. The differences in axle-group weights are scattered around the mean value with a standard deviation of 5.1 percent.

The calculated and observed weights from WLW/M400 and AX/GRP scales, respectively, for all axle groups weighed by the two scales are depicted in Fig 3-31. As shown in Fig 3-31(b), the deviations range from -9.5 percent to +24.7 percent (standard deviation = 5.2 percent) with 95 percent of the observed deviations falling within -8.6 percent and +12.3 percent. The observed deviations are mostly positive for the lighter axle-group weights and mostly negative for the heavier axle-group weights which fall near the weight-limit line.

In order to assess the effect of height of the scale on the axle-group weights, the same method of analysis that was used for the other portable scales was also employed for this scale. The purpose is to study the behavior of individual axles and axle groups as they are weighed on the WLW/M400 scale. Thus, the axle-group weights for all trucks of the 3-S2 type from both scales were separated into front, drive-tandem, and rear-tandem axle weights and then each group was analyzed individually. These data are not shown graphically in this report.

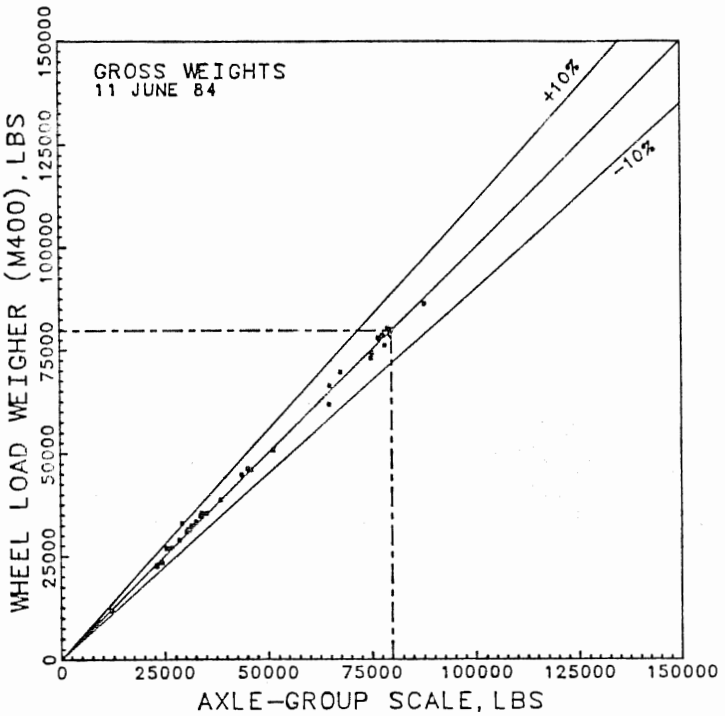
The WLW/M400 scale was very similar to the WLW/M300 scale except that no load-holding mechanism is provided; therfore, the wheels had to be stopped on the weighing surface before the weight readings could be made. Statistical interpretation of the front axle weights indicates that, on average, they were weighed 6.7 percent heavier



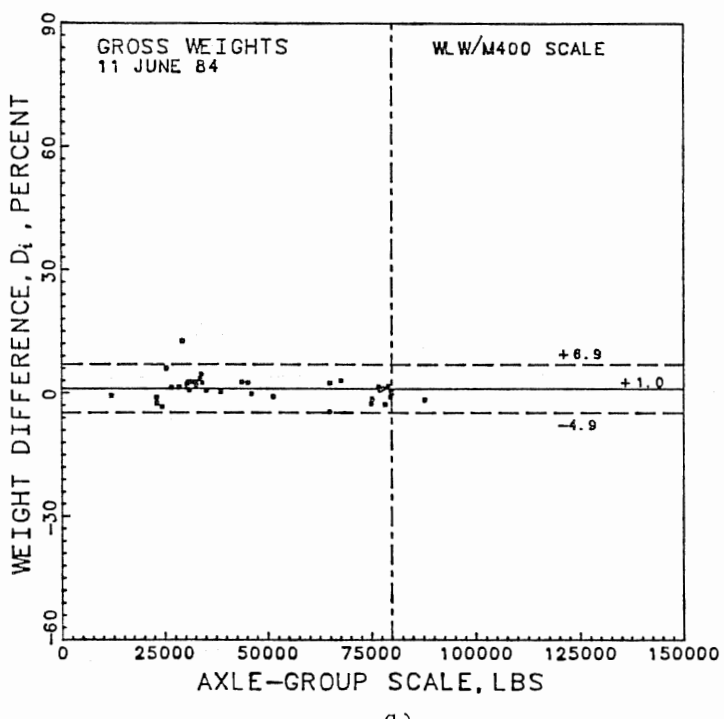


(b)

Figure 3-28. (a) Gross-vehicle weights of 38 trucks weighed on the WLW/M400 and AX/WHL scales, (b) percentage difference in weights for the WLW/M400 vs the AX/WHL scale weights.

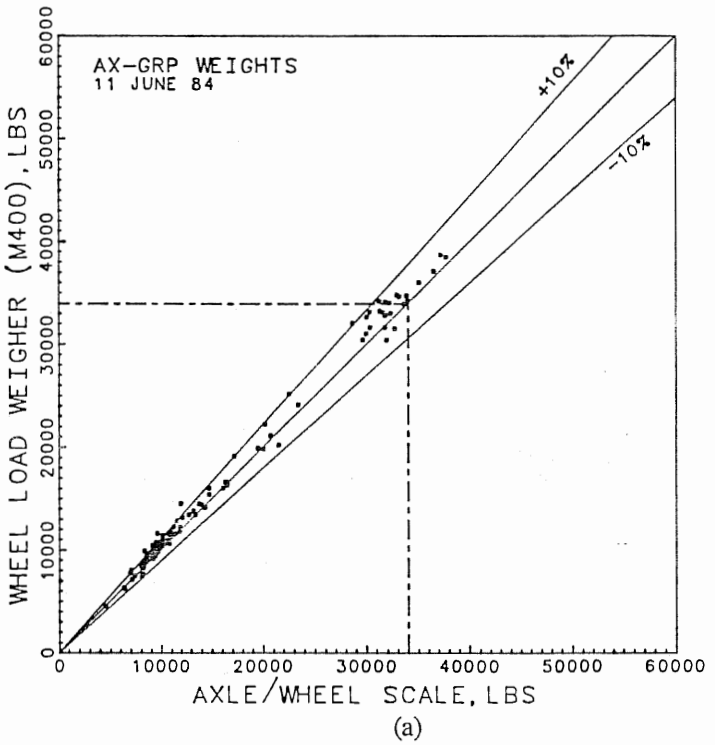


(a)

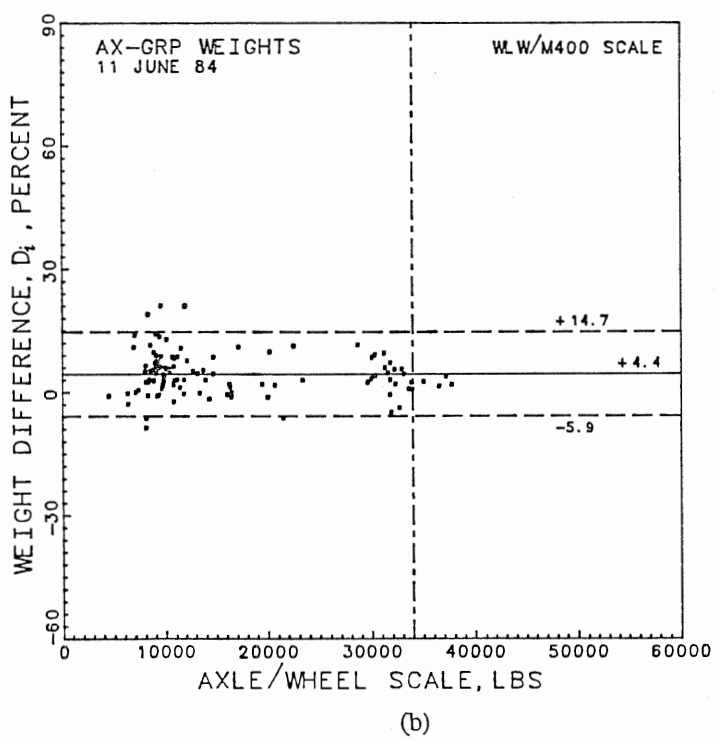


(b)

Figure 3-29. (a) Gross-vehicle weights of 38 trucks weighed on the WLW/M400 and AX/GRP scales, (b) percentage difference in weights for the WLW/M400 vs the AX/GRP scale weights.

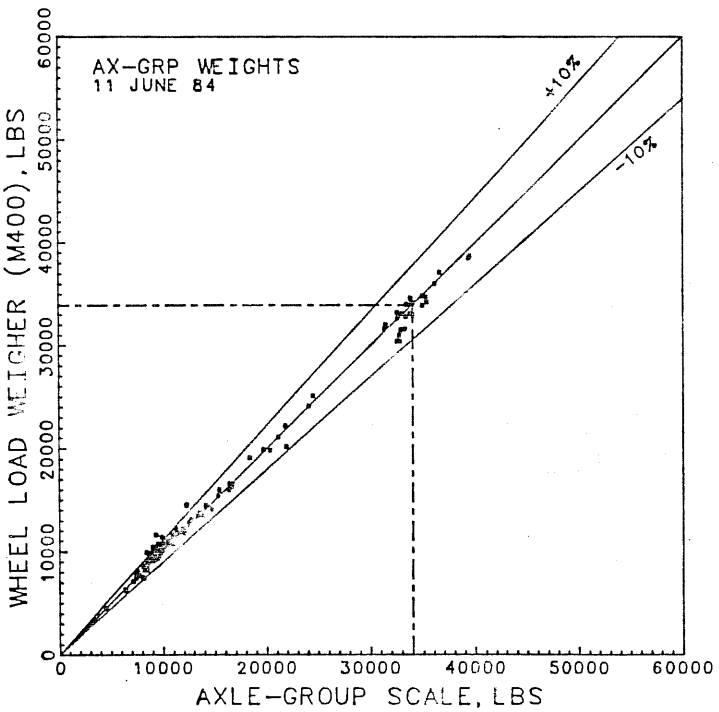


(a)

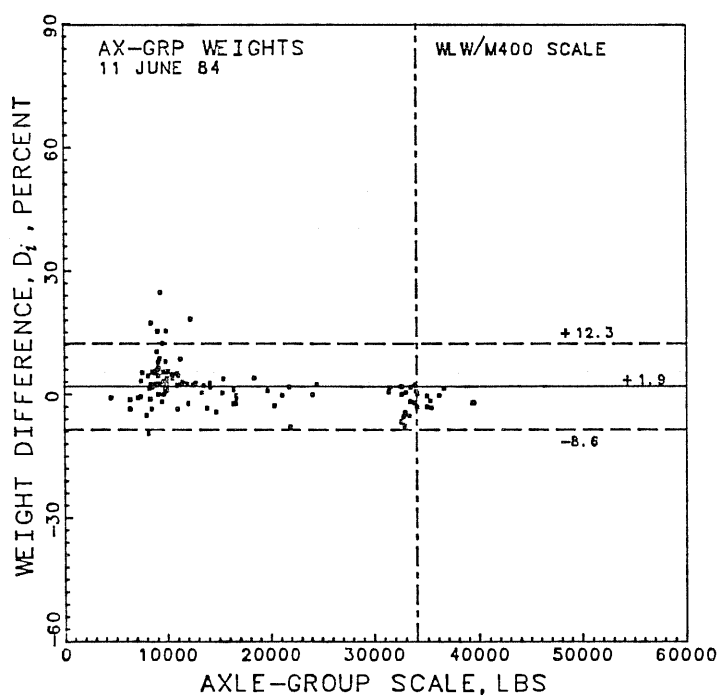


(b)

Figure 3-30. (a) Weights of 111 axle groups calculated from the WLW/M400 and AX/WHL scales, (b) percentage difference in weights for the WLW/M400 vs the AX/WHL scale weights.



(a)



(b)

Figure 3-31. (a) Weights of 111 axle groups computed from WLW/M400 weighings vs those measured by the AX/GRP scale, (b) percentage difference in weights for the WLW/M400 vs the AX/GRP scale weights.

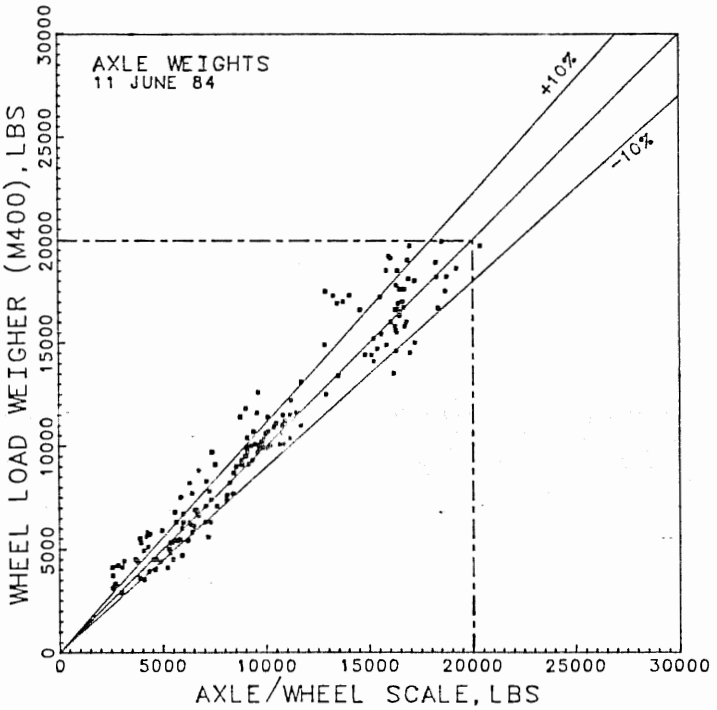
on this scale when compared to the respective readings from the AX/GRP scale. Furthermore, with 95 percent confidence, the differences in front axle weights of the 28 3-S2 trucks will lie between -3.7 percent and +17.1 percent with a standard deviation of 5.2 percent. The drive-tandem and rear-tandem axle weights, analyzed separately, do not reveal any systematic difference when compared to the AX/GRP scale. As a matter of fact the differences in weights on the drive-tandem and the rear-tandem axles averaged to zero and very close to zero (mean value = 0.12 percent), respectively, with standard deviations of 4.6 and 3.3 percent. This indicates that the height effect of the WLW/M400 caused overweighing of the tandem-axle groups of the same order of magnitude as the tendency of the AX/GRP scale to overweigh heavy axle groups compared to the AX/WHL (referee scale). It is also interesting to compare the weighings of front axles of 3-S2 trucks on the WLW/M400, which is 3 1/4 inches high with those on the AX/GRP (RAM) scale (see Fig 3-11) which is about 4 inches high.

Figure 3-32(a) is a plot of weight values for 175 individual-axle weights that were determined on both the AX/WHL and the WLW/M400 scales. About 38 percent of the axle weights fall outside the ten-percent deviation lines. As shown in Fig 3-32(b) on average, the WLW/M400 scale weights are heavier (mean value = 5.6 percent) than the AX/WHL scale weights. Statistical analysis of the data indicates that the differences lie in the range of -23.1 percent to +34.2 percent if 95 percent of all possible comparisons are made.

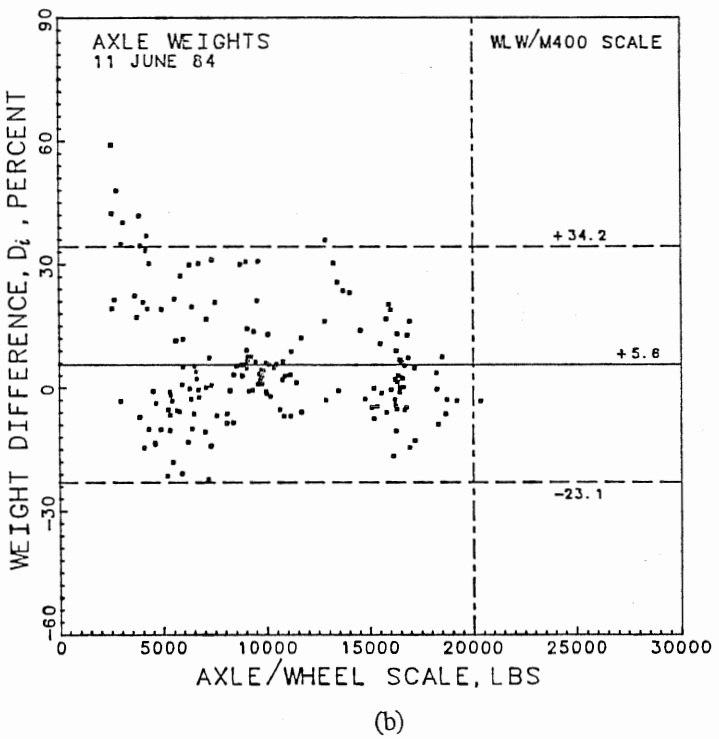
The 350 individual wheel weights that were summed to compute the respective axle weights which are shown in Fig 3-32(a) are depicted for the same scales in Fig 3-33(a). Approximately 42 percent of the data points lie outside the ten-percent deviation lines. On average, the WLW/M400 weights are heavier than those obtained by the AX/WHL scale (mean value = 5.7 percent). In a statistical sense, when a wheel is weighed on both scales, the weight from the WLW/M400 scale will be expected to differ from that from the AX/WHL scale by an amount between -26.4 percent and +37.9 percent of the AX/WHL scale weight, as shown in Fig 3-33(b), 95 pecent of the time. It is important to note again that the AX/WHL (reference) scale had level surfaces on the approaches and should, therefore, have been giving appropriate indications of the proportion of the gross-vehicle weight on the wheel being weighed. Much of the variation in the wheel weights from the WLW/M400 can probably be attributed to the redistribution of the gross-vehicle weight among the wheels as the truck moved forward and stopped on the elevated weighers.

SUMMARY

In the experimental program, a proportional sample was drawn from the population of truck types on IH-10 near Seguin, Texas and weighed statically on three different axle-load scales and on three different types of wheel-load weighers during a ten-day period in the summer of 1984. Wheel, axle, axle-group, and gross-vehicle weights obtained from these scales were compared using graphical and statistical analysis techniques. A specially-designed axle-load scale with two side-by-side load receiving platforms (the AX/WHL scale) was used as the basic reference scale in these comparisons. The permanent flush-mounted axle-load scale at the weigh site (the AX/GRP scale) was also used as a reference scale in some cases.

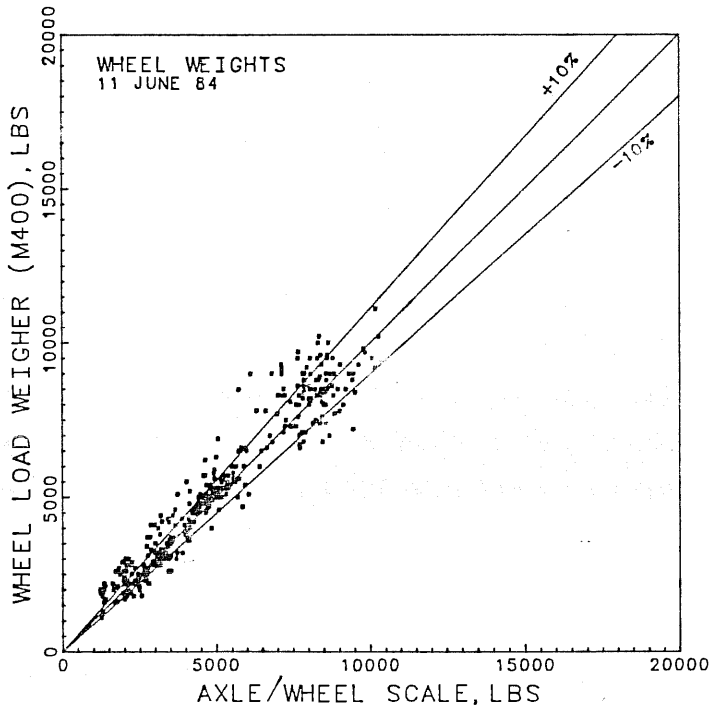


(a)

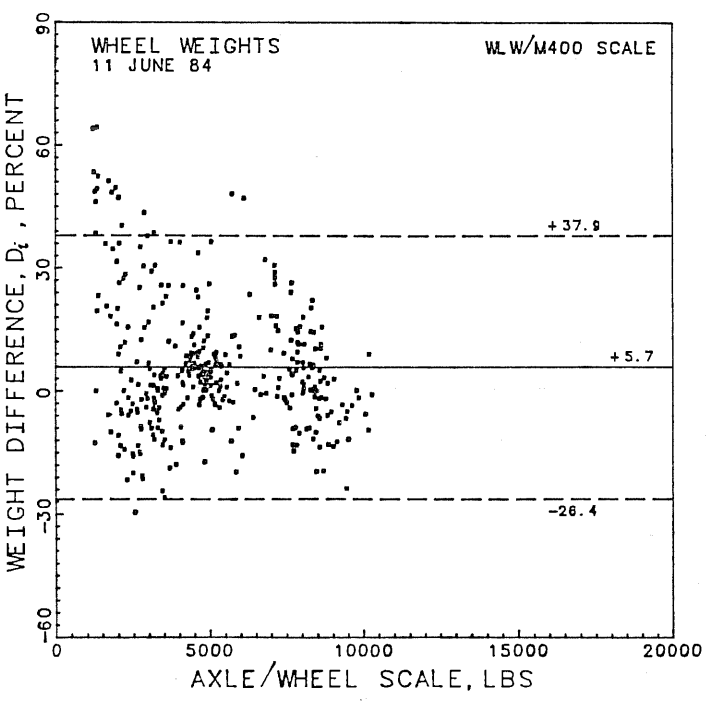


(b)

Figure 3-32. (a) Weights of 175 individual axles determined from the WLW/M400 and AX/WHL scales, (b) percentage difference in weights for the WLW/M400 vs the AX/WHL scale weights.



(a)



(b)

Figure 3-33. (a) Values of 350 wheel weights observed from the WLW/M400 and AX/WHL scales, (b) pecentage difference in weights by the WLW/M400 vs the AX/WHL scale weights.

Results of the statistical analyses of the observed weight data when using the AX/WHL scale as a reference are summarized in Table 3-3. The following summary statements are made regarding the performance of each scale when it was operated under representative field conditions.

(1) For best accuracy, axle-load scales must be installed and maintained in a level, horizontal plane surface that is free of any unevenness. The deflection of the scale load-receiving surface under load must also be very small. Wheel-load weighers and portable axle-load scales should be operated on a relatively-level horizontal surface.

(2) Except for the lighter loads, the AX/GRP scale weights (axle-group and gross-vehicle) were generally higher than those from the AX/WHL reference scale, particularly for trucks with gross-vehicle weights above about 50,000 lbs. Almost all axle-group weights above 15,000 lbs were weighed heavier by the AX/GRP scale than by the AX/WHL scale. At the 95 percent confidence level, the range in the expected accuracy for axle-group weights when the surface around the scales was level (see Fig 3-5) was -3.8 to +6.4 percent (mean +1.3 percent) and for gross-vehicle weights (see Fig 3-6), -1.6 to +4.5 percent (mean = +1.5 percent).

The sample of 101 trucks in this data set included 66 tractor-semitrailer trucks of the 3-S2 type. Separate analysis of the weight differences for these 3-S2 trucks (see Figs 3-7 and 3-8) showed that the tendency for the AX/GRP scale to indicate higher weights than the AX/WHL scale for all truck types was somewhat more pronounced for these heavier 3-S2 trucks than for all truck types when weight differences were expressed as a percent difference with respect to the weight from the reference scale.

(3) The gross-vehicle weights measured by the AX/GRP (RAM) scale differed less than ten percent when compared against those from the AX/WHL scale; however, almost every truck with a gross-vehicle weight above about 30,000 lbs was weighed heavier (see Fig 3-14) by the ramped scale. It can be expected that 95 percent of the gross-vehicle weight differences from these two scales will be within the range from -2.4 to +8.6 percent. Except for several axle-group weights that were under 12,000 lbs, all the other axle groups were weighed heavier on the AX/GRP (RAM) scale and were within the positive ten-percent deviation range (see Fig 3-9). The range of weight difference for axle-groups weighed on this scale compared to the AX/WHL scale is -3.4 to +10.2 percent 95 times out of 100. Most of the front axles on 3-S2 trucks weighed heavier on this scale, probably because the height of the scale caused a transfer of load among the wheels as the front axle was moved up onto the scale for weighing.

(4) On average, the wheel, axle, axle-group, and gross-vehicle weights determined from the WLW/M300 scale varied less than 2.5 percent from the corresponding weights from the AX/WHL reference scale, but the deviations in the weights were extremely large. About 5 percent of the weight measurements using the WLW/M300 would be expected to vary more than $\pm$35 percent (1,850 lbs) for wheels, $\pm$25 percent (2,700 lbs) for axles, $\pm$16 percent (2,300 lbs) for axle groups, and $\pm$10 percent (4,200 lbs) for gross-vehicle weights if past experiences were repeated. Some unknown, but probably relatively small, amount of the variation in weights from the WLW/M300 as compared to the respective weights from the AX/WHL scale can be attributed to the fact that the road surface beyond the level 10 ft long approach aprons to the AX/WHL scale was sloped transversely to the left about 3 percent and the WLW/M300 scales were used on a plane surface which also sloped at approximately the same rate to the left (see Chapter 2). Conceptually, the effect of this adverse cross slope would be most pronounced on wheel weights

TABLE 3-3. SUMMARY OF STATISTICAL INFERENCE VALUES FOR COMPARISON OF VARIOUS SCALES AGAINST THE AX/WHL SCALE AS A REFERENCE

REFERENCE SCALE: AX/WHL						
WEIGHT	STATISTIC	COMPARED SCALE				
		AX/GRP	AX/GRP (RAM)	WLW/M300	WLW/M400	WL/100
Gross Vehicle	Number of Observations	101	131	93	38	94
	Mean Weight (AX/GRP)	41535	46750	50360	46720	38200
	Mean of Differences, %	1.5 (1.6)*	3.1 (3.3)	0.7 (3.7)	4.0 (4.5)	1.4 (2.8)
	+2 Standard Deviations	+4.5	+8.6	+11.2	+11.1	+7.6
	-2 Standard Deviations	-1.6	-2.4	-9.9	-3.2	-4.9
	Mean of Differences, lbs	720	1840	230	1900	610
	+2 Standard Deviations	+2520	+5500	+4480	+5360	+3300
	-2 Standard Deviations	-1080	-1825	-4020	-1555	-2075
Axle Group	Number of Observations	285	355	260	111	278
	Mean Weight (AX/GRP)	14720	17250	18010	15995	12915
	Mean of Differences, %	1.30 (1.9)	3.4 (3.8)	0.3 (5.7)	4.4 (5.2)	1.3 (3.6)
	+2 Standard Deviations	+6.4	+10.2	+16.5	+14.7	+11.1
	-2 Standard Deviations	-3.8	-3.4	-15.9	-5.9	-8.5
	Mean of Differences, lbs	255	680	80	650	205
	+2 Standard Deviations	+1255	+2220	+2370	+2310	+1470
	-2 Standard Deviations	-745	-865	-2210	-1010	-1055
Axle	Number of Observations			398	175	406
	Mean Weight (AX/GRP)			11770	10145	8845
	Mean of Differences, %			1.27 (9.6)	5.6 (10.8)	1.8 (5.2)
	+2 Standard Deviations			+27.0	+34.2	+16.9
	-2 Standard Deviations			-24.5	-23.1	-13.2
	Mean of Differences, lbs			55	410	140
	+2 Standard Deviations			+2725	+2775	+1275
	-2 Standard Deviations			-2615	-1950	-995
Wheel	Number of Observations			796	350	812
	Mean Weight (AX/GRP)			5885	5070	4420
	Mean of Differences, %			2.4 (13.0)	5.7 (11.9)	3.2 (10.8)
	+2 Standard Deviations			+38.5	+37.9	+24.7
	-2 Standard Deviations			-33.8	-26.4	-25.4
	Mean of Differences, lbs			25	205	70
	+2 Standard Deviations			+1890	+15.65	+1165
	-2 Standard Deviations			-1835	-1150	-1025

* values in parentheses are computed without regard to their signs (i.e., these numbers are means of the absolute differences)

and less noticable on axle, axle-group, and gross-vehicle weights since axles and axle groups were always weighed with all wheels in the group passing over the WLW/M300's at the same time.

(5) The WL/100 scale indicated, on average, slightly heavier weights than the AX/WHL reference scale with average differences of +3.2 percent for wheels, +1.8 percent for axles, +1.3 percent for axle groups, and +1.4 percent for gross-vehicle weights (see Table 3-3). Deviations about the mean weight difference at the 95 percent confidence level were ±1,100 lbs for wheels, ±1,100 lbs for axles, ±1,300 lbs for axle groups, and ±2,700 lbs for gross-vehicle weights. These variations were about half those observed for the WLW/M300 but only 300 lbs greater than those observed for axle groups and 900 lbs greater for gross-vehicle weights as indicated by the AX/GRP scale. Part of the tendency for the WL/100 scales to indicate heavier weights than the AX/WHL scale can be attributed conceptually to the fact that the scale is approximately 3/4 inch above the road surface when wheels are weighed. The road surface near the AX/WHL scale was also warped transversely as described above during this day of the 5-day data-taking sessions.

(6) When 38 trucks were weighed on the WLW/M400 scales, all gross-vehicle weights except those for three trucks were heavier than the corresponding weights from the AX/WHL reference scale. On average, gross-vehicle weights were 4 percent or 1,900 lbs heavier, axle groups were 4.4 percent or 650 lbs heavier, axles were 5.6 percent or 410 lbs heavier, and wheels were 5.7 or 205 lbs heavier. Deviations about the mean difference at the 95 percent confidence level for this relatively small sample were quite large: ±32 percent (1,350 lbs) for wheels, ±28 percent (2,400 lbs) for axles, ±10 percent (1,700 lbs) for axle groups, and ±7 percent (3,500 lbs) for gross-vehicle weights. These deviations are quite similar to those for the WLW/M300 and somewhat greater than the deviations from the WL/100. This sample contained 28 trucks (74 percent) of the 3-S2 type. The front axles of these trucks were weighed 6.7 percent heavier on average than the AX/GRP scale readings. Tandem-axle groups, on average, were weighed the same as on the AX/GRP scale, which tended to overweigh heavy axle groups. The surface around the AX/WHL scale was level on the day when these data were taken, but the WLW/M400 scales were used on a 3 percent cross slope to the left.

In addition to the comparisons summarized above, the axle-group and gross-vehicle weights obtained from the AX/GRP (RAM), WLW/M300, WLW/M400, and WL/100 scales were each compared against the corresponding weights from the AX/GRP scale as a reference using the same statistical and graphical techniques as were used for the AX/WHL scale. The summary statistics obtained from these analyses are shown in Table 3-4.

TABLE 3-4. SUMMARY OF STATISTICAL INFERENCE VALUES FOR COMPARISON OF VARIOUS SCALES AGAINST THE AX/GRP SCALE AS A REFERENCE

REFERENCE SCALE: AX/GRP						
WEIGHT	STATISTIC	COMPARED SCALE				
		AX/WHL	AX/GRP (RAM)	WLW/M300	WLW/M400	WL/100
Gross Vehicle	Number of Observations		131	93	38	94
	Mean Weight (AX/GRP)		48115	51775	48335	39080
	Mean of Differences, %		0.7 (1.4)*	-1.6 (4.1)	1.0 (2.2)	-0.5 (2.1)
	+2 Standard Deviations		+4.0	+8.7	+6.9	+5.4
	-2 Standard Deviations		-2.6	-11.9	-4.9	-6.4
	Mean of Differences, lbs		475	-1190	285	-270
	+2 Standard Deviations		+2115	+3360	+2730	+2025
	-2 Standard Deviations		-1165	-5735	-2160	-2570
Axle Group	Number of Observations		355	260	111	278
	Mean Weight (AX/GRP)		17755	18520	16550	13215
	Mean of Differences, %		1.5 (2.3)	-1.5 (5.8)	1.9 (3.8)	-0.3 (3.2)
	+2 Standard Deviations		+8.6	+14.3	+12.3	+9.5
	-2 Standard Deviations		-5.6	-17.2	-8.6	-10.1
	Mean of Differences, lbs		175	-425	100	-90
	+2 Standard Deviations		+1070	+2065	+1575	+1010
	-2 Standard Deviations		-715	-2195	-1380	-1195

* values in parentheses are computed without regard to their signs (i.e., these numbers are means of the absolute differences)

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CHAPTER 4. EVALUATION, CALIBRATION, AND ACCURACY OF THE WIM SYSTEM

INTRODUCTION

The concept of in-motion-weighing is that the weight of a vehicle, a wheel, an axle, or an axle group on the vehicle can be estimated by measuring instantaneously, or during a discrete time period, the vertical component of dynamic force that is applied to the road surface by the wheels of the moving vehicle. This concept of weighing highway vehicles has been recognized for the past three decades and has promoted reserach and development of hardware, software, and application of weigh-in-motion (WIM) systems in the United States and in several other countries around the world.

The initial efforts of Normann and Hopkins with the Bureau of Public Roads (BPR), now the Federal Highway Administration (FHWA) circa 1950, utilized a large concrete slab and the strain-gage instrumentation technology of the time [Ref 15]. In the 1950's Michigan, Iowa, Ohio, Minnesota, Oregon, Indiana, Illinois, and perhaps other states experimented with the BPR design with similar disappointments due mostly to natural oscillations of the massive slab [Ref 16]. A hydraulic-capsule transducer was tried in W. Germany, and a 2-load-cell, broken-bridge design was used in W. Germany and Denmark without satisfactory results. In the late 1950's, the University of Kentucky experimented with the BPR and broken-bridge designs and experienced similar mass-oscillation problems.

