NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 124

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

TRANSPORTATION RESEARCH BOARD
National Research Council

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

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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to planners, pavement designers, administrators, and others interested in knowing the actual weights of vehicles using the highways. Information is presented on current uses of weigh-in-motion systems that can obtain the data needed to properly plan and design highways.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

As truck volumes and weights have increased, it has become more important for highway agencies to have better knowledge of the actual weights of the trucks that are using the highways. This report of the Transportation Research Board describes how weigh-in-motion scales can be used to collect data on truck weights, what uses those data have, and the advantages and disadvantages of using weigh-in-motion systems to collect the data.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

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

SUMMARY

Truck weight data have been obtained for many years for a wide variety of reasons. Originally, this information was acquired by weighing vehicles statically. However, advances in weigh-in-motion (WIM) technology over the past 10 years have produced equipment that is effective in measuring the dynamic wheel forces of moving vehicles.

The need to effectively monitor truck weights has been well documented. For example, an FHWA study showed that, during the 10-year period between 1969 and 1979, although truck volumes increased by 25 percent, the total equivalent standard axle loads attributable to the trucks increased by 150 percent. This was caused by both an increase in the number of trucks and a shift in the truck population to heavier types. Similar results were found in a study of Interstate truck weight data from Oregon, Washington, and Montana.

The uses of truck-weight data can be categorized into the following areas: (a) pavement design, monitoring, and research; (b) bridge design, monitoring, and research; (c) size and weight enforcement; (d) legislation and regulation; and (e) administration and planning. Pavement design requires data from truck-weight studies to provide estimates of the characteristics of axle loads that must be accommodated by the roadway. A revised approach to obtaining data for this and other purposes has been recommended by the Federal Highway Administration's (FHWA) Traffic Monitoring Guide. Pavement monitoring has recently received increasing attention, leading to the inclusion of the long-term pavement performance monitoring (LTPPM) element within the upcoming Strategic Highway Research Program. The LTPPM work will include a significant level of truck-weighing activity in conjunction with the monitoring of pavement condition to allow researchers to develop mathematical relationships between measures of pavement condition and factors that affect it. The levels of effort required to provide an effective LTPPM program and to meet the truck-weighing activity recommended by the FHWA Traffic Monitoring Guide will require the effective use of WIM systems.

Truck-weight data are important for bridge design in determining both the maximum loading and frequency distribution of heavy load applications. The data are also used both for revisions to design codes for new structures and bridge rating evaluation of existing structures. Researchers are also using the loading spectra of bridges to develop probabilistic design procedures. Relationships between applied load and bridge stress for bridge calculations have been developed using data obtained with WIM equipment.

Truck weighing is an important function of size and weight enforcement. This function requires several levels of activity: (a) assessment of the magnitude of the overweight vehicle problem; (b) actual weighing of trucks to determine whether they are operating legally; and (c) monitoring the traffic stream in an unobtrusive manner to determine whether enforcement efforts are effective. WIM equipment can be used to increase the effective capacity and efficiency of enforcement operations and personnel. It is also effective in assessing both the magnitude of the truck overweight problem and degree of compliance with size and weight laws.

Legislative and regulatory uses of truck-weight data include the development of statutory size and weight limits. Enforcement programs are often mandated by legislation and regulations. Data from truck size and weight studies are also used to establish geometric design criteria. Decisions in the area of cost allocation are dependent on truck weight data. The fundamental issues to be considered in this topic include which costs of providing the states' highway facilities are attributable to which types of vehicles and how those costs should be funded. The application of equitable weight-distance taxation schemes in those states that use that approach also requires truck-weight information.

Administration and planning needs for truck-weight data include a wide variety of system use, economic, and other types of studies and evaluations. Assessments of the effects of changing policies and regulations, economic activity, and technology are provided using truck-weight information. Estimates of annual vehicle-miles of travel by truck type and ton-miles of goods movement on each highway system are important to many of these analyses. Information obtained from truck-weight studies provides the basis for developing trends in truck body size, weight, and axle configuration, which are useful in policy formulation. Financial investment, work programming, revenue estimation and forecasting, energy predictions, and commodity movement studies all require truck weight data.

In general, WIM equipment is not capable of obtaining information that is traditionally derived from interviews of drivers or from close inspection of vehicles. States that adopt the use of WIM systems must obtain these data from other sources, including separate interview studies (as suggested in the FHWA's Traffic Monitoring Guide) and state and national motor vehicle data files. However, research now ongoing in the Crescent Demonstration Project is investigating the use of automatic vehicle identification (AVI) systems to provide such information.

The advantages of WIM technology include: high vehicle processing rate; improved safety to both the trucks and the driving public; fewer management difficulties; automated processing of truck-weight data; increased coverage; minimized scale avoidance and the resulting biasing of the data; reduced unit cost for trucks weighed; and the availability of dynamic loading information. Disadvantages of WIM systems include: difficulty in comparing the accuracy of WIM equipment versus static weighing devices; unavailability of data usually obtained from driver interviews; the complexity of installing, activating, or deactivating a WIM site; high initial cost; and increased staff technical requirements.

Important operational characteristics for WIM devices include accuracy, portability, conspicuousness, durability, reliability, efficiency, maintainability, calibration requirements, data storage characteristics, communications capability, and safety.

Seven vendors are currently (January 1985) offering WIM equipment in this country. The products offered include low, medium, and high operating speeds. Sensors can be mounted on the surface, in shallow or deep excavations, or on the underside of longitudinal bridge girders. System prices range from about $50,000 to $150,000 per site.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Truck-weight data have been obtained for more than 50 years for a wide variety of reasons. Principally, the devices used to perform this function have been static weighers; that is, the trucks were weighed while at rest on scales designed for static operation. The types of static scales range from those that can weigh the entire truck at once (single draft), to axle load weighers that weigh all wheels on a single or tandem axle at once, to single wheel load weighers that weigh only one or possibly two dual tires on one side of an axle. Static weighing has long been recognized as inefficient and unsafe for people working with heavy truck volumes. For many years researchers and practitioners have sought to remedy the disadvantages of static weighing by working to perfect techniques for weighing trucks while they are in motion. Significant advances have been made in this area and devices are now available that have proved to be effective in measuring the dynamic wheel forces of moving vehicles.

The following section presents a brief overview of the evolution of weigh-in-motion (WIM) technology. A more complete description of equipment currently available in the United States is presented in Chapter 4.

BRIEF HISTORY OF WIM DEVELOPMENT

One of the earliest efforts to develop dynamic weighing equipment was reported in 1952 by Normann and Hopkins of the U.S. Bureau of Public Roads (BPR) (now Federal Highway Administration) (*1*). The weighing device included a "floating" reinforced concrete platform that was constructed in the surface of a traffic lane. The weighing surface measured 12 ft wide by 3 ft long by 1 ft deep (3.7 × 0.9 × 0.3 m) and was supported at each corner by columns to which resistance-wire strain gages were bonded. Each of these strain-gage load cells was incorporated into a Wheatstone bridge electrical resistance network such that the electrical potential difference at the output terminals of the network was proportional to the compressing force. Temperature-compensating components also were included. The four load cells were connected in parallel so that the total weight on the platform was directly obtainable. The experimental instrumentation was a complex arrangement of analog devices. The system output consisted of oscilloscope traces from the load cells and from a pneumatic tube; the traces were photographed as they occurred. It took 10 seconds to acquire the oscilloscope reading for each truck. Axle weights, axle spacings, and vehicle speeds were computed by manually analyzing the oscilloscope readings.

The BPR research effort was followed by similar installations in Iowa, Minnesota, Oregon, Michigan, Indiana, and Illinois. Each of these included one or more platforms of concrete or steel supported on strain-gage load cells. The instrumentation used with these sensors was generally either housed permanently at the site or installed in a van. These installations were used for truck weight surveys, detection of overweight vehicles for law enforcement, and acquisition of data for pavement research (*2*).

The United Kingdom's (U.K.) Transport and Road Research Laboratory (TRRL) installed a system similar to that developed by the BPR in 1957 (*3–6*). The system was installed at 30 locations throughout the United Kingdom and is still operational in modified form. Similar systems were installed in Sweden (*7–9*) and Japan (*10*). The current TRRL system is less massive and consists of three aluminum plates, 20 in. (500 mm) square, that are mounted in a steel frame across one wheel path. The assembly is supported on a reinforced concrete foundation. Each set of plates is separated by four load cells and preloaded by bolts and springs. System installation involves excavation of a pit, placement of reinforced concrete, and resurfacing.

Researchers continued to work with large platform scales in both the United States and Europe. One variation, a "broken platform," which consisted of a hinged platform partially supported on two load cells, was developed in West Germany (*11–14*). The system that included this sensor was designed to accumulate the frequency of axle loads in each of several weight classes for a given time interval. The equipment was used in both West Germany and Denmark for several years. This design was an improvement on earlier systems but still had the disadvantages associated with using a massive platform.

Further studies at the University of Kentucky and the BPR involved preloading the platforms using coil springs and steel rods, but these were not sufficient to make the massive, stiff platform into a practical sensor (*15–17*). Research with multiple platform sensors was conducted in Michigan beginning in 1958 (*18*). This research also used closed circuit television to monitor some operations. It concluded that improved instrumentation and portable axle-load transducers should be considered.

By the early 1960s, most of the efforts to use massive BPR-type WIM devices had been abandoned (*19*). Several factors contributed to this result. The great mass, stiffness, and inertia of the platform was significant in relation to the forces it was intended to measure so that the scale could not respond to rapid changes, nor could it return to a static state before subsequent axles could pass over it. As described in the BPR study report, leveling and lateral translation of the platform were significant problems. Moisture effects on the load cells caused difficulties. The extensive construction and maintenance required at the weighing sites was a significant disadvantage. The lack of system portability meant that it could be used only at expensive, prepared locations.

Research into portable WIM devices began at about the same time as the above-mentioned massive platform research. This work was begun in Mississippi in 1952 (*20*) and has continued since then in the United States as well as in Sweden, England, West Germany, and South Africa (*21–27*).

One direction of portable sensor research has been to produce a unit that includes a lightweight weighing platform that rests on strain-gage load cells, which in turn rest on a supporting foundation (*28–31*). The Radian Corporation's WIM system is the most notable example of this type. This equipment was developed at the University of Texas in research sponsored by the Texas Highway Department. The depth of the weight sensor assembly is about 2 in. (50 mm) and it is installed in an excavation of about 3.5 in. (90 mm). The weighing area is 4 ft 6 in. wide by 1 ft 8 in. long (1.4 × 0.5 m) in each wheel path. The weight-bearing surface comprises six triangular steel plates that are supported on eight load cells. Like those in the BPR system, these load cells are connected in a Wheatstone bridge circuit. The equipment has been used extensively in the United States.

Another principle also uses strain gages, but in this case they are bonded to the underside of steel plates such that the strain measured is proportional to the load. One device that uses this concept was developed by the German Bundesanstalt fur Strassenwessen (BAST). The weight sensor consists of steel plates with the strain gages bonded within milled grooves in the bottom surface. This system has been used extensively in West Germany. The weighplates are ⅝ in. (16 mm) thick and measure 4 ft wide by 1 ft 8 in. long (1.2 × 0.5 m). A frame is used to support the plates. The weighing assembly requires a 2 in. (50 mm) deep excavation. The system is manufactured for the U.S. market by the Prozess-Automatisierungstechnik (PAT) and marketed in the United States by Siemens-Allis. It has been installed in Idaho, Delaware, Pennsylvania, and California (*32–34*).

Another WIM system by German researchers involved a hydraulic displacement concept. Development of this equipment began in 1964. A 2 to 3 mm (0.08 to 0.12 in.) thick space was formed between two steel plates welded together at the edges. The cavity was filled with a fluid. Application of a load to the upper plate forced the fluid out, thereby causing a diaphragm to deflect. This movement was monitored and interpreted as a weight. Deployment of those systems was begun in 1972 (*35–38*).

The French government, through its Laboratoire Central des Ponts et Chausees, completed development in 1967 of a WIM system that uses three piezoelectric quartz crystals to support a weighing platform. An applied load causes the crystals to deform, producing an electrical signal that is monitored and interpreted as weight. The French began installation of these units in 1969 and ultimately installed more than 50 of them (*39–42*).

Another weighing system developed in France uses a coaxial cable filled with pressure-sensitive powdered piezoelectric ceramic material. The cable is placed in a groove cut across the lane of travel and covered with a sealing material. The load is transmitted through the road surface to the cable, causing it to deform. The change in pressure generates an electric charge on the conductive surfaces of the cable. The accumulated charge is used to produce a voltage differential that is proportional to the applied load. The French government is now installing a network of about 30 of these sites. Approximately 50 installations of this type have been made in West Germany (*43–48*).

Efforts to produce a truly portable WIM system have been longstanding. As early as 1967, South Africa's National Institute for Road Research began development of a weighing mat that consisted of layers of rubber and steel. The unit was designed to convert load into a change in capacitance. The resulting system was marketed as the Viatec Axle Weight Analyzer by Plessey South Africa, Ltd. The current version is now offered by Electromatic, Ltd. The Viatec system was tested extensively in both the United States and Canada and has been used for more than ten years in South Africa (*49–62*).

