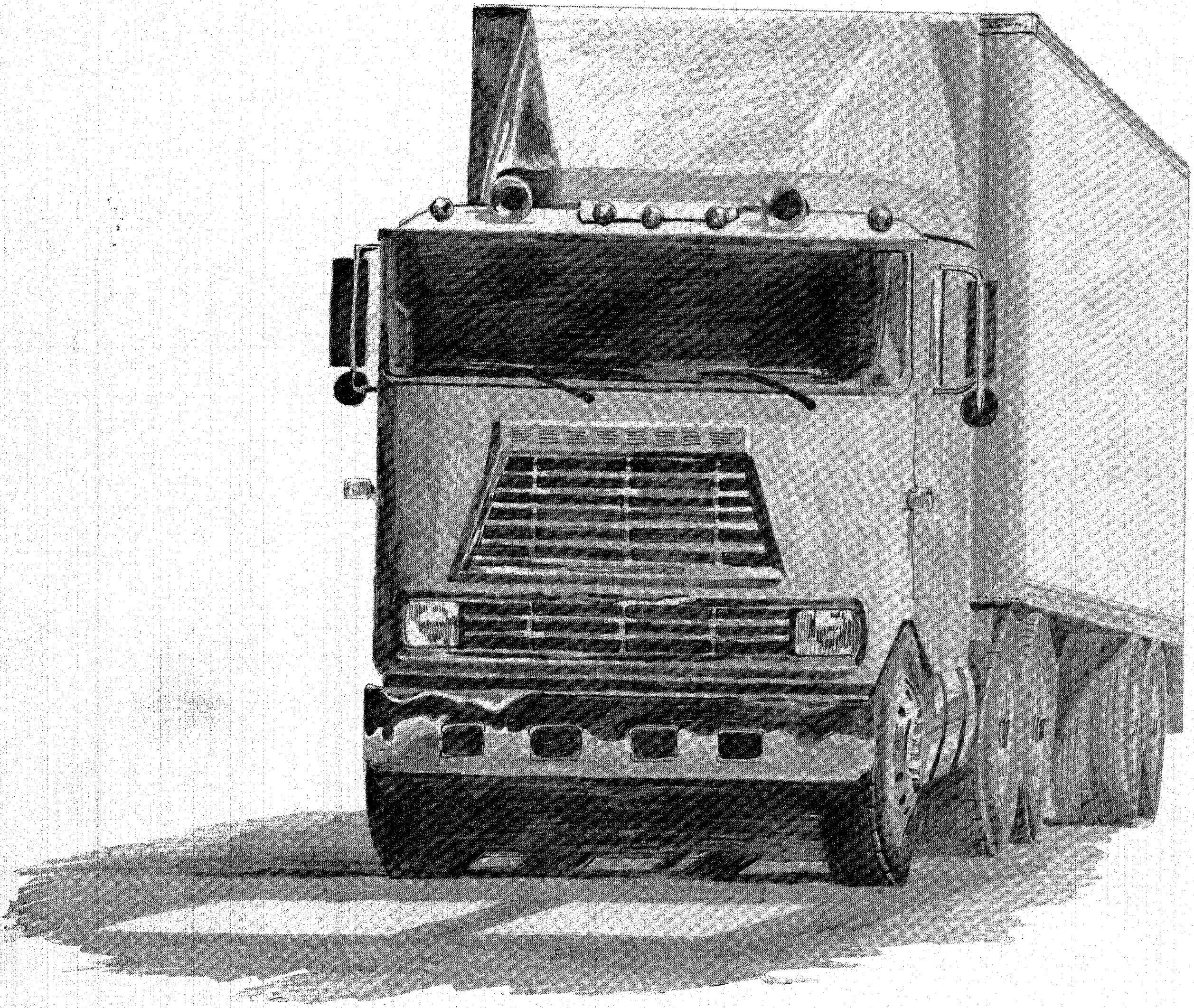
# THIRD NATIONAL CONFERENCE ON WEIGH-IN-MOTION

"Applications and Future Directions"
St. Paul, Minnesota, October 17-21,1988



State of Wisconsin Department of Transportation

Weigh
Wisconsin

In
Iowa

Minnesota Department of Transportation

Motion
Minnesota

# PROCEEDINGS

# THIRD NATIONAL CONFERENCE
# ON
# WEIGH-IN-MOTION

"Applications and Future Directions"
October 17-21, 1988 St. Paul, MN

## PROCEEDINGS

Wisconsin Department of Transportation
Iowa Department of Transportation
Minnesota Department of Transportation

In cooperation with the
U.S. Department of Transportation
Federal Highway Administration
Demonstration Projects Division

March 1989

The views and opinions expressed in this report are those of the authors and do not necessarily reflect those of the sponsoring agencies nor the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

# FOREWARD

The Third National Conference on Weigh-in-Motion (WIM) was held to share information and experience on this rapidly advancing technology. The first such conference was held in Denver, Colorado in 1983 and explored the technology in its infancy. The Conference looked ahead to experimentation, testing, and demonstrating the capabilities of WIM. A second conference was held in Atlanta, Georgia in 1985. WIM use and interest had grown from a handful of states to a majority of states and the conference looked ahead to the use of WIM data for enforcement, design, and pavement management.