During the 1960's, the Road Research Laboratory (RRL) in England, the Bundesanstalt fur Strassenwesen in W. Germany, General Motors (GM), Philco-Ford, the Michigan and Illinois highway departments, and a number of other agencies experimented with WIM systems. In 1963 work began in Texas on the development of a WIM system for collecting statistical data, and by 1968 a low-mass strain gage wheel force transducer with a solid-state electronics system had been developed and field tested [Ref 1]. Other research on in-motion weighing was conducted in New York, Pennsylvania, California, Mexico, and Canada using the Texas WIM system in the late 1960's.

In the 1970's several states including Texas, Florida, New Mexico, Nevada and others began using the Texas WIM system for collecting statistical truck weight data, and the FHWA accepted the technique in lieu of static weighing. In about 1974, following the imposition of the 55 mph speed limit and an accompanying increase in truck weight limits, the FHWA cited several states for marginal or inadequate truck weight enforcement programs. This inspired several states for the first time to consider in-motion vehicle weighing as an aid to enforcement even though the idea had been proposed two decades earlier.

The Federal Highway Administration (FHWA) has encouraged and supported the development and application of WIM systems for many years. They have funded, among other WIM programs, this technology implementation and research project. Texas was selected by the FHWA as one of the states to paticipate in the first phase of a nationwide WIM demonstration program under the Rural Technical Assistance Program (RTAP). Perhaps the most significant advancement in WIM technology under the Texas RTAP project was the development of a 4-lane transportable WIM instrument system by the Radian Corporation. This unique system made it possible to study speed effects on WIM accuracy and to collect much-needed statistical data concerning truck traffic at multiple locations in Texas.

Although WIM systems have been operational for two decades, the accuracy with which static vehicle loads can be estimated at high, intermediate, and slow traffic speeds when compared with static scale measurements, has not been systematically investigated or documented for mixed traffic. Previous studies [Refs 2, 3, and 17] addressed the accuracy of the Texas WIM system by analyzing data sets from test trucks. As with the static weighing technique discussed in Chapter 3, the overall accuracy of a WIM system is determined not only by the accuracy with which force measurements can be made by the system, but also by the signal processing technique and by how the system is used.

It is well known that road surface roughness in the vicinity of WIM scales has a pronounced effect on the dynamic tire forces that result from the vehicle/road interaction. Every vehicle will interact differently, and vehicle speed will affect the dynamic forces to different degrees. Therefore, even though a particular type of WIM system can meet given tolerances at one particular site, this does not necessarily mean that it will perform within the same tolerances at another location. The variability and systematic bias in weight estimates made by a WIM system can be significantly reduced if the system is properly calibrated at each site where it is used.

In this chapter the results of analyses of in-motion-weighing data that were obtained from a series of field experiments are presented. The experiments were conducted to evaluate and demonstrate the feasibility of using WIM systems for statistical weight-data acquisition and for enforcement purposes. Estimates of wheel, axle, axle-group, and gross-vehicle weights for various types of trucks crossing the WIM system scales at slow, intermediate, and high speeds are compared with corresponding static weights from the reference AX/WHL scale described in Chapter 2. The importance of on-site calibration of the WIM system is illustrated also.

ON-SITE CALIBRATION

General Concepts

The load cells which are used as WIM wheel-force transducers can be calibrated individually in the factory under static load, but the response of the transducer/roadway/tire-loading system under dynamic loads cannot be easily evaluated in the laboratory. There is a complex interaction among the various components of this physical system that is unique for every location and vehicle load that is applied to the transducer.

A properly-damped wheel-force transducer and a supporting instrument system that is capable of measuring accurately the vertical component of dynamic tire loads in the actual roadway environment is the essential hardware element of a weigh-in-motion system. A software system which converts these dynamic force measurements into an estimate of the proportion of the gross-vehicle weight that the wheel would carry if weighed statically must complement the hardware element for an overall WIM system to function.

A number of site-specific conditions such as road-surface roughness, grade, cross-slope near the WIM transducers, behavior of the transducer/roadway combination under dynamic laod, and the speed and composition of traffic at the site affect rather significantly the overall accuracy with which a system can estimate static wheel loads. Every vehicle will interact differently; therfore, an on-site WIM system calibration procedure is necessary.

The objective of calibration is to make the weights estimated by the WIM system agree as closely as possible with the corresponding weights that would be measured by static scales. It is important to recognize that the porportion of the gross-vehicle weight carried by each wheel of a vehicle changes as the vehicle moves over the road surface; thus the wheel force applied to a static scale can vary according to the relative position of the interconnected vehicle components at the time of weighing. Perfect agreement between WIM weight estimates and static weight measurements is not expected since the quantity that is being estimated can vary with respect to time and position of the vehicle when it is measured on static scales. By calibration, the mean value of WIM weight estimates should be made to agree as closely as possible with the best estimate of static weight that can be obtained feasibly in practice.

Techniques

Two basic calibration techniques can be used for on-site calibration of WIM systems: static-weight loading, or moving-vehicle loading. In the first method, a known weight is applied to the WIM transducer in a highway lane either by standard test blocks or by the wheels of a standing test vehicle. Standard test blocks give a more accurate reference weight than the standing test vehicle as the proportion of the gross-vehicle weight carried by any given wheel of the test vehicle changes as it moves onto the transducers and stops (see Chapter 3). The static-weight technique is perhaps appropriate for low-speed weigh-in-motion (LSWIM) systems as the dynamic effects of the slow-moving vehicle are relatively small. This will be discussed later.

The moving-vehicle calibration technique is applicable for intermediate and high-speed in-motion weighing (ISWIM and HSWIM) when the dynamic interaction of the vehicle with the WIM system is much more pronounced. In this method, a single test vehicle with known static wheel weights can make multiple runs over the WIM system transducers at a representative speed of traffic to be weighed; then the system can be adjusted to make the mean value of the estimated wheel weights from these runs equal the mean value of the known static wheel weights. More than one type of test vehicle, each making multiple runs, can also be used to obtain a better representation of the various patterns of vehicle/roadway/WIM-system interaction. Or, different trucks, each with known wheel weights, can each make a single run over the WIM system to provide a basis for on-site calibration settings on the WIM instrument system.

The importance of on-site calibration and the relative effectiveness of various loading techniques are illustrated by the data shown in Tables 4-1 through 4-3. In these tables, the mean values of a large number of weight measurements made by the WIM system after calibration by three different loading techniques are compared with the respective weight values determined by weighing each wheel of the same vehicles statically on the AX/WHL reference scale. Differences in the individual weight values were computed and expressed as a percentage of the reference scale weights. The mean of these percent differences is given along with statistical inference values which define the 95 percent confidence intervals into which an individual weight difference would probably fall if it were determined in the same way and under the same conditions that the sampled weight differences were measured.

Calibration of the WIM system for this comparative study involved the calculation and application of a single factor (discussed in the following section) that could be applied to the force signals from each WIM system wheel-load transducer to make the mean of the weight differences for all wheels weighed on each transducer equal zero with respect to the reference-scale weight means. This mathematical adjustment would be exactly equivalent to setting the calibration adjustment on the WIM instruments to a particular value in the field.

The information in Table 4-1 pertains to weight measurements on 86 trucks that were weighed on the low-speed weigh-in-motion (LSWIM) scales on July 6, 1984. On this day, the adverse cross-slope in the pavement surfaces beyond the level approach aprons to the AX/WHL reference scale, as described in Chapter 2, had been removed and the LSWIM scales had been reinstalled in the leveled surface. Thus, no effect on weighing performance of either scale can be attributed directly to an uneven surface. It can be seen from the tabulated values that the mean difference in weights from the LSWIM system was 1.0 percent or less for all calibration techniques including dead-weight test blocks. Variability in the percentagewise differences, as indicated by the 95 percent confidence range, systematically increased from about ±6 percent for gross-vehicle weights to about ±16 percent for wheel weights. The performance of the LSWIM scale was about the same as the AX/GRP (RAM) scale with respect to variability and better on average; it was better than all the wheel-load weighers that were evaluated. It weighed more consistently throughout the range of loads but exhibited somewhat more variability than the flush-mounted AX/GRP scale (see Chapter 3) when compared against the AX/WHL scale as a reference.

Table 4-2 presents information concerning the performance of the HSWIM system after calibration by three different moving-vehicle techniques involving 60 trucks. On June 6, 1984, the pavement surfaces surrounding the AX/WHL reference scale were slightly warped transversely beyond the 10-ft-long approach aprons as described in Chapter 2. Calibration of the HSWIM scales attempted to make the estimated weight values agree with the static weights determined on the AX/WHL scale under these conditions. A pronounced improvement in the agreement of the mean weights was made when seven loaded 3-S2 trucks were used as the basis for calibration as compared to five runs of a loaded 2-axle test truck. The means were virtually the same as those obtained from using the seven 3-S2 trucks when all 60 trucks in the data set were taken as the basis for calibration. The variability in weight differences about the means, as indicated by the 95 percent confidence range, was not affected significantly by the calibration technique.

Table 4-3 shows information about HSWIM weights for 61 trucks on June 11, 1984. The road surface surrounding the AX/WHL referee scale had been leveled with premixed asphalt paving material on this day. Again, a

TABLE 4-1. SUMMARY STATISTICS OF WHEEL, AXLE, AXLE-GROUP, AND GROSS-VEHICLE WEIGHTS AS COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 86 TRUCKS CROSSING THE LSWIM SCALES AFTER CALIBRATION, JULY 6, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		STANDARD 1000 LB TEST WEIGHTS	7 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	86 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 5180	5190	5200	5140
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+1.0 (6.5)	+1.0 (6.0)	0.0 (6.0)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-16.4 to +18.4	-15.2 to +17.2	-16.0 to +16.0
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 10350	10,390	10350	10290
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.9 (4.7)	+0.9 (4.7)	-0.1 to (4.7)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-12.3 to +14.1	-12.2 to +14.1	-13.1 to 13.0
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 15700	15750	15760	15600
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.2 (3.9)	0.2 (3.8)	-0.8 (3.9)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-10.6 to +10.9	-10.5 to +10.9	-11.4 to +9.8
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 44180	44320	44340	43900
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.4 (2.6)	0.4 (2.6)	-0.6 (2.6)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-6.0 to +6.7	-5.9 to +6.8	-6.8 to +5.7

TABLE 4-2. SUMMARY STATISTICS OF WHEEL, AXLE, ALXE-GROUP, AND GROSS-VEHICLE WEIGHTS AS COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 60 TRUCKS CROSSING THE HSWIM SCALES AFTER CALIBRATION, JUNE 6, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		5 RUNS OF A LOADED 2-AXLE TEST TRUCK	7 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	60 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 4650	4950	4590	4580
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+9.3 (15.0)	+0.8 (11.2)	0.0 (10.5)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-27.7 to +46.3	-29.0 to +30.6	-27.2 to +27.2
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 9300	9910	9180	9170
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.5 (9.5)	-0.3 (7.4)	-0.5 (7.4)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-13.3 to +28.3	-19.6 to +18.9	-19.8 to +18.8
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 13750	14660	13590	13560
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+6.4 (8.2)	-1.4 (6.1)	-1.6 (6.1)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-10.9 to +23.6	-17.5 to +14.7	-17.7 to +14.6
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 39200	41780	38720	38640
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+5.9 (6.6)	-1.8 (3.8)	-2.0 (3.8)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-3.8 to +15.6	-10.8 to +7.2	-10.9 to +7.0

TABLE 4-3. SUMMARY STATISTICS OF WHEEL, AXLE, AXLE-GROUP, AND GROSS-VEHICLE WEIGHTS AS COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 61 TRUCKS CROSSING THE HSWIM SCALES AFTER CALIBRATION, JUNE 11, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		5 RUNS OF A LOADED 2-AXLE TRUCK (2D)	6 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	61 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 5400	5740	5510	5350
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.2 (10.9)	+3.0 (9.0)	0.0 (8.4)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-17.5 to +31.9	-20.3 to +26.3	-22.3 to 22.3
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 10800	11470	11010	10690
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.2 (9.2)	+2.9 (7.1)	-0.1 (6.6)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-11.8 to +26.2	-15.4 to +21.2	-17.8 to +17.7
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 17000	18040	17320	16820
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+6.1 (7.8)	+1.8 (5.7)	-1.1 (5.6)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-9.5 to 21.7	-13.1 to +16.8	-15.7 to +13.4
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 49600	52650	50540	49080
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+5.8 (6.4)	+1.6 (4.0)	-1.3 (3.8)
	95% CONFIDENCE RANGE $\mu \pm 2\sigma$	-3.8 to +15.4	-7.6 to +10.8	-10.6 to +7.6

noticable improvement in the agreement between mean weight values occurred when 3-S2 type trucks were used for calibration rather than five runs of a loaded-2-axle test truck. Slight improvement over the 3-S2 trucks resulted from taking all 61 trucks in the data set as the basis for calibration. The range in variability of the weights was slightly less on this day than it was on June 6, 1984.

This experience indicates that a much better HSWIM system calibration was achieved with loaded tractor-trailer, 3-S2, trucks than with multiple runs of a loaded 2-axle, 2D, test truck. These data sets contained approximately 60 percent 3-S2 type trucks, which was representative of the truck mix in the traffic stream at this location.

Computation of Calibration Factors

In this section, a procedure for deriving calibration factors is developed. This procedure utilizes left and right-side wheel weight data from an adequate sample of trucks weighed by the WIM (to be calibrated) and reference scales. The procedure uses the relative difference in the wheel weight data for each truck. This relative difference is computed and expressed as a fraction of the weight measured by the reference scale. The differences are determined separately for the right and left wheel weights from the following equation:

$$D_i = (W_i - W_{o,i})/W_{o,i} \tag{4-1}$$

where D_i = difference in the wheel weight determined by the WIM scale expressed as a fraction of the wheel weight determined by the static scale,

W_i = wheel weight measured by the WIM scale for observation i, and

$W_{o,i}$ = wheel weight measured by the reference scale for observation i.

And the average relative difference is:

$$\overline{D} = \frac{1}{n} \sum_{i=1}^{n} [(W_i - W_{o,i}) / W_{o,i}] = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{W_i}{W_{o,i}} \right] - 1 \tag{4-2}$$

where n = number of observations

For a given sample of wheel weight data, the value of this average relative difference, for left and/or right wheels, will fall into the following two categories:

(1) $\overline{D} = 0$; meaning that it is not necessary to perform an on-site calibration for that transducer.

(2) $\overline{D} \neq 0$; in this case the system needs to be calibrated on the site. Thus, the calibration factors are computed from the experimental wheel data, again separately for left and right wheels, and then applied to the WIM system. Notice that calibration factors may be different for each transducer.

For the second category, the calibration factors are derived, using a set of wheel weight data, as follows. The value of $\overline{D}$ from the left wheel weights equals the required adjustment, a; that is

$$\overline{D} = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{W_i}{W_{o,i}} \right] - 1 = a \qquad (4\text{-}3)$$

This expression (4-3) can also be stated as:

$$\frac{1}{n} \sum_{i=1}^{n} \left[\frac{W_i}{W_{o,i}} \right] = 1 + a \qquad (4\text{-}4)$$

In order for $\overline{D}$ to fall into the first category mentioned above (i.e., $\overline{D} = 0$ so that estimated weights from the WIM system will be correct, on the average), the right-hand side of expression (4-4) must equal 1.0. Both sides of the expression can be divided by (1 + a). This puts the expression for $\overline{D}$ in the form:

$$\overline{D'} = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{W_i / (1 + a)}{W_{o,i}} \right] - 1 = 0 \qquad (4\text{-}5)$$

The required calibration factor,CF, is computed by increasing the value of $\overline{D}$ (as derived from the data set for each wheel-force transducer, separately) by one. This calibration factor can then be applied appropriately to magnify (if CF < 1) or reduce (if CF > 1) the magnitude of the force measurements produced by the WIM system after passage of a wheel over a transducer.

DISTRIBUTION OF AXLE WEIGHTS ON LEFT AND RIGHT-SIDE WHEELS

The weight on an axle is usually assumed to be equally distributed on the right and left wheels of the axle. This is equivalent to assuming that the weight of a truck is equally shared by all wheels on the right and on the left sides of the truck. This assumption is frequently made in analyzing truck weight data for pavement design and other purposes and is sometimes used for estimating axle loads after the wheels on only one side of a truck have been weighed either statically or dynamically. For example, in Texas, over many years the practice of collecting statistical truck weight data was to weigh only the right wheels of selected vehicles on a wheel-load weigher and assume that axle weight were twice these wheel weights.

Since the design of pavement and bridge structures is based to a significant extent on the analysis of stress in the structures caused by loads applied to the road surface by the individual wheels of a moving vehicle, wheel weight data are fundamental. In some procedures, however, simplifying assumptions which account only for axle loads are made. In order to satisfy the design information needs of all users, a code-specified WIM system should indicate both

wheel weights and axle weights for each vehicle. In addition, since the most significant uncontrollable vehicle factor affecting in-motion weighing is tire condition, and since all axle loads are not equally distributed between the wheels of an axle, there is a need for weighing all individual wheels on both sides of a vehicle. Furthermore, weighing on both sides reduces the chance of losing weight data on a truck completely when one of the two WIM system transducers malfunctions or breaks down. One operable transducer can provide wheel-weight data and serve as a basis for estimating axle loads with some degree of reduced reliability.

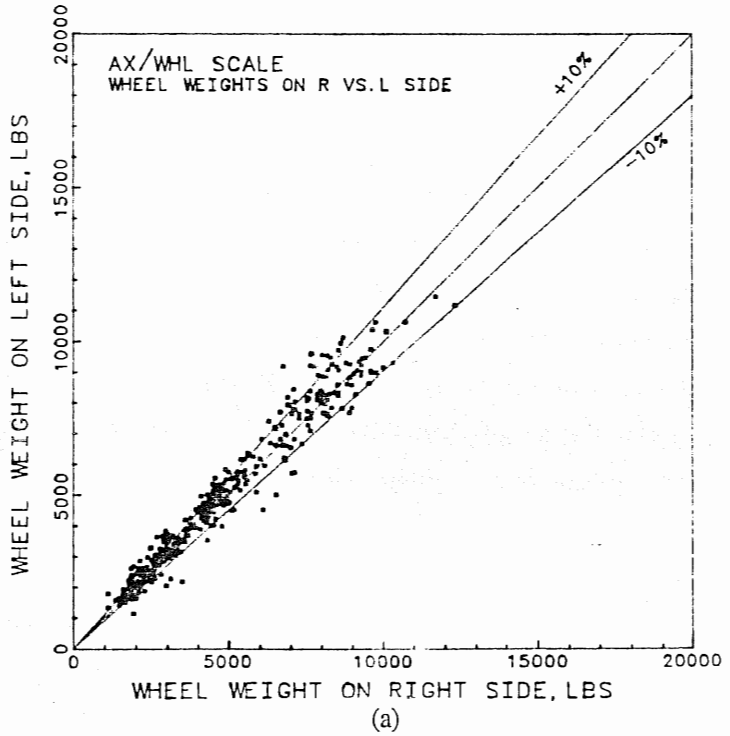
An analysis of the wheel-weight data set which was obtained on 6 July 1984 from the static AX/WHL scale indicated that the total weight carried on a tandem axle-group (on trucks of the 3-S2 type) was not equally distributed among all four wheels in the group. Furthermore, the analysis indicated that differences between individual wheel weights and the mean wheel weight of all wheels in the trailer-tandem axle sets were larger than those of wheels in the drive-tandem axle groups. By examining this same set of wheel-weight data, a comparison was made of the wheel weights on the left and right sides of 100 trucks weighed statically on the AX/WHL scale. Results of this comparison can be presented in a graphical representation of the data along with summary statistics.

As shown in Fig 4-1(a), individual wheel weights are represented by plotting the left wheel weights against those on the right side of the same axle. This graph clearly indicates that the assumption of equal wheel weights on an axle is not valid, as most of the plotted points do not lie exactly on the 45-degree sloping line of equality. Another form of graphical representation of the data, as shown in Fig 4-1(b), indicates the relative difference in the left-wheel weight as a percentage of the right-wheel weight. The right wheel was selected arbitrarily as the reference wheel. It may be noted from Fig 4-1(b) that on average, the left-side wheels on these trucks were 3.7 percent heavier than the right-side wheels and that the percent difference in the left-side wheel weight as compared to the respective right-side wheel weight on the same axle ranged from 42 percent less to 60 percent more. The results of the Shapiro-Wilk W test indicated that these percentage differences are normally distributed; therefore, statistically-based inferences can be drawn concerning the probability of wheel weight differences exceeding certain magnitudes due to chance alone. The statistical interpretation of the information shown in Fig 4-1(b) indicates that with 95 percent probability the relative difference in the left-side and right-side wheel weights on an axle will be within the -18.1 and +25.4 percent levels for this population of trucks.

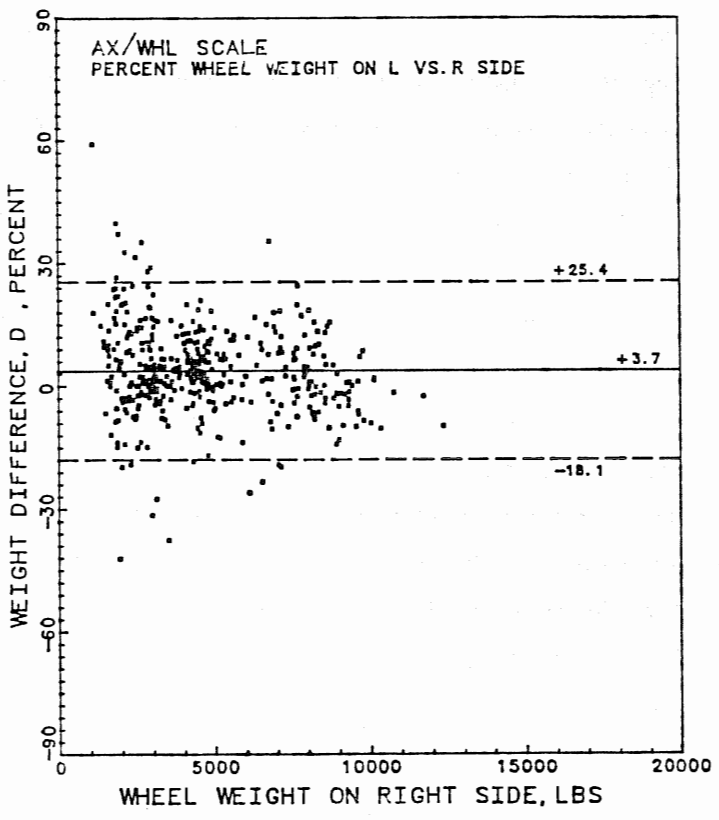
In addition, one can test the null hypothesis that the average of the absolute difference in the left and right wheel weights $\mu_{\bar{D}}$ is equal to zero against the alternative that the average is different from zero (usually stated "H_0: $\mu_{\bar{D}} = 0$ versus H_1: $\mu_{\bar{D}} \neq 0$"). In the analysis, the sample mean difference $\bar{D}$ is assumed to be normally and independently distributed about $\mu_{\bar{D}}$ with standard error, $\sigma_{\bar{D}} = \sigma_D/\sqrt{n}$ where σ_D is the standard deviation of the population of differences. An estimate $s_{\bar{D}} = s_D/\sqrt{n}$ of σ_D, is based on (n-1) degrees of freedom (d.f.), where n is the number of pairs (i.e., axles). Hence, the quality

$$t = (\bar{D} - \mu_{\bar{D}})/s_{\bar{D}}$$

which follows the student's t-distribution may be used to test the null hypothesis that $m_{\bar{D}} = 0$. For this data set since n is large the normal distribution is used instead, and the value of z is:



(a)



(b)

Figure 4-1. (a) Comparison of the weight of the wheels on the same axle weighed simultaneously on the AX/WHL scale, (b) percent difference in left-side wheels with reference the right-side wheels.

$$z = (\bar{D} - \mu_{\bar{D}})/s_{\bar{D}} = 121.4/(483.0\ 431\ ) = 5.22$$

A z-table shows that the 5 percent level of significance in a two-tailed test is 1.96. The calculated value of 5.22 lies far beyond even the 0.1 percent level (table value = 3.29). Hence, the test provides no evidence to accept the null hypothesis, and the statement can be made that the mean value of left-side wheel weights are different from the mean value of right-side wheel weights. Similar statistical tests were performed to determine whether or not there was a statistically significant difference in the average side-to-side loading of axle groups in the proportion of the gross-vehicle weight carried on the wheels on each side of the trucks. Results of this analysis are summarized in Table 4-4. The tests indicated that there was a significant difference in the average side-to-side loading of trucks when considering individual axles, axle-groups, or gross-vehicle weight.

ANALYSIS OF WIM DATA

The sum of the vertical forces exerted on a perfectly smooth and level road surface by the perfectly round and dynamically-balanced, rolling wheels of a vehicle (i.e., an ideal vehicle) at a constant speed in a vaccum is exactly equal to the gross weight of the vehicle. In reality, these ideal conditions do not exist. But if the deviations from the ideal are small, static weight estimates of acceptable precision and accuracy for certain purposes can be obtained from samples of dynamic wheel force. The field data collected in the experimental program as detailed in Chapter 2 are representative of actual truck traffic conditions under normal road and environmental conditions. The data sets are analyzed to determine mainly the accuracy with which static wheel, axle, axle-groups, and gross-vehicle weights can be estimated from dynamic wheel forces measured with a properly-calibrated WIM system at three different speeds. The same graphical and statistical methods used in the previous chapter as well as regression techniques are utilized here for the comparison and correlation analysis of the data sets. Static weights that are used as a basis for comparison were obtained from the AX/WHL scale as explained in Chapter 2. To assess the effect of speed on the WIM system estimates of the static weight, Analysis of Variance (ANOVA) results and Equivalent Single Axle Loads (ESAL's) calculated from both the AX/WHL and WIM scale weights are used. Three different data sets, two taken on 6 and 11 June 1984 over all three WIM scales and a third set taken on 6 July 1984 only over the LSWIM scale, are analyzed and presented in the following order.

First, gross-vehicle weights determined from the LSWIM, ISWIM, and HSWIM scales are compared and regressed against the respective weights from the AX/WHL scale. Second, axle-group weights from the same scales and for the same trucks are analyzed. These procedures are then followed for axle weights and finally for the wheel weights measured directly from the WIM and AX/WHL scales. Axle weight and axle-group weight has been taken as the sum of all wheel weights for the particular axle or axle group under consideration, and gross-vehicle weight has been computed as the sum of all axle and axle-group weights on a truck or truck-trailer combination.

Results of the weight comparison are presented and analyzed, as explained in the following sections using two different techniques.

TABLE 4-4. SUMMARY STATISTICS FOR LEFT AND RIGHT WHEEL WEIGHTS FROM AX/WHL SCALE

STATISTIC	WHEEL WEIGHT	AXLE GROUP WEIGHT	GROSS VEHICLE WEIGHT
Average Right, Lbs	4719	7213	20340
Average Left, Lbs	4841	7398	20863
Mean Difference, Lbs	121.4	185.6	523.4
Standard Deviation of Differences	483.1	642.3	1328.2
Size of Sample	431	282	100
Z-Value	5.22*	4.82*	3.94*
+ Mean Relative Error, %	+3.67	+3.41	+2.73
+ Absolute Mean Relative Error	8.40	6.72	5.37
+ Standard Deviation for Relative Error	10.88	7.97	6.23

* Significant at 95% Confidence Level
+ Weights on the Left With Reference to Right-Side Weights

Graphical Representation

In the graphical approach, the weight data from the static weighings is plotted on the horizontal axis, labeled AXLE/WHEEL SCALE, and the corresponding weight for each vehicle as estimated by the WIM system at each speed is plotted along the vertical axis, labeled WIM SCALE, in each figure. Bounds of +10 percent and -10 percent difference in the WIM-estimated weight and that obtained from the static AX/WHL scale are shown as divergent sloping lines in each figure. Dot-dash lines on these figures indicate the legal weight limits. In another graphical approach the relative difference in the WIM-estimated weight, which is calculated and expressed as a percentage of the weight measured by the reference scale, is plotted against that of the corresponding reference weight. For details of this procedure see Chapter 3.

Statistical Procedures

Statistical tests of normality (discussed in Chapter 3) indicated that the frequency of relative differences in WIM-estimated weights are normally distributed; therefore; by applying the properties of a normal frequency distribution, certain inferences are drawn from analysis of the data sets. The sampled data are considered to be representative samples drawn from a large parent population.

For further analysis of the data, in order to examine the relationship between the WIM estimates of the static weights and the respective weights from the AX/WHL scale numerically, a linear regression analysis was used. For each data set, the regression was performed on the WIM-estimated weights against the corresponding observed weights from the static scale. Although, the obvious purpose of this analysis is to determine the accuracy and precision, on the average, associated or attainable with WIM systems for predicting the "true" weights from samples of dynamic wheel forces, the equations are derived by using weights measured from the AX/WHL (referee) scale to predict weights from the WIM scales. This is necessary since in a normal regression equation $y = b_0 + b_1x$, the predictor or independent variable x is assumed to be virtually error free whereas the response or dependent variable y is not. Thus, weight determined from the referee scale is taken as the predictor variable x in developing the needed regression equation. The fitted straight line, in essence, provides a "calibration curve" for the WIM scales, related to the static weight data from the referee scale. The problem of estimating true weight from a WIM system measurement of dynamic force is called in statistics the inverse regression problem and is fully documented in Refs 18, 19, and 20. So, the equation, for a given y, namely y_0, may be inverted, or solved for the inverse estimate of x, defined by solving $y_0 = b_0 + b_1x_0$ for x_0, namely

$$x_0 = (y_0 - b_0)/b_1$$

so that a weight from the WIM scales can be used to estimate the weight that would result from weighing on the referee scale.

Results of the regression analysis are tabulated for axle-group and gross-vehicle weights in later sections of this chapter. These regression equations are developed for each WIM scale - LSWIM, ISWIM, and HSWIM - used in the experiment. For cases in which it is known or in which it has been found empirically that the standard deviation

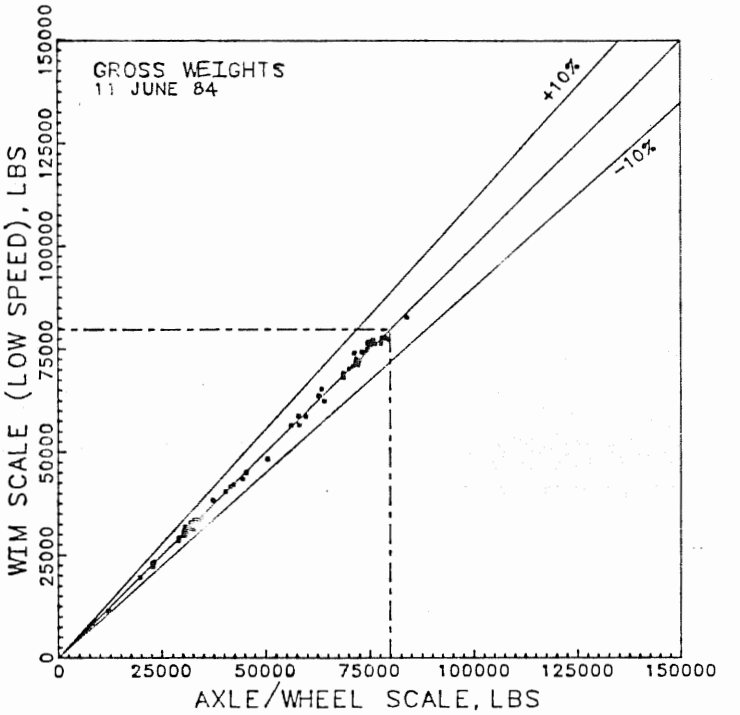
of the untransformed response y, s_y say, is a function of the mean value, $\mu = E[y]$, a natural-log transformation of the data is utilized in the analysis. The coefficient of variation (c.v.) which is a measure of the precision with which true weight can be estimated by the equation is computed for each equation. As explained above, the coefficients are computed on the basis of the referee scale weight being the predictor variable; therefore, small inaccuracies can result from applying the coefficients to the inverted equations. These inaccuracies, however, cannot possibly be large because of the relatively small scatter in the untransformed or transformed weight information. The coefficients of variation can be treated as standard deviations of the relative difference in weights. That is, true weights estimated by the regression equations from weight measurements by the WIM scales will yield estimates within [$\pm 2 *$ coefficient of variation] of the actual weight values, approximately 95 percent of the time (i.e., within the 95 percent confidence limits). The regression coefficient or the slope of the line, on the other hand, is the measure of correlation or agreement between the WIM estimates of the static weights and the corresponding measurements from the AX/WHL scale. A slope of 1.0 and a coefficient of variation equal to zero percent would result if perfect agreement existed between the two sets of weight readings.