The capacitive mat sensor has since been incorporated into WIM systems now offered both by the Golden River Corporation and by the Streeter Richardson Division of the Mangood Corporation.

The Streeter Richardson Division of the Mangood Corporation also developed an axle weight sensor that consists of steel plates supported at its corners by load cells; it requires an 8 in. (200 mm) deep pit. This equipment is used in several states for enforcement weighing.

The Weighwrite Company in England developed and is marketing a low-speed (2.5 miles per hour, 4 km/h) WIM system. It consists of a steel platform 10 ft wide by 3½ ft long (3.0 × 1.1 m) in a pit 1 ft (0.3 m) deep. Like the BPR system, strain-gage load cells support each corner. The load cells are supported on a foundation frame. This equipment is widely used in England for enforcement purposes.

An important WIM development effort began in 1972 at the University of Saskatchewan in Canada. The device produced in that research uses a single oil-filled piston as a load cell to which the load is mechanically transmitted. Each weighing assembly measures 5 ft 4 in. wide by 1 ft 9 in. long (1.6 × 0.5 m) and is 9 in. (230 m) deep. One of these is installed in each wheel track on a common concrete foundation. The equipment is marketed by International Road Dynamics (IRD) through CMI-Dynamics in the United States (*63–67*).

A portable system was developed in the early 1970s at Case Western Reserve University in research sponsored by the Ohio DOT. This system uses strain-gage load cells clamped to the support beams on the under side of a highway bridge. Tape switches are used to sense axles. The equipment is marketed in the United States by Bridge Weighing Systems (*68–72*).

The above description illustrates the wide variety of research and development efforts that have been conducted for more than 30 years to provide effective tools for weighing vehicles while they are in motion. A diverse range of physical properties, operating principles, and construction concepts have been applied to the problem of obtaining the weights of vehicles as they travel down the highway. Chapter 4 includes a discussion of the characteristics of available WIM equipment. Chapter 5 describes state experiences with WIM technology. Except where noted otherwise, information in this synthesis is current as of January 1985.

CHAPTER TWO

WIM DATA NEEDS AND USES

NEED FOR WEIGHT MONITORING

The need for effective monitoring of truck weights has been documented in a number of studies. One analysis conducted by the Office of Highway Planning of the Federal Highway Administration covered the ten years between 1969 and 1979. This study demonstrated that, although truck volumes on rural Interstate highways increased 25 percent during that period, equivalent single-axle loadings (ESALs) increased 150 percent. This was due to two factors. The first was an increase in both total and percent of trucks in the vehicle population. The second was a shift in the truck population to larger and heavier types (five axles or more). These larger vehicles in 1969 made up 8 percent of the traffic stream on Interstate rural highways. By 1979 they were 16 percent and in 1983 they were 17 percent. This shift was due to the economic advantages of larger and heavier loads as well as federal legislative changes that occurred in 1974 and 1978 (*73*).

Similar results were found in a study of Interstate truck weigh sites in Oregon, Washington, and Montana. The analysis of data for this effort examined three vehicle groups: total vehicle volume, all trucks (excluding pickup and panel trucks), and trucks with five or more axles. The latter group was chosen for study owing to the fact that it accounts for more than 80 percent of the ESALs at the sites studied in the three states. The researchers found that the average annual growth rates were 3.5 percent for all vehicles, 7.3 percent for all trucks, and 9.7 percent for trucks with five or more axles. During the same period, the average annual growth rate for ESALs was 12.1 percent, more than three times the rate for total traffic volume. These results were attributed to three factors. The first is the reduction in the number of empty trucks, probably as a result of deregulation. The second factor is that the mix of truck types in the traffic stream is shifting toward those types with five or more axles. The third factor is the evolution of new axle configurations, which increase the total number of ESALs (*74*).

A recent study conducted by the Wisconsin DOT Division of Planning and Budget considered the needs of users of data produced in that state's biennial Truck Weight Study. This effort included a detailed evaluation of the truck characteristic data elements being collected as well as the specific elements and levels of detail needed by users. There were 18 data elements that at least one program indicated were "very important" to its activities. The data elements most frequently mentioned were truck type, gross vehicle weight, and axle weight. Most of the 18 data elements are acquired in the traditional truck weight studies using static scales and driver interviews (*75*).

Based on its inventory of truck characteristic data needs, Wisconsin DOT identified four programs that were the primary users of the information: pavement design, motor carrier enforcement, highway cost allocation, and pavement research.

Another factor contributing to the need for weight monitoring is the increase in legal weight limits. The Federal-Aid Highway Amendments of 1974 allows individual states to increase maximum allowable weights as follows: single-axle weights to 20,000 pounds (from 18,000); tandem axles to 34,000 lbs (from 32,000); and gross weight to 80,000 lbs (from 73,280) provided the following maximum Bridge Formula weight is not exceeded (*76*).

$$W = 500\left(\frac{LN}{N-1} + 12\,N + 36\right) \tag{1}$$

where

W = the maximum weight in pounds that can be carried on a group of two or more axles to the nearest 500 pounds.
L = spacing in feet between the outer axles of any two or more consecutive axles.
N = number of axles being considered.

A study published in 1979 by the General Accounting Office (GAO) provided an analysis of the 1975 National Truck Characteristics Report and other information supplied by the FHWA. These data were primarily analyses and summaries of the Truck Weight Study (TWS) information submitted by the states. After eliminating empty and two-axle trucks from the data, the GAO found that 22 percent of the remaining loaded trucks were overweight. This corresponded to 11 percent of all vehicles weighed in the FHWA TWS. The importance of this fact is this: not only are the legal weights increasing, but also trucks are likely to exceed those weights (*77*).

The detrimental effects of these trends are obvious to state agencies. Ten- or twenty-year total loading projections are often occurring within half of the design time period. The changing nature of heavy vehicle characteristics trends has caused both state and federal officials to greatly expand their use of available data and to seek ways to provide more truck data as well as to improve the effectiveness of truck weight limit enforcement activities. Weigh-in-motion equipment and systems have much to offer in meeting these needs.

USES OF TRUCK WEIGHT STUDY DATA

The uses of WIM equipment have been defined largely by the data requirements of the FHWA TWS and by the need to provide more effective truck weight enforcement tools. The following discussion provides a general description of the uses of data obtained under these and related activities. Subsequent sections will include technical information relevant to the application of WIM equipment to meet these needs.

The uses of truck weight data may be categorized into the following areas:

1. Pavement design, monitoring, and research.
2. Bridge design, monitoring, and research.
3. Size and weight enforcement.
4. Legislation and regulation.
5. Administration and planning.

Pavement Issues

For many years, the major impetus for state collection of truck weight data has been the provision of Section 307 (c), Title 23 of U.S. Code for participation in the FHWA TWS. The principal basis for this provision was to ensure that reasonable estimates of truck weight characteristics were included in the design of highways partially funded from federal sources. All states have adopted pavement design criteria based directly or indirectly on data obtained from truck weight studies (*78–88*).

The specifics of the use of truck weight data for pavement design vary from state to state, depending on the level of data collection activity and the possible use of stratification by highway system and geographical area. The recently published FHWA Traffic Monitoring Guide suggests that a minimum of 90 truck weighing sessions should be conducted by each state over a three-year period. Of these, 30 sessions should be assigned to Interstate locations. The FHWA estimates that this procedure and level of effort will allow the estimation of the average ESAL for 3S2 (three-axle tractor with two-axle semitrailer) trucks on the Interstate system with a precision of ± 10 percent at the 95 percent confidence level. The remaining 60 truck weighing sessions will be conducted on non-Interstate roadways (*89*).

Under current procedures and those included in the 1985 AASHTO Guide for Design of Pavement Structures, average ESAL values per truck are computed from historical and base-year truck weight data for each highway system type and geographical region. Annual growth rates for each truck type and the lane distribution of loadings may also be considered. These calculated average ESALs are combined with data from more extensive and intensive vehicle classification (which produces estimates of the percentage of heavy trucks) and traffic volume programs to estimate the total number of ESALs that are applied each year to the roadway section for which the design is to be done.

More specifically, the total traffic count is projected for the design period, a constant percentage of trucks is applied to determine the total number of heavy trucks to be accommodated, and a constant average total ESAL factor is then applied to compute the total number of equivalent single-axle loads. The resulting historical and projected axle loadings are used as the basis from which to estimate total pavement loading for the design period. Unfortunately, the assumptions of constant average ESAL per truck and constant percentage of trucks have not held true in many areas. As indicated in the examples presented earlier in this chapter, both factors have been increasing, with the result that many facilities are not achieving their design lives.

Both state and federal officials recognize that improved data collection procedures are needed to more closely monitor these changing traffic characteristics. The recently issued FHWA Traffic Monitoring Guide referenced above is intended to assist the states in designing comprehensive traffic data collection programs that address this issue. This document is discussed more fully in Chapter 3.

Another use of WIM data is in pavement performance monitoring. This activity is designed to give the states a better understanding of how pavement condition is related to traffic loading and environmental conditions so that predictive relationships can be developed. The information is also used to improve the states' pavement design procedures and to develop design equations. To initiate a nationwide pavement performance monitoring program, the FHWA recently funded eight states to establish an extremely detailed pavement performance monitoring system. This FHWA program is scheduled to be expanded to cover many more states. In addition, the proposed Strategic Highway Research Program includes a 20-year long-term pavement performance monitoring (LTPPM) effort. One key to the success of the planned pavement monitoring work will be accurate and reliable measurements and estimates of truck weights (*90*).

Although not all states are collecting the detailed level of data that is being acquired in the LTPPM program, nearly all states have instituted pavement management systems, which provide information on network conditions, locations of candidate rehabilitation projects, and estimates of required funding levels. Effective pavement management systems generally include several modules that require truck loading data: monitoring pavement performance; pavement performance modeling, improving design procedures; developing rehabilitation programs based on models of aggregate or individual distress mechanisms; evaluating the procedures for calculating ESAL values; scheduling maintenance; and developing procedures to optimize the utilization of resources. Accurate and reliable truck-weight data are critical for these activities.

Bridge Issues

Traffic loading data are also essential to bridge design, monitoring, and research (*78, 91–94*). Both gross weight and tandem (or tridem or quadrem) weights as well as single-axle weights are important in bridge design. The increasing sizes and weights of heavy trucks in recent years has caused some states to raise their design loads and to reassess their bridge designs in accordance with the regulations concerning special permits for heavy vehicles. Because both maximum loading and the frequency distribution of heavy load applications are important for bridges, complete information about the weight characteristics of the traffic stream is needed. However, gross weight accuracy is usually more important than individual axle loads because bridges are usually long relative to the spacing of axles. In addition, information about truck headways or spacing on bridges is important, since maximum loading will occur when several heavy trucks are on the same span.

Bridge loading data are also important for both revisions to design codes for new structures and bridge rating evaluation of existing structures. This latter point is an especially important issue now since more than 200,000 U.S. bridges have been categorized as deficient and must be rehabilitated or replaced in the near future.

Researchers are also using estimates of the loading spectra of bridges to develop probabilistic design procedures. This effort requires significantly more information than traditionally has been acquired in truck-weight studies. Relationships between applied load and bridge stress also have been successfully developed for use in bridge calculations. In addition, the lateral wheel placement distributions of trucks on bridges has become important for some designers.

Enforcement Issues

Control of the weights of vehicles on the nation's highways is critical to the management of those facilities (*81, 95–102*). As demonstrated in many reports, excessive weights can cause pavements and bridges to fail prematurely, and illegal operators have an unfair competitive advantage over their legal counterparts. Overweight vehicles also may present safety hazards and cause congestion on the roadway network because of their lack of acceleration, poor maneuvering and braking capabilities, and increased likelihood of mechanical or structural failure. For these and other reasons, all states and the Congress have enacted legislation to control truck weights. Enforcement legislation in this area has evolved rapidly; in large part because of the increasing size and weight of trucks in the traffic stream. Additional impetus has been provided by federal requirements that the states meet certain enforcement guidelines or face the loss of significant amounts of federal funding for highways.

Since 1980, the Federal Highway Administration has required that each state submit and annually revise a plan for truck-weight enforcement that includes the facilities and equipment used, resources and staff allocated, and an operating plan. The FHWA annually evaluates the performance of each state in carrying out its enforcement plan. It is anticipated that enforcement plan requirements will be considerably strengthened over the next several years. Truck-weight data categorized by day and hour can and have been used to design enforcement programs. Analysis of the truck-weight data, particularly for occurrences of overloaded vehicles at consistent days of the week, hours of the day, and locations, has been effectively used to target enforcement efforts.

Although WIM equipment has not yet been certified as sufficiently accurate to be used for enforcement weighing, its use in conjunction with certified static scales is now commonplace. The WIM equipment is placed in advance of the static scale and is used to "sort" truck traffic so that only suspected overweight trucks need be stopped for static enforcement weighing. The result is an increase in both the efficiency and practical capacity of the truck enforcement weighing activity. From the truck operator's viewpoint, delay caused by the weighing process is imposed only on suspected violators.