The third national conference on WIM was attended by representatives from all 50 states and eight foreign countries. Presentations and demonstrations clearly revealed wide spread acceptance and use of WIM for both enforcement of vehicle weight laws, pavement design, and management.

This conference looked forward toward wide deployment of WIM made possible by low cost WIM sensors; toward expanded use of WIM data for enforcement planning, screening, and possibly even prosecution of overweight vehicles; and toward integration of WIM with other technologies as an accepted, powerful tool for states to effectively manage the highways.

The immediate prospects for WIM are exciting, the future outlook is bright, and the applications seem endless! We thank all of the participants, speakers, and equipment suppliers who helped make this an exciting and successful conference. A special thank you to the Federal Highway Administration whose sponsorship and support made it possible.

| Wisconsin | Iowa | Minnesota |
|---|---|---|
| George Novenski | Bill McCall | Dick Stehr |

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## CLOSING GENERAL SESSION

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# APPLICATIONS AND FUTURE DIRECTIONS

*Richard Morgan, Executive Director, Federal Highways Adminsitration*

## INTRODUCTION

o On behalf of the sponsoring organizations, let me offer our sincere thanks to:

Darrel Rensink, Director, Iowa DOT,
Len Levine, Commissioner, Minnesota DOT, and
Ron Fiedler, Secretary, Wisconsin DOT

for their willingness to host this conference.

o Particular thanks must also be extended to Dick Stehr of the Minnesota DOT, Bill McCall of the Iowa DOT, and George Novenski of the Wisconsin DOT who have managed the logistics of arranging the conference.

o In addition to the State personnel, each of the associated FHWA division and region staffs is to be congratulated for the strong support they have given to getting this effort under way.

o Within FHWA Headquarters, Perry Kent, of the Office of Highway Information Management, has been contract manager for this project, and Charles Stockfish, of the Demonstration Projects Division, has been providing administrative and funding support.

o If I have overlooked anyone involved in the planning and organizing of this conference, please look upon it as reflecting the limits of time and understand my appreciation for your efforts also.

o Although the possibility of another conference was discussed even as the Second National Conference was finishing in Atlanta in May of 1985, only within the last year have actual preparations been under way. I'm sure you all recognize the tremendous logistical effort a conference of this type involves and which all the more shows the strong commitment to its success made by its planners and organizers.

o An important element of a conference of this type is the participation by the various equipment vendors in setting up and manning the various displays. Their continuing support and participation are very much appreciated.

o The most important aspect of a successful conference is the interest shown by the attendees. Each of you has a significant impact on how well we will succeed over the rest of this week in making this conference meaningful to the better administration of the Nation's highway program. Together we can better understand what WIM technology will mean to the present and future information needs of the highway program.

o FHWA's support of this conference reflects the agency's long-term interest in automated traffic data collection, but more importantly, reflects our agency's commitment to the application of weigh-in-motion (WIM) and other automated traffic data gathering technologies to current highway issues. This approach to WIM is reflected in the name of the conference. FHWA no longer feels that WIM is simply an interesting research novelty but, rather, can be a powerful management tool for anyone willing to use it.

## THE EVOLUTION OF WIM

automated techniques are the products of a long-term evolutionary process of a number of efforts within the highway community.

o For example, FHWA's earliest involvement with WIM was in the early 1950's. This early attempt was less than successful because it required low vehicle speeds and was relatively costly. Sensing devices, at that time, could not keep up with the massive number of data inputs that mainline traffic could transmit to the weighing system.

o In the late 1950's an early WIM system was used on the AASHO Road Test. Bridges were instrumented with stain gages to determine the effects of live loading.

o The advent of successful WIM devices required the development of high speed microprocessor technologies in the 1970's. In 1974 and 1976, national conferences were held on automating data collection for transportation planning which included WIM.

o In 1983 and again in 1985, the Federal Highway Administration-sponsored National WIM Conferences focused specifically on the use of WIM equipment.

o To the time of the Second National WIM Conference in 1985, much of the WIM activity at the State and Federal level was directed to the assessment of WIM as a new technology. WIM was viewed as an interesting research activity rather than a valuable method of obtaining data for use in highway program administration.

o During the same time as these conferences, FHWA was beginning to provide funding through the Rural Transportation Assistance Program for the purchase and field assessment of various types of WIM devices by the States.

o Since the time of the Second WIM conference, I feel we have been seeing a maturing of WIM technology so as to make it readily usable by highway program managers. I feel this Third National WIM Conference should be looked upon as a watershed event in which WIM moves from a specialized data-gathering device to being a standard tool used in management of the highway program.

o This is not intended to imply that the technology will not continue to improve because, as we will hear this week, it will.