Gross-Vehicle Weights

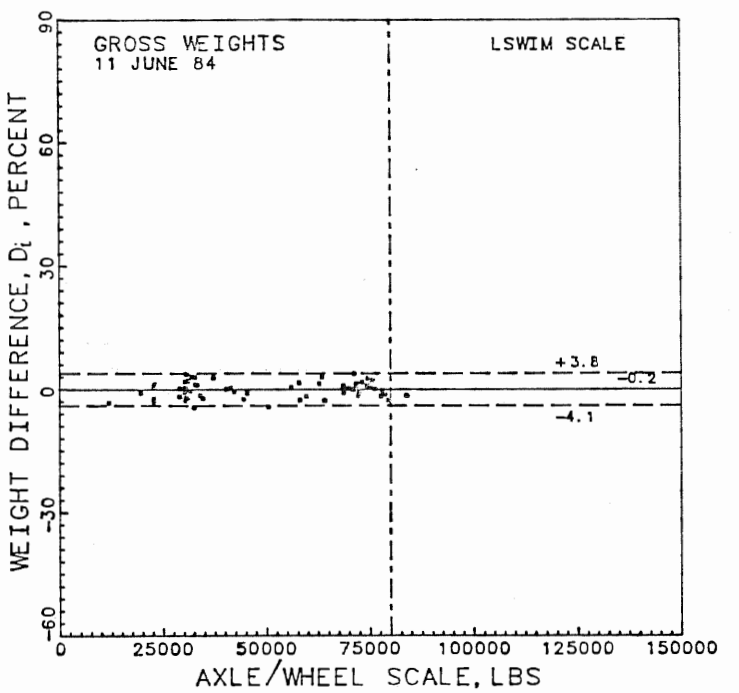
Figures 4-2, 4-3, and 4-4 illustrate the variability that was observed in gross-vehicle weight estimates for 61 trucks when each truck was weighed at three different speeds (low $\leq$ 10 mph, intermediate = approximately 30 mph, and high = approximately 50 mph) on 11 June 1984 by three properly-calibrated WIM scales. Each graph illustrates the relationship between the WIM system weight estimates and the corresponding weights from the AX/WHL reference scale. The static gross-vehicle weight that was used for reference was taken as the sum of the weights of all axles on the vehicle after each axle was weighed in sequence on the static AX/WHL scale as described previously in Chapter 2. Careful examination of each of the plots was made to check for abnormalities in weight data and a few extreme outlying points were removed with discretion from the data sets.

As shown in these figures, if there were perfect agreement between the two weights, all the plotted points would lie exactly on the 45-degree line of equality. The pattern of data points shown in these three figures indicates that there was a small, but consistent, increase in the range of gross-vehicle weight difference as the speed of the vehicles being weighed by the WIM system increased. For all three scales, the data points are clustered rather evenly with small scatter about the 45 degree line of perfect agreement. The gross-vehicle weights from the HSWIM scales are, on the average, 1.3 percent lower than the respective static weights. Several light trucks produced large percentagewise negative weight differences; these had a rather large influence on this mean value. Although the dynamic effects of vehicle/road/WIM-system interaction on these gross-vehicle weights tend to be greater at higher speeds, virtually all the WIM-estimates of gross-vehicle weights at high speed differed less than ten percent from the observed static gross-vehicle weights (see Fig 4-4).

Results of the regression analysis along with the statistical inferences drawn from the sample distribution of the relative difference in gross-vehicle weights, are summarized in Table 4-5. A linear regression equation (with zero intercept) was developed for each of the three WIM scales used in the experiment. The regression coefficient (i.e.,

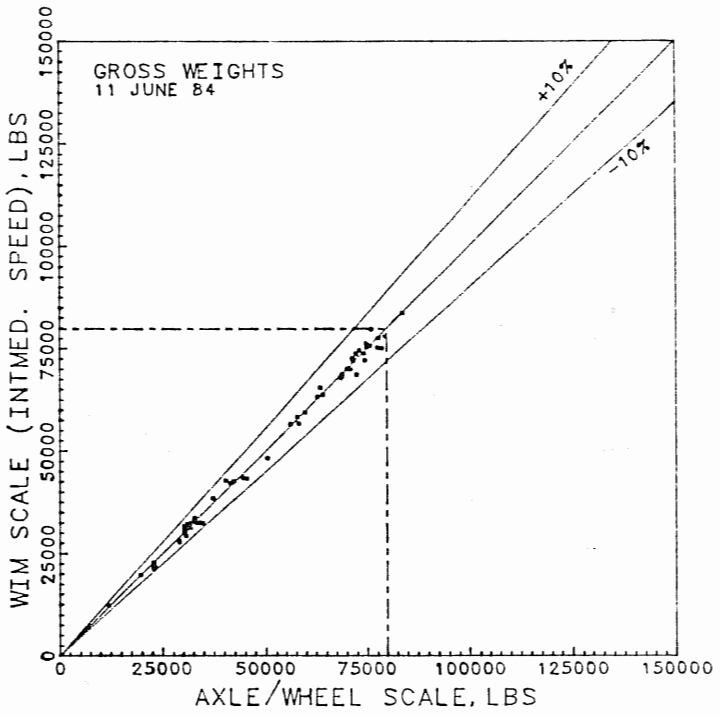


(a)



(b)

Figure 4-2. (a) Gross-vehicle weights for 61 trucks crossing the LSWIM scale at less than 10 mph vs weights summed from the AX/WHL scale, (b) percent difference in gross-vehicle weights from the LSWIM scale with reference to the static weights.



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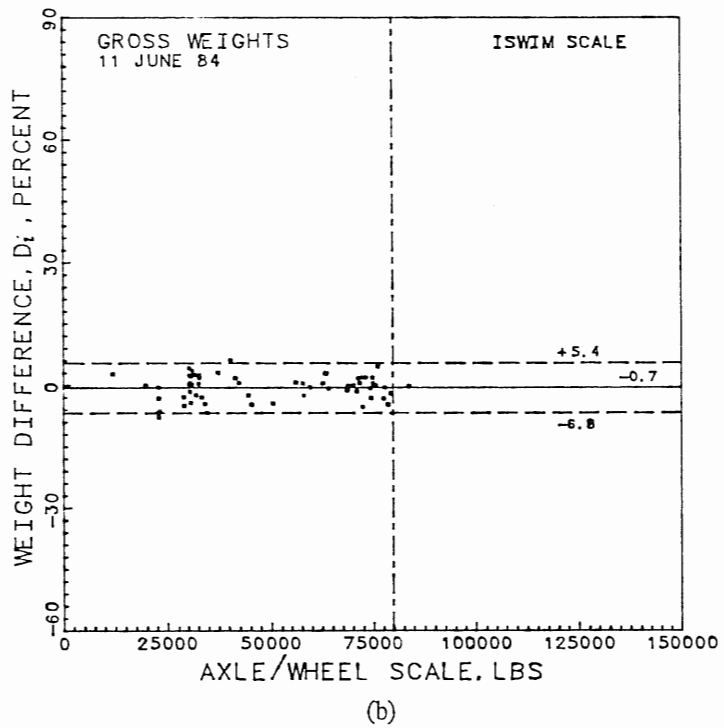

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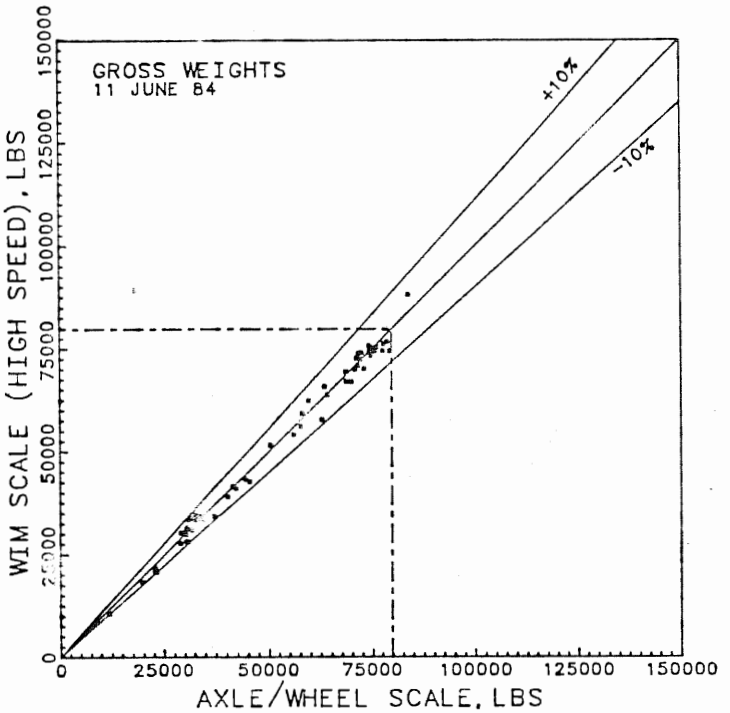
Figure 4-3. (a) Gross-vehicle weights for 61 trucks crossing the ISWIM scales at about 30 mph vs weights summed from the AX/WHL scale, (b) percent difference in gross-vehicle weights from the ISWIM scale with reference to the static weights.



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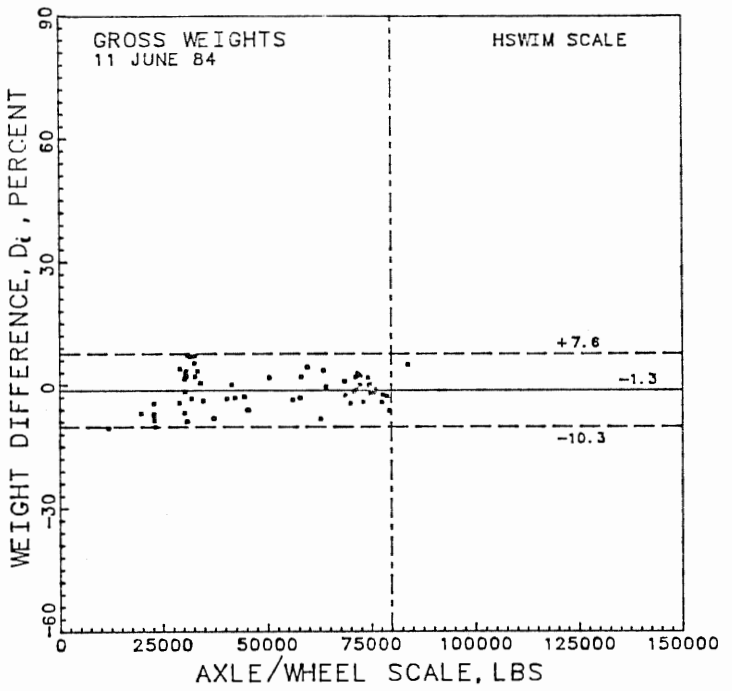


(b)

Figure 4-4. (a) Gross-vehicle weights for 61 trucks crossing the HSWIM scales at about 55 mph vs weights summed from the AX/WHL scale, (b) percent difference in gross-vehicle weights from the HSWIM scale with reference to the static weights.

TABLE 4-5. SUMMARY STATISTICS OF WIM GROSS-VEHICLE WEIGHTS AS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

DATE	SPEED AT WIM SCALES	STATISTIC				
		MEAN WEIGHT, LBS	MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), %	95% CONFIDENCE RANGE, $\mu \pm 2\sigma$, %	REGRESSION ANALYSIS	
					SLOPE	C.V.*
June 11, 1984 n = 61	LSWIM (10 mph)	49570 (49600)+	-0.2 (1.6)	-4.1 to +3.8	1.00003	2.0
	ISWIM (30 mph)	49310	-0.7 (2.4)	-6.8 to +5.4	0.99494	2.8
	HSWIM (55 mph)	49080	-1.3 (3.8)	-10.3 to +7.6	0.99054	3.8
June 6, 1984 n = 60	LSWIM (10 mph)	38870 (39200)+	-1.3 (2.8)	-7.8 to +5.2	0.99344	2.6
	ISWIM (30 mph)	39000	-0.8 (2.8)	-7.7 to +6.1	0.99729	3.2
	HSWIM (55 mph)	38640	-2.0 (3.8)	-10.9 to +7.0	0.98803	4.0
July 6, 1984 n = 86	LSWIM (10 mph)	43900 (44180)+	-0.6 (2.6)	-6.8 to +5.7	0.99174	2.8

* Coefficient of Variation, %
+ Reference Scale Mean Weight

slope of the line) and coefficient of variation are also presented in this table. The slope and the coefficient of variation for each regression equation are measures of the accuracy with which estimates of static gross-vehicle weight can be predicted by the equation. It can be concluded, for example, that approximately 95 percent of the weight observations would produce estimates of static weight from the HSWIM scales that would be within [±2 (c.v.) = ±2 (3.8 percent) = ± 7.6 percent] of the actual values of the static gross-vehicle weights. The respective accuracies for the LSWIM and ISWIM scales are ±4 and ±5.8 percent. Or, without using a regression equation, gross-vehicle weights can be predicted with 95 percent confidence within ±4.0, ±6.0, and ±9.0 percent for trucks running over the scales at speeds of 10, 35, and 55 mph, respectively (see the confidence bands in Figs 4-2(b), 4-3(b), and 4-4(b), respectively).

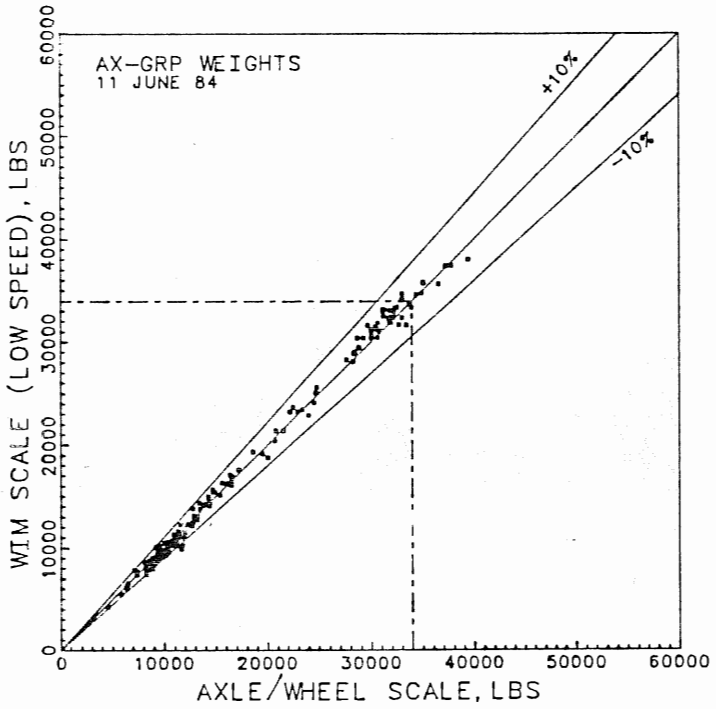
The value of the slope of the regression line, on the other hand, is a good indication of how well the static gross-vehicle weights are predicted by the estimated weights from the sampled dynamic wheel forces by the WIM scales. For the HSWIM scale, for example, the value of the slope of the regression line is 0.99054. This figure is very close to 1.0 and it implies, on the average, the system makes accurate predictions of gross-vehicle weights. The respective values for LSWIM and ISWIM, respectively are 1.00003 and 0.99494. Again these numbers are very close to 1.0, indicating that a small improvement in predictive accuracy can, on the average, be achieved by applying the regression technique. The confidence bands are reduced slightly.

The observed differences in the WIM-estimated gross-vehicle weights and the comparable static weights cannot be attributed entirely to WIM system error or to inaccuracy in the WIM system. Part of the difference comes from the redistribution mechanism of the gross-vehicle weight among the axles on the vehicle as it moves into different positions and stops for successive weighing of each axle on the static reference scale. This redistribution, which is governed to a large extent by the interaction of the vehicle with the road surface, the scale, and the atmosphere, occurs continually as the vehicle moves over the WIM system scales. Additionally, the dynamic behavior of the various inter-connected vehicle components contributes to the magnitude of this difference at the time of weighing.

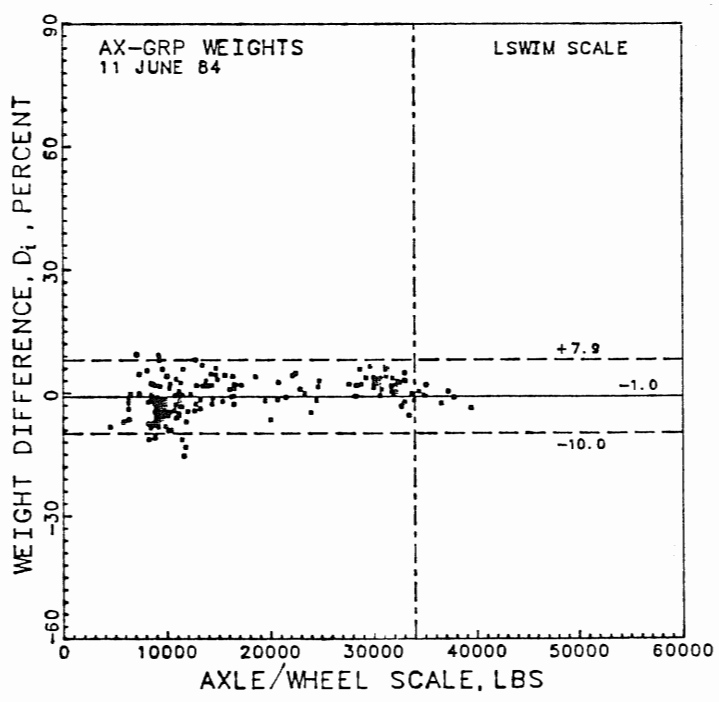
Axle-Group Weights

The total weight on a group of closely-spaced axles is important in the engineering design of pavement and bridge structures, and also in enforcement weighing. The WIM and AX/WHL scales indicated the weight of each wheel. Axle-group weights were calculated from these scales by summing the weights of all wheels on the axles in the group.

The calculated values for all axle-group weights when each axle was weighed on LSWIM, ISWIM, and HSWIM scales indicated that there was a small but consistent, increase in the range of axle-group weight differences as the speed of the vehicles being weighed by the WIM scales increased (see Figs 4-5, 4-6, and 4-7). Statistical tests indicated that the relative difference in axle-group weights, computed from the WIM estimates with reference to those from the AX/WHL scale, are normally distributed. Therefore, some important statistical inferences are developed from analysis of the three data sets mentioned previously; these are tabulated in Table 4-6. These statistics can be interpreted to say that accuracies of about ±9 percent, ±10, and ±14 percent can be expected when comparing

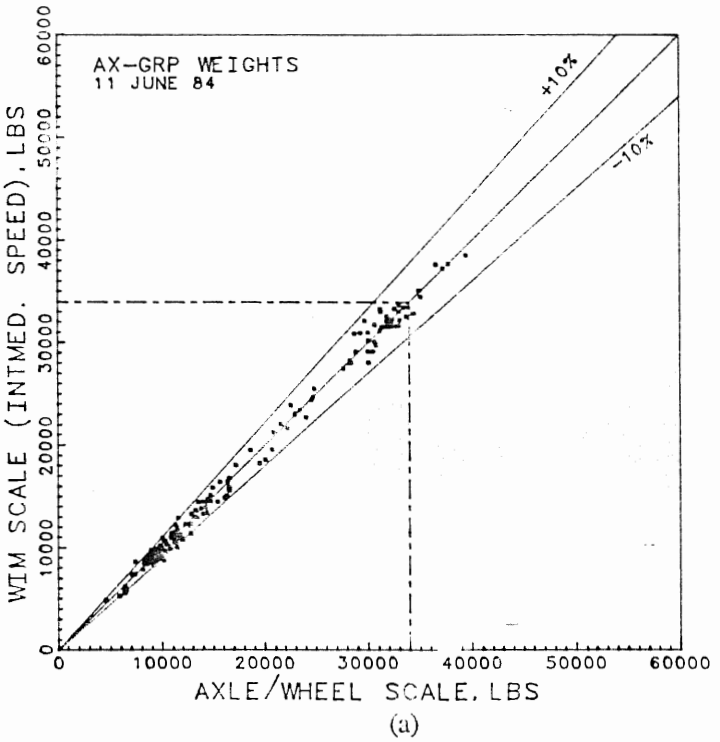


(a)



(b)

Figure 4-5. (a) Axle-group weights for 61 trucks crossing the LSWIM scale at less than 10 mph vs weights summed from the AX/WHL scale, (b) percent difference in axle-group weights from the LSWIM scale with respect to the static reference scale weights.



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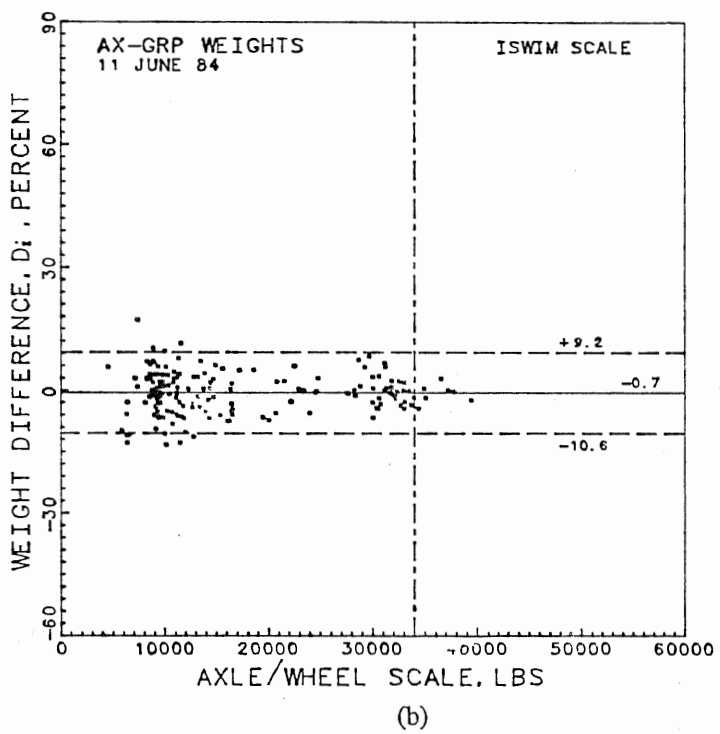
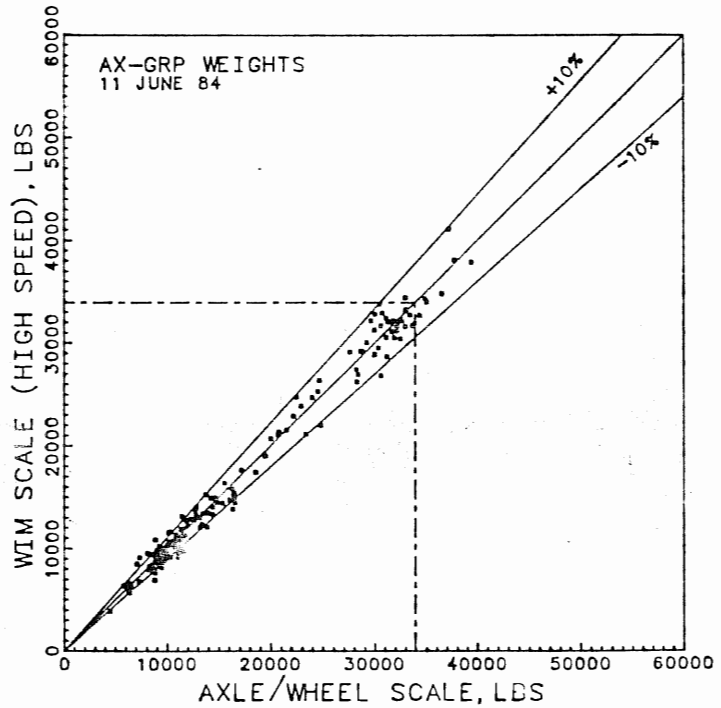


(b)

Figure 4-6. (a) Axle-group weights for 61 trucks crossing the ISWIM scales at about 30 mph vs weights summed from the AX/WHL scale, (b) percent difference in axle-group weights from the ISWIM scale with respect to weights from the static reference scale.



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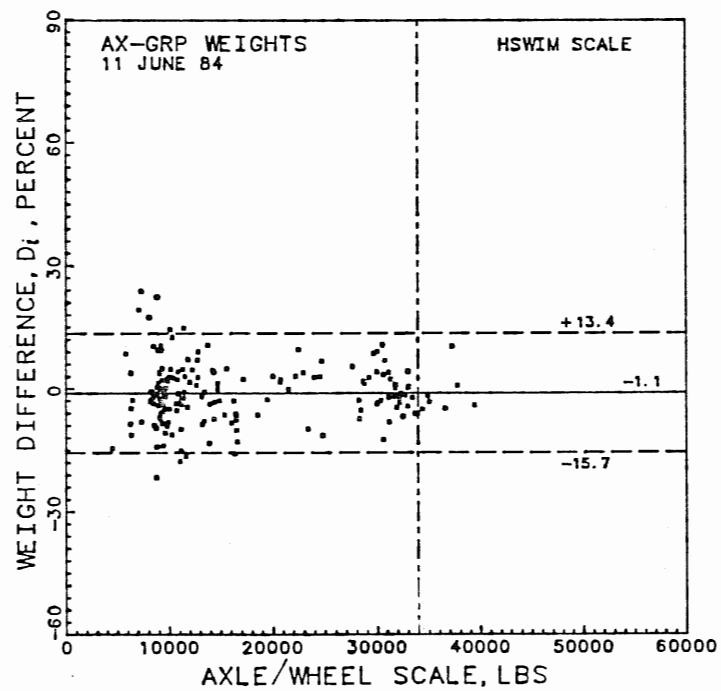


(b)

Figure 4-7. (a) Axle-group weights for 61 trucks crossing the HSWIM scales at about 55 mph vs weights summed from the AX/WHL scale, (b) percent difference in axle-group weights from the HSWIM scale with respect to weights from the static reference scale.

TABLE 4-6. SUMMARY STATISTICS OF WIM AXLE-GROUP WEIGHTS COMPARED AND CORRELATED WITH AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

DATE	SPEED AT WIM SCALES	STATISTIC				
		MEAN WEIGHT, LBS	MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), %	95% CONFIDENCE RANGE, $\mu \pm 2\sigma$, %	REGRESSION ANALYSIS	
					SLOPE	C.V.*
June 11, 1984 n = 178	LSWIM (10 mph)	16990 (17000)+	-1.0 (3.7)	-10.0 to +8.0	1.00594	4.0
	ISWIM (30 mph)	16900	-0.7 (3.8)	-10.6 to +9.2	0.99538	4.4
	HSWIM (55 mph)	16820	-1.1 (5.6)	-15.7 to +13.4	0.99052	6.7
June 6, 1984 n = 171	LSWIM (10 mph)	13640 (13750)+	-1.9 (4.8)	-13.4 to +9.7	0.99962	5.0
	ISWIM (30 mph)	13690	-0.8 (4.6)	-12.6 to +11.0	0.99888	5.4
	HSWIM (55 mph)	13560	-1.6 (6.1)	-17.7 to +14.6	0.98754	6.7
July 6, 1984 n = 242	LSWIM (10 mph)	15600 (15700)+	-0.8 (3.9)	-11.4 to +9.8	0.99934	4.3

* Coefficient of Variation, %

\+ Reference Scale Mean Weight

LSWIM, ISWIM, and HSWIM estimates of axle-group weights with the corresponding weights from the static reference scale, respectively, at 95 percent confidence level. Or, using the regression equation estimates described above, axle-group weights can be predicted at the same level of confidence within ±8.0, ±8.8, ±13.4 percent.

Axle and Wheel Weights

Summary statistics for axle and wheel weights are given in Tables 4-7 and 4-8, respectively. These results further support the fact that the distribution of weight among the axles of a vehicle changes as the vehicle moves over the road surface and stops for successive weighing of axles and wheels on static scales.

SUMMARY

The importance of on-site calibration of WIM systems has been illustrated by comparing the results of WIM weight estimates made after calibrating the system by various techniques against weights measured on an accurate static reference scale. Mixed truck types were included in the analysis, and high, intermediate, and low speeds were considered. A pronounced improvement in the accuracy with which weights were estimated by the HSWIM and ISWIM systems was achieved when six or seven loaded 5-axle, tractor-trailer trucks chosen randomly from the traffic stream were used as the basis for calibration as compared to multiple runs of a loaded 2-axle, single-unit test truck. The variability in WIM weight estimates was not affected appreciably by the type of moving-vehicle used for calibration. A static-weight calibration basis was found to be adequate for LSWIM calibration.

The LSWIM system performed about the same as the AX/GRP (RAM) scale with respect to variability and better on average. It was better in both respects than all three types of wheel-load weighers that were evaluated in the tests with respect to producing weights that agreed with those from the AX/WHL reference scale. It weighed more consistently throughout the range of loads than the flush-mounted AX/GRP scale but exhibited somewhat more variability.

Statistical analysis of the static wheel weights for a representative group of trucks indicated that there was a significant difference in the loads carried on the left and right-side wheels of an axle. Also, the distribution of load among the wheels of tandem axle sets was found to vary significantly.

Analysis of the performance of the Radian WIM system at different speeds indicated that a properly-calibrated system could produce results shown in Table 4-9 as compared to the respective weights from the AX/WHL reference scale.

These values imply that tolerances of about ±4 percent, ±6 percent, and ±9 percent would be appropriate when interpreting LSWIM, ISWIM, and HSWIM estimates of the gross-vehicle weight from the static reference scale, respectively, if the WIM-estimated weight is expected to be within the chosen tolerance value for 95 out of 100 vehicle weighings. Likewise, tolerances of about ±9 percent, ±10 percent, and ±14 percent should be applied to WIM-estimated axle-group weights for the same level of confidence.

TABLE 4-7. SUMMARY STATISTICS OF WIM AXLE WEIGHTS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

DATE	SPEED AT WIM SCALES	STATISTIC		
		MEAN WEIGHT, LBS	MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), %	95% CONFIDENCE RANGE, $\mu \pm 2\sigma$, %
June 11, 1984 n = 280	LSWIM (10 mph)	10800 (10800)+	-0.1 (4.6)	-11.8 to +11.7
	ISWIM (30 mph)	10740	-0.1 (5.5)	-14.7 to +14.6
	HSWIM (55 mph)	10690	-0.1 (6.6)	-17.8 to +17.7
June 6, 1984 n = 253	LSWIM (10 mph)	9220 (9300)+	-0.6 (5.3)	-13.9 to +12.7
	ISWIM (30 mph)	9250	-0.5 (5.5)	-14.6 to +13.7
	HSWIM (55 mph)	9170	-0.5 (7.4)	-19.8 to +18.8
July 6, 1984 n = 367	LSWIM (10 mph)	10290 (10350)+	-0.1 (4.7)	-13.1 to +13.0

+ Reference Scale Mean Weight

TABLE 4-8. SUMMARY STATISTICS OF WIM WHEEL WEIGHTS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

DATE	SPEED AT WIM SCALES	STATISTIC		
		MEAN WEIGHT, LBS	MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), %	95% CONFIDENCE RANGE, $\mu \pm 2\sigma$, %
June 11, 1984 n = 560	LSWIM (10 mph)	5400 (5400)+	0.0 (8.7)	-21.8 to +21.8
	ISWIM (30 mph)	5370	0.0 (6.8)	-17.8 to +17.8
	HSWIM (55 mph)	5350	0.0 (8.4)	-22.3 to +22.3
June 6, 1984 n = 506	LSWIM (10 mph)	4610 (4650)+	0.0 (8.8)	-22.6 to +22.6
	ISWIM (30 mph)	4630	0.0 (8.1)	-21.3 to +21.3
	HSWIM (55 mph)	4580	0.0 (10.5)	-27.2 to +27.2
July 6, 1984 n = 734	LSWIM (10 mph)	5140 (5180)+	0.0 (6.0)	-16.0 to +16.0

+ Reference Scale Mean Weight

TABLE 4-9. COMPARISON OF WIM WEIGHT ESTIMATES WITH STATIC WEIGHTS FROM AX/WHL SCALE

SPEED AT WIM SCALE	STATISTICAL INFERENCE	GROSS-VEHICLE WEIGHT (Percent Difference)	AXLE-GROUP WEIGHT (Percent Difference)
LSWIM (10 mph)	Mean of Differences Range for 95%	-0.2 +3.8 to -4.1	-1.0 +7.9 to -10.0
ISWIM (30 mph)	Mean of Differences Range for 95%	-0.7 +5.4 to -6.8	-0.7 +9.2 to -10.6
HSWIM (55 mph)	Mean of Differences Range for 95%	-1.3 +7.6 to -10.3	-1.1 +13.4 to -15.7

CHAPTER 5. TOLERANCES FOR STATIC AND WEIGH-IN-MOTION SCALES

CONCEPT OF TOLERANCES

In dealing with weight measurements, a distinction should be made between accuracy and precision. Accuracy is the degree of conformity of a measurement to a standard or to a true value. Precision, on the other hand, refers to the exactness with which a measurement is made. A measurement can be precise without necessarily being accurate. Errors in precision are generally random or accidental and can therefore be explained by applying appropriate statistical concepts and techniques. Errors in accuracy are usually systematic and can frequently be minimized or eliminated by adjustment or calibration of a properly-designed weighing device which has good precision. In using a weighing device which has systematic errors that cannot be eliminated by calibration, the systematic errors combine with the random errors to determine the overall accuracy with which weight can be measured by the device.

In recognition of the fact that errorless performance of mechanical or electro-mechanical equipment is unattainable, tolerances are established to define the range of inaccuracy within which such equipment will be allowed to perform and still be approved for official use in a jurisdiction. The U.S. Department of Commerce, National Bureau of Standards through NBS HANDBOOK 44 (1986) sets out code requirements for wheel-load weighers, portable axle-load weighers, and axle-load scales in official use for the enforcement of traffic and highway laws or for the collection of statistical information by government agencies. Acceptance tolerances are defined in the code and are applied to new or newly reconditioned or adjusted equipment. Maintenance tolerances, which are generally twice the accepetance tolerances, are applied to the equipment that has been in service for some time; these tolerances define the maximum variation in accuracy that will be permitted when the equipment is tested against an official standard. The official standard for verifying the performance of these devices is a set of standard test weights of known value.