Another enforcement issue is the need to assess compliance of trucks with weight laws and regulations. In this context, WIM equipment has been used to unobtrusively monitor truck weights while enforcement weighing is *not* being performed. Various similar studies of this type have shown that, while weight violation rates at static enforcement locations are about 1 percent illegal, the population of trucks not being statically weighed can have as many as 30 percent overweight vehicles. The obvious conclusion is that overweight trucks avoid enforcement weighing. One countermeasure to this action is to deploy portable scales along parallel routes when enforcement operations are being conducted. WIM equipment can also be used to collect data about the times and locations of concentrations of likely overweight truck traffic so that enforcement activities can be targeted accordingly.

Real-time truck weighing has also been used in Europe to weigh vehicles approaching a weak bridge, thereby triggering a warning not to cross if the vehicle weight is too great.

Legislative and Regulatory Issues

Truck-weight data are used for a wide variety of legislative and regulatory purposes. Of course, different states use different combinations of direct legislation and regulatory authority.

Truck-weight data are used both to develop size and weight limits and to evaluate the enforcement of those regulations. Although the U.S. Congress has mandated specific maximum size and weight regulations on Interstate and access facilities, it has also legislated increased enforcement requirements. States also use the data from truck-weight studies to establish geometric design criteria related to the size and weight of vehicles.

Size and weight are obviously closely tied to cost allocation. The fundamental issues in this area are: which costs of providing and maintaining the states' highway facilities are attributable to which types of vehicles; and how should those costs be recovered? Such information as the vehicle-miles of travel and average ESAL by truck type are necessary for the equitable allocation of costs. These data are used will information obtained from other data collection activities, such as LTPPM, to develop the relationships that allow the calculation of damage caused by vehicles of given axle weight and axle spacing distributions. The use of WIM equipment can provide the data needed for these computations on a scale that will greatly increase the reliability of the results. The accuracy and reliability of these calculations are very important to the states, which need to assess permit and license fees (and possibly weight-distance taxes) based on a rational and reasonable decision procedure. The truck operators and the general public also have an interest in the equitable allocation of the costs of constructing, maintaining, rehabilitating, and preserving the nation's roadway infrastructure.

Ten states now have some type of weight-distance tax. The use of this tax has attracted much interest in recent years as concern with the deterioration of the nation's highways has increased. The more widespread use of weight-distance taxation based on realistic damage factors will undoubtedly lead truck owners and operators to shift to more economically efficient (considering both truck operating cost and highway cost) truck configurations with less total ESALs for the same freight tonnage. Current use of weight-distance taxation requires information about the gross weight of commercial vehicles over distances traveled on a state's highways. The acquisition of this information is both expensive (with state costs ranging from 2 to 6 percent of revenues) and burdensome to both the states and truck operators. WIM equipment, in conjunction with automatic vehicle identification (AVI) technology, has been proposed as a means for automating the assessment and collection of weight-distance taxes. This new application of existing technology is the subject of current research programs and is described in Chapter 5.

Administrative and Planning Issues

The FHWA Truck Weight Study is conducted as a planning activity with the states, which supply the actual data through the Highway Planning and Research (HP&R) Program. Truck-weight data are utilized for a wide variety of system use, economic, and other studies and evaluations. These include assessing the effects of changing policies and regulations, economic activity, and technology. Estimates of annual vehicle-miles of travel by truck type and ton-miles of goods movement on each highway system are important to many of these analyses. In addition, the information obtained from truck-weight studies provides the basis for developing trends in truck body type, size, weight, and axle configuration, which are useful in policy formation.

Financial investment and work programming also require truck-weight data as an input. Revenue estimation and forecasting, energy supply, consumption, and forecasting, as well as commodity movement studies all require information about truck weights.

CHAPTER THREE

WIM DATA REQUIREMENTS

In general, only a portion of the data that are available from static weighing operations can be obtained using weigh-in-motion (WIM) equipment. Data collection for the FHWA Truck Weight Study (TWS) provides an excellent example of this fact. Traditionally, the following data items were obtained:

1. State
2. Highway system
3. Station identification number
4. Direction of travel
5. Date
6. Hours of operation
7. Vehicle type
8. Body type
9. Engine type
10. Gross registered weight group code
11. Registered weight
12. Basis of registration
13. Model year of tractor
14. Class of operation
15. Commodity
16. Empty or loaded condition
17. Total weight of truck or combination
18. Axle weights
19. Total wheel base

Of course, the state, highway system, station number, direction of travel, date, and hours of operation are readily available from WIM equipment as well as from static weighing. Vehicle type is also available from WIM, but only to a limited extent. The TWS vehicle type classification scheme provides a very detailed six-digit code that indicates the basic vehicle type, total axles on the power unit, total axles on each trailer, presence of a light trailer, and a range of special conditions. However, it does this only for those trucks that are weighed (sampled). The proportion of trucks weighed typically has varied between 10 and 50 percent of the total truck traffic. Under static TWS weighing operations, an additional traffic classification scheme is used to acquire information about the total traffic stream from which the weighed trucks were taken. The latest version of this vehicle classification system is:

1. Motorcycles (optional)
2. Passenger cars
3. Other two-axle, four-tire, single-unit vehicles
4. Buses
5. Two-axle, six-tire, single-unit trucks
6. Three-axle, single-unit trucks
7. Four or more axle, single-unit trucks
8. Four or fewer axle, single-trailer trucks
9. Five-axle, single-trailer trucks
10. Six or more axle, single-trailer trucks
11. Five or fewer axle, multi-trailer trucks
12. Six-axle, multi-trailer trucks
13. Seven or more axle, multi-trailer trucks

The vehicle classification data thus obtained for the entire traffic stream are used to expand the information acquired from the sampled trucks. WIM equipment is not able to distinguish accurately and automatically among all of the vehicle types in either the six-digit or thirteen-type vehicle classification categories. Most commercially available WIM systems now in use either employ some other classification scheme or rely on manual operator input of vehicle type. Body type is available only as a manual operator input. Engine type, gross registered weight group code (i.e., how the gross weight is computed), registered weight, basis of registration, model year of tractor, and class of operation are not available with WIM systems. Commodity and empty or loaded condition can sometimes be input by the WIM operator, but only for certain body types, such as flatbed trailers. Total weight, axle weights, and total wheel base are readily obtainable from WIM equipment, as are vehicle speeds and headways, which are not available from static weighing.

As indicated in the previous paragraph, WIM equipment is not capable of obtaining information that is derived from interviews of drivers or from close inspection of the vehicles. To date, states that adopt the use of WIM systems must either ignore the need for interview data or obtain it by other means, including separate interview studies and state and national motor vehicle data files. However, research now ongoing in both Oregon and Arizona is evaluating the feasibility of installing automatic vehicle identification transponders on heavy vehicles. This program offers the potential for acquiring much of the interview data in conjunction with WIM activity (*103*).

ENFORCEMENT DATA REQUIREMENTS

Static weight enforcement locations have been used for purposes other than checking for size and weight violations. In many states, personnel also examine operator log books, fuel records, and permits. They also inspect the equipment for safety violations. Implementation of WIM devices for enforcement will require a modification to this strategy.

Federal legislation requires each state to submit an annual enforcement certification to the Federal Highway Administrator. By regulation the certification includes: compliance statements by the Governor; a copy of any new state size and weight regulations; and a comparison of the state's actual enforcement effort with the effort proposed in a previously submitted enforcement plan. The data required for this last element include the number of trucks weighed, the number of citations issued by type (axle, gross, or bridge formula), and the number and type of non-fine penalties levied (off-loads or load shifts).

The enforcement plan referred to must include the following information:

1. Facilities and equipment. Each state must use at least two of the following types of scales: fixed, weigh-in-motion, semiportable and portable. Locations of the fixed and WIM facilities must be provided.
2. Resources or staff allocated to size and weight enforcement.
3. Operational plan, including: hours of operation, geographical coverage, off-loading requirements, penalties, and special permit procedures.

The use of WIM systems for enforcement requires some unique enforcement practices, but at the same time provides an opportunity for more efficient use of enforcement resources. In using WIM devices for sorting suspected violators from the traffic stream, the weight data must be processed in real time and overweight indications displayed immediately. For the case of high-speed WIM installations, descriptions of the overweight trucks are usually radioed downstream to notify enforcement personnel. For the case of moderate- or low-speed WIM sites located in conjunction with static enforcement scales, active traffic control devices must divert suspected overweight vehicles for static weighing. These processed data also include the results of bridge formula compliance computations.

Truck axle and gross weight distributions by hour of the day and day of the week as well as by location can be used to perform enforcement activity targeting. These analyses permit states to efficiently schedule enforcement operations so as to apprehend the most violators possible with the available resources.

ADVANTAGES OF WIM

Vehicle Processing Rate

One major advantage of WIM systems is the rate at which vehicles can be processed. Equipment is available so that trucks can be weighed as they travel by at highway speeds. The result is that many more vehicles can be weighed in a much shorter period of time than could be processed with static scales. The WIM weighing operation also is continuous. Conversely, during static weighing operations it is often necessary to select a sample of trucks rather than weighing all of them. Weighing-in-motion thus eliminates a possible source of data bias introduced by the selection process. With WIM equipment it is also possible to conduct weighing operations during inclement weather, for 24-hour periods, and, indeed, to operate continuously. Minnesota has installed a WIM system that operates all of the time. As a result, the large amounts of data available make possible estimates of average or extreme total loading conditions on the highway with a high degree of confidence (*104,105*).

The high processing rate of weigh-in-motion also minimizes traffic disruption. Vehicles do not accumulate while waiting to be weighed. Several states use WIM systems at permanent static enforcement scales to sort out those vehicles that are likely to be in violation of the weight laws. The result is that the trucks that are clearly not violators are not delayed.

Safety

WIM operations also can improve safety. By not stopping and lining trucks up along the highway, a potential hazard is removed. Additionally, WIM systems have been installed in advance of bridge structures to detect and divert overweight vehicles that might cause the bridge to fail and collapse.

Management

Personnel problems are less significant with WIM equipment. This is particularly true in comparison with static wheel-load weigher operations when temporary employees are used. This latter procedure is very labor intensive and the labor costs can be significant. Several states have reported field crew reductions of as much as 75 percent by converting from "loadometer" operations to weighing-in-motion.

WIM operation used strictly for data collection does not require the presence of an enforcement officer, as is often the case with static operations.

Automated Data Processing

Data processing efficiency is considerably improved by using WIM systems. Under static weighing operations, data are usually recorded on field forms and then must be entered manually into a computer. Nearly all commercially available WIM equipment automatically stores the data and provides for automatic transfer of the data to a computer.

Increased Coverage

Another advantage of WIM equipment is that a larger number of sites can be monitored at the same cost using this automatic approach rather than by using portable static scales.

Minimized Scale Avoidance

With some WIM systems it is possible to monitor truck traffic without truck operators being aware of it. Under this condition, the universal scale avoidance problem is minimized. This enables the WIM equipment to provide more representative data and avoids causing heavy trucks to take parallel routes on roads that were not designed for such traffic.

Reduced Cost

The cost per truck weighed is generally much less for WIM than for static weighing. As a result, it is feasible to obtain truck-weight data for all users, improving the statistical accuracy of all of the different estimation procedures that use the information.

Dynamic Loading Data

Another advantage of WIM systems is that they provide some information about the dynamic wheel loads that are being imposed on the roadway. Because these are the forces that are actually being applied to pavements and bridge structures, some researchers believe that design procedures should be modified to use dynamic loads. However, current state design procedures as well as state weight laws are based on static weights. Also, the WIM scale may introduce a dynamic effect that is not the same as on a pavement without the scale.

DISADVANTAGES OF WIM

Accuracy in Measuring Static Weights

One major perceived disadvantage of WIM systems is their relative inaccuracy in comparison with static scales. Most WIM systems qualify as wheel-load weighers. According to the National Bureau of Standards, wheel-load weighers are required to have an accuracy of ±1 percent when tested for certification and must be maintained thereafter at ±2 percent (*106*). The very nature of dynamic weighing suggests that this will be very difficult to achieve. The following paragraphs provide an explanation of the problem of approximating static weights with dynamic weights and are based on work published by Lee (*19*).

In a study of the dynamic force applied to the roadway surface by a rolling truck tire, Lee deployed nine Radian-type wheel force transducers as shown in Figure 1. A sheet of ⅜ in. thick plywood was placed on the first pair of transducers to create a "bump" effect. Figure 2a shows the measured wheel forces for the left rear wheel (dual tires) of an unloaded two-axle truck for three successive runs. Also shown is the plot of a vehicle simulation model called DYMOL, which was developed by Lee. Figure 2b shows similar results for the loaded vehicle. Note that the static weight is shown as a horizontal line in Figures 2a and 2b. The small scatter of the observed wheel load force measurements suggests that the wheel force pattern for a specific vehicle proceeding along some paved surface at the same speed will repeat.

In addition, comparison of the loaded and unloaded results indicates that the mass of the vehicle affects both the magnitude and frequency of the dynamic wheel forces. Changes in mass will have different effects on vehicles with different spring characteristics and will respond differently to road roughness. Typically, wheels oscillate at a frequency of between 8 and 12 hertz (Hz) when displaced suddenly but the oscillations are quickly damped. As can be seen from the figures, the dynamic wheel force can be either greater or less than the static weight at any moment. Under some conditions, the dynamic wheel force can vary from twice the static weight to a zero value. In addition to the oscillation of the wheels, the body of the truck oscillates at between 0.5 and 4 Hz. Further variations in the dynamic wheel force can be caused by tires that are not truly round or balanced.