## APPLICATION OF WIM TO THE HIGHWAY PROGRAM

We have identified a number of significant highway issues that can be effectively approached using WIM. These issues can generally be termed to be either weight enforcement, pavement design, or planning oriented.

o Since WIM first began to be widely recognized as a technology, persons responsible for the weight enforcement program have sought to come to terms with the most appropriate uses of WIM in an enforcement effort.

- Because in most States WIM systems cannot be used as the sole basis for the issuance of an overweight citation, some enforcement agencies have tended to down play WIM's value to enforcement programs at the State or National level.

- We have long felt that WIM data can be a valuable adjunct to information collected through static enforcement weighing.

- The covert nature of WIM data gathering holds the potential for more clearly defining the magnitude and extent of the weight enforcement problem.

- WIM can also be a major tool in a State's effort to measure the general effectiveness of its enforcement program as well as helping to pinpoint the systems or locations that might gain from more rigorous enforcement actions.

- WIM has been successfully used by a number of enforcement agencies as a means of screening out those trucks in mainline operation that may be in excess of State or Federal weight limits. Once identified, such potentially overweight trucks are then weighed using static scales.

- These considerations led us to issue an August 2, 1985, memorandum to our field offices which clearly stated that WIM was an eligible item for Federal-aid construction funding. To be eligible for funding, the gathered data was to be used to measure the extent of the overweight problem or determine the effectiveness of the enforcement program.

- FHWA's determination of WIM being a legitimate cost within the weight enforcement program simply helps to highlight that WIM has become a valid data-gathering tool within the highway program.

o The use of WIM, in support of the pavement design and management process, has also gone through a period of controversy which focused on the comparability of static versus WIM-collected weight data.

- Admittedly, the early WIM devices may have produced data of limited value, but the improvement in equipment over the 1980's has radically changed that situation.

- Presently, the use of WIM data as part of the pavement design and management process has led to significant insights into the actual pattern of truck loadings, as well as a clearer picture of the relationship between pavement loadings and pavement deterioration.

- From State to State, we have been seeing a similar pattern of WIM revealing pavement loadings that are substantially greater than had previously been assumed to be occurring.

- You simply have to know what is running on your highways and WIM is a necessary tool to do this.

## FUTURE DIRECTIONS

The preceding discussion described efforts to make WIM an effective part of highway program management. The following are some of my thoughts on the issues we will need to address in the not too distant future and how I feel WIM will contribute to meeting these issues.

o The need for improved information for pavement management and design will continue to be a high emphasis area nationally into the next century.

- The Strategic Highway Research Program (SHRP) will be a major factor in how well we carry out management of the pavement improvement programs nationally.

- The success of the SHRP will depend heavily on our willingness to collect the data necessary to reach meaningful conclusions as to the inter-relationship of loading, soils, materials, design, and environment.

- WIM is the only method of providing the quantity and variety of loading data needed by the SHRP. It is imperative that each State recognize that adequate support for the SHRP will probably require more traffic data gathering, including weight data, than has been a normal part of each State's traffic data collection program. This situation means that each State will need to give serious consideration to providing additional equipment, personnel and fiscal resources to adequately support the SHRP activities in their State.

o FHWA's new Pavement Policy requires the States to have a cost-effective pavement design procedure, a pavement type selection process, and a Pavement Management System. All of these are greatly enhanced by WIM installations.

o FHWA will remain committed to supporting State highway agencies in the development of new approaches to WIM and to innovative application of existing technology.

- FHWA's support of the recently completed work on the use of piezo-electric cables for weighing in motion in Minnesota and Iowa is one such example.

- FHWA continues to be interested in the integrated gathering of count, class, weight and vehicle identification data being undertaken as part of the Heavy Vehicle Electronic License Plate program and its associated multi-State field demonstration.

- FHWA remains committed to supporting the States in the testing of new WIM technologies such as piezo-electric film, as well as other approaches leading to truly low cost WIM systems.

o Every State should have WIM as an integral part of their pavement and bridge management program. Similarly, every State should use WIM as a screening device for their weight enforcement program.

o It must be noted that this very Conference is indicative of FHWA's continuing commitment to WIM. The Conference is funded as a part of and kicks off Demonstration Project 76, "Automated Traffic/Truck Weight Monitoring Equipment." The demonstration will be available to all interested States and will provide State personnel with an understanding of the various types of WIM, their accuracies, cost, limitations, and appropriate applications. Bill Nostrand will be elaborating on this Demonstration Project later in the Conference.

o Finally, I would like to take this time as an opportunity to express my feeling on the highway program in general. Most of you are aware of the several national efforts underway to assess the future direction of the program as we move toward the twenty- first century. These far reaching initiatives both inside and outside of government agencies will continue on into the 1990's.