The variation in wheel, axle, axle-group, and gross-vehicle weights that were obtained when using scales that met the code toleances mentioned above has been presented and analyzed in the preceding chapters. The range of observed differences generally far exceeded the code toleances when weights from each axle-load scale or wheel-load weigher were compared with those from a selected reference axle/wheel scale. This indicates that the overall performance of these devices was a function not only of the accuracy of the device as required by the code, but also of the conditions and techniques of using the device. The inherent variability in the physical phenomenon being measured (i.e., static wheel weight) also contributed to the magnitude of the observed differences in that the portion

of the gross-vehicle weight carried on each wheel of the vehicle changed as the vehicle moved between successive weighings on each scale.

USE TOLERANCES

The objective of enforcement weighing is to identify overloaded wheels, axles, axle-groups, and vehicles and remove them from the roads. Since an individual is at risk when an enforcement officer charges that a weight violation has occurred, a high degree of certainty that the measured weight was actually in excess of the legal limit is necessary. Such certainty can be provided in practice by making appropriate allowances for the probable error in weight measurements that can occur when using a particular weighing device and technique. These allowances may be considered as use tolerances that incorporate all probable errors at a chosen confidence level.

Static Weighing

The rather extensive data sets that are described in Chapter 3 serve as a basis for defining use tolerances that can be applied when operating the types of static weighing devices that were incorporated in the field evaluation study. All the types of devices except the WLW/M300 (which could not be tested under the standard test weights) passed verification testing with standard test blocks and were operated in a typical manner by experienced personnel. The reference AX/WHL scale (see Chapter 2) was accurate under dead-weight testing and weighed a test truck that made more than 60 runs over the scales very consistently throughout the 6 days of data-taking sessions. Since the number of trucks weighed was large and the mix of truck types in the sample was similar to the mix in the total traffic stream, the sample can be considered as representative of the population of trucks that would be weighed in practice. A confidence level of 95 percent has been chosen for defining use tolerances for each type of device. These tolerances are shown in Table 5-1.

The use tolerances shown in Table 5-1 were derived by analyzing the cumulative frequency distribution of weight difference between the compared scale and the reference scale. The 95 percentile value of weight difference is the use tolerance. When applied to an observed weight, the use tolerance defines the probable minimum weight value that would be measured by the reference AX/WHL scale and thereby accounts for all but 5 percent of the expected tendency of the device to overindicate the actual weight. An example of the cumulative frequency distribution plot for axle-group weight differences from the WL/100 wheel-load weigher is shown in Fig 5-1. The 95 percentile frequency corresponds to a weight difference of 1250 pounds. The use tolerances shown in Table 5-1 agree closely in most cases with the values for the mean difference plus two standard deviations as calculated for the correpsonding normally-distributed population of weight differences (see Table 3-3).

To apply the use tolerances to weights from a particular device, the enforcement officer must calculate a probable minimum weight by subtracting the applicable tolerance value from the observed weight. The officer can then be sure that there is only 1 chance in 20 (5 percent probability) that the weight would be less than that calculated if it were measured on the reference scale.

TABLE 5-1. USE OF TOLERANCES FOR AXLE-GROUP AND GROSS-VEHICLE WEIGHTS FOR THE TYPES OF SCALES SHOWN (95 PERCENT CONFIDENCE LEVEL)

TYPE OF SCALE	AXLE-GROUP WEIGHTS (LBS)	GROSS-VEHICLE WEIGHTS (LBS)
WLW/M300	1900	3850
WLW/M400	2450	4650
WL/100	1250	2750
AX/GRP	1400	2500
AX/GRP (RAM)	2300	5100

TABLE 5-2. USE TOLERANCE FOR AXLE-GROUP AND GROSS-VEHICLE WEIGHTS FOR THE WIM SCALES

SPEED	AXLE-GROUP WEIGHT TOLERANCE (LBS)	GROSS-VEHICLE WEIGHT TOLERANCE (LBS)
LSWIM (< 10 mph)	+1100 (-1350 to +1350)*	+1650 (-2050 to +1950)
ISWIM (< 35 mph)	+1100 (-1550 to +1350)	+2000 (-3050 to +2450)
HSWIM (< 55 mph)	+1700 (-2400 to +2050)	+2650 (-4300 to +3250)

* Two-Tailed 95% Confidence Limits to Show Upper and Lower Limits of Tolerances

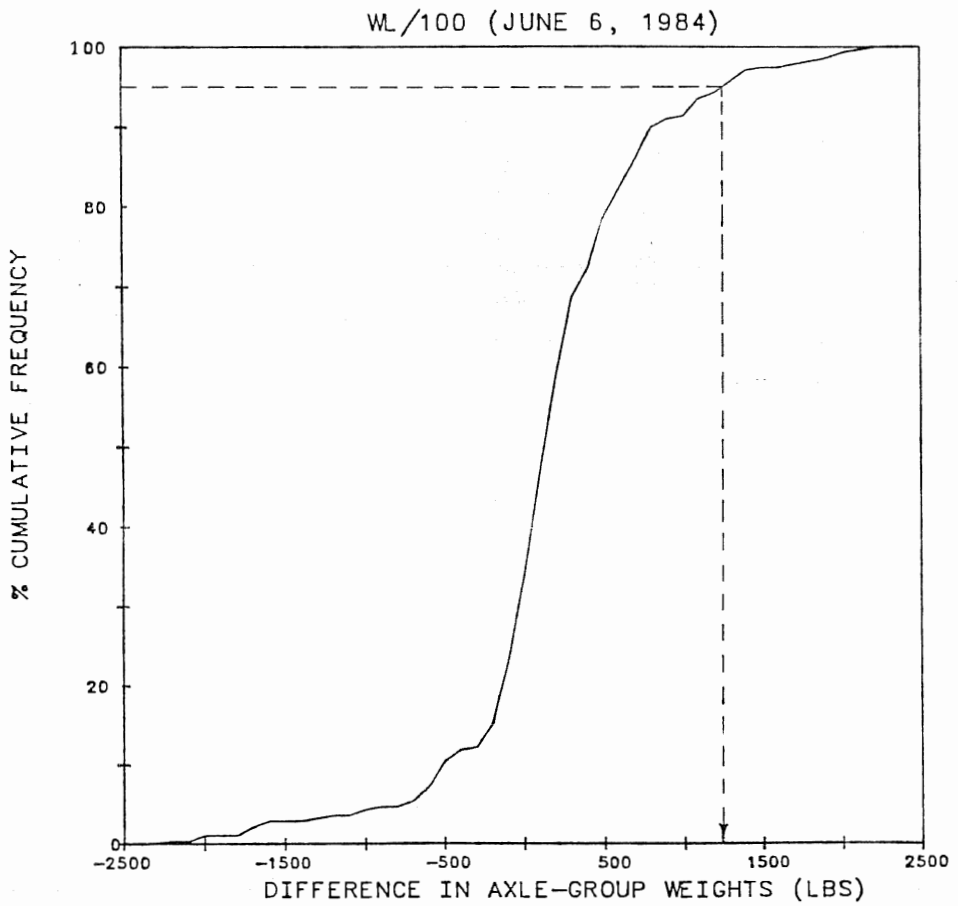


Figure 5-1. Cumulative frequency distribution plot of axle-group weight differences for WL/100.

For example, a tandem-axle group is weighed on a set of WL/100 wheel-load weighers at 35,700 lbs. The probable minimum weight would be 35,700-1,250 = 34,450 lbs. The enforcement officer could charge that the axle-group weight was in violation of the 34,000 lb legal limit and be sure that there was only 1 chance in 20 that it would weigh less than 34,450 lbs when weighed on the accurate reference scale.

In-Motion Weighing

In motion weighing involves two processes: (1) sampling a dynamic tire force, and (2) using the sampled force to estimate the corresponding portion of the gross-vehicle weight that this tire would carry if weighed statically. Neither of these processes, nor the corresponding measurement of static tire force, can be performed without error (see Chapters 3 and 4). Therefore, not only basic tolerances which protect the interests of both the users of the information obtained by WIM systems and the manufacturer of the system, but also use tolerances are needed. The use tolerances account for both the inherent variability in the physical phenomenon being estimated, i.e., static wheel force, and the accuracy with which a WIM system can possibly and practically peform each of the two processes mentioned above. As with static scales, the overall accuracy of a WIM system is determined partly by the accuracy that is attainable by the system itself and partly by how the system is used. As mentioned in Chapter 4, a number of site-specific conditions such as road profile, cross slope near the WIM transducers, interaction of the transducer/roadway system under dynamic load, and vehicle factors affect the overall accuracy of an installed WIM system.

An on-site calibration procedure was developed and recommended for calibration of WIM systems. However, the inherent variability in weight data due to factors such as torque in the vehicle drive train, dynamic behavior of the various inter-connected vehicle components, friction, and other factors cannot be completely accounted for, even by a properly-calibrated system. Therefore, use tolerances which recognize such variability must be utilized when interpreting and applying the WIM estimated measurements for weight enforcement or for other purposes.

Using regression techniques, the data set for axle-group and gross-vehicle weights described in Chapter 4 were analyzed. In the regression analysis, it was assumed that the reference weight, x, (i.e., the predictor variable) was not subject to random variation, but that the WIM estimate, y, (the response variable) was. The regression model $y = b_1x + \varepsilon$ is considered in the analysis because the nonzero intercept term is physically difficult to explain and justify. Since the actual observed value of y varies about the true mean value with the unknown variance s^2, therefore a predicted value of an individual observation, which is given by $y = b_1x$, has variation greater than s^2. This means that a prediction interval for the particular outcome of a weight reading from the WIM scale can be defined. A prediction interval is one that contains y with a desired level of confidence. A one-sided (upper band, w) 95 percent prediction interval for y at a fixed value x can then be constructed. The use tolerance for a given data set is then determined by subtracting the value of x (the reference weight) from the predicted value of the weight and its upper prediction interval. The results from the regression models are given in Table 5-2.

It is interesting that the use tolerances for the properly-calibrated LSWIM and ISWIM systems are lower than the corresponding use tolerances for all the static weighing devices utilized in the field study and that the HSWIM use tolerances are only slightly larger than those for the AXL/GRP scale and the WL/100 wheel-load weigher, which

were the best performers among the static weighing devices evaluated. The performance of the AXL/GRP scale, the WL/100, and the HSWIM system with respect to use tolerances, were all quite similar.

CHAPTER 6. COMPARISON OF STATIC AND IN-MOTION WEIGHING TECHNIQUES

INTRODUCTION

Techniques for collecting truck weight data for statistical use and for enforcement programs using fixed or portable static scales have certain advantages and disadvantages as compared with in-motion weighing techniques. The relative disadvantages of static weighing, among others, include time delays to truckers and occasionally to other motorists in the traffic stream, additional vehicle operating expenses incurred while waiting to be weighed and while being weighed, a limited number of trucks that can be weighed safely and economically within a given time period, specially-constructed off-road weigh sites, possibly hazardous working conditions with on-road (shoulder) weighing, intensive manpower requirements, and high cost per vehicle weighed. In addition, static weighing operations involve inherent sampling problems such as seasonal bias (e.g., conducting surveys only in summer months when less-expensive labor is available), locational bias (occupying only routes where off-road space is accessible for static weighing), and bias caused by selecting weigh sites where a high probability of truckers "by-passing" or "waiting-it-out" does not exist.

On the other hand, in-motion weighing involves a comparatively larger initial investment in equipment per weighing system and some limitations on the accuracy within which static weights can be estimated from samples of dynamic wheel forces. Mobility of the more-accurate types of in-motion weighing systems is somewhat limited. Many of the inherent operational disadvantages of static weighing are not present in weigh-in-motion (WIM) operations, however. WIM systems make it practicable to weigh, classify, and measure the speed of every vehicle that passes in each lane of a multi-lane highway over any chosen time period; therefore, a 100-percent sample of traffic statistical data can be obtained. Furthermore, this information can be transmitted immediately in real-time, or at some future time, to locations remote from the weighing site via conventional communications networks. Manpower requirements can be considerably reduced for statistical data-gathering operations which might extend over long periods of time, and travel requirements for equipment and personnel can be reduced. At present, WIM applications in enforcement are limited primarily to identifying individual vehicles that are suspected of being in violation of weight or size laws and to locating sites where relatively large numbers of probable violators operate.

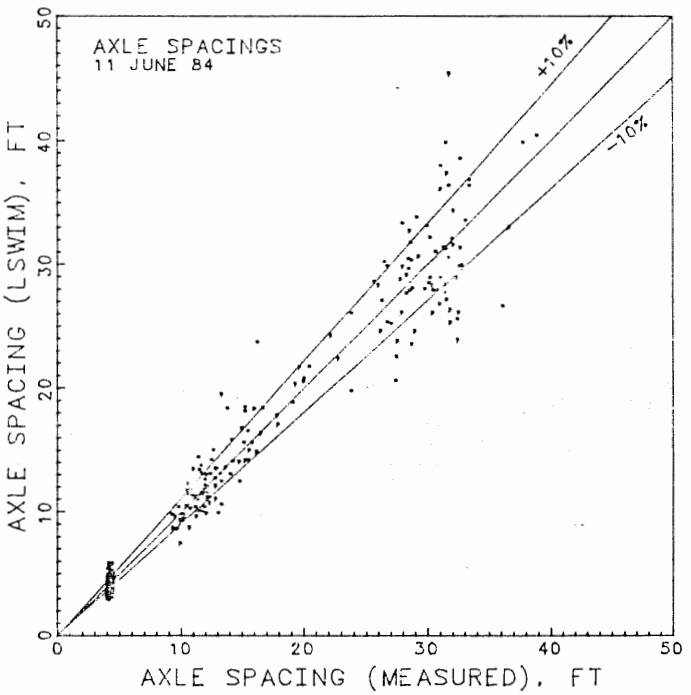
Previous chapters (3 and 4) dealt mainly with accuracies associated with using different static scales and a Radian WIM system operated at three different speeds. It was concluded that the performance of this WIM system was adequate for use (1) in gathering weight data at high speeds for statistical information, (2) as a means of sorting overweight trucks in enforcement programs and (3) in weighing trucks at low speeds for legal evidence of weight-law violation (compared to the performance of the static axle-load scales and wheel-load weighers which are being used at

the present time in enforcement programs). In Chapter 5, the concept of use tolerance was discussed and appropriate tolerance limits for static and WIM scales were derived. These values are intended to incorporate all probable errors associated with using a particular weighing device and technique so that a selected weighing device can be used with confidence. In this chapter, axle spacing measurements estimated by the WIM system are analyzed to evaluate the accuracy of these measurements in realtion to their use in identifying vehicles in probable violation of size-laws and in classifying vehicles for statistical data purposes. Next, data concerning the time required for weighing trucks on a particular static scale is analyzed to give efficiency rates attainable with static scales. Finally, the effect of permanent weigh station operations on "by-passing" truck traffic is discussed in light of a limited period of observation during the study.

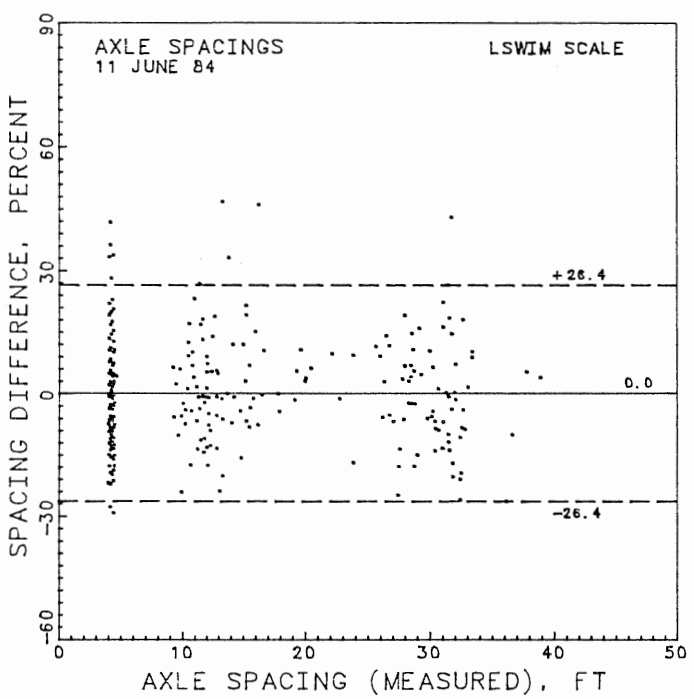
AUTOMATIC DIMENSIONING AND VEHICLE CLASSIFICATION

Weighing-in-motion usually means weight and vehicle classification measurements as well. Vehicle weight without the associated vehicle type provides less-useful information. In WIM, vehicle classification is based on the number of axles on the vehicle, and on the pattern of axle spacings. Observed measurements are used by a microprocessor to compare estimated axle spacings and number of axles with those contained in a classification look-up table stored in memory. Axle spacings are also used for identifying oversized vehicles. In addition, the WIM-estimated axle spacings are used in applying the "bridge formula" for weight law enforcement. Thus, it was desirable to study the performance of the WIM system in relation to the quality of these measurements and to the reliability of the information generated. The observed data were analyzed to determine the range of accuracy within which axle spacings were estimated by the WIM system. The same graphical and statistical analysis techniques that are described in Chapters 4 and 5 were also employed here for the comparative analysis of the data. Tape-measured axle spacing data were used as a basis for comparison. In the graphical representation, the axle spacing data measured manually are plotted on the horizontal axis and the corresponding spacings for each vehicle as estimated by the WIM system at each traffic speed is plotted along the vertical axis on each graph. Another graphical representation uses the relative difference in axle spacings, which is computed and expressed as a percentage of the respective axle spacings measured by a tape. These differences are plotted against those of the corresponding tape-measured axle spacings.

Figures 6-1, 6-2, and 6-3 illustrate the variability in estimated axle spacings for trucks which were dimensioned in-motion at three different speeds (LSWIM $\leq$ 10 mph, ISWIM = approximately 30 mph, and HSWIM = approximately 55 mph) on 11 June 1984 by three WIM scales. Each data set was carefully examined to check for abnormalities in the measurements and a few extreme outlying data points were discarded from the data sets. Furthermore, preliminary scatter plots indicated that there was a systematic bias in the WIM-estimated axle spacing data. The Radian WIM system utilizes signals from inductance loop detectors to sense vehicle presence and signals from the wheel-force transducers to sense the passage time for each wheel. This information is then processed to calculate estimates of speed, axle spacing, and overall vehicle length. Loop-detector characteristics (i.e., loop length, loop constant) can be entered into the system as variables for these computations. The loop constant can be

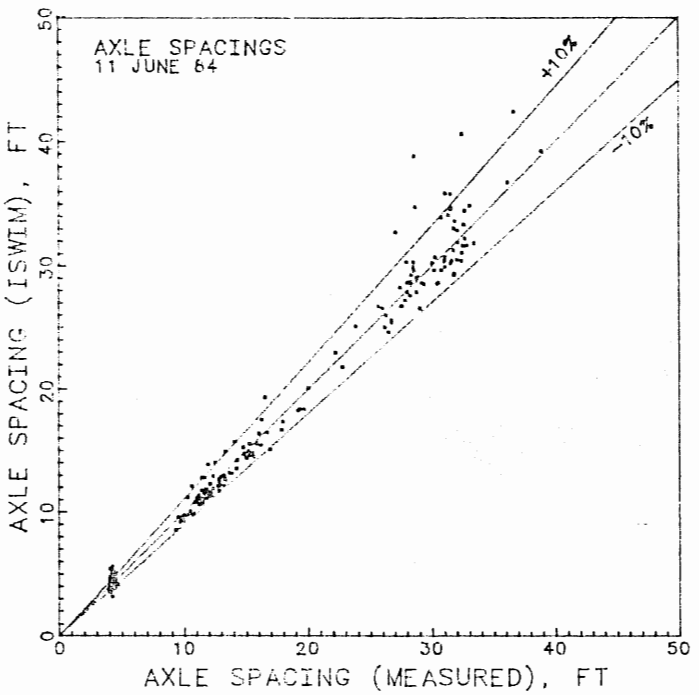


(a)

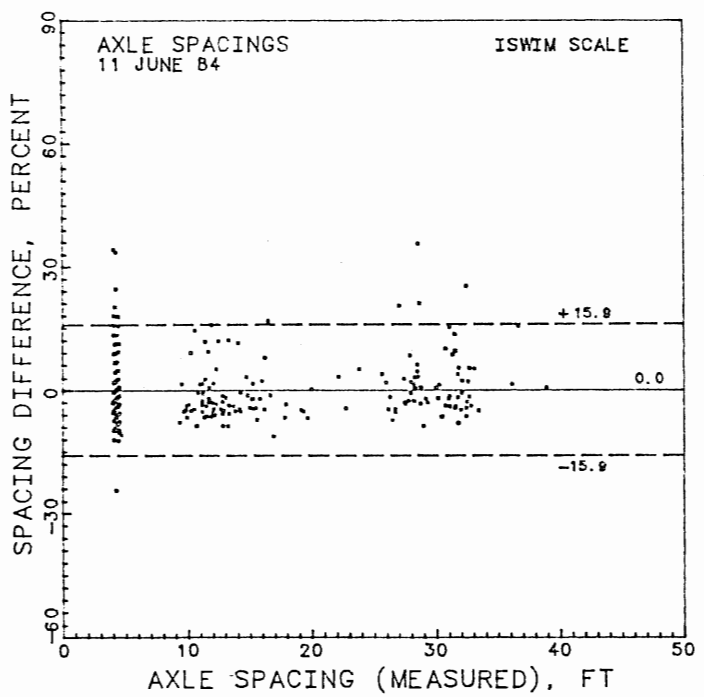


(b)

Figure 6-1. (a) Plot of LSWIM vs measured axle spacings for 83 trucks measured on 11 June 1984, (b) plot of percent difference in axle spacings from the LSWIM scale with reference to the taped measurements.

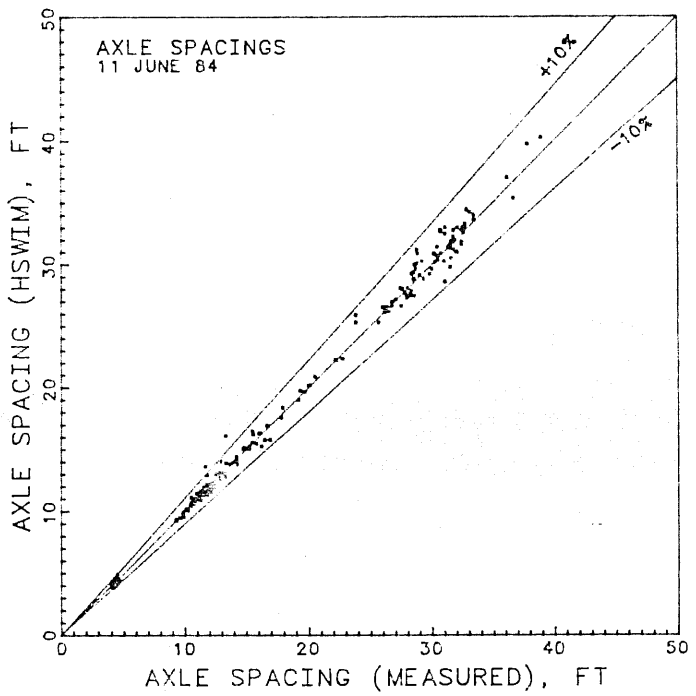


(a)

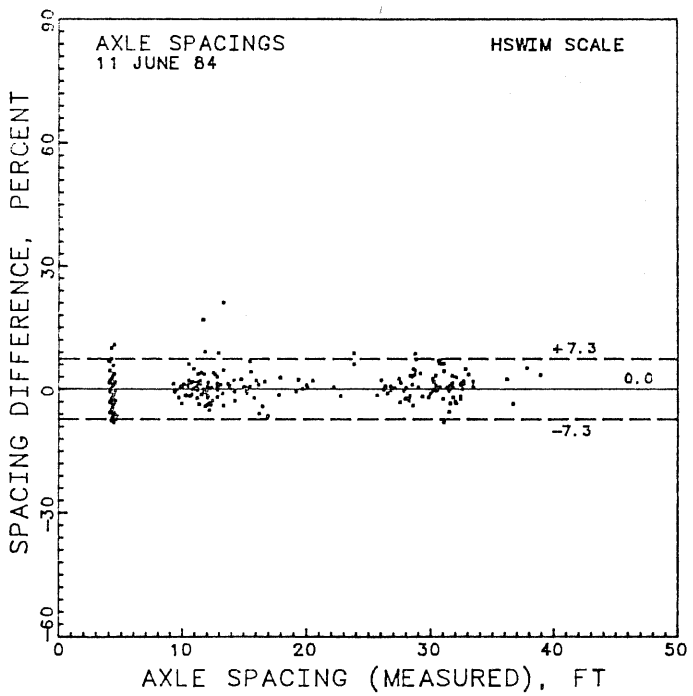


(b)

Figure 6-2. (a) Plot of ISWIM vs measured axle spacings for 79 trucks measured on 11 June 1984, (b) plot of percent difference in axle spacings from the ISWIM scale with reference to the taped measurements.



(a)



(b)

Figure 6-3. (a) Plot of HSWIM vs measured axle spacings for 87 trucks measured on 11 June 1984, (b) plot of percent difference in axle spacings from the HSWIM scale with reference to the taped measurements.

adjusted appropriately to give good estimates of known vehicle speeds in a field calibration precess. This procedure, however, was not carried out in the experiments; therefore, the WIM system estimates of axle spacings were systematically lower or higher than the comparable taped measurements. The data sets from the field experiments were adjusted to effect an on-site calibration of the system which should have been made before the experiment began. As these figures indicate, there was not perfect agreement between the two measurements, as all the points do not lie exactly on the line of equality. The pattern of scatter in the data plotted in these figures indicates that there was a rather moderate, but consistent decrease in the range of axle-spacing difference as the speed of vehicles being dimensioned by the WIM system increased. Virtually all the WIM-estimated axle spacings at high speed differed less than ten percent when they were compared against the taped measurements. In fact, 95 percent of the HSWIM observations are within $\pm$7.3 percent of the measured axle spacings (see Fig 6-3). The respective accuracies for the LSWIM and ISWIM scales are $\pm$26.2 and $\pm$15.9 percent at the 95 percent confidence level.

In summary, it appears that the performance of the HSWIM and ISWIM scale was adequate for automatically measuring axle spacings to be used by the system in classifying trucks and as a means of sorting trucks suspected of being in violation of size or axle-spacing laws. The amount of variability in axle-spacings estimated by the LSWIM scales is greater than would be accepted as a basis for citing violation of legal limits that are based upon axle spacing. This variation can be attributed largely to the change in speed as the trucks crossed over the loop detectors and the wheel-force transducers at attempted speeds less than about 10 mph.

The new 4-lane WIM system was found to be capable of counting and classifying (according to number of axles and patterns of axle spacing) vehicles in each of up to four lanes. A two-digit-code vehicle classification scheme which has been installed on the Texas WIM system is presented here and recommended for implementation on other standard WIM systems. The concept of this scheme is shown graphically in Fig 6-4. The first digit gives the total number of axles on the vehicle, or the vehicle combination, and the second digit identifies the pattern of axle spacing. Vehicle configurations with 2 to 10 axles are described exactly by the first digit, and those with more than 10 axles are coded with a 1 as the first digit. Up to nine axle-spacing patterns can be coded explicitly by the second digit, and all others can be indicated by a 0 as the second digit.

Table 6-1 gives a list of the recommended range of spacings between successive axles for the classes of vehicles shown graphically in Fig 6-4. These ranges were derived from an analysis of 1981, 1982, and 1983 WIM data tapes, which also included manually-observed classes. Less than five percent of the vehicles in the recorded data sets were coded in the 0 axle spacing pattern categories. This scheme was found to be reliable when it was checked against the tape-measured axle spacings which were obtained on 87 trucks of various classes.

The 2-digit WIM vehicle classification scheme is flexible and expandable. Up to 9 patterns of axle spacing can be defined uniquely for each vehicle or vehicle combination with 2 to10 axles. Vehicles with characteristics other than those defined by these 81 possible combinations will be coded into a miscellaneous category. The vehicle classes shown in Fig 6-4 are fundamental and presently dominant, but different patterns of axle spacings which occur in significant numbers at a given location can be added into the scheme easily. A timely examination of the actual axle-spacing patterns for vehicles which are classified automatically by the WIM system with a 0 as the second digit will indicate to the user the possible need for an adjustment in the axle-spacing ranges and the patterns. It is

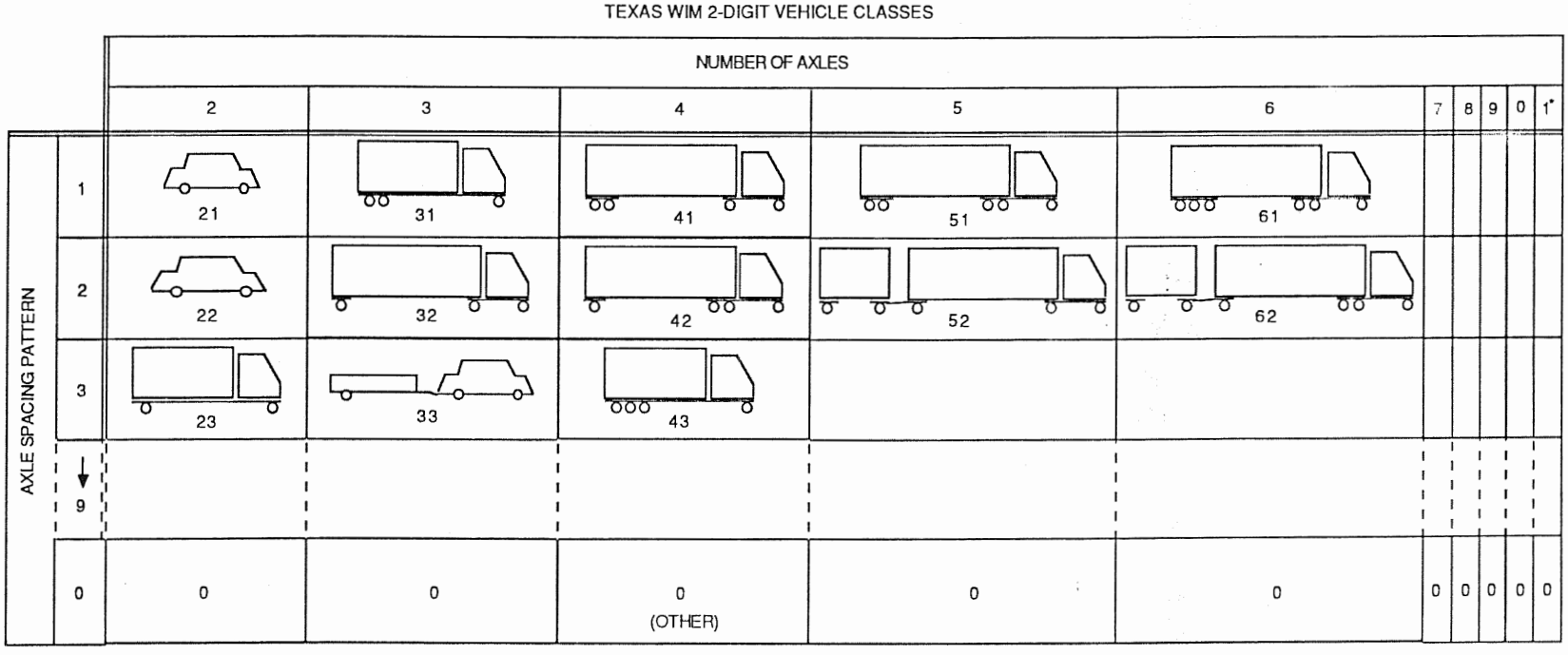
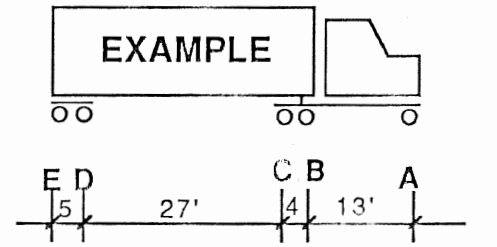


Figure 6-4. Graphical representation of 2-digit vehicle classification code.

TABLE 6-1. RANGE OF AXLE SPACINGS FOR 2-DIGIT VEHICLE CLASSIFICATION CODE

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 **********					



unlikely that more than about 20 classes of vehicles will be of practical interest, but the WIM 2-digit vehicle classification code can handle many more.

STATIC WEIGHING-TIME REQUIREMENT

In order to document the time requirements for static weighing and dimensioning, the time that was utilized for weighing each truck on the axle-load scales and the wheel-load weighers was measured and recorded. The AX/WHL scale weighed each individual axle separately and the processing time was recorded to the nearest second by a microcomputer on a hard-copy tape. The flush-mounted axle-group (AX/GRP) scale and the ramped axle-group AX/GRP (RAM) scales weighed groups of axles at one time. For these scales, weighing time on each truck was recorded to the nearest minute by a microcomputer in the readout device and printed on a hard copy. For all three wheel-load weighers the time that was required to weigh a truck was recorded manually to the nearest second indication on a stop watch. Axle-spacing measurements were made by a 2-person team using a steel tape while the truck was stopped for weighing on the AX/WHL scale. This measurement had no effect on the weighing times on the AX/WHL scale.