To approximate static wheel loads using WIM equipment, it is necessary to minimize all effects except for gravity. Lee has categorized the factors that affect the wheel loads of moving vehicles as roadway, vehicular, or environmental factors, as shown in Table 1. The roadway factors can be controlled to a reasonable extent. Selection of sites on tangent sections with a smooth surface, coupled with careful installation and maintenance of the equipment, can reduce those influences. Likewise, environmental factors can be minimized by scheduling if necessary. However, the vehicular factors are not easily addressed. Lee reports that the most significant of these is tire condition. At high speeds, tires that are not balanced or round can cause variations in the vertical component of the wheel-load force. The combination of these factors makes the attainment of ±1 percent accuracy (in comparison with static weights) unlikely using WIM equipment at highway speeds. Low speed [about 2.5 mph (4 km/h)] or moderate speed [less than 30 mph (50 km/h)] operation offers more hope for achieving this goal.

Reduced Information

A second disadvantage of WIM equipment is that information that requires a stopped vehicle cannot be obtained. For instance, data needed for the FHWA Truck Weight Study include fuel type, state of registry, year model, loaded or unloaded status, origin and destination, and other similar information that cannot be obtained if WIM devices are used. If WIM equipment is used for enforcement screening, it may have an adverse effect on checking log books, safety equipment, registrations, routings, and overweight permits or violations.

Installation

Another disadvantage can be the complexity and/or safety hazard associated with installing, activating, or deactivating a WIM site. Initial installation can require that the lanes be closed for as long as 72 hours. In addition, this initial equipment placement can require a fairly large crew and substantial amount of equipment. In most cases, installation is not possible except on a dry pavement surface with the temperature above 32° F

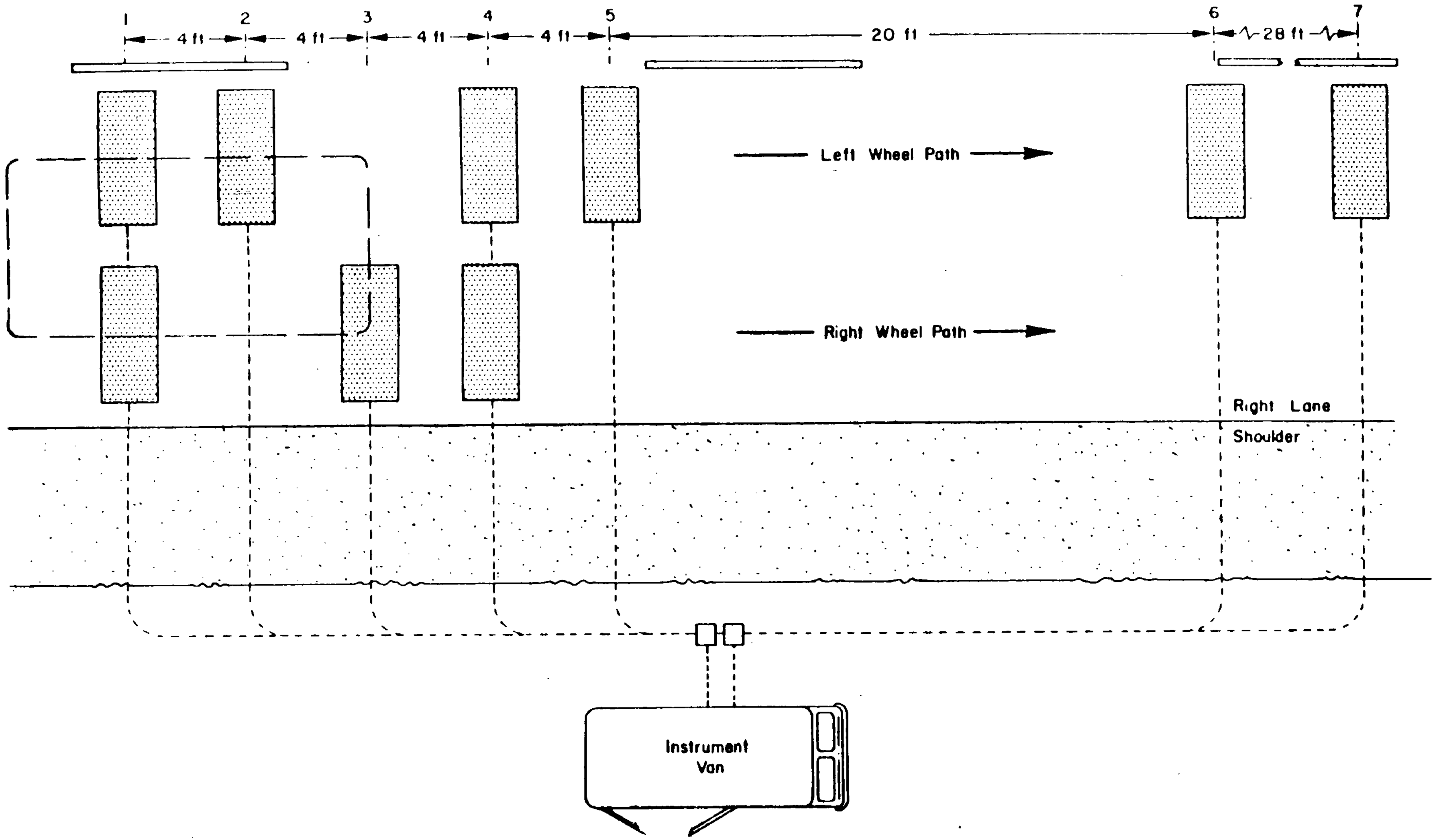

Figure 1 Arrangement of scales array.

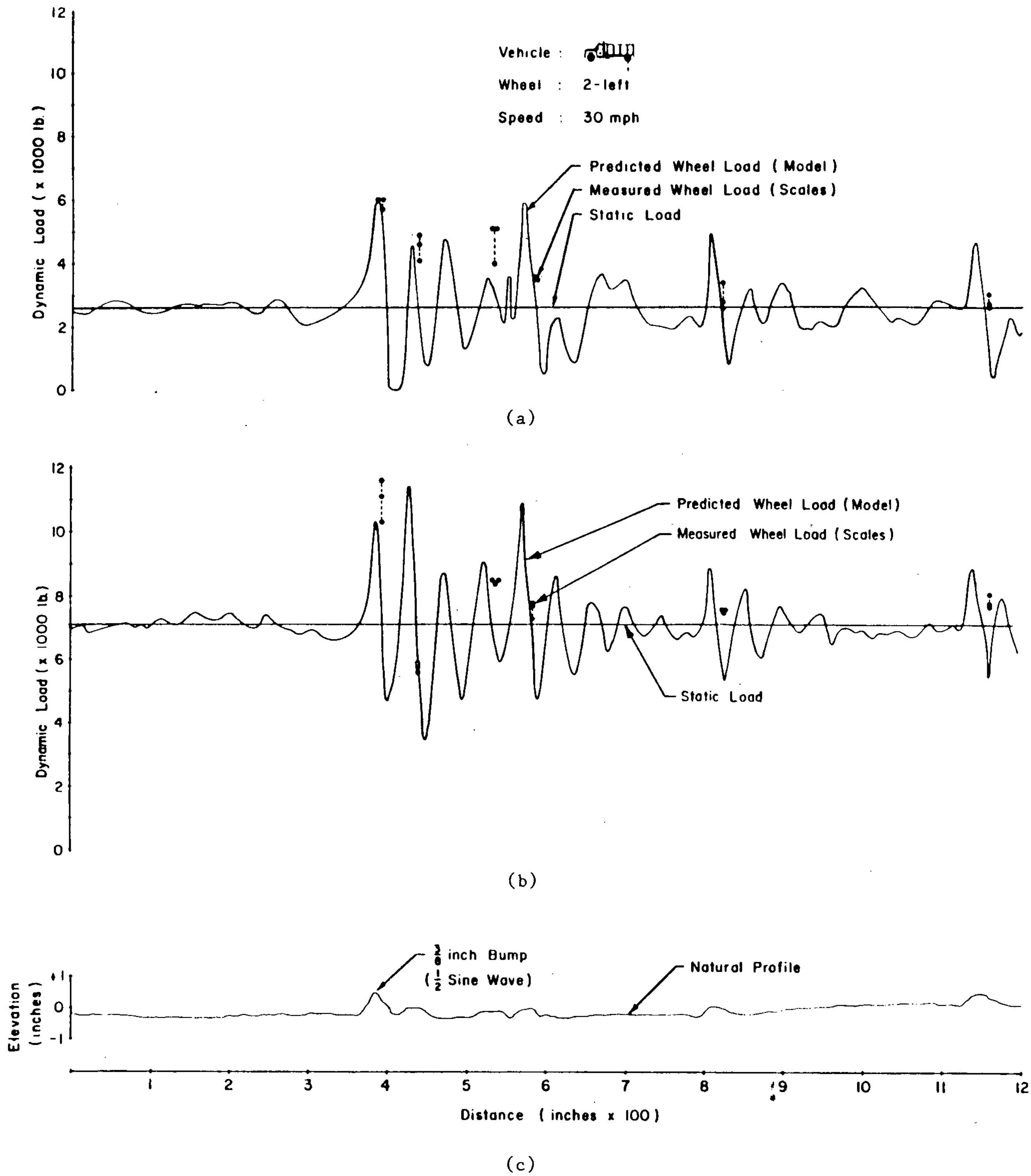

Figure 2 Predicted and measurable wheel loads: (a) unloaded truck, (b) loaded truck, (c) roadway profile.

TABLE 1

FACTORS THAT AFFECT WHEEL LOADS OF A MOVING VEHICLE

Roadway Factors	Vehicular Factors	Environmental Factors
Longitudinal profile	Speed	Wind
Transverse profile	Acceleration	Temperature
Grade	Axle configuration	Ice
Cross slope	Body type	
Curvature	Suspension system	
	Tires	
	Load, load shift	
	Aerodynamic characteristics	
	Center of gravity	

(0° C). A smooth pavement approach, needed to produce accurate weights, often requires a major resurfacing effort. Most WIM systems are not left in place for long periods and require calibration before each weighing session. Setup for each session can take as long as four hours.

High Initial Cost

Although many states have found WIM to be cost-effective, the initial capital costs can be quite high.

Increased Staff Technical Requirements

WIM also requires a more technically qualified operating crew if necessary maintenance and repair of the system is to be carried out in a timely manner.

Susceptibility to Damage from Electromagnetic Transients

Like all equipment that uses sensitive solid state electronic devices to operate, WIM equipment is sensitive to electromagnetic disturbances. The most severe of these are caused by lightning strikes in the vicinity of the equipment. It is not necessary for lightning to hit the installation directly for damage to occur. Similar effects can be caused by the switching of heavy electrical devices in industrial areas. Damaging transient energy can be introduced into the equipment through any of the conductors by which it is connected to a power source, communications, sensors, or grounding networks. In addition, radiated electromagnetic energy can induce damaging transient voltage and current conditions within the electronic subsystems.

Protection of the equipment is achieved by designing the equipment to withstand reasonable levels of electromagnetic disturbances. For those areas of the country where high levels of these phenomena occur, or for WIM systems not adequately designed to withstand these effects without damage or malfunction, it is necessary to take one or more of the following actions:

1. Install adequate grounding systems;
2. Shield against radiated electromagnetic energy; and/or
3. Use protective devices at the input terminals to the equipment.

Despite these disadvantages, state experiences of the last ten years have shown WIM to be a practical tool.

WIM OPERATIONAL CHARACTERISTICS AND REQUIREMENTS

WIM operational characteristics fall into the following categories:

1. Accuracy
2. Portability
3. Conspicuousness
4. Durability
5. Reliability
6. Efficiency
7. Maintainability and repairability
8. Need for and ease of calibration
9. Data storage mode
10. Data storage capacity
11. Communications capability
12. Safety (setup, installation, operation, takedown)
13. Power requirements

Accuracy

As discussed earlier in this chapter, the ability of a WIM device to accurately measure static weight is dependent on a number of roadway, vehicular, and environmental factors. Within those constraints, the purposes for which the measurements are being obtained determine the level of accuracy required. For traffic data collection for planning, pavement design, bridge design, and legislation and regulation formulation, it is sufficient that frequency distributions be obtained for axle, tandem, and gross weights by user-specified weight ranges, in addition to summaries of the numbers and characteristics of overweight vehicles. In this context, the accuracy being sought is the accurate aggregate assignment of weights to categories. This accuracy is much more easily obtained than is an accurate weighing of each individual axle or tandem weight, as is required for weight enforcement.

Review of the available literature on WIM equipment accuracy from both vendors and users is difficult. There is no standard method used to indicate the accuracy of these devices. A commonly used measure is the mean error expressed as a percentage of the weight, coupled with a confidence level. For example, "$\pm$5 percent at the 90 percent confidence level" means that 90 out of 100 measurements taken fall within 5 percent (over or under) of the true weights. However, this does not indicate whether it applies to an individual truck or all trucks or what range of weights is being measured.