Frequency histograms developed from the weighing-time data for the various static scales are shown in Figs 6-5 through 6-9. Tabular data of the average and the standard deviation values for weighing times measured on three different days are presented in Tables 6-2 through 6-4. Values are shown for each truck type and for all trucks weighed on each type of static scale. Weighing times on the AX/WHL scale included the time to stop each individual axle on the 2-section (side-by-side) scale and print the wheel weights from each scale section. Single axles or groups of axles were weighed in a single stop on the AX/GRP and the AX/GRP (RAM) scales. Similarly, the required number of wheel-load weighers (up to 6) were used to weigh single axles or groups of axles in a single stop for each axle or axle-group. The longest weighing times for weighing on wheel-load weighers were experienced when stopping the truck with all tires (or the outside dual tires) on the small, elevated platforms of the WLW/M400 wheel-load weighers. In some cases this required more than one attempt from the driver to mount the weighers and stop in the correct position. The WLW/M300 weighers did not require stopping on the device. The weighers were placed in front of each wheel, and the driver pulled over the weighers at a very slow speed before stopping again to allow removal of the devices from the wheel path. The low-height, large-surface WL/100 wheel-load weighers were relatively easy for trucks to mount. It was not necessary to remove the devices from the wheel path as successive axle groups were moved into position for weighing. The weighing times that were recorded included only the actual time required for positioning the truck and recording the weight. Waiting time in the queue before weighing was not included.

EFFECT OF PERMANENT WEIGH STATION OPERATIONS ON "BY PASSING" TRUCK TRAFFIC

As mentioned previously, size and weight enforcement activities in Texas are conducted by DPS. An extensive effort is made continually to deter any overweight or oversize truck from using Texas highways. One of the objectives of this research project was to study the effects of fixed weigh station operations on "by-passing" truck

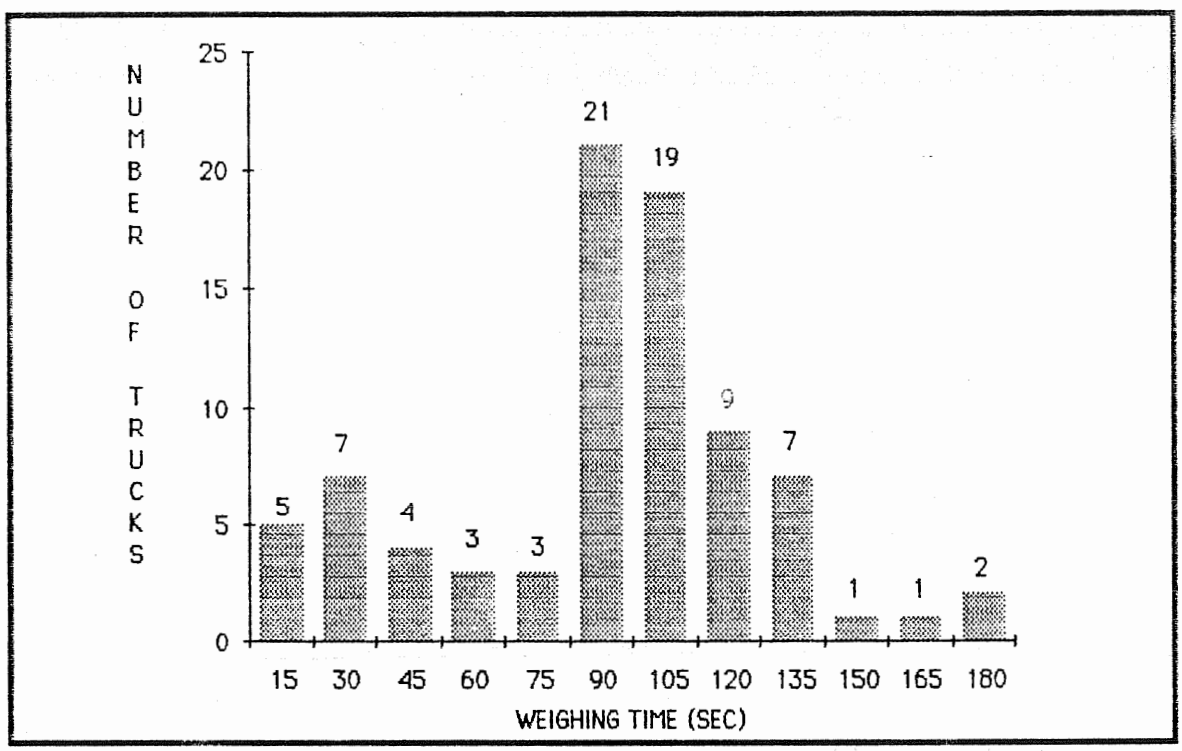


Figure 6-5. Frequency histogram for times required to weigh 82 trucks on the AX/WHL scale, 5 June 1984.

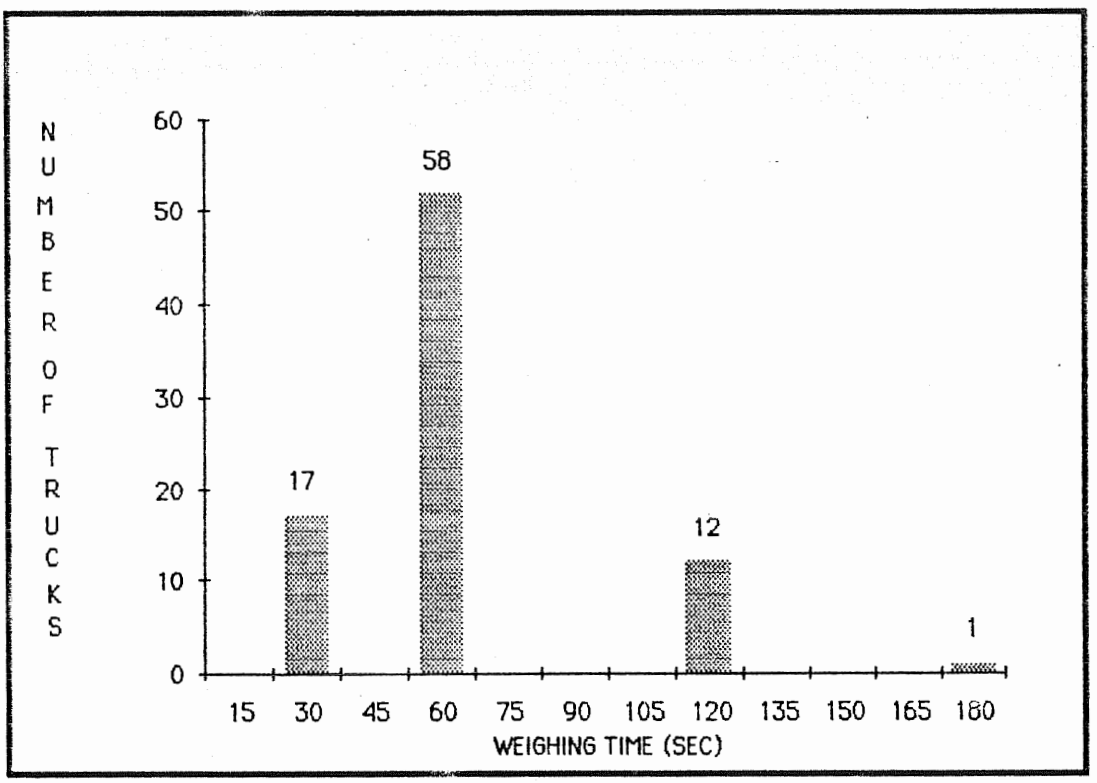


Figure 6-6. Frequency histogram for times required for weighing 82 trucks on the AX/GRP scale, 5 June 1984.

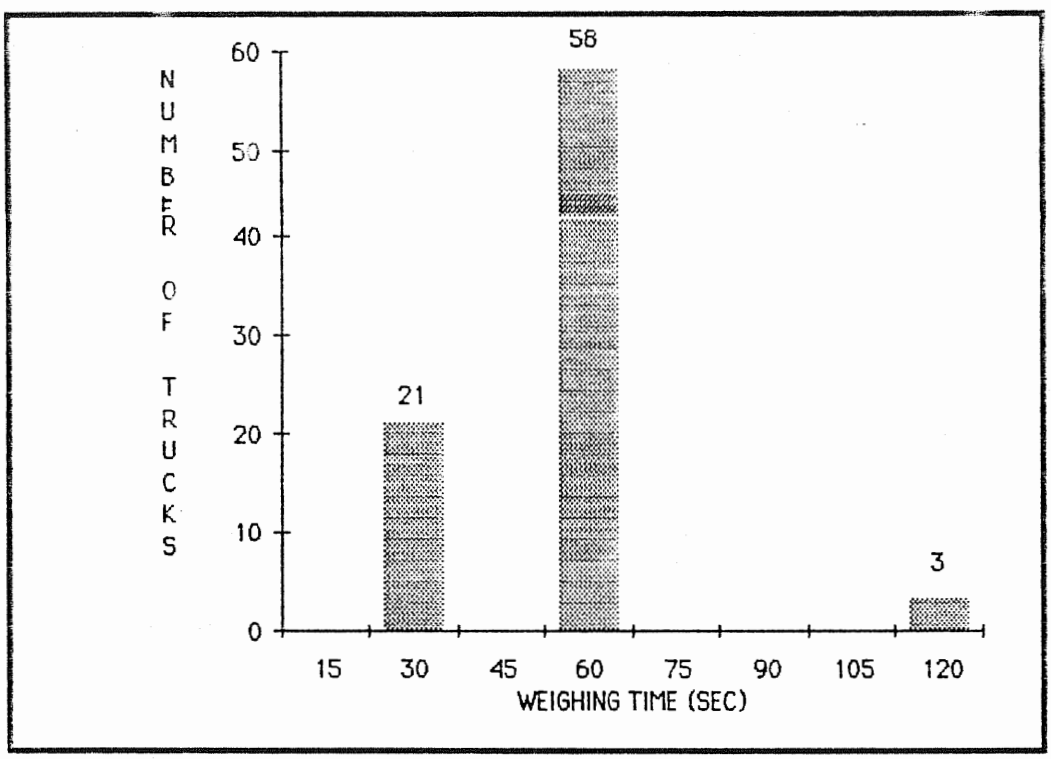


Figure 6-7. Frequency histogram for times required for weighing 82 trucks on the AX/GRP (RAM) scale, 5 June 1984.

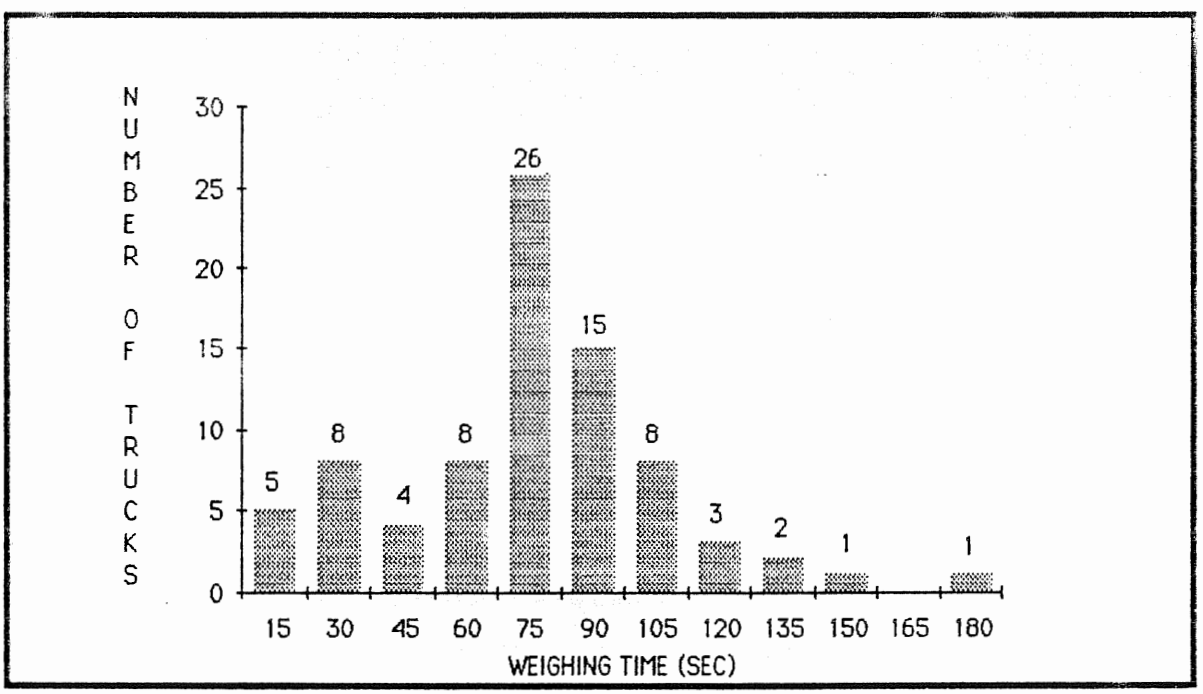


Figure 6-8. Frequency histogram for times required for weighing 82 trucks on the WLW/M300 scale, 5 June 1984.

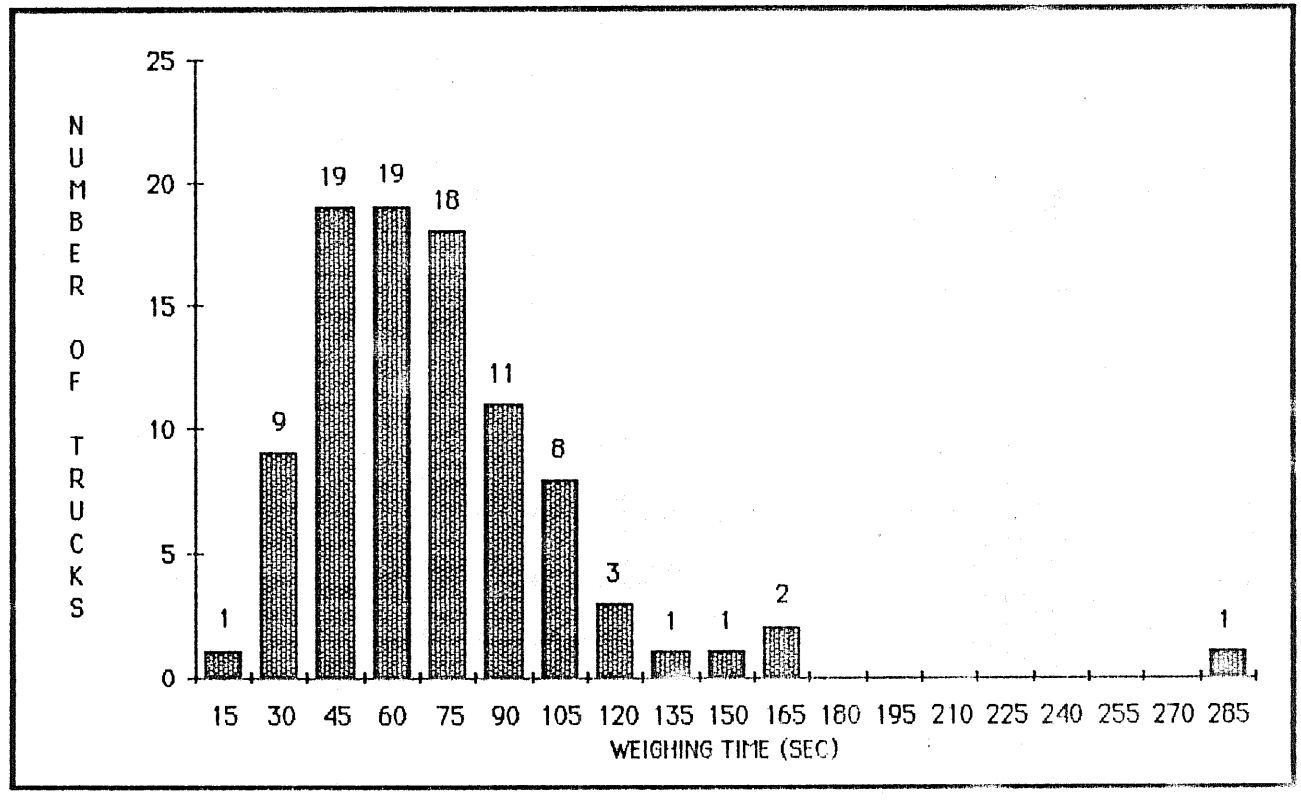


Figure 6-9. Frequency histogram for times required for weighing 93 trucks on the WL/100 scale, 6 June 1984.

TABLE 6-2. COMPARISON OF THE WEIGHING-PROCESS TIME (IN SECONDS) ON DIFFERENT TYPES OF STATIC SCALES OPERATED ON JUNE 5, 1984, FOR TYPES OF TRUCKS SHOWN

Type Truck	No. of Trucks	Type of Scale			
		AX/WHL	AX/GRP	AX/GRP (RAM)	WLW/M300
		Mean (S.D.)*	Mean (S.D.)	Mean (S.D.)	Mean (S.D.)
2D	14	25.6 (7.2)	36.4 (12.7)	36.4 (12.7)	28.0 (8.0)
3A	2	49.5 (9.2)	30.0 (0.0)	45.0 (21.2)	56.0 (5.7)
2S1	3	59.3 (14.6)	60.0 (0.0)	50.0 (17.3)	58.3 (17.0)
2S2	5	79.8 (11.2)	78.0 (40.2)	60.0 (0.0)	69.2 (11.6)
3S1	1	94.0 (-)	120 (-)	60 (-)	68 (-)
3S2	57	111.2 (22.7)	70 (28.0)	59.0 (17.9)	90.3 (36.6)
2S12					
3S12					
3S22					
All Trucks	82	91.0 (38.6)	64.0 (29.7)	54.5 (18.3)	76.1 (31.3)

* Standard Deviation

TABLE 6-3. COMPARISON OF THE WEIGHING-PROCESS TIME (IN SECONDS) ON DIFFERENT TYPES OF STATIC SCALES OPERATED ON JUNE 6, 1984, FOR TYPES OF TRUCKS SHOWN

Type Truck	No. of Trucks	Type of Scale		
		AX/WHL	AX/GRP	WL/100
		Mean (S.D.)*	Mean (S.D.)	Mean (S.D.)
2D	17	65.2 (16.6)	47.6 (15.2)	41.1 (24.3)
3A	2	126.5 (57.3)	60.0 (0.0)	52.0 (22.6)
2S1	2	105.5 (28.9)	60.0 (0.0)	52.5 (4.9)
2S2	7	123.7 (17.2)	60.0 (30.0)	69.1 (2.16)
3S1	1	111 (-)	60.0 (-)	89.0 (-)
3S2	55	145.5 (26.2)	61.2 (24.1)	77.4 (37.6)
2S12	3	165.3 (40.7)	100.0 (34.6)	119.0 (44.2)
3S12	4	179.2 (23.0)	75.0 (30.0)	103 (37.1)
3S22	2	170.0 (31.1)	90.0 (0.0)	82.5 (0.7)
All Trucks	93	130.2 (4.12)	61.3 (24.2)	71.8 (37.2)

* Standard Deviation

TABLE 6-4. COMPARISON OF THE WEIGHING-PROCESS TIME (IN SECONDS) ON DIFFERENT TYPES OF STATIC SCALES OPERATED ON JUNE 11, 1984, FOR TYPES OF TRUCKS SHOWN

Type Truck	No. of Trucks	Type of Scale		
		AX/WHL	AX/GRP	WLW/M400
		Mean (S.D.)*	Mean (S.D.)	Mean (S.D.)
2D	4	55.2 (35.4)	37.5 (15.0)	63.5 (49.8)
3A				
2S1				
2S2	5	115.8 (18.5)	54.0 (13.4)	80.6 (9.3)
3S1	1	204 (-)	60 (-)	96 (-)
3S2	28	137.6 (22.4)	62.1 (23.0)	96.4 (38.2)
2S12	1	121 (-)	60 (-)	108 (-)
3S12				
3S22				
All Trucks	39	127.6 (40.4)	58.5 (22.1)	91.3 (40.2)

* Standard Deviation

traffic. For this purpose, a manual classification survey of traffic, before and during the operation of a permanent weigh station, was conducted at the weigh site adjacent to the eastbound lanes of IH-10 (site of the experimental program) and on two alternative adjacent roads - U.S. 90A and U.S. 90.

Though continuous 24-hour surveys for at least a week before the weighing operation began was desired, the available manpower, environmental and safety-related problems made it feasible to conduct only 8-hour (7:00 a.m. - 3:00 p.m.) surveys on the days shown below.

Survey Days	Date	Status of Weigh Stations
Thursday	31 May 1984	Closed
Friday	1 June 1984	Closed
Monday-Wednesday	4-6 June 1984	Open
Thursday-Friday	7-8 June 1984	Closed
Monday-Wednesday	11-13 June 1984	Open

One observer was assigned to each direction of traffic on IH-10 and one to each adjacent road. Each observer was instructed to classify traffic as passenger cars (including pick-ups, vans, etc) and trucks by type (see Fig 6-1) for each direction of traffic. Count data were recorded for each class of traffic for every 15-minute time period. The hourly volumes of different classes of vehicles traveling in both directions of each road during the survey period were tabulated but are not included in this report. These tables also include the total truck and traffic volumes for each day of the survey.

Table 6-5 shows the average percentage of cars and trucks which make up the traffic on each road by direction. These results indicate that, on the average, truck traffic make up 30 percent of the traffic population on IH-30, and about 14 percent on the two alternative routes. This means that the main highway and the two alternative roads constitute a traffic corridor in which traffic consists of about 20 percent trucks and 80 percent passenger cars. The daily vehicular volumes are shown in Table 6-6, for both cars and trucks by direction. The total daily corridor volumes are shown in the last column of this table. The following observations can be made from the data in this table.

1. There were more trucks traveling eastbound than westbound - 803 daily average trucks as compared to 675 trucks during the period of 7:00-3:00 p.m..

TABLE 6-5. AVERAGE PERCENTAGE OF CARS AND TRUCKS BY DIRECTION OF TRAVEL

Vehicle Type	IH-10		U.S. 90A		U.S. 90	
	E	W	E	W	E	W
Cars	70.1	69.9	86.6	85.7	84.0	87.0
Trucks	29.9	30.1	13.4	14.3	16.0	13.0

TABLE 6-6. DAILY VEHICULAR VOLUMES IN THE ASSUMED CORRIDOR BY CLASS AND DIRECTION

Day and Date	Cars		Trucks		Directional Traffic		Total Traffic
	E	W	E	W	E	W	
Thu, 5/31	2363	2196	934	849	3297	3045	6342
Fri, 6/1	2536	2470	923	634	3459	3104	6563
Mon, 6/4	2585	2473	696	646	3231	3119	6350
Tue, 6/5	2434	2181	758	675	3102	2856	6048
Wed, 6/6	2484	1986	784	584	3268	2570	5838
Thu, 6/7	2245	2373	910	796	3155	3169	6324
Mon, 6/11	2512	2062	700	567	3212	2629	5841
Tue, 6/12	2087	1876	764	664	2851	2540	5391
Wed, 6/13	2209	1912	761	661	2970	2573	5543
Total	21,455	19,529	7,230	6,076	28,685	25,605	54,290

2. On the average, the corridor carried 6025 vehicles during the hours of 7:00 to 3:00 p.m. There was a moderate variation in traffic volume from day to day. Traffic volume reached its peak value on Mondays, Thursdays, and Fridays.

3. The system experienced heavy truck traffic two days out of the week - Thursday and Friday. Generally truck traffic was at its lowest level on Mondays and gradually picked up day after day, on the average 9 percent a day, and reached its peak value on Thursday. Nothing can be said about this trend on weekend days as no data were collected on weekends.

Bar charts showing the distributional variation of cars and trucks by count days are plotted in the Figs 6-10 thru 6-15. These figures indicate that there was a moderate decrease in eastbound truck traffic volume on IH-10 while the weigh station was in operation. Given in Table 6-9 are the total number of eastbound trucks on IH-10 and the other two roads and their corresponding percentages of the total eastbound truck traffic for each day. On the first Thursday and Friday of the traffic survey period when the eastbound weigh station was not in operation, a smaller percentage of trucks was observed travelling on alternative routes than the days when the station was open for weighing trucks; however, this pattern did not hold on the second Monday of the survey days. There was a slight shift in truck traffic on IH-10 to the alternative routes for the days when the station was in operation.

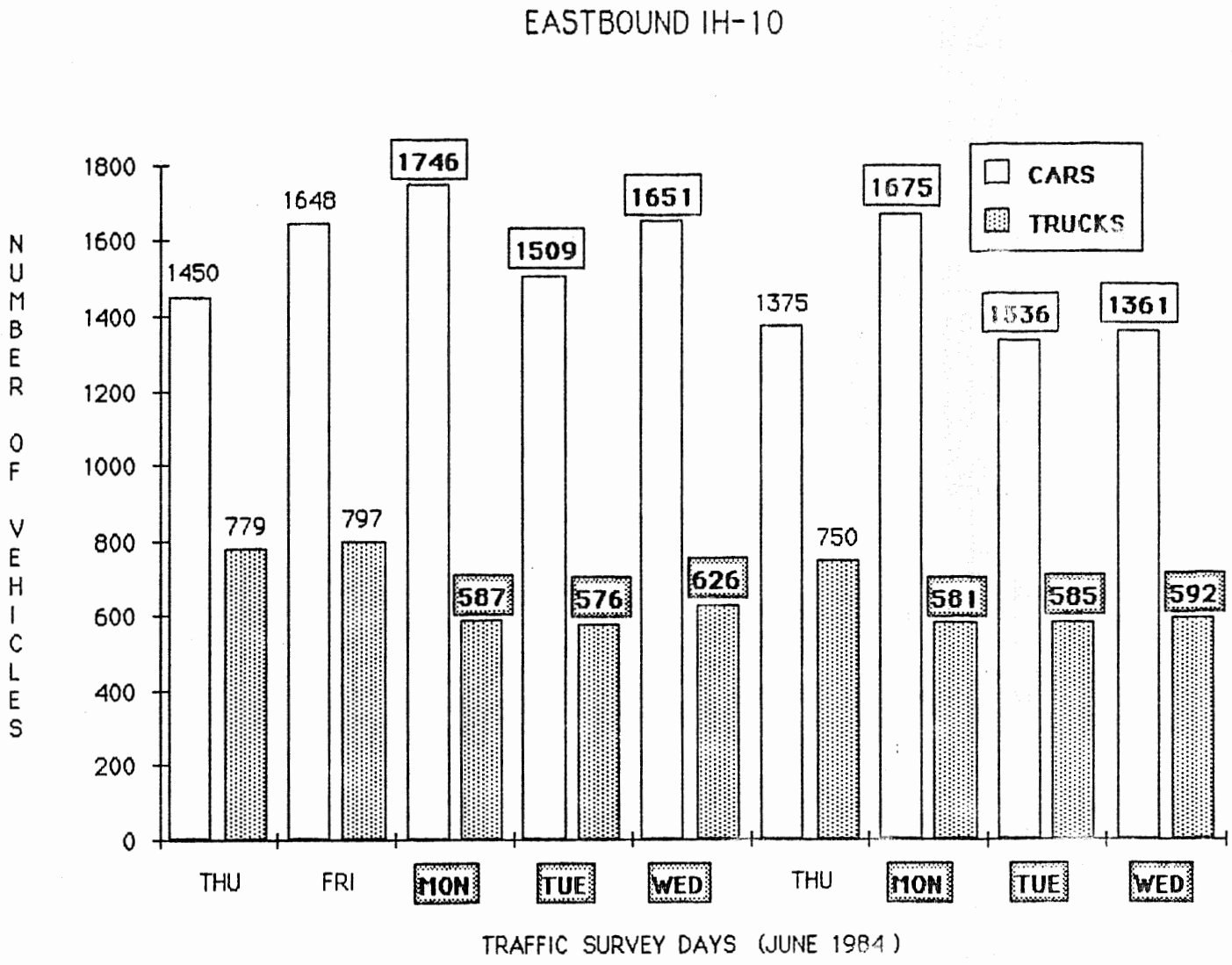


Figure 6-10. Daily traffic variation by vehicle class on eastbound IH-10.

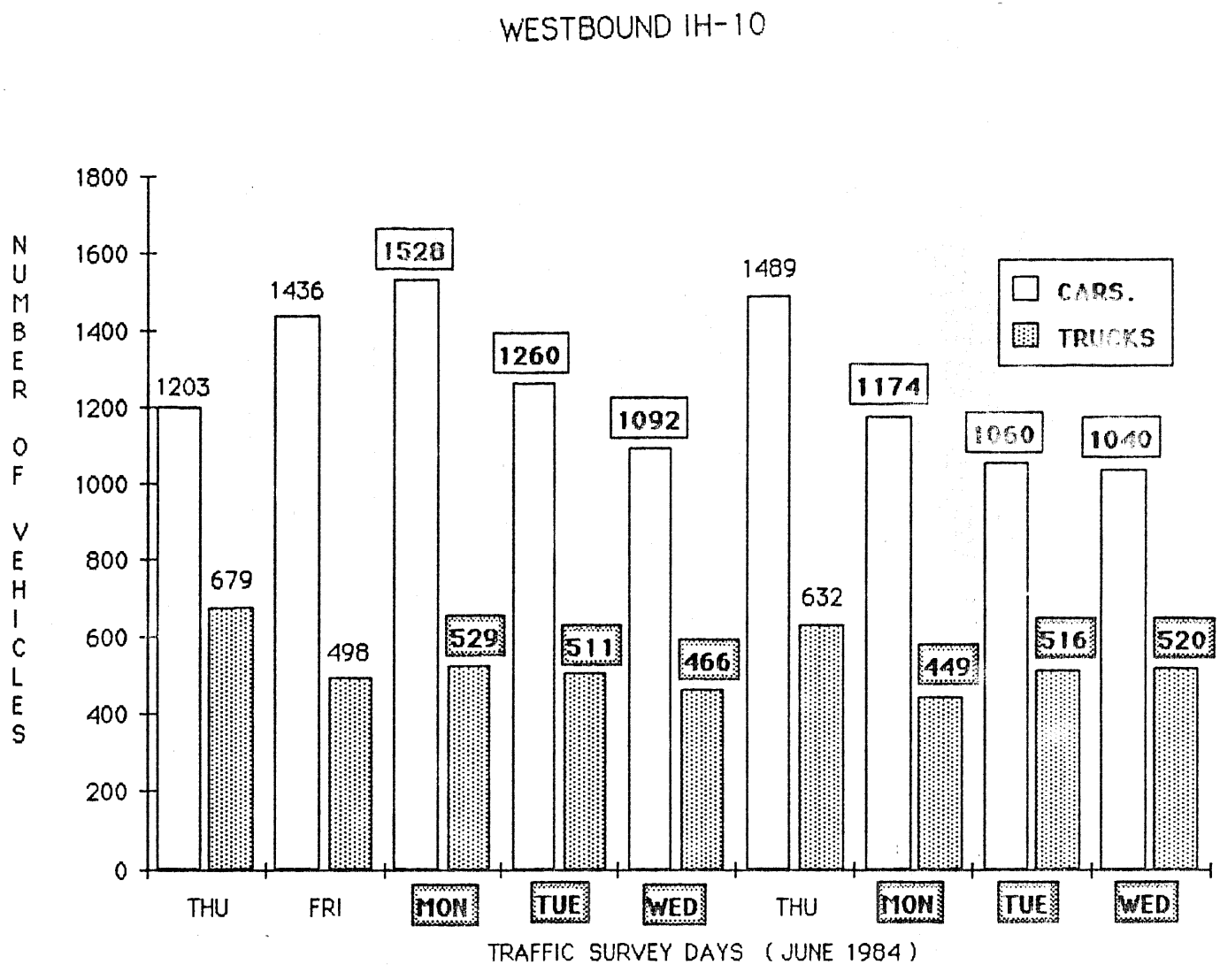


Figure 6-11. Daily traffic variation by vehicle class on westbound IH-10.

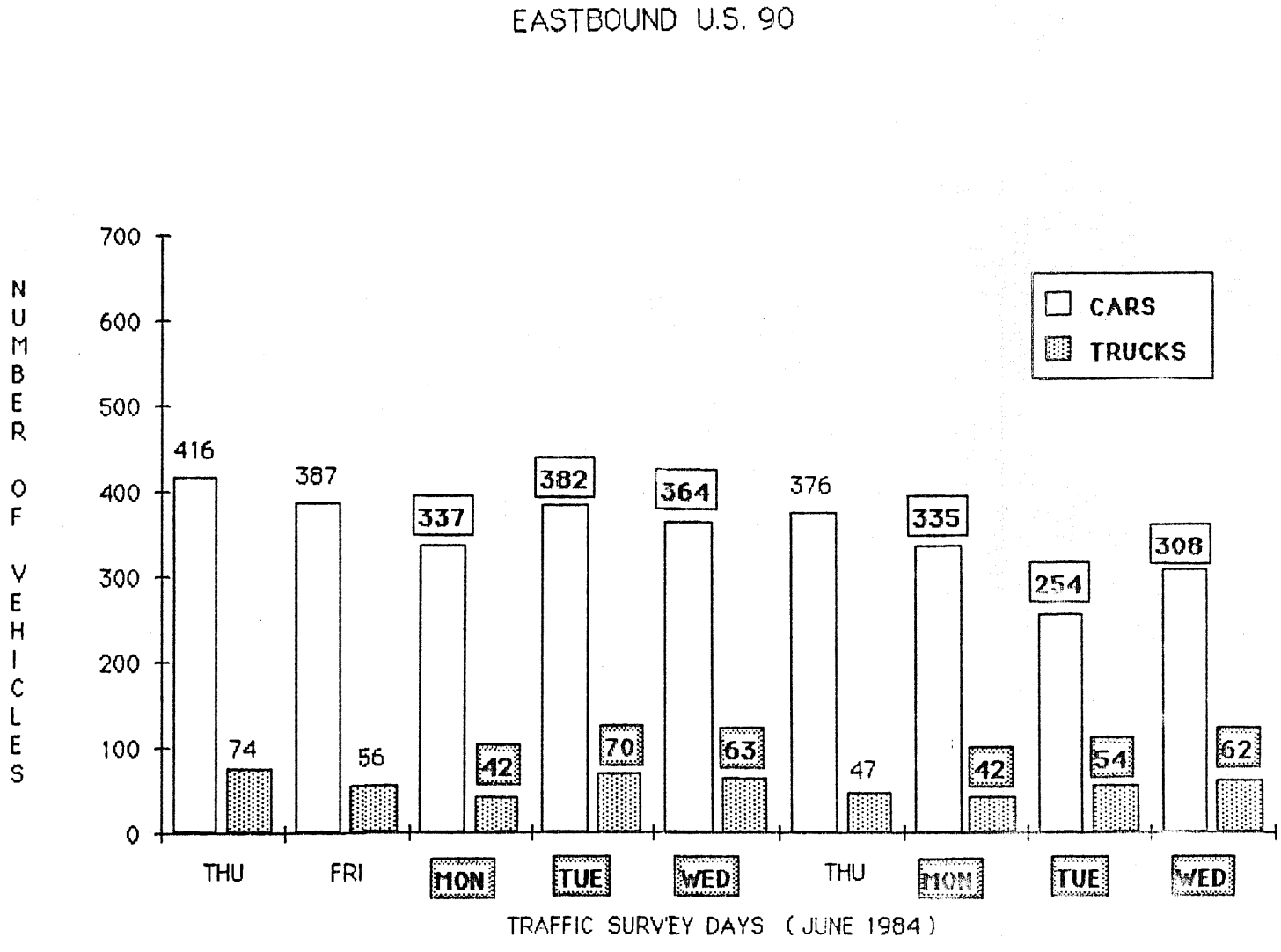


Figure 6-12. Daily traffic variation by vehicle class on eastbound U.S. 90.

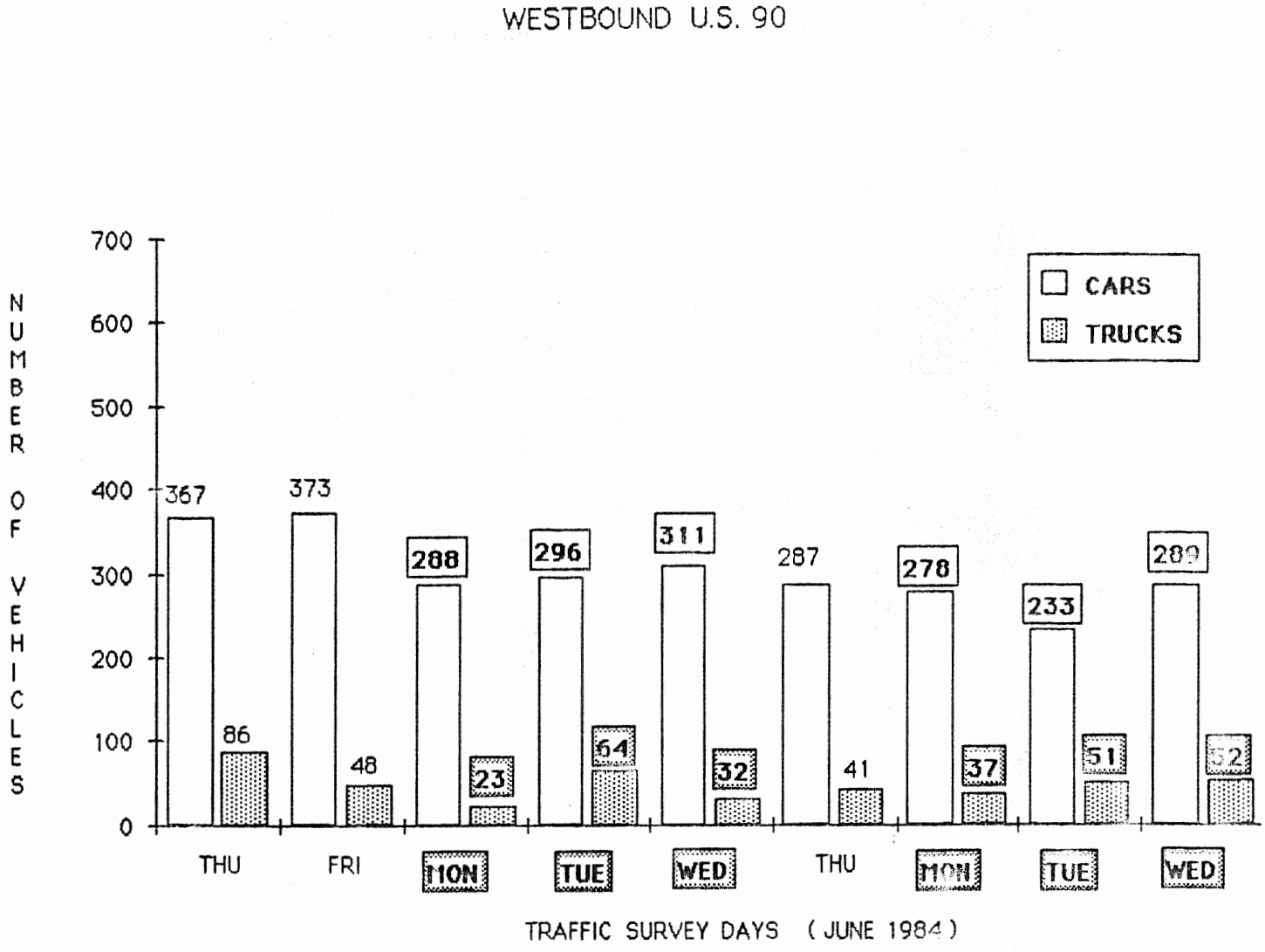


Figure 6-13. Daily traffic variation by vehicle class on westbound U.S. 90.

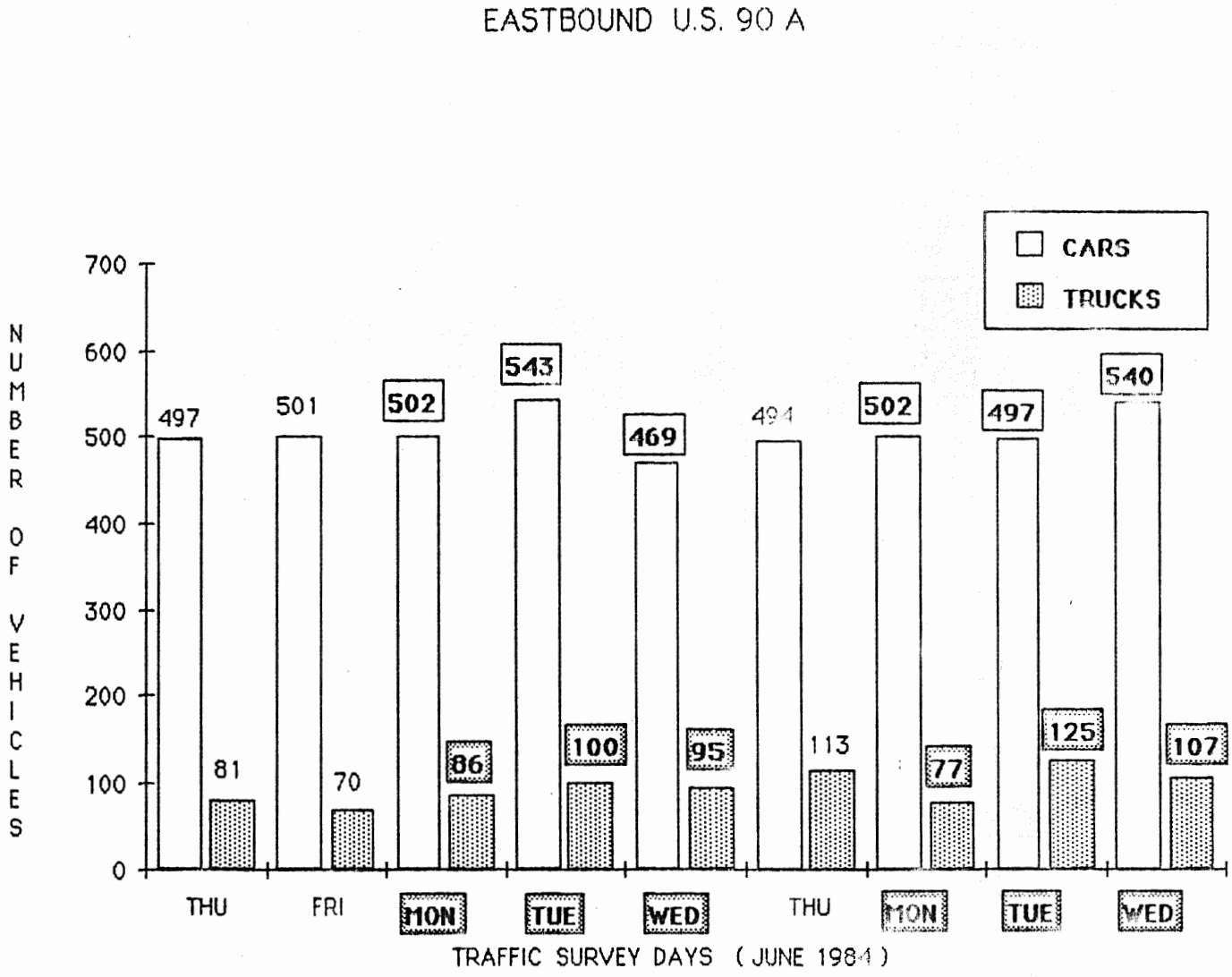


Figure 6-14. Daily traffic variation by vehicle class on eastbound U.S. 90A.

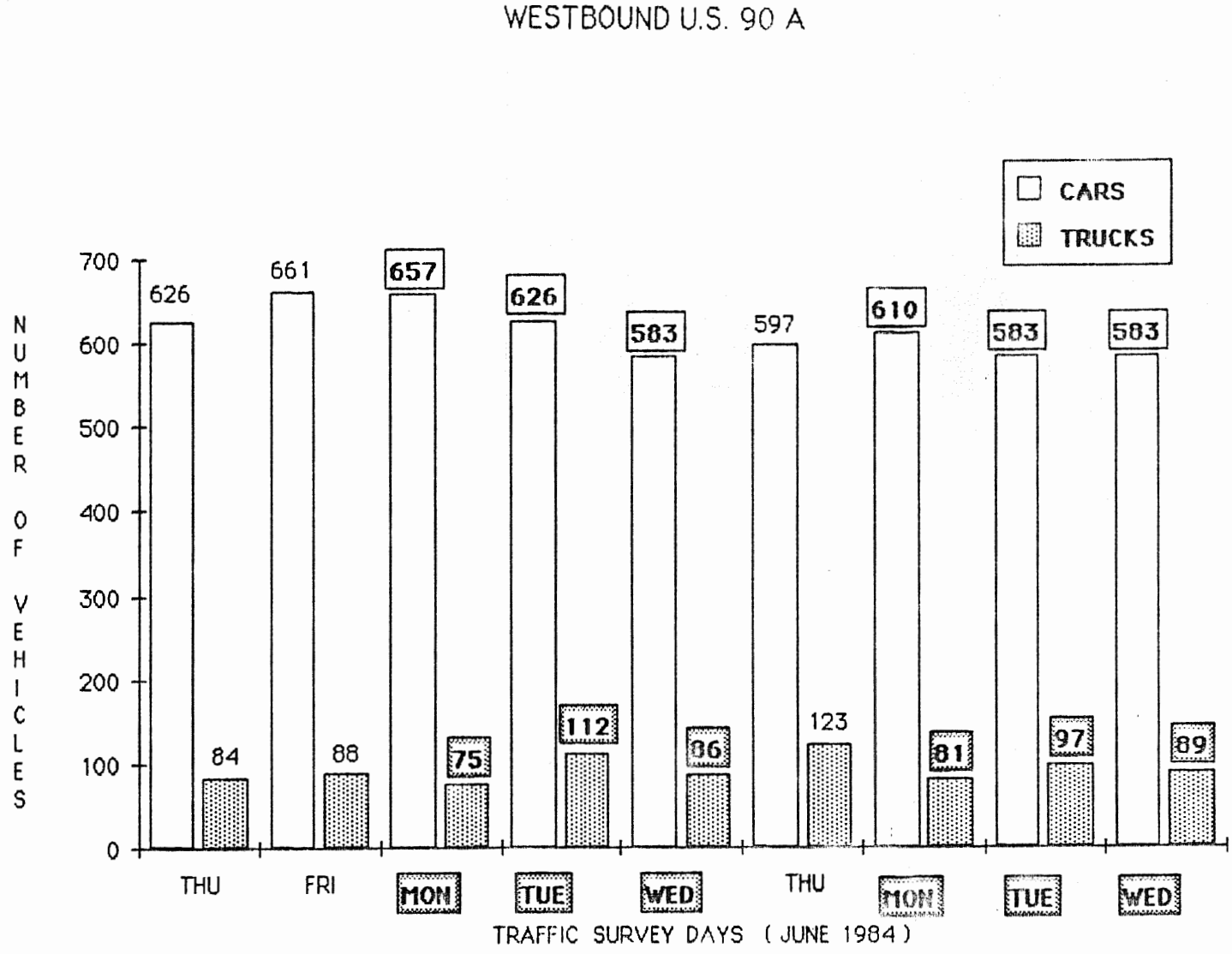


Figure 6-15. Daily traffic variation by vehicle class on westbound U.S. 90A.

TABLE 6-7. EASTBOUND TRUCKS AND PERCENTAGE OF TOTAL TRUCKS ON IH-10, U.S. 90A, AND U.S. 90 HIGHWAYS (7:00-3:00 P.M.)

Day/Date	IH-10		U.S. 90A		U.S. 90		Total Eastbound Trucks
	No. of Trucks	% of Eastbound Trucks	No. of Trucks	% of Eastbound Trucks	No. of Trucks	% of Eastbound Trucks	
Thu, 5/31	779	83%	81	9%	74	8%	100%
Fri, 6/1	797	86%	70	8%	56	6%	100%
Mon, 6/4**	587	82%	86	12%	42	6%	100%
Tue, 6/5*	576	77%	100	14%	70	9%	100%
Wed, 6/6*	626	80%	95	12%	63	8%	100%
Thu, 6/7	750	82%	113	13%	47	5%	100%
Mon, 6/11*	581	83%	77	11%	42	6%	100%
Tue, 6/12*	585	77%	125	16%	54	7%	100%
Wed, 6/13*	592	78%	107	14%	62	8%	100%

* Weigh Station Open
** Media Activity at Station

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CHAPTER 7. TRAFFIC LOADING PATTERN ON MULTILANE HIGHWAYS

INTRODUCTION

Highway pavements must be designed to withstand the combined stresses which result from external traffic loading and from internal volume changes in the pavement and subgrade materials. Since the cumulative damaging effects of stress variations over extended periods of time (i.e. the design life of the pavement) must be accounted for in pavement design and performance evaluation processes, adequate quantiative data concerning the stress-causing conditions in pavements are essential.

Historically, routine traffic surveys have not supplied the kind of detailed statistical data about traffic loading which was needed, particularly for multilane highways. Traffic loads are generally channelized into each lane of the roadway where they are applied to the pavement surface through the tires of moving or standing vehicles. The tire loads vary in magnitude, location, duration, frequency, and number of applications. In order to characterize these loads adequately, representative samples of data concerning vehicle speed, tire configurations and inflation pressures, wheel and axle weights, and number of repetitions of axles with different weights and spacings -- all with respect to time and lane -- are required. With static weighing and dimensioning techniques, it has been impossible to stop and weigh vehicles on a lanewise basis. The new 4-lane WIM system that was developed by the Radian Corporation and evaluated in this research project can, however, be used effectively to obtain such required data without stopping or delaying traffic.

This chapter describes a practicable technique for estimating the patterns of traffic loading in each lane of multilane highways. The essential statistical traffic data are obtained with the new weigh-in-motion (WIM) system which automatically measures vehicle speed and samples the dynamic tire forces of all, or selected, vehicles operating at normal road speeds in up to four highway lanes at a time. The system then instantaneouly computes, displays, and records estimates of static wheel and axle weights and classifies each vehicle by type according to the total number of axles on the vehicle and to the spacing between axles in any group (see Chapter 6). Since the system can operate automatically over extended periods of time without interference or hazard to traffic, a sampling program can be designed to reflect any important timewise variations in traffic patterns at any chosen site. The recorded digital data can then be transported either manually on magnetic disk or via telecommunication linkages between computers at various locations. The usual WIM data along with additional information concerning lanewise distribution of the traffic are arranged in a familiar format for conventional engineering and planning computations.

A procedure for converting samples of WIM data to estimated numbers of equivalent 18-kip single axle loads (ESALs) in each highway lane is outlined and illustrated with four multi-day data sets taken during 1984 and 1985 at

a 4-lane WIM site on IH-10 west of Seguin, Texas. The practicality of estimating ESALs from samples of truck classification data is also suggested, and steps for accomplishing this are included in a flow chart. A frequency distribution of axle weights on each class of truck must be utilized in this alternative method. To use the alternative method in practice, judgment must be exercised in selecting a reference WIM site which can be assumed to have trucks that are loaded comparably with those operating at the site where only classification data are available. Once this decision has been made, the ESAL computations are straightforward.

TRAFFIC SURVEYS

Traffic forecasting procedures usually project average daily vehicular traffic volumes for all lanes for both directions of travel on a highway. For pavement design and evaluation purposes, the truck traffic must be estimated and distributed by direction and by lanes. Directional distribution factors are developed from directional traffic volume counts on various types or classes of highways and used to estimate the directional flows which are to be accommodated at specific sites. Some policies suggest assigning half the total traffic to each direction unless conditions justify another directional split. Manual vehicle classification counts, which categorize each vehicle by type, then serve as a basis for estimating percentages of different types of vehicles in each directional traffic stream.

With regard to lane distribution, the objective is to further divide each directional flow and define the design traffic loading for each lane on a multilane highway. Design traffic loading needs to be described in terms of the cumulative number of wheel loads of given magnitude which can be expected in the lane during the design life of the pavement. Heavier wheel loads, which are usually associated with truck traffic, require stronger pavements, and each repetition of a heavy load causes relatively more damage than a lighter load; therefore, consideration must be given to the practicability of designing and constructing the pavement structure required for each lane. To do this, estimates of the lanewise distribution of traffic along with the frequency distribution of wheel loads of various magnitudes in each lane are required.

In arriving at a descriptive lane-distribution pattern for traffic loading on a section of roadway, it must be recognized that the lane placement which occurs at a given time and location results from each driver choosing to operate in a particular lane in response to a set of individual desires and to the constraints of the surrounding static and dynamic conditions. The basic tendency of most drivers seems to be towards driving in the right-hand lane while attempting to achieve and maintain comfortably the speed which is judged by the individual driver to be suitable for the roadway, terrain, and other prevailing conditions. When these desires can be realized more easily by traveling in another lane, an available lane to the left will usually be chosen. The decision by each individual driver to use a particular lane at any given time appears to be based on the momentary evaluation of a complex set of influencing factors -- some tangible (e.g., the legal speed limit, rough pavement surface, slower vehicles, other traffic, large vehicles, roadside obstructions) and some intangible (e.g., driver attitude, anxiety, frustration). The resulting pattern of lane distribution of vehicles on any selected highway section changes considerably with time. Both short-term and long-term fluctuations in this pattern must be recognized in estimating cumulative traffic loading in a lane over several future years.

The number of vehicles passing in each lane of a highway can be determined with conventional inductance loop detectors and recording traffic counters. While this information is very valuable, it is not sufficient for predicting the cumulative number of wheel loads of various magnitudes in a highway lane. The total number of wheels or axles must be estimated, and the magnitude of the load imposed on the pavement by each wheel or axle must be determined. Ideally, the wheel forces for each axle on every vehicle in each lane of a multilane highway would be measured, but this is not feasible, nor necessary for practical purposes. A suitable sampling process is required.

The new WIM system mentioned previously with four-lane weighing, dimensioning, and classifying capabilities was put into service by the Texas State Department of Highways and Public Transportation on 26 June 1984. This new WIM system, for the first time, provided, and will continue to provide, a practical means for obtaining directly the type of detailed directional and lanewise traffic data that are needed for predicting the design traffic loading on multilane highways. Representative samples of wheel and axle loads for selected classes of vehicles with respect to lane of operation and direction of travel can now be obtained periodically without interference to normal traffic flows.

With this site-specific weight information as a basis, lanewise vehicle counts and classification (according to axle arrangement) counts made at other comparable sites can be extrapolated to estimate the probable frequency of occurrence of wheel loads of given magnitudes in each highway lane over a period of time without actually measuring the loads. No easily-installed portable vehicle counting and classifying equipment which will function in a lane-by-lane mode on multilane highways is commercially available today. Application of such portable vehicle counter/classifiers in a properly designed sampling program can extend the coverage of the WIM survey system extensively and will also serve as a basis for identifying locations where truck traffic is significant and thus where additional WIM sites are needed. This concept, when implemented over a period of time which is sufficient to identify trends, will provide the type of detailed data upon which projections of design traffic loading for multilane highways at specific locations must be based.

ESTIMATION OF TRAFFIC LOADING

Among the most important factors to be evaluated in the structural design of highway pavements is the cumulative effect of traffic loading. Traffic loading consists of numerous passes of various vehicle types, usually classified according to axle configuration, in a highway lane within a selected traffic analysis period (20 years is often used). Each particular vehicle class has a statistically definable pattern of axle configuration, number of tires, axle spacing, axle load, and tire pressure. Furthermore, the lateral placement of the vehicle within the lane follows a stochastic pattern.

Most of the pavement design procedures which are now in general use have been based on theoretical considerations coupled with a complementary evaluation of cumulative traffic loading effects. Many of these procedures define the design thickness of the pavement as a function 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 axle load. The numerical factors

which relate the number of passes of a standard single-axle load which would be needed to cause pavement damage equivalent to that caused by one pass of a given axle load are called equivalent single axle load (ESAL) factors or traffic equivalence factors.

The equivalency factors that were derived from the AASHO Road Test [Ref 21] 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 [Ref 22]. The standard axle load used by AASHO is an 18-kip (80 kN) single-axle load. Analysis of the AASHO Road Test design equations [Ref 23] permits the determination of equivalency factors for both flexible and rigid pavements. These factors, which are modified and extended, will be utilized in the following procedure and therefore, are reviewed briefly here for both flexible and rigid pavements.

Flexible Pavement Equivalency Factors

The design equations for flexible pavements presented in the AASHO Interim Guide [Ref 23] are:

$$\log W_t = 5.93 + 9.36 \log(SN + 1) - 4.79 \log(L_1 + L_2) + 4.331 \log L_2 + G_t/\beta \tag{7-1}$$

$$\beta = 0.40 + \frac{0.081(L_1 + L_2)^{3.23}}{(SN + 1)^{5.19} L_2^{3.23}} \tag{7-2}$$

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

SN = structural number, an index number derived from an analysis of traffic, roadbed condition, and regional factor which may be converted to a thickness of flexible pavement layer coefficient that is 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,

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

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

$$P_t = 1.5, G_t = \log[(4.2 - P_t)/(4.2 - 1.5)] ,$$

β = a function of design and load variables that influences the shape of the p-versus-w serviceability curve, and

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).

As indicated above, for this design method the number of axle load repetitions to failure are expressed in terms of a pavement stiffness or rigidity value which is represented by Structural Number (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 serviceabilit, P_t, are 2.0 and 2.5.

The relationship between the number of applications of an 18-kip (80 kN) single-axle load (standard axle), W_{t18}, and the number of applications of any axle load, i, single or tandem, W_{ti}, to cause the same potential damage can be found from the following equation:

$$E_i = \frac{W_{t18}}{W_{ti}} \left[\frac{(L_1 + L_2)^{4.79}}{(18 + 1)^{4.79}} \right] \left[\frac{10^{G_t/\beta_{18}}}{(10^{G_t/\beta_i})L_2^{4.331}} \right] \quad (7\text{-}3)$$

The ratio shown in Eq 7-3 is defined as an equivalence factor, and is evaluated by solving the equation for any value i. Because the term b is a function of SN as well as L_i, the equivalence factor varies with SN.

Rigid Pavement Equivalency Factors

The basic equations for rigid pavements developed from the AASHO Road Test [Ref 23] are:

$$\log W_t = 5.85 + 7.35(\log D + 1) - 4.62 \log(L_1 + L_2) + 3.28 \log L_2 + G_t/\beta \quad (7\text{-}4)$$

and

$$\beta = 1.0 + \frac{3.63(L_1 + L_2)^{5.20}}{(D + 1)^{8.46} L_2^{3.52}} \quad (7\text{-}5)$$

where D = thickness of rigid pavement slab, inches,
$G_t = \log[(4.5 - P_t)/(4.5 - 1.5)]$,

and all other terms are defined above.

As can be seen from analyzing the two equations above, the pavement rigidity or stiffness value is expresed in terms of the pavement thickness, D.

The relationship between the number of passes of an 18-kip (80 kN) single-axle load and the number of passes of any axle load, i, single or tandem, to cause equivalent damage to a rigid pavement can be found from the following equation:

$$E_i = \frac{W_{t18}}{W_{ti}} \left[\frac{(L + L_2)^{4.62}}{(18 + 1)^{4.62}} \right] \left[\frac{10^{G_t/\beta_{18}}}{(10^{G_t/\beta_i})L_2^{3.28}} \right] \quad (7\text{-}6)$$

The ratio is defined as an equivalency factor, and is evaluated by solving Eq 7-6 for any value, i. Because the term b is a function of D as well as L_i, the equivalency factor varies with D.

As is illustrated in the following procedure, these factors are utilized to convert various magnitudes of axle loads to a common denominator by expressing the cumulative effect of the axle loads applied by mixed traffic as the sum of the effects that would be caused by a computed number of applications of an 18-kip (80kN) single-axle load.

A PROCEDURE FOR ESTIMATING TRAFFIC LOADING ON MULTILANE HIGHWAYS

A detailed procedure for using traffic survey data to estimate traffic loading in terms of the number of 18-kip (80 kN) single-axle load applications that will occur in each lane of a multilane highway in each direction is outlined below. It utilizes the following sets of information:

(1) frequency distributions for the weight of each axle on each class of truck in each lane from weight survey data,
(2) truck volume and classification (according to axle arrangement) data by lanes from vehicle classification surveys, and
(3) modified and extended AASHO axle-load equivalency factors.

Representative frequency distributions for the weight of each axle on each class (according to axle arrangement) of truck in each direction by lanes can be developed from WIM data or from any other adequate weight survey data which are obtained at representative weighing sites. Lanewise weight data can best be obtained with a multilane WIM system.

Statistical data related to the frequency with which various classes of vehicles operate in each lane of multilane highways can be obtained by sampling the operational patterns of various types of trucks. Manual observation and enumeration can be used to collect these data, or a technique for automatically classifying trucks can be utilized to supplement WIM data.

Appropriate equivalency factors can be applied to convert the numerical data concerning trucks and axles into estimates of the cumulative number of equivalent 18-kip (80 kN) single-axle loads in each lane, in each direction on multilane facilities for a selected period of time. With regard to suitable equivalency factors, the usual procedure for calculating equivalency factors for single-axle and tandem-axle sets from the AASHTO Road Test data is used.

A seperate set of equivalency factors for steering axle loads greater than 12 kips on flexible pavements that was developed recently [Ref 24] will also be used. This is appropriate as the data collection and analysis techniques employed at the AASHO Raod Test [Refs 21 and 22] combined the damage caused by the single-tired steering axle loadings up to 12 kips with the damage caused by the associated dual-tired axles in deriving equivalency factors. Charmichael, et al [Ref 24] developed equations, using Minor's hypothesis, which provide a means of separating such damage. They used a concept of pavement surface curvature and the resulting tensile strains in the asphalt mixture as a basis for computing equivalency factors for flexible pavements. In their analysis, single-tire loadings

generally produced somewhat more damage than the same loads on dual tires. This was also substantiated by Deacon's theoretical work [Ref 25]. He reported that axles with single tires are three times more damaging to flexible pavements than dual-tired axles with the same load. Because it is possible for steering axle loads to exceed those which were on the test trucks at the AASHTO Road Test (2 through 12-kips), their additional damaging effects should be assessed. The values adapted from Ref 24, as shown in Table 7-1, are applicable for this purpose.

In developing equivalency factors for tridem axles, Carmichael, et al utilized the curvature concept which had given good agreement with the AASHO factors for single and tandem axles on flexible pavements. A set of equivalency factors for tridem axles that agrees very closely with those in Ref 24 was calculated by setting $L_2 = 3$ in AASHO's flexible design equation (Eq 7-3). The results of these calculations are given as a rather complete set of equivalency factors for tridem axles on flexible pavements in Appendix B of Ref 26.

When applying the curvature concept to rigid pavements, Carmichael, et al found that the derived equivalency factors for single and tandem axle sets differed from the AASHTO values by a factor of two or more. They concluded that the curvature concept as they had used it was not applicable for this purpose. A set of equivalency factors for tridem axles on rigid pavements has been calculated by setting $L_2 = 3$ in AASHO's rigid pavement design equation (Eq 7-6). These values are shown in Appendix B of Ref 26. They appear to be reasonable, but they have not been validated through experimental work.

A procedure for estimating the truck traffic loading on multilane highways is outlined below in sequential order. The flowchart in Fig 7-1 shows schematically the order in which the traffic calculations proceed in order to estimate the total number of equivalent 18-kip (80-kN) single-axle loads in each lane during a selected period of time.

Steps in Estimating Lanewise Traffic Loading

(1) Obtain representative truck weight data from a selected weigh station(s) at which the patterns of truck traffic are similar to those at the location being analyzed.

(2) Develop a separate frequency distribution of axle weights for steering (heavier than 12 kips on flexible pavements), single, tandem, and tridem axles for each type of truck for each lane of determining the number of axle weights which fall into either 1-kip (4.45 kN) or 2-kip (8.9 kN) intervals.

(3) Multiply the number of axles of each type in each load interval for each type of truck by the appropriate equivalency factor to give the number of 18-kip equivalent single-axle loads (18-kip ESALs)

(4) Sum the number of equivalent 18-kip single-axle loads over all weight intervals for each type of truck and then divide these sums by the respective number of trucks of each type to obtain a series of weighted-average 18-kip ESAL factors.

(5) Adjust the weighted-average 18-kip ESAL factors for anticipated changes in truck weights during the analysis period. Use available prediction models, i.e., trend analysis, time series analsyis, etc., or engineering judgement as appropriate.

TABLE 7-1. 18-KIP EQUIVALENCY FACTORS FOR STEERING AXLE LOADS GREATER THAN 12 KIPS FOR FLEXIBLE PAVEMENTS (ADAPTED FROM REF 10)

Steering Axle Load		Terminal Present Serviceability Index, P_t			
kips	kN	1.5	2.0	2.5	3.0
2	8.9	Damaging Effects of Steering Axles Less than 12 Kips are Combined Into AASHO Dual-tire Equivalency Factors			
4	17.8				
6	26.7				
8	35.6				
10	44.5				
12	53.4				
14	62.3	0.92	0.86	0.93	0.94
16	71.2	1.42	1.31	1.33	1.28
18	80.1	2.12	1.94	1.90	1.74
20	89.1	2.95	2.52	2.44	2.16
22	97.9	4.02	3.35	3.15	2.70
24	106.8	5.29	4.40	3.95	3.28
26	115.7	6.73	5.49	4.82	3.89
28	124.6	8.31	6.67	5.83	4.59
30	133.4	10.19	8.05	6.80	5.23

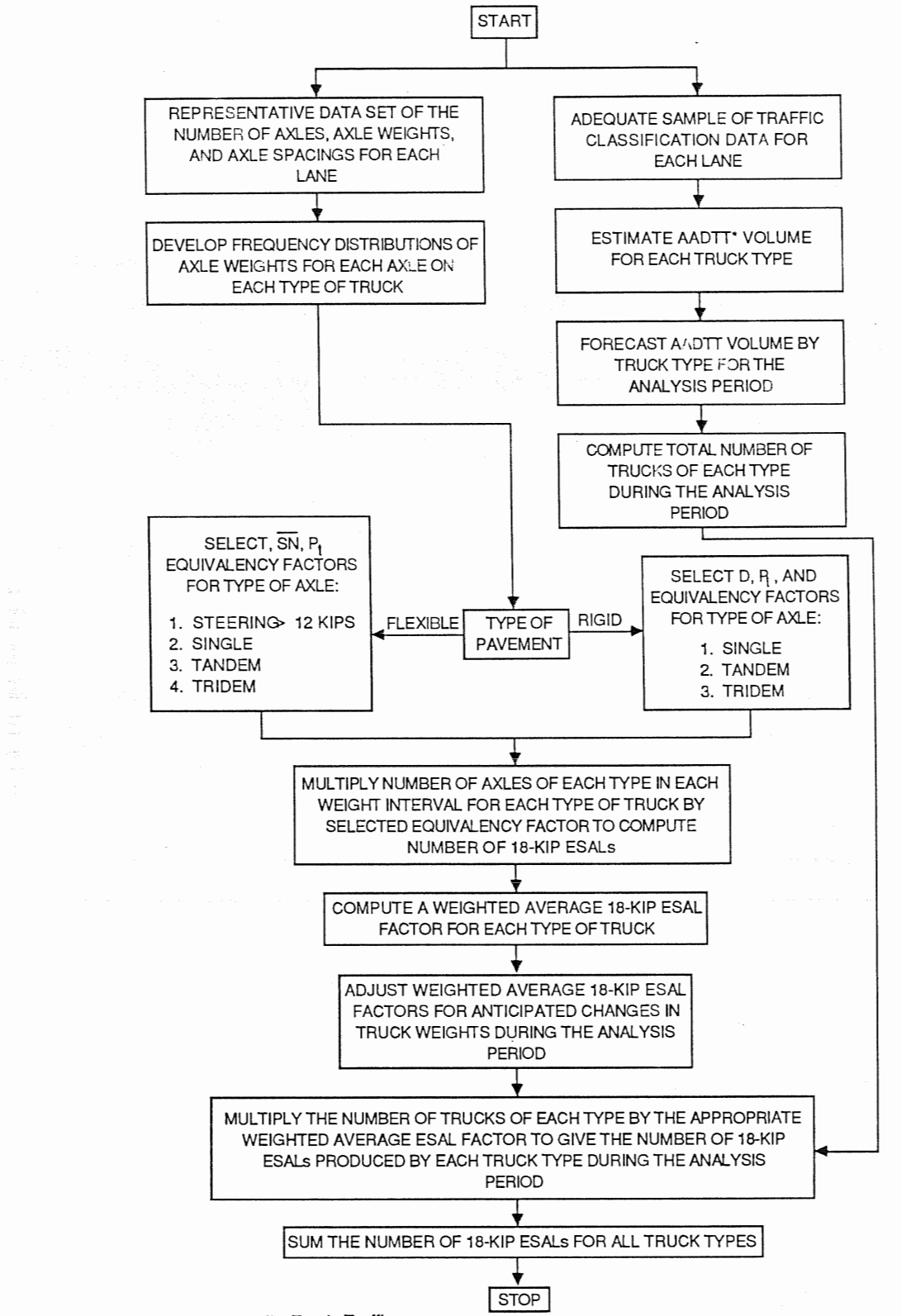

Figure 7-1. Flow chart of lanewise traffic load estimating procedure.