For enforcement weighing, wheel load weighers (static or dynamic) are required to be within $\pm$1 percent for acceptance ($\pm$2 percent for maintenance) at a 99 percent confidence level according to Handbook 44 of the National Bureau of Standards. No WIM device has yet achieved this latter level of accuracy with the result that WIM equipment is now used only to sort suspected trucks out of the traffic stream onto a certified static scale. In some cases, the WIM scale itself also serves as the certified static scale.

Portability

Portability is another important operational characteristic. Obviously, if the WIM system is permanently installed, portability is not a significant factor. Otherwise, mobility of the equipment can be very important. Existing WIM products vary widely according to the time and effort required to install, remove, transport, or reinstall the components. The most portable of the available devices include weight sensors that can be installed and removed in less than an hour (including deployment of traffic control devices and/or personnel). Other systems use permanently installed weight transducers at a number of sites with the data collection electronic subsystem moved from location to location. Another product can be operated in either mode, but removal or replacement of the wheel-load transducers takes about two hours. Typical installation, removal, and replacement times for WIM systems being marketed in the United States are included with the product summaries in Chapter 4.

Conspicuousness

Conspicuousness is an important issue for all truck-weighing operations. It is usually desirable that the WIM operation not be apparent to the truck operators. It is well known that overweight trucks can make up as much as 30 percent of the heavy vehicle population when the traffic stream is weighed inconspicuously or by surprise, but often drops to as low as 1 percent when the truck-weighing operation becomes known to the truck operators. Inconspicuous operation is clearly required if data representative of actual truck-weight distributions are to be obtained. This is also true for enforcement, but the very act of stopping vehicles to cite the drivers usually results in general awareness that weighing is occurring and consequent avoidance behavior.

Durability and Reliability

Durability refers to the number of wheel-load applications a weight sensor can be expected to endure before it must be replaced or rehabilitated. It also applies to the electronics subsystems, which often must withstand extreme and cyclic temperature and humidity effects. Reliability is related to durability, but refers to failures during the normal life of the device, rather than the "wearing out" characteristic (durability). The available WIM products vary widely in both durability and reliability. Some permanently installed sensors have remained in operation for years without failure, while other devices have failed repeatedly over a few weeks.

Efficiency

Efficiency of operation is particularly important to state agencies in the current climate of fiscal restraint. Devices that can acquire necessary truck-weight data with a minimum of personnel and then provide the data in a form that minimizes handling are desirable. WIM systems now being marketed in the United States differ greatly in the number of personnel required to install, remove, reinstall, and operate. Permanently installed equipment that is accessed by telephone lines is the most efficient type, but may not satisfy needs for geographic coverage. Most "manned" systems require a crew of at least two technicians to operate. This area is one where WIM equipment offers clear advantages over static equipment, both in number of trucks weighed and the cost per truck weighed.

Maintainability and Repairability

Maintainability and repairability are other important operational requirements. Each state must decide whether it has or wishes to have the technical staff required to maintain its WIM equipment in an operational condition and to repair it when it fails. As with the other operational characteristics, this requirement varies among WIM systems and the best decision depends on the nature of each. In general, however, it is desirable for state personnel to provide routine maintenance and minor repairs and to keep a stock of spare components.

Calibration

The need for and ease of calibration affects the efficiency of the truck-weighing program. WIM systems that require extensive calibration procedures will have costs per truck weighed significantly greater than equipment that does not have that requirement. One WIM product reportedly requires only a single calibration at its initial installation, while others should be recalibrated for each installation. In any case, at least a quick calibration check is advisable at each setup for any portable or semiportable WIM system, or periodically at a permanent WIM site.

Data Storage

The data storage mode and storage capacity are important characteristics of WIM systems. In some cases, truck data are stored by accumulating axle weights into weight cells (or bins) by hour (or by day) so that the data consist of a frequency distribution of weights for each hour (or day). Other WIM systems record information about each truck with the time of day at which it was observed. Unattended WIM systems almost always use the former approach, while operator-monitored equipment most often uses the latter. Clearly, the frequency distribution method requires much less data storage capacity, but the individual truck data will yield more accurate statistical results.

Communications

Communications capability is important for WIM locations that will not be manned and for which remote access to the collected data is desired. Several states are evaluating conversion of their telemetric automatic traffic recorder (ATR) sites to integrated automatic counting, vehicle classification, speed monitoring, and truck weighing operations with telemetry.

Safety

Safety is a major factor for all WIM operations. The most obvious aspect of this is the work zone traffic control required for safely installing, removing, or reinstalling wheel-load weighers. It cannot be overemphasized to the operating crews that all state work zone safety procedures should be followed. Another safety consideration concerns the use of moderate speed WIM devices to sort suspected overweight trucks from the traffic stream. In this case, the traffic control signs, markings, and signals must be designed to provide easily understood guidance to all trucks within the weighing area.

Power Requirements

The power requirements determine the portability and some of the costs associated with a WIM system. Permanently installed WIM equipment usually runs off of alternating current (a.c.) power. Some portable devices also require a.c. power from a portable generator while other units operate from batteries.

SYSTEMS CHARACTERISTICS AND REQUIREMENTS

As mentioned previously, the FHWA has recently issued its new Traffic Monitoring Guide, which clearly describes the relationships among traffic counting, vehicle classification, and truck weighing (Truck Weight Study) in systematic terms. If truck-weight data are to be used in conjunction with vehicle classification and traffic volume information to estimate historical and future axle loading on pavements and bridges and to meet other needs, the entire data collection program must be based on statistically sound sampling and analysis procedures. The questions of how many samples should be made, how often the samples should be taken, and how to obtain the samples must be addressed using the following concepts:

1. Statistical reliability is directly related to the variability of the quantity being measured.
2. Variability may be reduced by careful stratification.
3. The sample size required to achieve a given level of confidence is reduced by decreasing the variability of the quantity.

Based on a statistical analysis of the extensive Truck Weight Study data files maintained by the FHWA, it was concluded that a minimum sample of 90 truck-weighing sessions taken over a three-year cycle was needed for each state. Of these, the FHWA recommends that one-third (30) be obtained on the Interstate system. The result is that the *best* estimate of average equivalent single-axle load (ESAL) for one type of truck, the 3S2 (18 wheeler), on the Interstate system will be within ± 10 percent with 95 percent confidence. Estimates for other truck types would be less accurate.

The 30 truck-weight sessions that are recommended each year for each state are also specified as being of 48-hour continuous duration. It is clear that only the use of automated equipment will allow a data collection effort of this intensity and extent to be accomplished. WIM equipment is the only feasible alternative.

CHAPTER FOUR

WIM TECHNOLOGY

The development of WIM technology was presented in Chapter 1. In this chapter, more detailed descriptions of currently available WIM equipment will be provided. As indicated in Table 2, seven commercial WIM products are being marketed currently in the United States. Each of these products is described in the following sections. Table 3 presents a summary of the most important characteristics of each available WIM device.

BRIDGE WEIGHING SYSTEMS

The Bridge Weighing Systems product is a bridge instrumentation system that was first developed at Case Western Reserve University with research support from Ohio DOT and FHWA. Reusable strain transducers are clamped to the longitudinal support beams of a highway bridge. Strain data are interpreted as axle weights by a computer algorithm. Portable tape switches or permanent piezocable axle sensors are placed on the road surface for the measurement of vehicle speeds and to assist in the classification of vehicle types. An optional manual input is available for entering detailed vehicle classification information via a portable keyboard. Data are recorded using a microcomputer-based system with dedicated electronic subsystems. This equipment is usually mounted in a mobile instrumentation van parked under the bridge. Individual truck speeds, axle weights, and gross vehicle weights are displayed on a video monitor or printed in real time. These data are also stored on a flexible diskette.

This WIM system is very portable. Once a bridge has been instrumented and the equipment calibrated for that site, subsequent returns to that bridge do not require recalibration, although some users have reported a need for annual recalibration. Setup time is then less than half an hour. The only weak link in the system appears to be the tape switches, which require lane closure and are not easily installed on wet or damp pavements or when temperatures are below freezing. Both the weight sensors and the electronics have been very reliable in use. An unmanned version is now in use in Iowa. It operates continuously at a site but can be moved quickly to a new site.

GOLDEN RIVER CORPORATION

The Golden River Corporation's WIM system (Figure 3) uses the Electromatic Ltd. weighmat mentioned in Chapter 1. This weighmat is used with two inductive loops that provide speed and presence information. The weight sensor is a rubber and steel mat, 6 ft wide by 20 in. long by ⅜ in. thick (2.4 m × 510 mm × 9.5 mm). Three sheets of steel, separated by soft rubber, act as a three-plate capacitor. Compression of the mat under load produces an increase in capacitance, which is interpreted as a weight by the attached microprocessor-based data collection system. The mat is nailed down to the road surface through disposable perforated plates Pop-riveted to its edges. Additional attachment is provided by a bituminous adhesive tape. The weighmat is placed in one wheel path of a traffic lane. Installation takes less than an hour, but the equipment may need calibration with every installation.

The roadside data collection unit operates automatically and can be left unattended, although the weight sensor would then be subject to vandalism. Data can be stored in bins or individual vehicle data can be stored. The latter mode would require frequent data retrieval since memory would be quickly depleted. The equipment has internal correction for both speed and temperature effects. It is very portable, but the sensor should not be installed on damp or wet surfaces. In addition, the weighmat is vulnerable to vandalism or dragging vehicle parts.

INTERNATIONAL ROAD DYNAMICS

The International Road Dynamics (IRD) product (Figure 4) includes two rectangular weighing platforms measuring 5 ft 4 in. by 1 ft 9 in. by 9 in. deep (1.6 m × 530 mm × 230 mm), resting on a common concrete foundation, with an associated electronic roadside monitoring system. One platform is located in each wheel path. Loads applied to the platform produce a vertical movement in a centrally located oil-filled piston, which acts as a load cell. Inductive loops are used in conjunction with the weight sensor to provide speed and presence data. The IRD system is permanently installed and requires heavy equipment for placement. The system can acquire data from four lanes of traffic simultaneously. The equipment is offered in the United States by CMI-Dynamics.

RADIAN CORPORATION

The Radian Corporation WIM system (Figure 5) also requires excavation of the roadway for installation. The sensor consists of a steel frame that supports the load sensors and six triangular load plates. The overall dimensions for this assembly are 4 ft 6 in. by 1 ft 6 in. by 3.5 in. deep (1.4 m × 460 mm × 90 mm). One of these transducers is installed in each wheel path. Each transducer contains eight active load cells and eight matching load cells, which are used for temperature compensation. The roadside electronics include an IBM XT microcomputer with

TABLE 2

WIM EQUIPMENT IN USE (JULY 1986)

State	Manufacturer[a]	State	Manufacturer
Alabama	RAD	Mississippi	RAD
Alaska	GR	Missouri	GR
Arizona	GR	Nevada	RAD
Arkansas	RAD, SR	New Jersey	PAT
California	PAT, SR	New Mexico	RAD
Connecticut	SR	North Carolina	BWS, WW[b]
Delaware	PAT	North Dakota	SR
Florida	GR, IRD, RAD	Ohio	BWS
Georgia	RAD, SR	Oklahoma	RAD[b]
Hawaii	PAT	Oregon	IRD, BWS
Idaho	BWS, PAT[b], RAD[b]	Pennsylvania	PAT, SR
Illinois	SR	South Dakota	c
Indiana	SR	Tennessee	SR
Iowa	BWS	Texas	RAD, SR, GR
Kansas	BWS	Utah	BWS
Kentucky	RAD[b]	Virginia	RAD
Louisiana	RAD	Washington	BWS, PAT
Maine	IRD, c	West Virginia	SR
Maryland	BWS, SR	Wisconsin	BWS
Massachusetts	PAT	Wyoming	RAD
Michigan	WW	Canada	IRD
Minnesota	IRD		

[a]BWS = Bridge Weighing Systems
GR = Golden River
IRD = International Road Dynamics
PAT = PAT Equipment
RAD = Radian Corporation
SR = Streeter Richardson
WW = Weighwrite

[b]Removed

[c]State's own bridge device

additional electronic interfacing and signal conditioning circuitry. The Radian system can acquire data from four lanes of traffic simultaneously. The weight sensors for this system can be (and usually are) moved from site to site.

STREETER RICHARDSON

The Streeter Richardson Division (formerly Streeter Amet) of the Mangood Corporation is marketing two different WIM systems. The permanent version uses two weighing platforms that are 4 ft 10 in. wide by 2 ft 3 in. long by 8 in. deep (1.5 m × 690 mm × 200 mm). One transducer is placed in each wheel path. The platform is manufactured using a "honey-comb" construction to increase its stiffness. Each scale uses four load cells, each of which has a 10,000-pound (44 kN) capacity. The transducer assembly has height adjustment to allow it to be positioned for a smooth transition from the roadway to the scale surface. The sensor subsystem also includes two vehicle detection inductive loops. The remaining parts of this system are a microprocessor-based data acquisition, processing, and recording unit and a video terminal. The system is designed for weighing trucks at 30 mph (50 km/h). The company is now marketing a version of this product that operates at 55 mph (90 km/h). This WIM equipment is not portable.