(6) Obtain an adequate sample of traffic classification data for each lane at a site where traffic loading is to be estimated.

(7) Estimate the Average Annual Daily Truck Traffic (AADTT) count of each truck type from the traffic classification data.

(8) Forecast AADTT volume of each truck type for the analysis period.

(9) Compute the total number of trucks of each type for the analysis period.

(10) Multiply the number of trucks of each type by the appropriate adjusted, weighted-average ESAL factors to give the number of equivalent 18-kip (80-kN) single-axle loads produced by each truck type during the analysis period.

(11) Sum the number of equivalent 18-kip single-axle loads over all types of trucks for each lane.

LOADING PATTERN ON A MULTILANE HIGHWAY

To illustrate the results of applying the procedure for defining the traffic loading pattern on a multilane highway, four multi-day WIM data sets which were taken periodically from 26 June 1984 through 11 July 1985 on IH-10 at Milepost 602 near Seguin, Texas are used. This survey site is located on a 4-lane rural freeway between Houston and San Antonio where trucks comprise some 35 percent of the total weekday traffic volume during daylight hours. From 1976 until the summer of 1984, WIM scales had been installed only in the right-hand westbound lane, and data samples had been taken periodically. WIM Scales were added in the remaining three lanes in May 1984 in preparation for the new 4-lane instrument system. The new system was operated for four periods as described above, and the recorded data were analyzed. The results of this analysis are summarized in the following tables.

Table 7-2 shows the results of applying the first four steps in the procedure to the observed data for all 2-axle, single-unit trucks in one lane. The total number of equivalent 18-kip single axle loads in the right-hand westbound lane during the six-day period in June 1984 is calculated and a weighted-average ESAL factor for this truck type at this site is determined. These steps were also carried out for all other truck types included in the other data sets.

The truck volumes of each type were factored to obtain an estimated average daily volume of trucks of each type in each lane, separately for each data set. These volumes are tabulated in Tables 7-3 thru 7-6 with the number of 18-kip ESAL's, for an 8-inch rigid pavement taken to a $P_t = 3.0$, that are attributable to each truck type in each lane during an averge day in each period. The weighted average ESAL factors for each truck type in each lane for an average day in each period are also given in parentheses in these tables along with the overall lanewise totals and the percentage of truck traffic and loads in each lane.

The directional distribution of truck traffic volumes at this site were nearly equal; however, the loading was about 40 percent heavier in the westbound direction. Approximately 80 percent of the traffic loading was in the right-hand lane in both directions. The predominant truck type at this site was the 5-axle combination tractor/semitrailer (3-S2). This truck type constituted about 77 percent of all trucks and accounted for approximately

TABLE 7-2. FREQUENCY DISTRIBUTIONS OF OBSERVED AXLE WEIGHTS, NUMBERS OF 18-KIP ESAL'S, AND WEIGHTED AVERAGE EQUIVALENCY FACTORS FOR 2-AXLE SINGLE-UNIT TRUCKS IN RIGHT-HAND WESTBOUND LANE

Steering Axles - No Separate Effects				
Drive Single Axles, Rigid Pavement, P_t = 2.5, D = 8.0 inches				
Axle Load Group, Kips	Axle Load, Kips	Equivalency Factor	Number of Axles	Number of Equivalent 18-Kip Single Axles
.5 - 1.5	1	.0000	0	0
1.5 - 2.5	2	.0002	0	0
2.5 - 3.5	3	.0008	4.	.00
3.5 - 4.5	4	.0022	7.	.02
4.5 - 5.5	5	.0051	18.	.09
5.5 - 6.5	6	.0104	34.	.35
6.5 - 7.5	7	.0193	39.	.75
7.5 - 8.5	8	.0332	45.	1.50
8.5 - 9.5	9	.0540	35.	1.89
9.1 - 10.5	10	.0838	30.	2.51
10.5 - 11.5	11	.1250	19.	2.38
11.5 - 12.5	12	.1805	20.	3.61
12.5 - 13.5	13	.2533	16.	4.05
13.5 - 14.5	14	.3468	20.	6.94
14.5 - 15.5	15	.4646	8.	3.72
15.5 - 16.5	16	.6102	7.	4.27
16.5 - 17.5	17	.7875	10.	7.87
17.5 - 18.5	18	1.0000	8.	8.00
18.5 - 19.5	19	1.2525	6.	7.51
19.5 - 20.5	20	1.5454	6.	9.27
20.5 - 21.5	21	1.8854	3.	5.66
21.5 - 22.5	22	2.2751	2.	4.55
22.5 - 23.5	23	2.7186	1.	2.72
23.5 - 24.5	24	3.2202	1.	3.22
24.5 - 25.5	25	3.7849	0	0
25.5 - 26.5	26	4.4187	1.	4.42
26.5 - 27.5	27	5.1280	0	0
TOTAL =			340	85.30
WEIGHTED-AVERAGE EQUIVALENCY FACTOR = 85.30/340 = 0.251				

TABLE 7-3. AVERAGE DAILY TRUCK VOLUME AND 189-KIP ESAL'S OF EACH TRUCK TYPE ON EACH LANE AND THEIR TOTAL PECENTAGES, JUNE 1984, IH-10, SEGUIN, TEXAS

TRUCK TYPE	AVERAGE DAILY TRUCK VOLUME				18-KIP ESAL's FOR AN AVERAGE DAY (RIGID PAVEMENT, p_t = 3.0, D = 8")			
	WESTBOUND		EASTBOUND		WESTBOUND		EASTBOUND	
	L1	L2	L3	L4	L1	L2	L3	L4
2A	57	9	10	64	14.48 (0.25)*	2.26 (0.24)	2.18 (0.21)	13.08 (0.21)
3A	21	5	3	22	6.18 (0.30)	0.64 (0.14)	1.96 (0.59)	11.21 (0.50)
2-S1	14	1	1	11	7.29 (0.53)	0.21 (0.16)	1.47 (0.98)	7.47 (0.65)
2-S2	38	5	5	35	27.75 (0.73)	3.04 (0.59)	5.15 (1.00)	27.31 (0.78)
3-S1	8	1	3	6	0.86 (0.11)	0.05 (0.03)	0.14 (0.04)	0.92 (0.16)
3-S2	495	118	117	496	731.66 (1.48)	184.52 (1.56)	191.19 (1.63)	798.52 (1.61)
3-S3	6	2	1	5	7.42 (1.20)	2.47 (1.48)	0.66 (0.99)	8.26 (1.71)
2-S1-2	13	1	1	12	18.12 (1.38)	3.83 (3.28)	1.16 (1.16)	24.17 (2.10)
3-S1-2	4	<1	1	4	5.08 (1.33)	0.37 (0.87)	0.73 (0.87)	3.54 (0.88)
Total	656	142	142	655	818.84 (1.25)	197.39 (1.39)	204.64 (1.44)	894.48 (1.37)
Percent	41	9	9	41	39	9	10	42

* Numbers in Parentheses are Weighted 18-kip ESAL Factors for an Average Day in December 1984.

TABLE 7-4. AVERAGE DAILY TRUCK VOLUME AND 18-KIP ESAL'S OF EACH TRUCK TYPE ON EACH LANE AND THEIR TOTAL PERCENTAGES, DECEMBER 1984, IH-10, SEGUIN, TEXAS

TRUCK TYPE	AVERAGE DAILY TRUCK VOLUME				18-KIP ESAL's FOR AN AVERAGE DAY (RIGID PAVEMENT, p_t = 3.0, D = 8")			
	WESTBOUND		EASTBOUND		WESTBOUND		EASTBOUND	
	L1	L2	L3	L4	L1	L2	L3	L4
2A	69	10	8	69	18.24 (0.26)*	2.17 (0.22)	1.91 (0.23)	11.97 (0.17)
3A	15	2	3	15	4.70 (0.30)	0.20 (0.12)	0.17 (0.06)	5.19 (0.35)
2-S1	8	1	2	7	3.19 (0.41)	0.88 (0.84)	0.64 (0.36)	1.98 (0.27)
2-S2	28	5	5	27	16.16 (0.59)	2.15 (0.46)	3.01 (0.63)	11.80 (0.43)
3-S1	4	1	3	3	0.27 (0.07)	0.05 (0.05)	0.14 (.04)	0.49 (0.15)
3-S2	389	109	124	410	619.48 (1.59)	207.50 (1.91)	156.65 (1.26)	413.58 (1.01)
3-S3	4	2	1	6	4.15 (0.85)	2.35 (1.24)	0.25 (0.41)	10.33 (1.45)
2-S1-2	3	1	1	5	6.62 (2.21)	1.47 (2.33)	0.58 (0.92)	5.39 (1.14)
3-S1-2	1	<1	<1	2	4.09 (3.24)	0.26 (0.83)	0.69 (1.47)	1.62 (0.79)
Total	521	131	147	544	676.9 (1.30)	217.03 (1.66)	164.04 (1.12)	472.35 (0.87)
Percent	39	10	11	40	44	14	11	31

* Numbers in Parentheses are Weighted 18-kip ESAL Factors for an Average Day in December 1984.

TABLE 7-5. AVERAGE DAILY TRUCK VOLUME AND 18-KIP ESAL'S OF EACH TRUCK TYPE ON EACH LANE AND THEIR TOTAL PERCENTAGES, JANUARY 1985, IH-10, SEGUIN, TEXAS

TRUCK TYPE	AVERAGE DAILY TRUCK VOLUME				18-KIP ESAL's FOR AN AVERAGE DAY (RIGID PAVEMENT, p_t = 3.0, D = 8")			
	WESTBOUND		EASTBOUND		WESTBOUND		EASTBOUND	
	L1	L2	L3	L4	L1	L2	L3	L4
2A	74	11	10	71	21.18 (0.26)*	1.86 (0.17)	2.62 (0.26)	15.31 (0.21)
3A	20	2	2	21	7.17 (0.35)	0.75 (0.31)	0.82 (0.34)	5.22 (0.25)
2-S1	9	2	1	8	4.60 (0.50)	0.52 (0.30)	0.42 (0.32)	2.83 (0.37)
2-S2	27	4	3	24	15.16 (0.56)	2.40 (0.68)	1.58 (0.46)	14.76 (0.62)
3-S1	4	1	3	2	0.63 (0.15)	0.16 (0.11)	0.23 (.08)	0.57 (0.24)
3-S2	411	85	89	375	728.66 (1.77)	168.53 (1.98)	126.01 (1.41)	449.05 (1.20)
3-S3	4	1	1	5	6.46 (1.74)	0.33 (0.38)	1.04 (0.81)	6.33 (1.27)
2-S1-2	4	1	1	5	9.62 (2.17)	0.67 (1.17)	1.89 (3.31)	6.83 (1.37)
3-S1-2	1	<1	<1	2	0.87 (0.87)	0.26 (1.84)	0.44 (1.03)	2.10 (1.15)
Total	554	107	110	513	794.55 (1.43)	175.48 (1.64)	135.05 (1.23)	553.0 (1.08)
Percent	43	8	9	40	48	11	8	33

* Numbers in Parentheses are Weighted 18-kip ESAL Factors for an Average Day in January 1985.

TABLE 7-6. AVERAGE DAILY TRUCK VOLUME AND 18-KIP ESAL'S OF EACH TRUCK TYPE ON EACH LANE AND THEIR TOTAL PERCENTAGES, JULY 1985

TRUCK TYPE	AVERAGE DAILY TRUCK VOLUME				18-KIP ESAL's FOR AN AVERAGE DAY (RIGID PAVEMENT, p_t = 3.0, D = 8")			
	WESTBOUND		EASTBOUND		WESTBOUND		EASTBOUND	
	L1	L2	L3	L4	L1	L2	L3	L4
2A	71	9	12	69	18.59 (0.26)*	2.19 (0.23)	2.43 (0.20)	14.18 (0.20)
3A	20	<1	3	23	9.51 (0.47)	1.47 (1.47)	0.10 (0.04)	7.64 (0.33)
2-S1	11	1	2	14	7.74 (0.73)	3.60 (2.70)	0.43 (0.26)	9.12 (0.64)
2-S2	50	8	5	54	29.84 (0.60)	4.08 (0.53)	3.19 (0.60)	32.4 (0.60)
3-S1	2	1	0	5	0.39 (0.19)	0.02 (0.04)	0 -	2.35 (0.50)
3-S2	737	152	161	742	1229.70 (1.67)	302.17 (1.99)	229.62 (1.42)	924.12 (1.24)
3-S3	10	3	1	11	9.44 (0.91)	2.79 (1.05)	0.47 (0.36)	13.83 (1.30)
2-S1-2	19	2	2	22	42.02 (2.17)	0.20 (0.10)	1.60 (0.80)	33.27 (1.51)
3-S1-2	6	<1	1	1	4.32 (0.76)	0.22 (0.66)	0.40 (0.40)	0.45 (0.45)
Total	926	176	187	941	1351.55 (1.46)	316.74 (1.80)	238.24 (1.27)	1037.36 (1.10)
Percent	42	8	8	42	46	11	8	35

* Numbers in Parentheses are Weighted 18-kip ESAL Factors for an Average Day in July 1985.

90, 95, and 80 percent of the loading on the outside lane in the westbound direction, inside lanes in both directions, and outside lane in the eastbound direction, respectively.

The truck traffic volume and the loading in July 1985 was about 74 percent and 78 percent, respectively, heavier than in January 1985. The average daily truck traffic volume in July 1985 was 1.75 times greater than that in January 1985 with 1,284 trucks. The lanewise distribution of truck traffic volume and traffic loading in December 1984 was somewhat different than that observed in January 1985. The average daily truck traffic volume in December was about 5 percent higher, but the loading was about 8 percent lighter than that in January 1985. These data sets emphasize the monthly and seasonal variability in the truck traffic volume and the loading pattern at this site. Figure 7-2 illustrates the seasonal variability in the truck traffic loading (in terms of 18-kip ESAL's), in each lane during an average day in each period.

SUMMARY

A step-by-step procedure for using data from a multilane weigh-in-motion (WIM) system as the basis for estimating lanewise traffic loading has been outlined and illustrated with data sets from the WIM site at Seguin, Texas on IH-10, Milepost 602. A procedure for using classification data as the basis for estimating cumulative weight patterns from traffic is also presented.

The timewise variability in traffic volume and loading pattern is illustrated. Traffic surveys, including WIM studies, must be scheduled and conducted in such a way that data-taking sessions reflect all significant variations adequately. These data are essential for forecasting the future traffic loading patterns that directly affect all decisions concerning the planning, financing, design, operation, maintenance, and management of highways.

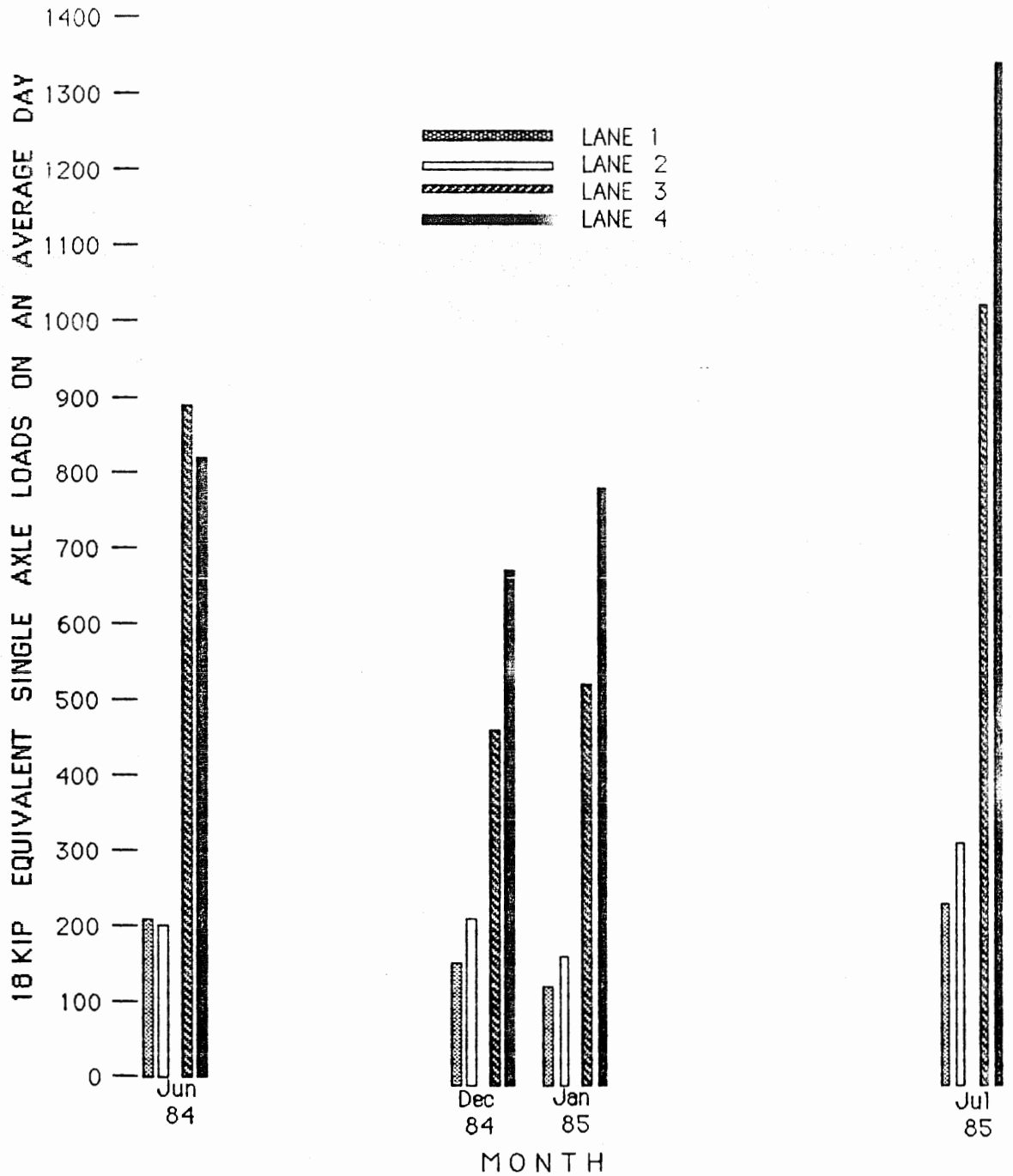

Figure 7-2. Average daily truck traffic loading (18-kip ESAL's) in each lane of IH-10, Seguin, Texas for four periods in 1984-1985.

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CHAPTER 8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The continuing need for accurate, representative samples of traffic loading data, coupled with an ongoing concern about the excessive damage to highway pavements by overweight trucks, stimulated this research project. The work relates to the practical application of weigh-in-motion technology as an efficient, safe, and economical means of obtaining vital vehicle weight and classification information for both statistical data and enforcement applications and to a study of static vehicle weighing techniques and equipment. Results of the effort are presented below.

SUMMARY

A major field experiment was conducted to evaluate the practicability of applying state-of-the-art weigh-in-motion (WIM) equipment for the above mentioned purposes. The experiment was designed to insure that a representative sample of empty and loaded trucks would be selected ramdomly from the traffic stream. A proportional sample of more than 800 trucks was drawn from the population of truck types at an enforcement station on a rural interstate highway in Texas for static and dynamic weighing and dimensioning. A unique 4-lane WIM system, which was developed especially for this project by the Radian Corporation, was used to measure dynamic tire forces, center-to-center spacings between successive axles on each truck, and overall truck length for speeds of approximately 55, 30, and less than 10 miles per hour. Three axle-load scales and three different types of wheel-load weighers were used to make static weight measurements. The time required to process each truck over each scale was measured and recorded to indicate the relative efficiency with which each weighing device and technique of use could perform under normal operating conditions. In addition, the center-to-center spacings between successive axles on each truck were measured with a steel tape.

Each scale that was used in the field experiment is described in Chapter 2. A specially-designed axle-load scale with two 4x6 foot, side-by-side platforms (the AX/WHL scale) was used as the basic reference scale against which all others were compared. The WIM scales were calibrated before the data-taking sessions began by using several runs of a loaded 2-axle dump truck of known weight. The axle-load scales were checked for accuracy by accumulating 15 standard 1,000-pound test blocks on each scale; these scales indicated correctly to within 20 pounds (the smallest reading shown) throughout the range of applied loads.

Adverse cross-slope of the pavement surface on the weigh strip surrounding the static scales was a matter of concern during the first two days of the data-taking sessions. It was felt that the 3-percent cross slope might affect the accuracy with which wheel, axle, and axle-group weights could be determined. After the second day of data taking, the existing asphalt concrete surface on the right-hand side of the weighing lane was removed, and the entire

lane was leveled with the axle-load scale platforms by using premixed asphalt concrete. This surface remained level for only two days in the hot summer weather under concentrated truck traffic. Considerable rutting occurred during the fifth day of data taking. The entire surface for some 400 feet surrounding the static scales and the low-speed weigh-in-motion (LSWIM) scales was replaced with hot-mixed asphalt concrete prior to the final day of data taking on a transversely and longitudinally level surface in July 1984. An evaluation of the effects of the transversely-warped weighing surface on weighing accuracy is presented in the report. As might be expected, the effect is most pronounced on wheel weights and less on axle-group and gross-vehicle weights.

Static Scales

The Texas Department of Public Safety (DPS) enforces weight and size regulations by weighing wheel, axle, axle-group, and gross-vehicle weights as well as measuring the spacing between adjaceant axles and the overall size of individual truck units. Data obtained in the field experiment with the static axle-load scales and wheel-load weighers which are used in routine enforcement programs are analyzed and presented in the report. Variability in the data are shown in graphical and tabular form, and overall use tolerances that would be indicated as appropriate when interpreting the readings from each type of weighing device are described. The results of a statistical analysis of the static weight data obtained in the experiment are summarized in Table 8-1. The AX/WHL scale mentioned above was used as the reference scale for these analyses.

Axle-Group (AX/GRP) Scale.

The range in the variability of weights from the flush-mounted AX/GRP scale, as shown in this table, indicates a tendency for this scale to show heavier weights for axle-group and gross-vehicle weights than the reference scale; this was true when the surface surrounding the scales was level as well as when it was warped slightly in the transverse direction (see Fig 3-5). In particular, trucks with gross-vehicle weights above about 50,000 pounds, and axle-group weights above about 15,000 pounds had higher readings on this scale than on the reference scale. The time required for weighing a truck on this scale averaged only 62 seconds as each axle group was weighed in a single stop. The use tolerance for gross-vehicle weights on this scale was 2,500 pounds at the 95 percent confidence level. This was the smallest value for all types of scales that were included in the experiment. The use tolerance derived for axle-group weights was 1,400 pounds. As a subgroup, 5-axle, tractor-semitrailer (3-S2) trucks were weighed heavier by this scale than were all trucks considered as a whole.

Axle-Group Ramped (AX/GRP RAM) Scale.

Every truck with a gross-vehicle and an axle-group weight of about 30,000 pounds and 12,000 pounds, respectively, was weighed heavier by this surface-mounted portable axle-load weigher than by the reference AX/WHL scale. The range in the variability at the 95 percent confidence level was less than 10 percent, however, for gross-vehicle and axle-group weights as shown in Table 8-1. The pronounced tendency of this scale to overweigh heavy axle-group loads resulted in comparatively large use tolerances. The gross-vehicle weight use tolerance of 5,100

TABLE 8-1. VARIABILITY, TOLERANCES, AND MEAN WEIGHING TIMES FOR STATIC SCALES

TYPE OF SCALE	WEIGHT	RANGE IN VARIABILITY WITH RESPECT TO MEAN DIFFERENCE IN WEIGHT, 95% CONFIDENCE, (%)	USE TOLERANCE (LBS)	MEAN WEIGHING TIME (SEC/TRUCK)
AX/WHL (Reference)	Gross-Vehicle Axle-Group			115
AX/GRP	Gross-Vehicle Axle-Group	-1.6 to +4.5 -3.8 to +6.4	2500 1400	62
AX/GRP (RAM)	Gross-Vehcile Axle-Group	-2.4 to +8.6 -3.4 to +10.2	5100 2300	55
WLW/M300	Gross-Vehicle Axle-Group	-9.9 to +11.2 -15.9 to +16.5	3850 1900	76
WLW/M400	Gross-Vehicle Axle-Group	-3.2 to +11.1 -5.9 to +14.7	4650 2450	91
WL/100	Gross-Vehicle Axle-Group	-4.9 to +7.6 -8.5 to +11.1	2750 1250	72

pounds was the largest of the values determined for scales evaluated in the experiment. Most of the steering (front) axles on 5-axle, tractor-semitrailer (3-S2) trucks indicated heavier weights on this scale than on the reference scale. This can be attributed almost certainly to the fact that these axles were raised approximately 4 inches onto the surface-mounted scale for weighing. The drive-tandem axle groups on these trucks were also weighed somewhat heavier on this scale in many cases. The average time required for weighing a truck (55 seconds) was slightly less than that for the flush-mounted AX/GRP scale described above.

Wheel-Load Weigher (WLW/M300).

When compared to the AX/WHL reference scale, the WLW/M300 wheel-load weigher performed on the average very consistently as the average percent difference in the gross-vehicle and axle-group weights were less than 1 percent. That is, there was no pronounced tendency for this roll-over type weigher to overweigh or underweigh within the range of loads that was measured. The range in the variability of axle-group and gross-vehicle weights at the 95 percent confidence level was the largest of any of the scales used in the experiment, however. These values were ±16 and ±10 percent, respectively. Some small, unknown portion of this variation in weights can be attributed to the 3-percent cross slope in the surface beyond the level 10-foot-long approach aprons around the reference scale and to the fact that these wheel-load weighers were operated on this same slope. Theoretically, the effect of this cross slope whould be less pronounced on axle-group and gross-vehicle weights since axle groups were weighed with all wheels in the group passing over the scales simultaneously. Use tolerances for the WLW/M300 that were developed from the device being used in an ordinary situation are shown in Table 8-1. These values are larger than those for the AX/GRP and the WL/100 scales, but smaller than those for the AX/GRP (RAM) and the WLW/M400 scales. The average time required for weighing a truck on this scale was 76 seconds.

Wheel-Load Weigher (WLW/M400).

On average, gross-vehicle and axle-group weights determined by this wheel-load weigher varied from those measured by the reference scale by less than 4.5 percent for the 38 trucks that were weighed. The deviations about the mean relative difference in these weights at the 95 percent confidence level, as shown in Table 8-1, are smaller than those for the WLW/M300 but larger than those for the WL/100. The use tolerances that were derived for this weigher on the basis of a relatively small sample of trucks being weighed in the experiment are larger than for either of the other wheel-load weighers. The front axles of 5-axle, tractor-semitrailer (3-S2) trucks were weighed heavier by this 3.25-inch high, surface-mounted device. The time required for weighing the axles or axle groups of each truck on this static scale averaged 91 seconds.

Wheel-Load Weigher (WL/100).

This low-height wheel-load weigher indicated gross-vehicle and axle-group weights that were, on average, somewhat higher than the corresponding weights from the reference scale. Variability in the weights from the WL/100 was less, however, than the weights from either of the other wheel-load weighers used in the experiment, but larger than that from the flush-mounted AX/GRP scale for gross-vehicle weights. The range in the variability of

axle-group and gross-vehicle weights at the 95 percent confidence level are shown in Table 8-1 for this weigher. The average weighing time for each truck on the WL/100 was 72 seconds.

Weigh-in Motion (WIM) Scales

The Radian WIM system was deployed in the experiment to weigh and dimension the same trucks operating at three different speed ranges -- approximately 55, 30, and less than 10 miles per hour. Analysis of the resulting data set provides a basis for evaluating the feasibility of using in-motion weighing for collecting statistical truck-weight and classification data and for weighing and dimensioning trucks for enforcement. The WIM system samples the dynamic force applied to the scale surface by the wheels of a moving vehicle and estimates the weight of these same wheels that would be measured by weighing on a static scale. On-site calibration of the WIM system is an important consideration as far as the attainable accuracy of the weight estimates is concerned. The importance of on-site calibration is illustrated in Chapter 5. Two basic types of calibration were used in the experiment: (1) static weight loading of the wheel-force transducers, and (2) dynamic loading of the transducers by the wheels of in-motion vehicle(s) with known static weights.

Analysis of the WIM data sets indicated that the static-weight calibration technique is adequate and practicable for the low-speed weigh-in-motion (LSWIM) scales. The in-motion calibration technique was used for the intermediate-speed (ISWIM) and the high-speed (HSWIM) systems. Considerable improvement in the accuracy of the mean value of static weight estimates resulted from using six loaded 5-axle, tractor-semitrailer (3-S2) trucks as the basis for calibration as compared to using multiple runs of the same loaded 2-axle, single-unit truck. The truck traffic population at the experimental site was made up of over 60 percent 3-S2 type trucks. The variability in WIM weight estimates was not affected appreciably by the type of truck utilized for in-motion calibration, however.

The range in the variability of axle-group and gross-vehicle weights at the 95 percent confidence level from a properly-calibrated WIM system at three traffic speeds is shown in Table 8-2. These values imply that tolerances of about ±4 percent (±1,350 pounds), ±6 percent (±1,450 pounds), and ±9 percent (2,200 pounds) are appropriate when interpreting the static weight estimates of gross-vehicle weight that will result from the LSWIM, ISWIM, and HSWIM scales, respectively. Similarly, tolerances of about ±9 percent, ±10 percent, and ±14 percent are applicable to axle-group weights. All the difference between the observed static weights and the WIM-estimated weights cannot be attributed to error in the WIM system, however, as recognition must be made of the fact that the gross weight of the vehicle was redistributed among the axles and wheels as the vehicle moved into position for successive weighing of its axles on the reference scale. This redistribution also occurred to some extent as the vehicle traversed the WIM scale transducers. There was a small, but consistent, increase in the variability of estimated static weights as speed increased, but speed had only a slight effect on the mean value of estimated static weight throughout the range of speeds observed in the experiment after the system had been properly calibrated with moving vehicles of known weight.

Some WIM systems measure the dynamic wheel forces on only one side of the vehicle and then double these values to estimate static axle weights. This raises a question about the side-to-side load distribution on truck axles. A study of static wheel weights that were measured on the special AX/WHL scale indicated that there was a

TABLE 8-2. VARIABILITY AND USE TOLERANCES WITH RESPECT TO MEAN VALUES FOR AXLE-GROUP AND GROSS-VEHICLE WEIGHTS FROM THE WIM SYSTEM

WIM SCALE	FACTOR	GROSS-VEHICLE WEIGHT	AXLE-GROUP WEIGHT	AXLE SPACING
LSWIM (10 mph)	Range in Variability, %	+3.8 to -4.1	+7.9 to -10.0	±26.4
	Tolerance, lbs	+1350 to -1350	-1950 to -2050	
ISWIM (30 mph)	Range in Variability, %	+5.4 to -6.8	+9.2 to -10.6	±15.9
	Tolerance, lbs	+1350 to -1550	+2450 to -3050	
HSWIM (55 mph)	Range in Variability, %	+7.6 to -10.3	+13.4 to -15.7	±7.3
	Tolerance, lbs	+2050 to -2400	+3250 to -4300	

statistically significant difference in the left and right-side wheel weights on the same axle. This finding implies that both wheels on every axle must be weighed and that each wheel-force transducer must be calibrated separately if the best attainable performance is to be realized from a WIM system.

Table 8-2 also includes the range in the variability of axle spacings at the 95 percent confidence level as computed by the Radian WIM system for traffic operating at three different speed ranges in comparison to corresponding axle spacings on the same trucks measured with a steel tape. Axle spacing is computed by the WIM system as a function of speed that is measured by inductance-loop type vehicle detectors placed in advance of the wheel force transducers. Any change in speed as the vehicle passes over the transducers affects the accuracy of axle-spacing calculations. Variation in calculated axle spacings was greatest for the low-speed (LSWIM) operations and considerably less for intermediate-speed (ISWIM) and high-speed (HSWIM) operations. The WIM-calculated axle spacings are considered to be sufficiently accurate for classifying vehicles according to number of axles per vehicle and axle spacing patterns for statistical data-gathering purposes and for identifying overlength vehicles and suspected violators of bridge-formula weight limits in enforcement operations.

Application of state-of-the-art WIM systems with the capability of weighing and dimensioning trucks in up to four highway lanes simultaneously makes it possible to collect the type and quantity of traffic data that are essential for the structural design of pavements and bridges. A step-by-step procedure for using multilane WIM data as the basis for estimating lanewise traffic loading is described and illustrated in Chapter 7 with four multi-day data sets from a rural interstate highway location in central Texas. These data indicate that significant variations in truck traffic volume and loading occurred at this site on a lanewise as well as on a seasonal basis. Although this conclusion cannot be generalized for all locations, it suggests that such timewise and lanewise variations may possibly exist regardless of the location. The analysis procedure for interpreting WIM statistical data samples and for forecasting traffic loading on a site-specific basis can be easily implemented. A procedure for combining representative WIM data with vehicle classification data to estimate traffic loading is outlined.

CONCLUSIONS

After analyzing the data from about 800 trucks that were selected from the population of truck types on a rural interstate highway in Texas and weighed statically on three different axle-load scales (including a special reference scale), on three different wheel-load weighers, and at three traffic speeds over a WIM system, the following conclusions are drawn.

1. The overall accuracy with which axle-group and gross-vehicle weights can be determined when using static axle-load scales and wheel-load weighers is not only a function of the accuracy of the weighing device itself, but also of the conditions and techniques of using the devices. Moving a vehicle usually changes the relative positions of its interconnected components due to such factors as torque in the drive train, friction in the brake and suspension systems, and unevenness in the road/scale surface. Gross-vehicle weight does not change as the vehicle is moved into position for successive weighing of its axles or groups of axles; however, the portion of the total weight that is carried by each wheel or axle at the time of each weighing changes.

2. Elevating or lowering (e.g., by deflection of the scale load-receiving platforms) an axle or axle-group that is being weighed causes a redistribution of the gross-vehicle weight among axles and thus affects tha actual force that is applied to the scale at the time of weighing. Location of the center of mass of the various vehicle components is affected by the tilting of the vehicle frame due to unevenness of the scale platform and to the displacement of suspension system components. Friction in the connectors between vehicle components also influences the proportion of gross-vehicle weight that is carried by the wheel or axle at the time of weighing.

3. Axle-by-axle static weighing of a vehicle on an axle-load scale or on wheel-load weighers that measure applied load within small tolerances does not necessarily result in axle-group or gross-vehicle weights which all fall within these same tolerances.

4. Gross-vehicle weights calculated by summing the applicable axle-group weights have less percentagewise variation than the individual axle-group weight observations. There appears to be an averaging effect due to the redistribution of gross-vehicle weight among axle groups during successive weighings of the groups.

5. The only way to measure axle-group and gross-vehicle weight to a very high degree of accuracy by successive positioning of the vehicle wheels on a scale (or weigher), or a series of scales, is to maintain all wheels of the vehicle in a horizontal plane and have no redistribution of weight during the weighing process. This is virtually impossible to achieve in practice.

6. In recognition of the fact that errorless performance of weighing equipment is unattainable, appropriate tolerances should be established to define an acceptable range of inaccuracy within which such equipment will be allowed to perform.

7. When compared to the AX/WHL (reference) scale, both the AX/GRP and the AX/GRP(RAM) scales generally indicated heavier weights than the reference scale

8. The WLW/M300 roll-over type wheel-load weigher performed on the average very consistently throughout the range of loads measured, but the range of variability in measured loads was extremely large.

9. The WLW/M400 static type wheel-load weigher indicated, on average, heavier weights then the other two wheel-load weighers used in the experiment, and the variation in indicated weights was greater than for the WL/100 but less than for the WLW/M300.

10. The WL/100 low-height wheel-load weigher performed, on average, with a small positive deviation in weight from the reference scale weights. The range in variability of weights was smaller than for the other two wheel-load weighers.

11. The new 4-lane WIM system which was developed for initial use in the experiment can be deployed effectively and efficiently for collecting truck weight and vehicle classification data that are essential to highway operations. A sampling program utilizing this system can be devised to provide the quality and quantity of statistical data that are needed on a statewide basis.

12. Proper on-site calibration of the WIM system is an important factor in attaining accurate static weight estimates. Considerable improvement in accuracy was attained when loaded 5-axle, tractor-semitrailer trucks were used as the basis for calibration as compared to the use of a single 2-axle, single-unit truck.

13. Static-weight calibration for low-speed weigh-in-motion (LSWIM) is adequate, and in-motion calibration is needed for intermediate-speed (ISWIM) and high-speed (HSWIM) weigh-in-motion systems.

14. The low-speed weigh-in-motion (LSWIM) system performed, on average, better than the AX/GRP(RAM) scale and about the same with respect to variability in weights. It performed better in both respects than all wheel-load weighers used in the experiment. It weighed more consistently than the flush-mounted AX/GRP scale throughout the range of loads measured, but it exhibited somewhat more variability. This implies that low-speed in-motion weighing can equal or better the weighing accuracy that is now being accepted as the basis for weight enforcement. Additionally, the time needed to weigh a truck moving at a low speed is very much less than that needed for static weighing.

15. The performance of the high-speed (HSWIM) weigh-in-motion scales is sufficiently accurate for use in gathering weight, size, and classification data for statistical applications and for identifying locations where oversize and overweight trucks operate for enforcement purposes. The WIM system can also be used effectively to sort suspected weight violators from the traffic stream for subsequent static weighing to determine actual violations in enforcement operations.

16. Implementation of combined statistical data-collection and enforcement operations is feasible. Improved efficiency and effectiveness of weighing programs will result from innovative utilization of WIM technology in this way. Properly designed, installed, and maintained equipment and adequately-scheduled weighing operations are basic requirements. Appropriate use of the equipment and interpretation of the measurements is equally important if satisfactory results are to be achieved with the WIM technique.

17. There is considerable evidence that static weighing operations associated with enforcement cause weight violators to by-pass the weigh site or otherwise avoid being weighed when possible. Such behavior at WIM sites where the transducers are in the main lanes continually and where enforcement activities are not conspicuous is much less prevalent.

18. There are significant monthly, seasonal, and lanewise variations in traffic loading in terms of the number of equivalent 18-kip single axle loads (ESAL's) and in traffic volume at specific sites on the highway network. Appropriate sampling plans must be utilized in statistical data-collection programs to recognize these variations and to account for them in estimating current and future traffic effects on structural design and maintenance activities.

RECOMMENDATIONS

Experience gained in the conduct of this research and an overview of the results obtained from analysis of the data sets warrants the following recommendations for future consideration.

1. For best accuracy, axle-load scales must be installed and maintained in a level, horizontal plane surface that is free of any unevenness. Wheel-load weighers and portable axle-load scales should be operated on the most nearly-level surface that is feasible.

2. Appropriate use tolerances for axle-group and gross-vehicle weights must be applied when using axle-load scales or wheel-load weighers as the basis for enforcement. These tolerances should be determined carefully to assure

that proper allowance is made for the probable inaccuracies which might occur in routine enforcement weighing operations.

3. Standard procedures for on-site calibration of every WIM system installation should be developed. The type, or types, of calibration vehicles and the number of passes over the transducers at what speed, or speeds, must be defined within the procedure. This calibration process should be applied upon initial installation of the transducers at every site and periodically thereafter if the WIM system is operated over extended periods of time.

4. The WIM benefits of improved safety, reduced delay, efficiency, ease of operation, and overall economy and accuracy in data acquisition all recommend extension and/or adoption of WIM systems into statistical data collection and enforcement programs. The magnitude of accuracy demonstrated by weigh-in-motion systems appears entirely adequate at high speeds for traffic safety purposes and at low speed for enforcement applications, particularly when the feasibility of taking up to 100 percent samples for extended periods of time on each lane of a multilane highway is considered. Standards of accuracy and tolerances should be developed for various types of WIM systems and installations.

5. Procedures for processing, storing, analyzing, and interpreting WIM data in such a way that pertinent information is gleaned from the raw data in an efficient and economical way are needed. The practicability of utilizing vehicle classification data in combination with WIM data for estimating traffic loading at sites where it is not feasible to weigh vehicles directly should be investigated.

6. Routine WIM opeations should be planned so that 24-hour weight and volume data are obtained continuously for a seven-day period each calendar quarter for at least three years. These data sets should be analyzed for loading patterns and trends, and revised small sample procedures should be developed for continuing surveys at these sites. Improved procedures should be developed for using WIM and vehicle-classification data for estimating future traffic loading at specific sites on the highway network.

7. Truck weight studies should be coordinated at the national level to attain maximum benefits from WIM systems technology and applications. Research should be continued to advance the state-of-the-art in WIM equipment and data processing, and especially in the timely interpretation and application of traffic data in design and enforcement operations.

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APPENDIX A.
COMPUTER PROGRAM LISTING OF THE SHAPIRO-WILK TEST FOR NORMALITY

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```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION X(2000),A(1500),Y(2000),RANGE(4),ICHAR(1)
      DOUBLE PRECISION XBAR, SSQX, DIFF
      DIMENSION ITITLE(7),IXLABL(3),IYLABL(2)
      DATA IXLABL/'I-TH ORDER',' STATISTIC',' X(I)     '/
      DATA IYLABL/'STD NORMAL',' QUANTILE '/
      DATA IPLUS/1H+/
      NXDIM = 2000
      REWIND 5
C
C*** READ IN THE DATA
C
      N = 0
C
C*** DATA SET TITLE
C
      READ (5,5,END=20) ITITLE
5     FORMAT (7A10)
C
C*** SUCCESSIVE OBSERVATIONS
C
10    READ (5,100,END=20) (X(I),I=N+1,N+10)
100   FORMAT(10(2X,F8.4))
      N = N + 10
      IF (N .GT. NXDIM) THEN
         WRITE (6,*) ' MAXIMUM SAMPLE SAMPLE SIZE EXCEEDED'
         STOP
      END IF
      GO TO 10
C
C*** SORT THE X-VALUES IN ASCENDING ORDER
C
20    DO 40 I=N-10,N
      IF (X(I) .EQ. 0.0) GO TO 50
 40   CONTINUE
      GO TO 60
 50   N = I - 1
 60   IF (N .EQ. 0) THEN
         WRITE (6,*) ' DATA SET EMPTY'
         STOP
      END IF
      CALL VSRTA(X,N)
C
C*** PERFORM THE SHAPIRO-WILK TEST FOR NORMALITY
C
      N2 = N/2
C   DOUBLE-PRECISION COMPUTATION OF SUM OF SQUARED DEVIATIONS
C   ABOUT THE SAMPLE MEAN
C
      XBAR = 0.0
      SSQX = 0.0
      DO 200 I = 1, N
      XBAR = XBAR + DBLE(X(I))
200   CONTINUE
      XBAR = XBAR/(DBLE( FLOAT(N) ))
```

```
      DO 210 I=1,N
      DIFF = DBLE(X(I)) - XBAR
      SSQX = SSQX + DIFF*DIFF
210   CONTINUE
C
C   CONVERT THE FINAL RESULT TO SINGLE PRECISION
C
      SSQ = SNGL( SSQX )
C
C   SET UP THE A-COEFFICIENTS FOR THE SHAPIRO-WILK TEST
C
      CALL WCOEF(A,N,N2,EPS,IFAULT)
      IF (IFAULT .NE. 0) THEN
         WRITE (6,*) ' FAULT INDICATION ',IFAULT,' IN COMPUTING A(.) '
         STOP
      END IF
C
C   PERFORM EXTENDED SHAPIRO-WILK TEST
C
      CALL WEXT(X,N,SSQ,A,N2,EPS,W,PW,IFAULT)
      IF (IFAULT .NE. 0) THEN
         WRITE (6,*) ' FAULT INDICATION ',IFAULT,' IN NORMALITY TEST'
         STOP
      END IF
      WRITE (6,230) ITITLE
230   FORMAT ('1'///1X,7A10//' THE ORDERED DATA --')
      WRITE (6,240) (X(I),I=1,N)
240   FORMAT (1X,8(G13.6,2X))
      WRITE (6,*) ' '
      WRITE (6,*) ' SAMPLE SIZE = ',N
      WRITE (6,*) ' SAMPLE MEAN = ',SNGL(XBAR)
      VAR = SSQ/FLOAT(N-1)
      WRITE (6,*) ' SAMPLE VARIANCE = ',VAR
      WRITE (6,*) ' THE COMPUTED VALUE W = ',W
      WRITE (6,*) ' HAS SIGNIFICANCE PROBABILITY ',PW
C
C***  NOW GENERATE THE NORMAL PROBABILITY PLOT FOR THIS SAMPLE
C
C
C*** SET UP THE Y-VALUES CORRESPONDING TO THE N(0,1) DISTRIBUTION
C
      RN= N
      DO 30 I=1,N
      RI = I
      Q = (RI - 0.5)/RN
      CALL MDNRIS(Q,Y(I),IER)
      IF (IER .GT. 0) THEN
         WRITE (6,*) ' ERROR NUMBER ',IER,' IN INVERSE NORMAL CDF'
         STOP
      END IF
30    CONTINUE
C
C*** GENERATE THE NORMAL PROBABILITY PLOT
C
      IY = NXDIM
```

```
      M = 1
      INC = 1
      NTITLE = 70
      NXLABL = 30
      NYLABL = 20
      RANGE(1) = X(1)
      RANGE(2) = X(N)
      RANGE(3) = Y(1)
      RANGE(4) = Y(N)
      ICHAR(1) = IPLUS
      IOPT = 1
      CALL USPLO(X,Y,IY,N,M,INC,ITITLE,NTITLE,IXLABL,NXLABL,
     $           IYLABL,NYLABL,RANGE,ICHAR,IOPT,IER)
      IF (IER .GT. 0 ) THEN
         WRITE (6,*) ' ERROR NUMBER ', IER, ' IN PLOTTING ROUTINE'
         STOP
      END IF
      STOP
      END
      SUBROUTINE WEXT(X,N,SSQ,A,N2,EPS,W,PW,IFAULT)
C
C  ALGORITHM AS 181 APPLIED STATISTICS (1982) VOLUME 31, NO. 2
C
C  CALCULATES SHAPIRO-WILK W STATISTIC AND ITS SIGNIFICANCE LEVEL
C
      REAL X(N),A(N2),LAMDA,WA(3),WB(4),WC(4),WD(6),WE(6),WF(7),
     $  C1(5,3),C2(5,3),C(5),UNL(3),UNH(3)
      INTEGER NC1(3),NC2(3)
      LOGICAL UPPER
      DATA WA(1),WA(2),WA(3)
     $  /0.118898, 0.133414, 0.327907/,
     $   WB(1),WB(2),WB(3),WB(4)
     $  /-0.37542, -0.492145, -1.124332, -0.199422/,
     $   WC(1),WC(2),WC(3),WC(4)
     $  /-3.15805, 0.729399, 3.01855, 1.558776/,
     $   WD(1),WD(2),WD(3),WD(4),WD(5),WD(6)
     $  /0.480385, 0.318828, 0.0, -0.0241665, 0.00879701, 0.002989646/,
     $  WE(1),WE(2),WE(3),WE(4),WE(5),WE(6)
     $  /-1.91487, -1.37888, -0.04183209, 0.1066339, -0.03513666,
     $   -0.01504614/,
     $   WF(1),WF(2),WF(3),WF(4),WF(5),WF(6),WF(7)
     $  /-3.73538, -1.015807, -0.331885, 0.1773538, -0.01638782,
     $   -0.03215018, 0.003852646/
      DATA C1(1,1), C1(2,1), C1(3,1), C1(4,1), C1(5,1),
     $     C1(1,2), C1(2,2), C1(3,2), C1(4,2), C1(5,2),
     $     C1(1,3), C1(2,3), C1(3,3), C1(4,3), C1(5,3) /
     $     -1.26233, 1.87969, 0.0649583, -0.0475604, -0.0139682,
     $     -2.28135, 2.26186, 0.0, 0.0, -0.00865763,
     $     -3.30623, 2.76287, -0.83484, 1.20857, -0.507590/
      DATA C2(1,1), C2(2,1), C2(3,1), C2(4,1), C2(5,1),
     $     C2(1,2), C2(2,2), C2(3,2), C2(4,2), C2(5,2),
     $     C2(1,3), C2(2,3), C2(3,3), C2(4,3), C2(5,3) /
     $     -0.287696, 1.78953, -0.180114, 0.0, 0.0,
     $     -1.63638, 5.60924, -3.63738, 1.08439, 0.0,
     $     -5.991908, 21.04575, -24.58061, 13.78661, -2.835295/
```

```
      DATA UNL(1), UNL(2), UNL(3)/-3.8, -3.0, -1.0/,
     $     UNH(1), UNH(2), UNH(3)/8.6, 5.8, 5.4/
      DATA NC1(1), NC1(2), NC1(3)/5,5,5/,
     $     NC2(1), NC2(2), NC2(3)/3, 4, 5/
      DATA PI6/1.90985932/, STQR/1.04719755/, UPPER/.TRUE./,
     $     ZERO/0.0/, TQR/0.75/, ONE/1.0/, ONEPT4/1.4/, THREE/3.0/,
     $     FIVE/5.0/
      IFAULT = 1
      PW = ONE
      W = ONE
      IF (N.LE. 2) RETURN
      IFAULT = 3
      IF (N/2 .NE. N2) RETURN
      IFAULT = 2
      IF (N .GT. 2000) RETURN
C
C       CALCULATE W
C
      IFAULT = 0
      W = ZERO
      AN = N
      I = N
      DO 10 J=1,N2
      W = W + A(J)*(X(I) - X(J))
      I = I - 1
10    CONTINUE
      W = W*W/SSQ
      IF (W .LT. ONE) GO TO 20
      W = ONE
      RETURN
C
C      GET SIGNIFICANCE LEVEL OF W
C
20    IF (N .LE.6) GO TO 100
C
C      N BETWEEN 7 AND 2000 ... TRANSFORM W TO Y, GET MEAN AND STANDARD
C      DEVIATION, STANDARDIZE, AND GET SIGNIFICANCE LEVEL
C
      IF (N .GT. 20) GO TO 30
      AL = ALOG(AN) - THREE
      LAMDA = POLY(WA,3,AL)
      YBAR = EXP(POLY(WB,4,AL))
      SDY = EXP(POLY(WC,4,AL))
      GO TO 40
30    AL = ALOG(AN) - FIVE
      LAMDA = POLY(WD,6,AL)
      YBAR = EXP(POLY(WE,6,AL))
      SDY = EXP(POLY(WF,7,AL))
40    Y = (ONE-W)**LAMDA
      Z = (Y-YBAR)/SDY
      PW = ALNORM(Z,UPPER)
      RETURN
C
C
C      DEAL WITH N LESS THAN 7 (EXACT SIGNIFICANCE LEVEL FOR N = 3)
```

```
C
100   IF (W .LE. EPS) GO TO 160
      WW = W
      IF (N .LE. 3) GO TO 150
      UN = ALOG((W-EPS)/(ONE-W))
      N3 = N - 3
      IF (UN .LT. UNL(N3)) GO TO 160
      IF (UN .GE. ONEPT4) GO TO 120
      NC = NC1(N3)
      DO 110 I = 1, NC
110   C(I) = C1(I,N3)
      EU3 = EXP(POLY(C,NC,UN))
      GO TO 140
120   IF (UN .GT. UNH(N3)) RETURN
      NC = NC2(N3)
      DO 130 I = 1, NC
130   C(I) = C2(I,N3)
      UN = ALOG(UN)
      EU3 = EXP(EXP(POLY(C,NC,UN)))
140   WW = (EU3 + TQR)/(ONE + EU3)
150   PW = PI6 *(ATAN(SQRT(WW/(1.0-WW))) - STQR)
      RETURN
160   PW = ZERO
      RETURN
      END
C
      SUBROUTINE WCOEF(A,N,N2,EPS,IFAULT)
C
C      ALGORITHM AS 181.1 APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
C      OBTAIN ARRAY A OF WEIGHTS FOR CALCULATING W
C
      REAL A(N2), C4(2), C5(2), C6(3)
      DATA C4(1),C4(2)/0.6869,0.1678/,C5(1),C5(2)/0.6647,0.2412/,
     $  C6(1),C6(2),C6(3)/0.6431,0.2806,0.0875/
      DATA RSQRT2/0.70710678/, ZERO/0.0/, HALF/0.5/, ONE/1.0/,
     $ TWO/2.0/, SIX/6.0/, SEVEN/7.0/, EIGHT/8.0/, THIRT/13.0/
      IFAULT = 1
      IF (N .LE. 2) RETURN
      IFAULT = 3
      IF (N/2 .NE. N2) RETURN
      IFAULT = 2
      IF (N .GT. 2000) RETURN
      IFAULT = 0
      IF (N .LE. 6) GO TO 30
C
C
C      N .GT. 6 CALCULATE RANKITS USING APPROXIMATE ROUTINE
C      NSCOR2 (AS 177)
C
      CALL NSCOR2(A,N,N2,IFAULT)
      SASTAR = ZERO
      DO 10 J=2,N2
10    SASTAR = SASTAR + A(J)*A(J)
      SASTAR = SASTAR *EIGHT
```

```
      NN = N
      IF (N .LE. 20) NN = NN - 1
      AN = NN
      A1SQ = EXP(ALOG(SIX*AN + SEVEN) - ALOG(SIX*AN + THIRT)
     $   + HALF*(ONE +(AN-TWO)*ALOG(AN+ONE) - (AN - ONE)
     $   *ALOG(AN+TWO)))
      A1STAR = SASTAR /(ONE/A1SQ - TWO)
      SASTAR = SQRT(SASTAR + TWO *A1STAR)
      A(1) = SQRT(A1STAR)/SASTAR
      DO 20 J = 2, N2
20    A(J) = TWO*A(J)/SASTAR
      GO TO 70
C
C      N .LE. 6 USE EXACT VALUES FOR WEIGHTS
C
30    A(1) = RSQRT2
      IF (N .EQ. 3) GO TO 70
      N3 = N - 3
      GO TO (40, 50, 60), N3
40    DO 45 J=1,2
45    A(J) = C4(J)
      GO TO 70
50    DO 55 J=1,2
55    A(J) = C5(J)
      GO TO 70
60    DO 65 J=1, 3
65    A(J) = C6(J)
C
C      CALCULATE THE MINIMUM POSSIBLE VALUE OF W
C
70    EPS = A(1)*A(1)/(ONE - ONE/FLOAT(N))
      RETURN
      END
C
      FUNCTION POLY(C,NORD,X)
C
C      ALGORITHM AS 181.2 APPLIED STATISTICS (1982) VOL. 31, NO. 2.
C
C      CALCULATES THE ALGEBRAIC POLYNOMIAL OF ORDER NORD-1 WITH ARRAY
C      OF COEFFICIENTS C.  ZERO ORDER COEFFICIENT IS C(1).
C
      REAL C(NORD)
      POLY = C(1)
      IF (NORD .EQ. 1) RETURN
      P = X*C(NORD)
      IF (NORD .EQ. 2) GO TO 20
      N2 = NORD- 2
      J = N2 + 1
      DO 10 I = 1, N2
      P = (P + C(J))*X
      J = J - 1
10    CONTINUE
20    POLY = POLY + P
      RETURN
      END
```

```
      SUBROUTINE NSCOR1(S,N,N2,WORK,IFAULT)
C
C       ALGORITHM AS 177  APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
C       EXACT CALCULATION OF NORMAL SCORES
C
      REAL S(N2), WORK(4,721)
      REAL ZERO, ONE, C1, D, C, SCOR, AI1, ANI, AN, H, ALNFAC
      DATA ONE/1.0E0/, ZERO/0.0E0/, H/0.025E0/, NSTEP/721/
      IFAULT = 3
      IF (N2 .NE. N/2) RETURN
      IFAULT = 1
      IF (N .LE. 1) RETURN
      IFAULT = 0
      IF (N .GT. 2000) IFAULT = 2
      AN = N
C
C       CALCULATE NATURAL LOG OF FACTORIAL(N)
C
      C1 = ALNFAC(N)
      D = C1 - ALOG(AN)
C
C       ACCUMULATE ORDINATES FOR CALCULATION OF INTEGRAL FOR RANKITS
C
      DO 20 I=1,N2
      I1 = I - 1
      NI = N - I
      AI1 = I1
      ANI = NI
      C = C1 - D
      SCOR = ZERO
      DO 10 J = 1, NSTEP
10    SCOR = SCOR + EXP(WORK(2,J) + AI1*WORK(3,J) + ANI*WORK(4,J) + C)*
     $           WORK(1,J)
      S(I) = SCOR*H
      D = D + ALOG((AI1 + ONE)/ANI)
20    CONTINUE
      RETURN
      END
      SUBROUTINE INIT(WORK)
C
C       ALGORITHM AS 177.1 APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
      REAL WORK(4,721)
      REAL XSTART, H, PI2, HALF, XX, ALNORM
      DATA XSTART/-9.0E0/, H/0.025E0/, PI2/-0.918938533E0/,
     $     HALF/0.5E0/, NSTEP/721/
      XX = XSTART
C
C       SET UP ARRAYS FOR CALCULATION OF INTEGRAL
C
      DO 10 I=1, NSTEP
      WORK(1,I) = XX
      WORK(2,I) = PI2 - XX*XX*HALF
      WORK(3,I) = ALOG(ALNORM(XX,.TRUE.))
```

```
      WORK(4,I) = ALOG(ALNORM(XX,.FALSE.))
      XX = XSTART + FLOAT(I)*H
10    CONTINUE
      RETURN
      END
      REAL FUNCTION ALNFAC(J)
C
C       ALGORITHM 177.2 APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
C       NATURAL LOGARITHM OF FACTORIAL FOR NONNEGATIVE ARGUMENT
C
      REAL R(7), ONE, HALF, A0, THREE, FOUR, FOURTN, FORTTY,
     $     FIVFTY, W, Z
      DATA R(1), R(2), R(3), R(4), R(5), R(6), R(7)/0.0E0, 0.0E0,
     $ 0.69314718056E0, 1.79175946923E0, 3.17805383035E0,
     $ 4.78749174278E0, 6.57925121101E0/
      DATA ONE, HALF, A0, THREE, FOUR, FOURTN, FORTTY, FIVFTY/
     $ 1.E0, 0.5E0, 0.918938533205E0, 3.0E0,4.0E0,14.0E0, 420.0E0,
     $ 5040.0E0/
      IF (J .GE. 0) GO TO 10
      ALNFAC = ONE
      RETURN
10    IF (J .GE. 7) GO TO 20
      ALNFAC = R(J+1)
      RETURN
20    W = J + 1
      Z = ONE/(W*W)
      ALNFAC = (W-HALF)*ALOG(W) - W + A0 + (((FOUR - THREE*Z)
     $  *Z - FOURTN)*Z + FORTTY)/(FIVFTY*W)
      RETURN
      END
      SUBROUTINE NSCOR2(S,N,N2,IFAULT)
C
C       ALGORITHM AS 177.3  APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
C       APPROXMIATION FOR RANKITS
C
      REAL S(N2),EPS(4),DL1(4),DL2(4),GAM(4),LAM(4),BB,D,B1,AN,
     $ AI,E1,E2,L1,CORREC,PPND
      DATA EPS(1), EPS(2), EPS(3), EPS(4)
     $ /0.419885E0, 0.450536E0, 0.456936E0, 0.468488E0/,
     $ DL1(1), DL1(2), DL1(3), DL1(4)
     $ /0.112063E0, 0.121770E0, 0.239299E0, 0.215159E0/,
     $ DL2(1), DL2(2), DL2(3), DL2(4)
     $ /0.080122E0, 0.111348E0, -0.211867E0, -0.115049E0/,
     $ GAM(1), GAM(2), GAM(3), GAM(4)
     $ /0.474798E0, 0.469051E0, 0.208597E0, 0.259784E0/,
     $ LAM(1), LAM(2), LAM(3), LAM(4)
     $ /0.282765E0, 0.304856E0, 0.407708E0, 0.414093E0/
     $ BB/-0.283833E0/, D/-0.106136E0/, B1/0.5641896E0/
      IFAULT = 3
      IF (N2 .NE. N/2) RETURN
      IFAULT = 1
      IF (N .LE. 1) RETURN
      IFAULT = 0
```

```
      IF (N .GT. 2000) IFAULT = 2
      S(1) = B1
      IF (N .EQ. 2) RETURN
C
C       CALCULATE NORMAL AREAS FOR 3 LARGEST RANKITS
C
      AN = N
      K = 3
      IF (N2 .LT. K) K = N2
      DO 5 I = 1, K
      AI = I
      E1 = (AI - EPS(I))/(AN + GAM(I))
      E2 = E1**LAM(I)
      S(I) = E1 + E2*(DL1(I) + E2*DL2(I))/AN - CORREC(I,N)
5     CONTINUE
      IF (N2 .EQ. K) GO TO 20
C
C       CALCULATE NORMAL AREAS FOR REMAINING RANKITS
C
      DO 10 I = 4, N2
      AI = I
      L1 = LAM(4) + BB/(AI + D)
      E1 = (AI - EPS(4))/(AN + GAM(4))
      E2 = E1**L1
      S(I) = E1 + E2*(DL1(4) + E2*DL2(4))/AN - CORREC(I,N)
10    CONTINUE
C
C       CONVERT NORMAL TAIL AREAS TO NORMAL DEVIATES
C
      IER = 0
20    DO 30 I= 1, N2
30    S(I) = -PPND(S(I),IER)
      IF (IER .NE. 0) IFAULT = 4
      RETURN
      END
      REAL FUNCTION CORREC(I, N)
C
C       ALGORITHM AS 177.4 APPLIED STATISTICS (1982) VOL. 31, NO. 2
C
C       CALCULATES CORRECTION FOR TAIL AREA OF NORMAL DISTRIBUTION
C       CORRESPONDING TO THE ITH LARGEST RANKIT IN SAMPLE SIZE N
C
      REAL C1(7), C2(7), C3(7), AN, MIC, C14
      DATA C1(1), C1(2), C1(3), C1(4), C1(5), C1(6), C1(7)
     $  /9.5E0, 28.7E0, 1.9E0, 0.0E0, -7.0E0, -6.2E0, -1.6E0/,
     $ C2(1), C2(2), C2(3), C2(4), C2(5), C2(6), C2(7)
     $ /-6.195E3, -9.569E3, -6.728E3, -17.614E3, -8.278E3, -3.570E3,
     $ 1.075E3/,
     $ C3(1), C3(2), C3(3), C3(4), C3(5), C3(6), C3(7)
     $ /9.338E4, 1.7516E5, 4.1040E5, 2.157E6, 2.376E6, 2.065E6,
     $ 2.065E6/,
     $ MIC/1.E-6/, C14/1.9E-5/
      CORREC = C14
      IF (I*N .EQ. 4) RETURN
      CORREC = 0.0
```

```
      IF (I .LT. 1 .OR. I .GT. 7) RETURN
      IF (I .NE. 4 .AND. N .GT. 20) RETURN
      IF (I .EQ. 4 .AND. N .GT. 40) RETURN
      AN = N
      AN = 1.0/(AN*AN)
      CORREC = (C1(I) + AN*(C2(I) + AN*C3(I)))*MIC
      RETURN
      END
      FUNCTION ALNORM(X,UPPER)
C
C      ALGORITHM AS 66  APPLIED STATISTICS (1973) VOL. 22, NO. 3
C
C      EVALUATES THE TAIL AREA OF THE STANDARDISED NORMAL CURVE
C      FROM X TO INFINITY IF UPPER IS .TRUE. OR FROM MINUS
C      INFINITY TO X IF UPPER IS .FALSE.
C
C*** NOTE: INSTEAD OF ALGORITHM AS 66, WE HAVE SUBSTITUTED THE IMSL
C*** ROUTINE 'MDNOR'.  BOTH ROUTINES HAVE MACHINE-DEPENDENT PARAMETERS.
C
      LOGICAL UPPER
      Z = X
      IF (UPPER) Z = -Z
      CALL MDNOR(Z,TAIL)
      ALNORM = TAIL
      RETURN
      END
      REAL FUNCTION PPND(P, IFAULT)
C
C      ALGORITHM AS 111  APPLIED STATISTICS (1977), VOL. 26, NO. 1
C
C      PRODUCES NORMAL DEVIATE CORRESPONDING TO LOWER TAIL AREA OF P
C
C*** NOTE: INSTEAD OF ALGORITHM AS 111, WE HAVE SUBSTITUTED THE IMSL
C*** ROUTINE 'MDNRIS'.
C
      CALL MDNRIS(P,Y,IER)
      PPND = Y
      IFAULT = 0
      IF (IER .EQ. 0) RETURN
      PPND = 0.0
      IFAULT = 1
      RETURN
      END
```

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