Streeter Richardson is also offering a portable WIM system (Figure 6) that uses the same capacitive weight sensor described above for the Golden River Corporation. This equipment includes a microcomputer with customized printed circuit boards and electronic circuitry similar to that found in the Streeter Richardson permanent scale product. This portable WIM system requires alternating electrical current at 110 volts, which is provided by a gasoline-powered generator. Although the sys-

Figure 3 Golden River WIM system.

TABLE 3

WIM PRODUCT CHARACTERISTICS

Manufacturer and Model	Scale Dimensions	Principle of Operation	Temperature Range	Load Range
Bridge Weighing Systems	Bridge deck and beams	Strain gages on beams	-50^{o} to $+60^{o}$ C	
Golden River	6 ft wide 1 ft 8 in. long 3/8 in. thick	Capacitance	-40^{o} to 175^{o} F (electronics) 32^{o} to 175^{o} F (weighmat)	
International Road Dynamics	5 ft 4 in. wide 1 ft 9 in. long 9 in. deep	Hydraulic load cell		
Radian	4 ft 6 in. wide 1 ft 6 in. long 3.5 in. deep	Strain gage load cells		
Siemens-Allis/PAT WIM 300	25 mm profile	Strain gage load cells	14^{o} to 122^{o} F	40,000 lb
Siemens-Allis/PAT WIM 400	4 ft 1 in. wide 1 ft 8 in. long 1 in. deep	Strain gages on bending plate		40,000 lb
Streeter Richardson 5150 SS, XT	4 ft 10 in. wide 2 ft 3 in. long 8 in. deep	Strain gage load cells		40,000 lb
Streeter Richardson 5150 XT portable	6 ft wide 1 ft 8 in. long 3/8 in. thick	Capacitance	32^{o} to 175^{o} F	
Weighwrite	10 ft wide 3 ft 6 in. long 1 in. deep	Strain gage load cells		

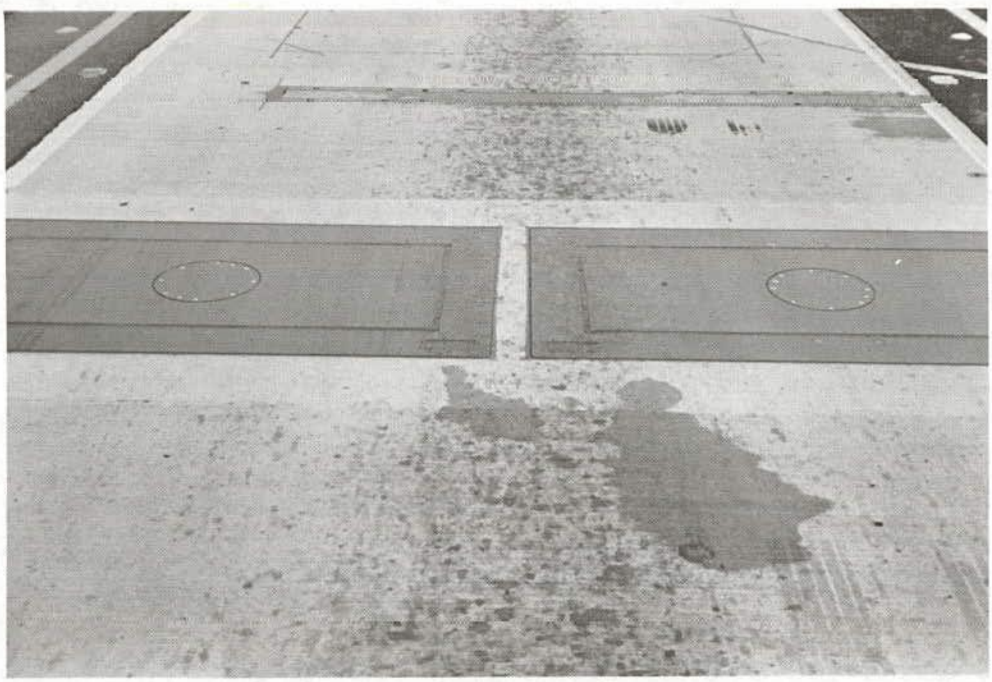

Figure 4 IRD WIM system.

Figure 5 Radian WIM system.

tem is portable, the weighmat is not easily installed on damp or wet surfaces.

SIEMENS-ALLIS (PAT)

The Siemens-Allis Corporation in the United States is marketing PAT Equipment Corporation WIM sensors in conjunction with Siemens-Allis electronics (Figure 7). The system includes two wheel scales; two inductive loops; a microprocessor-based electronic data acquisition, processing, and storage subsystem; and a video display unit. The vehicle weight sensor is a steel plate that is 4 ft 1 in. wide by 1 ft 8 in. long by 0.9 in. deep (1.2 m × 510 mm × 23 mm). This transducer is supported along its longer side at a height of 0.75 in. (19 mm). Bending of the plate under load is measured by strain gages

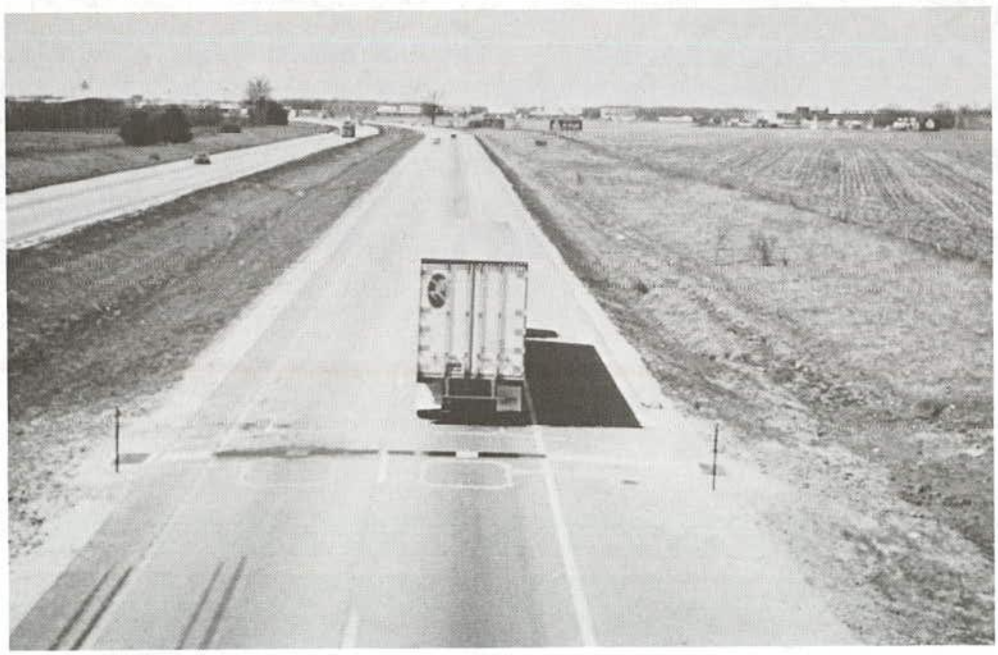

Figure 6 Streeter Richardson WIM system (Courtesy Streeter Richardson).

Figure 7 PAT WIM equipment.

Figure 8 Weighwrite WIM equipment (Courtesy CMI-Dynamics, Inc.).

located in two slots milled in the underside. For environmental protection, the entire sensor unit is encapsulated in vulcanized synthetic rubber. The Siemens-Allis/PAT system is usually permanently installed.

WEIGHWRITE

Weighwrite produces a system that is used for static and slow-speed measurements (Figure 8). A typical configuration consists of a steel platform 10 ft by 3 ft 6 in., in a pit 12 in. deep (3 m $\times$ 1.1 m $\times$ 300 mm). The plate is supported on electrical resistance strain gage load cells at each corner, standing on a foundation frame. Slow-speed weighing involves vehicles passing over the platform at 2 or 3 mph (3 to 5 km/h), yielding individual axle weights and total vehicle weights by summation. Recording equipment is normally in a small hut next to the scales. The Weighwrite system is permanently installed. This equipment is offered in the United States by CMI-Dynamics.

CHAPTER FIVE

USER EXPERIENCES

The most significant recent program for user WIM experience has been the Rural Transportation Assistance Program's (RTAP) Demonstration of Coordinated Weight Monitoring and Enforcement Using WIM Equipment. Twelve states and the FHWA have committed approximately $2 million in total funding to this effort. One objective of this work is to have the participating states purchase and evaluate available WIM products and then to publish the results so that future users will have the benefit of their experiences in selecting equipment. The three states that first received funding under this program (Arizona, Texas, and Wisconsin) were to submit their preliminary results in mid-1985. Arizona is using the Golden River Corporation's capacitive weighmat system. Texas is evaluating the Radian Corporation's multilane system. Wisconsin chose to use the Bridge Weighing System. The remaining nine RTAP demonstration states are: Alabama (Radian); Iowa (Bridge); Maine (IRD); Maryland (Bridge); Minnesota (IRD); Kansas (Bridge); West Virginia (Streeter Richardson portable); Utah (Bridge); and Oregon (IRD and Bridge).

Although the RTAP program is designed to provide up-to-date, specific knowledge about the advantages and disadvantages, costs, and operational characteristics of the available WIM systems, a significant amount of information has already been published. The following presents a summary of available information by state for each WIM system.

BRIDGE WIM

Wisconsin

Wisconsin reported (*107, 108*) that they chose this particular WIM system in part because they do not require extensive rehabilitation of the approach pavement. By choosing this equipment, they were able to reduce the field crew size from six or eight people to two. They found that, after initial calibration, the two-person crew could set up or deactivate a site. Wisconsin also was able to obtain multivehicle bridge-load information. The data were adequate for planning purposes and could be obtained automatically without operator input. They found that they could obtain twice as much data in less time than with static scale operations, thereby reducing the cost per sample. The weighing operations were undetectable by the truck operators, resulting in more representative data. Vehicles could be weighed at highway speeds so that traffic flow was not interrupted. The equipment could be operated at night and under most weather conditions. Wisconsin also noted that the system is very portable as long as suitable bridge structures are available.

Some deficiencies with the Bridge WIM equipment were also identified. The first was that data could not be collected at points where a suitable bridge was not present. The second deficiency was that individual truck data were difficult to isolate when high volumes of traffic were present. The third problem was that results were less accurate for certain bridge types. Wisconsin's last observation was that the accuracy was not adequate for enforcement. Instead, this system (like others) can be used for sorting overweight vehicles from the traffic stream.

Ohio

Ohio (*109*) has used a Bridge WIM system since 1979 for a variety of planning and enforcement activities and special studies. Although they do not use this equipment to acquire their Truck Weight Study data, they have used it for before, during, and after studies of static scale operations. It has been used for Ohio's Cost Allocation Study and for developing ESAL design data, as well as for pavement management studies. Ohio has used their Bridge WIM system to target enforcement operations by location, time of day, and day of the week. The device has also been used to monitor bypassing of permanent scales and as a sorting tool. It was used in the FHWA's Truck Weight Case Study to establish seasonal variations for truck weights.

An accuracy test was performed by comparing the gross weights of trucks at a permanent static scale with the gross weights from the Bridge WIM device. Less than ±10 percent difference was observed. Accuracy for individual axles was more variable.

Ohio has found their equipment to be very flexible and portable. The system cost in 1979 was $80,000 (excluding vehicle). Trucks can be weighed at highway speeds. The setup time for the two-person crew is two hours maximum initially, then thirty minutes per site thereafter. The system is not detectable, thereby contributing to more representative data. The equipment is very reliable, requiring very little maintenance. Night and inclement weather operations are feasible, and calibration is required only once, although it is suggested that an annual recheck of the calibration factor be done.

Ohio mentioned several difficulties with the Bridge WIM system. First, reliability of the data decreases with the angle of bridge skew. Second, contrary to the Wisconsin findings, Ohio states that a smooth approach slab is needed. Finally, steel and prestressed girder bridges were the only types instrumented in Ohio. Difficulty was found with monitoring the center lane of a three-lane section. Tape switches were mentioned as a source of problem because traffic control is required to place them, and placement on damp or wet surfaces is difficult. Recently, road tubes and piezocables have been used to circumvent this problem.

Maine

The Maine DOT designed and installed a bridge instrumentation system analogous to the commercial Bridge Weighing System in a study beginning in 1981 (*110*). A coaxial cable was used as an axle sensor in place of the tape switches. Cost of the strain gages and their installation was approximately $12,000 for one bridge. Cost of a computer and installation was about $15,000. Because a long-span bridge was used and because a microcomputer was not used for processing data, it was not possible to accurately measure axle weights.

South Dakota

South Dakota, like Maine, designed and installed its own bridge weighing system (*111*).

Iowa

Iowa (*87, 112*) has recently obtained a Bridge Weighing System as part of the RTAP program. One of the goals of the Iowa study is to reduce the cost of acquiring data. In 1983–1984, static equipment was used in Iowa to weigh 17,500 trucks at a cost of $80,000, or about $4.50 per truck. Another $40,000 was spent for classification, data processing, and analysis. The capital cost for Iowa's bridge weighing system was $95,520, which included provision for unmanned operation. Total initial costs, including utilities and hardware, for four WIM sites is projected to be $176,000. The first site is now in place. Accuracy has been assessed by repeated weighing of a certified weights and measures truck. In ten passes of the truck, steering axles were weighed with a mean error of approximately ± 6 percent and a standard deviation of 6 percent. Tandem axles were weighed with a mean error of ± 3 percent and a standard deviation of 7 percent. Gross weights were obtained with a mean error of ± 1 percent and a standard deviation of 4 percent.

Because Iowa only recently received their equipment, they have not documented any experiences as yet. However, several items associated with this WIM technology that can affect its accuracy have been identified. The first of these is that both the horizontal alignment of the road and the skew of the bridge can affect the performance of the vehicles being weighed and therefore they can affect axle-weight readings. Iowa also believes that a maximum of 65 ft (20 m) for single span or a series of noncontinuous spans is required. The approach roadway must be smooth and free of distress. The site must also be located where electrical power is available. The monitoring equipment deployment should be designed so that the equipment is accessible for servicing. Iowa has designed their WIM operations to require minimum personnel on site. Data transmission by telephone lines or other means is desired. The cost of maintenance should be included in the estimated cost of any WIM system in comparing relative system costs.

Maryland

Maryland (*98*) has acquired their first WIM system as part of the RTAP Demonstration of Coordinated Weight Monitoring and Enforcement Using WIM Equipment. They purchased their equipment from Bridge Weighing Systems, Inc., and are in the initial stages of their effort. They have had some problems with tape switches and road tubes and will permanently instrument high-volume sites with piezocable. Location of sites near traffic signals where queueing occurs causes problems with arrival rates.

RADIAN CORPORATION

Florida

Florida (*113*) has conducted its Truck Weight Study data collection using the Radian Corporation WIM systems since 1974. Data now are collected in alternate years at each of 21 sites. In a given year each of 10 (or 11) sites is monitored each season of the year for a 48-hour period. The equipment can acquire data from four lanes simultaneously. Some difficulties were experienced initially with designing installation procedures that would prevent the steel frames that must be placed in the pavement from working loose. This problem was finally solved by pouring a 12 in. (300-mm) thick slab under the frames and inserting anchor bolts to which the frames could be bolted. The transition from pavement to steel frame requires careful attention to prevent a discontinuity from developing, principally caused by rutting.

The Radian equipment has proved to be both durable and reliable over long periods of use.

Nevada

Nevada (*100*) implemented their Radian System in 1978 for a total cost of $90,000, including a modified motor home, the WIM system, hardware for 18 installations, software, and training. Calibration is done every time the transducers are installed at a site, using a maintenance truck that is weighed on portable wheel-load weighers and then driven over the weight sensors five times. Unit cost per truck weighed was $2.60 with the Radian equipment, versus $17.40 using static equipment. Nevada is now able to conduct their Truck Weight Study using two employees at a direct cost of $5,000 versus a previous direct cost using static equipment of $35,000 for eight people. The WIM operation weighs all trucks, whereas the static operation could weigh only 30 percent. The WIM system also is able to help in enforcing the bridge formula. Installation of a new site requires two days and four people. Thereafter, transducer installation or removal takes 30 minutes. Electric power is provided by a 10-kilowatt portable generator.

New Mexico

New Mexico (*114*) was one of the first states to use WIM equipment to perform their Truck Weight Study data collection. The mobile equipment and the hardware for three sites were purchased in 1974. Three more locations were selected in 1975. The mobile equipment was upgraded in 1981. At that time, the mobile home, electronics, and hardware for one site cost $63,270. Hardware for each additional site was priced at $8,900, not including weight sensors. Maintenance costs averaged $400 per site per year.

New Mexico has found it necessary to hire an expert electronics technician to troubleshoot and perform repairs on its Radian WIM system. This employee has been able to significantly reduce both down time and repair cost. The electronics technician also maintains and repairs the photologging system.

Texas

Texas operates six Radian WIM sites annually. Each location is surveyed quarterly for 72 hours. One person is used to operate the system. A crew of five persons is required for site installation and to conduct the continuous 72-hour study. The equipment can operate automatically, but Texas prefers to perform editing at the site rather than after the data collection study. Trucks avoiding the scale by straddling the sensors seems to be a problem resulting in erroneous data. Texas is currently investigating the need for a wider geographic and system distribution of its truck-weighing activity.

Alabama

Alabama has installed 12 sites using Radian Corporation WIM hardware. Initial cost, including the WIM system, motor home, and hardware for three sites was $103,000. Alabama views this equipment as an alternative to constructing a permanent static weighing station.

INTERNATIONAL ROAD DYNAMICS

Minnesota

Minnesota (*104, 105*) selected the IRD WIM system principally because it could operate continuously and function at extremely low temperatures. Installation of the equipment in an old section of Interstate highway required reconstruction of 90 ft (27 m) of pavement. This provided a smooth surface and allowed installation of expansion joints to protect the scale. Frames were installed in both lanes of one direction of a four-lane Interstate highway, one in each wheel path. The electronics were installed in a permanent 10-ft (3-m) square building. To further improve the smoothness of the new concrete pavement and to improve the calibration results, the section was planed. Actual installation of the WIM frames required three days per lane. Removal or installation of the scale required four hours and heavy equipment. Original cost, including rehabilitation of the pavement, construction of the instrumentation building, installation of frames in both lanes, weight sensors in one lane, and the WIM electronics system, was $230,000. The cost of an additional set of scales was $35,000. Initially, data storage was by cassette tape. The data are now retrieved over telephone lines.

Oregon

Oregon (*103*) has installed a medium-speed IRD WIM system at its Woodburn weight enforcement station to operate as a sorting device in conjunction with its static scale. Overloaded or overheight trucks are directed to proceed to the static enforcement scale, while the others receive a signal to return to the main highway lanes. The WIM system stores all weight data and has a storage capacity of approximately one month's information. However, the data are transferred weekly by telephone line communication to an IBM PC/AT at the central office.

A high-speed IRD WIM data collection system has been installed in both northbound lanes of a location 28 miles (45 km) south of the Woodburn enforcement station. Both the high-speed and moderate-speed WIM systems are interfaced with automatic vehicle identification (AVI) equipment, which makes possible the association of weights with specific trucks. Twenty-five trucking firms have installed 200 coded passive transponders on their vehicles for this purpose on an experimental basis.

The high-speed WIM system was operational by February 1984 and has performed flawlessly since that time. The medium-speed sorter WIM was in place by March 1984, but software problems delayed full operation until April of that year.

Oregon found that 20 percent of the vehicles crossing the high-speed WIM site were missing the scale. By the end of April 1985, more than seven million vehicles had been weighed with minimal equipment failures, which were attributed to power outages. Approximately 25 percent of the vehicles at the medium-speed WIM device missed the scales. However, a significant amount of downtime occurred because of software problems.

Canada

The province of Quebec, Canada, began construction for the installation of an IRD scale system in the summer of 1984 (*115*). The site became operational in March 1985. The scales are located in the right lane only and serve as both a sorting scale to identify overweight vehicles and a weight survey data collection device. The equipment and materials cost was approximately $150,000 and the personnel cost for site preparation and installation was approximately $50,000. Trucks that are determined to be in violation of size or weight laws or that have avoided being weighed on the WIM scale are directed to proceed to the static scale for more accurate weighing. The IRD system has also been used in Alberta and Ontario.

SIEMENS-ALLIS (PAT)

California

The California Department of Transportation (Caltrans) has performed research on WIM equipment since 1969 (*84, 116*). In 1979, they performed a detailed evaluation of available systems and concluded that the PAT system best met California's need for a WIM enforcement sorting system and for acquiring truck-weight data at highway speeds for planning and design. During the course of their evaluation, Caltrans also identified the need for an automated traffic management capability within combined WIM/static weighing areas to ensure safe and efficient operation. Caltrans recommends installing WIM equipment in a concrete slab that extends 200 ft (60 m) in advance and 75 ft (23 m) past the sensors. Surface grinding should be considered if the surface is not sufficiently smooth.

Caltrans intends to install up to 28 WIM sites over the next five years. The first site has been installed, consisting of four PAT weight sensors, two in each wheel path, in each of two westbound truck lanes of I-80 near Sacramento. A total of eight transducers will be connected to the electronic data collection system. This is the first of 12 WIM sites to be installed for long-term pavement performance monitoring and has been used for development of the overall system. Similarly, an initial enforcement screening installation has been constructed through an upgrade of an existing high-volume permanent static weigh station on I-580 near Livermore.

Caltrans has decided that WIM systems should be capable of monitoring truck weights, axle spacing, and speed on a total of six lanes, using separate systems if necessary. To minimize erroneous data caused by trucks straddling the sensors, Caltrans recommends that the weight transducer should cover the entire width of the traffic lane. For WIM scales used in enforcement sorting, Caltrans suggests implementing a feedback system whereby the WIM equipment can be self-calibrated by using the results of the static weighing platform and computer. They also recommend on-site recording of data on magnetic tape as well as communication capability through a modem to the central or district office. The need to standardize electronic subsystems was also identified.

Caltrans suggests that accuracy criteria vary according to need and the criticality of the measurements. They suggest ±5 percent (no confidence level specified) at moderate speeds for enforcement sorting. Caltrans found that calibration using a single vehicle did not produce acceptable results. They recommend that a sample of at least 100 randomly selected, representative vehicles be used, although they acknowledge that this may be difficult to achieve for high-speed, high-volume facilities.

The analysis of available systems by Caltrans researchers indicated that simpler sensor designs yield higher reliability. Their criteria for selection of a device included minimizing the number of parts, the number of required adjustments after installation in the pavement, and the susceptibility to environmental conditions. In tests conducted by Caltrans, the PAT weight sensors weighed between 1.5 and 2.5 million truck axle loads before their performance was degraded.

Caltrans estimates that implementation of its 28-site WIM system will result in a benefit-to-cost ratio of approximately 6:1. The program will also provide a much better estimate of truck loading and volume characteristics. The results will include more effective weight enforcement, more dependable data for formulating highway system improvements, and more accurate data to use in pavement and bridge design and research.

Idaho

Idaho (*117*) acquired a PAT system in 1978 and installed it on I-84 near Bliss. The equipment cost was $12,000, although the market price was $65,000. Installation costs totalled an additional $9,900. A long series of problems was encountered with the system, including the failure of electronic components and grouting for the frames. Calibration was done using a three-axle truck with 30,000 pounds (14,000 kg) gross weight. The vehicle was run at speeds of 20, 40, and 60 mph (32, 64, and 97 km/h) for several times each. The Bliss site is monitored monthly for a 24-hour period.

Like California, the Idaho PAT installation includes four weight sensors in each lane, two in each wheel path. This configuration enables the system to make reasonableness checks on the same wheel weight and between wheels on the same axle. This approach also allows the system to cancel obviously erroneous readings automatically. In addition, by sampling the same axle weight twice, the average weight theoretically should be closer to the static weight.

Delaware

Delaware (*97*) has installed one WIM site for enforcement purposes only. It is located on a ramp leading from the main highway lanes. Delaware reports that approximately 500 trucks per hour can be processed when passing through at 15 mph with 100-ft spacings. Because the weighmats are installed flush with the ground, they can be used when ice and/or snow are on the road. Delaware is very happy with this installation and believes this approach is cost-effective.

Pennsylvania

Pennsylvania (*81*) purchased three portable PAT Model 100 low-speed WIM systems in 1979. Two of these were assigned to enforcement teams working on the Interstate system. The third system was used by county personnel on primary highways. The operating speed of the equipment was from 3 to 6 mph (5 to 10 km/h). Pennsylvania found that longitudinal grades caused trucks to accelerate or brake, thereby reducing the accuracy and consistency of weighing. Pennsylvania personnel commonly weighed between 400 and 600 vehicles per six-hour shift using this equipment.

The weight plates and indicators were very reliable, requiring only five repairs over four years of daily use. However, some system problems were encountered. One of these was moisture intrusion into cable connections, which was corrected with a dielectric compound. The dummy grids failed within six months; plywood was substituted. There was also some difficulty in determining individual axle weights. This difficulty was addressed by replacing the PAT Model 100 weight indicator with the Siemens-Allis Model 300 indicator. Finally, vehicle-induced damage to the interconnect cables was experienced.

In 1982, Pennsylvania investigated a concept of using moderate-speed WIM technology to replace both fixed permanent sites and portable WIM setups in rest areas. They implemented an enforcement strategy that would use existing rest areas. Flush-mounted weighmats and loops were installed in the exit ramps. Computer software was specified that would compare truck axle weights, axle spacings, and classification and determine if each vehicle violated any of the state's weight laws, including the bridge formula. The computer would be housed in a motor home that would travel among the sites, each of which had permanently installed weight sensors and interface electronics. Pennsylvania called this system "Semi-Permanent Weigh Stations (SPWS)" and began its implementation using the Siemens-Allis Model 400 WIM system.

Four flush-mounted weighmats (two in each wheel path) and two inductive loops are installed at each site. The loop and weight signals are amplified by a preamplifier permanently installed in a cabinet, which also contains the junction point for connecting the mobile portion of the system. The equipment is operational for speeds between 3 and 40 mph (5 and 64 km/h).

Three mobile "command centers" and the hardware for ten sites have been purchased. The first two sites were scheduled for use in the summer of 1985. A network of 35 sites is planned. The relative cost advantages of the Pennsylvania SPWS truck-weight enforcement strategy allow the construction of more sites than would be possible otherwise. The result is greater flexibility and productivity. Pennsylvania estimates the marginal cost of the permanent installations to be $150,000 per site, including full lighting and manually activated traffic control signing. Portable wheel-load weighers are used to weigh suspected overweight vehicles for enforcement. Complete activation or deactivation time is less than ten minutes. Pennsylvania believes that this short lead time will increase the effective weighing period before violators are alerted that the enforcement site is operating.

STREETER RICHARDSON

Georgia

Georgia (*118*) has been using Streeter Richardson WIM equipment for enforcement screening since 1978, when two systems were installed. A total of 15 sites are now operational. Like Caltrans, Georgia recommends that the WIM equipment be installed in concrete, since early asphalt ramps were subject to rutting and corrugation because of axle loads as well as leaking fuel and oil. Georgia suggests using concrete at least 600 ft (180 m) before and 50 ft (15 m) after the WIM weight sensors. Georgia also reported the need for lightning protection for the system.

Illinois

The first high-speed weigh-in-motion equipment in Illinois was installed in early 1985 (*119*). A total of six such sites are planned for the 1985 and 1986 fiscal years. These WIM installations will be capable of operation in several different modes, including automatic polling and telemetry, truck weight study, selective weight enforcement, remote monitoring, and diagnostic and initial setup. Calibration in Illinois is done using both a three-axle dump truck and a five-axle tractor with semitrailer to make repeated runs over the scales.

Pennsylvania

Pennsylvania (*81*) installed a pilot permanent enforcement weighing station in 1981 using a Streeter Richardson Rollweigh 5150 WIM system for sorting suspected violators out of the truck traffic. The system is capable of this performance at speeds up to 35 mph (56 km/h).

Following a three-year period of operation, this program was discontinued, largely because of the expense and inflexibility of constructing and operating a fixed enforcement weighing site. In 1981, the cost of constructing the permanent weighing station was $1.9 million (excluding real estate). It was also observed that after a short time the number of violators was reduced dramatically. This was probably due in part to the fact that the station was operated only 7.5 hours per day and five days per week. The operation weighed 191,000 vehicles per year, of which 600 were identified as illegal (much less than one percent) with an average fine of $490.

The equipment had an 89 percent reliability (operational 693 out of 780 days). However, Pennsylvania adopted the bridge formula after the WIM sorting system was designed and procured, with the result that automatic determination of all violations was not possible without major software modifications.

Pennsylvania subsequently implemented a concept of installing sensors permanently in exit ramps to a paved weighing area, with interfacing electronics located in a cabinet. The WIM electronic subsystems were then located in "command centers," which were housed in a motor home.

West Virginia

West Virginia has recently acquired a Streeter Richardson capacitive weighmat system as part of the RTAP program. It will be used to obtain planning data and to assist in the state's weight enforcement program. The state hopes to improve the effectiveness of these two efforts by implementing coordinated data collection and enforcement efforts.

GOLDEN RIVER

Arizona

Arizona first obtained a Golden River capacitive weighmat system in 1982 (*120*) A refined version was obtained a year later. The equipment is portable, can be set up by a crew of two in less than an hour, and can operate unattended. Tests of the system led to the conclusion that the mats can be properly calibrated with a number of runs by a test vehicle; however, actual measurements are influenced by speed of the vehicle, ambient temperature, axle weight, and site selection. The last is very important; sites should be level, have a smooth approach profile, and not be subject to heavy braking.

CHAPTER SIX

CURRENT PROGRAMS AND RESEARCH

The evaluations of WIM equipment currently being conducted by 12 states under the FHWA RTAP studies will provide a rich source of material for use in the selection and application of WIM equipment.

An FHWA-sponsored research study, entitled "Development of a Low-Cost Truck Weighing System," is directed toward producing a truck-weighing system that can be sold for $5,000. The prototype system has been delivered and is undergoing testing by FHWA. Another study, begun in 1985, is entitled "Calibration of Weighing-in-Motion (WIM) Systems"; this will address the question of criteria for pavement smoothness on the approach to WIM devices. Also included is consideration of the feasibility and installation criteria for using multiple WIM sensors placed in series.

NCHRP Project 3-36, "Development of a Low-Cost Bridge Weigh-in-Motion System," has as its objective the development of a low-cost ($5000 to $10,000) bridge weigh-in-motion system capable of providing traffic data used in design and maintenance of highways and bridges. Work on this study is scheduled to begin early in 1987.

A research project being conducted by Lehigh University for the FHWA ("Structural Strength Evaluation of Existing Reinforced Concrete Bridges") will determine what bridge response and loading information is necessary for a detailed evaluation of structural performance. The researchers are developing methods for using WIM technology to obtain the required data. An FHWA bridge WIM system is being modified for this purpose. The system software is being enhanced to enable the evaluation of structural performance under known load conditions. The revised hardware and software will be used to test and evaluate four structures (*94*).

An Ohio HP&R study being conducted at Case Western Reserve University ("Weigh-in-Motion Applied to Bridge Evaluation Operation") is also addressing the application of WIM technology to bridges. In this effort, bridge WIM devices will be used to obtain information needed for bridge evaluation and rating. These data will include truck axle loads, impact, load distribution, extreme loads, and stresses. Several bridges that were previously rated have been instrumented. The data are being processed and the results will be compared with other methods. Another Ohio HP&R study ("Implementation of a Continuous Fixed Site Bridge WIM Operation") will involve the installation of an operational WIM system at a bridge site such that it can be operated unattended continuously (*94*).

In Maine, a demonstration project is testing and comparing several different types of WIM systems at the same time.

Ongoing research in both Arizona and Oregon is evaluating the feasibility of incorporating WIM and automatic vehicle identification and automatic vehicle classification technologies. A multi-state study to demonstrate this concept is under way. The states of Alaska, Washington, Oregon, California, Arizona, New Mexico, Texas, and Arkansas, as well as the Canadian province of British Columbia, are participating in the research to develop hardware and software for this purpose and to test the resulting system in the field. Both private industry and the FHWA are actively participating in the development of this effort, commonly known as the "Crescent Demonstration Project" because of the composite shape of the participating jurisdictions (*103, 121*).

The feasibility of implementing this concept on a national scale is being investigated in National Cooperative Highway Research Program (NCHRP) Project 3-34, entitled "The Feasibility of a National Heavy-Vehicle Monitoring System." If these efforts are successful, the resulting WIM/AVI technology will be useful for a wide variety of applications, including enforcement and data collection. This concept also will allow the automatic acquisition of many data items that now require driver interviews. It will enable the automatic identification of vehicles that are likely to be exceeding legal weight limits as well as automatically checking vehicle documentation and outstanding warrants.

CHAPTER SEVEN

CONCLUSIONS

Weighing trucks while they are in motion is no longer only a research procedure. Over the past 10 years, several technologies have evolved and been used to collect truck-weight and other data under a wide range of conditions. Commercial products are now available that will allow the states to respond to several critical areas of concern as well as respond to their traditional needs for truck-weight and related data. The following sections present some conclusions derived from the preparation of this synthesis.

CRITICAL AREAS OF NEED FOR WIM SYSTEMS

Three areas of critical need, in terms of the demand for state truck-weighing activities, have reached a point of requiring a significant increase in the level of effort. These areas are: the long-term pavement performance monitoring (LTPPM) activity within the Strategic Highway Research Program (SHRP); the revised traffic monitoring programs within the highway planning and research (HP&R) program; and truck size and weight enforcement certification requirements that may be necessary to meet the statutory requirement of protecting the highway infrastructure.

Long-Term Pavement Performance Monitoring

LTPPM is vital to the success of the SHRP effort. Truck weighing is a critical element of LTPPM. It has been estimated that as many as 4,000 highway sections will be selected nationally to meet the data needs of SHRP. It is also likely that the traffic data collection activity within LTPPM must be much more intensive at the selected highway sections than is currently the case. Although it may be possible to locate many of the LTPPM highway sections such that existing truck-weighing sites can be used, the scope of SHRP far exceeds the magnitude of current truck-weighing programs. Although this problem is now being addressed in the experimental design portion of the SHRP work, it is clear that automated systems integrating WIM with vehicle classification and traffic volume counting will be needed if the SHRP data needs are to be addressed in a cost-effective and efficient manner.

Traffic Monitoring

Another area of critical need for WIM is the need to meet even the minimum levels of truck-weight data collection recommended by the new FHWA Traffic Monitoring Guide. FHWA estimates that a minimum of 30 truck-weighing sessions of at least 48 hours each will be needed in each state to meet this objective. Although the states are free to design their own truck-weighing programs according to the new FHWA statistical procedures included in the Traffic Monitoring Guide, it is expected that, overall, the total number of sessions will be approximately 30 per state. This means that about 1,500 weighing sessions of 48 hours each are needed nationally. This is in marked contrast to the current level of about 600 sessions nationally, many of which are only eight hours in duration.

WIM technology will certainly be necessary in each state if the traffic monitoring goals of obtaining statistically reliable data for users is to be met.

Truck Weight Enforcement

It is probably only a matter of time until truck-weight study data will be required as part of the support data submitted by the states to show that they are complying with U.S. statutory requirements to enforce truck size and weight limits. Although static truck weighing is effective for determining size and weight compliance on an individual truck basis, it is not effective for assessing compliance with size and weight laws for the aggregate truck population. Therefore, the use of WIM devices for enforcement monitoring (rather than for issuing citations), as is currently being done in a joint effort by the Wisconsin DOT and the FHWA, can provide the data needed to document the effectiveness of state efforts to enforce these laws.

INTEGRATED DATA COLLECTION SYSTEMS

The integration of WIM equipment into comprehensive data collection systems has been carried out as an ad hoc activity in the past and is now receiving more organized attention. The work on the Crescent Demonstration Project and the related NCHRP study of the feasibility of a national heavy vehicle monitoring system are both directly addressing this issue. The incorporation of WIM with automatic vehicle identification and automatic vehicle classification technologies could change the way traffic data and other information are acquired in the United States within the next 10 years.

WIM EQUIPMENT ACCURACY

Review of the available literature on WIM equipment accuracy from both vendors and users is extremely difficult. There is no standard method used to indicate the accuracy of these devices. The most easily understood measure used is the mean error expressed as a percentage of individual weights, coupled with a confidence level. For example, "±5 percent at the 90 percent confidence level" means that 90 out of 100 weight measurements taken fall within 5 percent, over or under, of the true weights. The use of a percent accuracy by itself is difficult to interpret, since it seems to imply that *all* of the measurements fall within those limits. This may in fact be the case, but it should be clearly stated.

Another form of accuracy measure that has been used is a percent accuracy coupled with a standard deviation. This may be a good approach to use, but comparison with other accuracy measures requires assumptions about the statistical distribution of the data. The normal distribution is commonly used to construct these comparisons.

In any case, there is a clear need to define a standard method of measuring and specifying accuracies so that users can easily compare products as well as the experiences of other users.

CALIBRATION AND ACCEPTANCE TESTS

Calibration is the process whereby a measurement device is adjusted to give accurate and precise readings under given operating conditions. It is common practice in the United States to use one or two state vehicles of known weight and axle configuration to pass repeatedly over the WIM sensor to provide calibration information. This procedure includes the assumption that adjusting the WIM system to accurately weigh the calibration vehicles will enable the system to accurately weigh the vehicles in the traffic stream. Unless the user is certain that the equipment and installation do not require calibration for each weighing session, it is advisable to perform at least a brief calibration each time. Although coordination may be a problem, there are usually local highway maintenance yards in the vicinity of the WIM site that could provide a loaded and weighed truck for this purpose.

Acceptance tests are those tests that the customer requires the vendor's equipment to satisfy before it is put into use. Acceptance tests vary widely. The best approach seems to be concurrent weighing operations at both the WIM scale being tested and at a static scale location. Permanent static scales are easiest to use for this purpose, but portable static scales may be used if necessary.

RESEARCH NEEDS

One of the most significant areas of evolving technology is in the area of low-cost WIM devices. An FHWA research study to develop a low-cost (less than $5,000) WIM system that can measure heavy axles has recently been completed and the system is being tested. This device uses a weight sensor that is a capacitive strip, operating on the same principles described for the capacitive weighmat. An NCHRP study to develop a low-cost bridge WIM system will being early in 1987.

Other research in Europe and the United States has addressed the use of a piezoelectric cable, about 3 mm (⅛ in.) in diameter, embedded in the road surface, as a weight and/or axle sensor. Iowa and Minnesota, in cooperation with the FHWA, are conducting a demonstration study using this device. The Washington DOT also will be sponsoring research on piezoelectric cable in conjunction with the University of Washington.

Further research that will assist in getting these technologies to the users is important if the goals of the long-term pavement performance monitoring effort, truck weight studies for traffic monitoring, and certification of enforcement efforts are to be achieved.

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