- Recently, a great deal of the discussions concerning the highway program has been in the context of whether we should get it off budget. Such discussions are a waste of time. They are diverting our attention from what should be the real concerns of the Nation's highway managers.

- These concerns include doing more with less, meeting the needs of urban and suburban congestion, and effectively supporting the highway's role as an major factor in the Nation's economic well being. Good data is essential to addressing these issues and arms us well in competing for scarce resources.

- Conferences, such as this one, mark the need to maintain better data on what is happening to the highway infrastructure. In the future we should expect that our data needs may demand even more detailed information on the use of the highway resource and may demand the use of automatic vehicle identification and vehicle location systems.

- The highway industry has been challenged in the past and has met each challenge. The future holds greater challenges and I feel that we will provide the innovation to meet each need.

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# AN EVALUATION OF CURRENTLY AVAILABLE WIM SYSTEMS

Conducted by the Maine Facility Labs.
Research Group-Technical Services Division
Maine Department of Transportation

*John H. Wyman*

## Currently Available W.I.M. Systems

During the summer of 1987 the Maine D.O.T. Technical Services Division conducted an evaluation of those W.I.M. systems that could be made available for testing. This program was sponsored by the F.H.W.A. under a "Demonstration Project."

Comments made in this paper about the operational characteristics of the various systems are the result of observation of their behavior during this study. Some changes have been made since by the manufacturers, to several of the systems, which may result in improvements in the operation of the currently available units.

## 1.0 SYSTEMS EVALUATED

The following WIM systems were available and were tested:

1. GOLDEN RIVER: CAPACITANCE PAD
2. CMI/IRD SYSTEM: LOAD CELL SCALE
3. BRIDGE WEIGHING SYSTEM: CLAMP ON GAUGES
4. PAT SYSTEM: BENDING PLATE
5. STREETER RICHARDSON: BENDING PLATE
6. STREETER RICHARDSON: CAPACITANCE PAD

Also of interest, although not tested, is a Radian system which is a multiple load cell system embedded in the pavement.

For the future, there are developments under way sponsored by the FHWA and others: one is a low cost B.W.I.M. System, hopefully to cost under $ 10,000, at least two years away, and a Piezo Electric system. Studies on this system are being conducted by the Iowa D.O.T.

## 2.0 GENERAL PROBLEMS

WIM systems do not actually weigh the axles crossing the sensors. The dynamic force present when each axle crosses the sensing unit is what is measured. This occurs as a result of several different phenomena acting simultaneously. Vertical and lateral oscillation of the vehicle occur, due to movement of the suspension, body and the load, caused by unbalance in these various components. Pavement unevenness also produces excitation of the suspension and body and this excitation can increase errors due to the factors above. Both of these conditions result in levels of dynamic forces being observed by the weigh sensors which are either greater or less than the true static weight. Such variations can be as much as plus or minus 30 to 40% of the static weight. Dr. Clyde Lee will be telling about these effects in detail in a subsequent paper.

## 3.0 EVALUATION TECHNIQUES

The final evaluation in Maine was conducted at Sidney, in the Northbound travel lane of I-95. The average daily traffic was approximately 9000 vehicles, with a high percentage of trucks. The average speed was over 60 mph.

The CMI-Dynamics system was installed at Sidney, in 1985. The other systems under evaluation on this project were installed at Sidney with the PAT Bending Plate System placed about 100 feet beyond the CMI system, the Streeter Richardson bending Plate and the Capacitance Pad System followed at approximately 100 foot intervals. The Golden River Capacitance Pad system also followed, approximately 100 feet further. The Bridge Weighing System was installed in a utility van and situated under an overpass 3.1 miles beyond the rest of the system. The van was not visible from I-95. Tape switches were used for vehicle presence and classification. As there was no escape road between the rest of the system and the bridge, no traffic was lost.

Thus all the systems were in a gauntlet pattern so that all received the various vehicle in sequence.

### 3.1 Precalibration Runs at Sidney.

One of the most serious problems with all types of WIM systems is the difficulty of effecting a suitable initial calibration for each system. Repeated runs with a preweighed 3S2 proved to be the best compromise for effecting this calibration at Sidney. A leased 3S2 loaded to about 75,000 pounds was run repeatedly through the scale system at several speeds. The static weights were obtained by weighing each set of wheels with 6 Haenni Scales calibrated to N.B.S. requirements. The calibration factors in each system were then adjusted to be as close as possible to the norm. The results of these tests were also used to verify the systems' ability to accurately calculate the axle spacings.

Speed is calculated by measuring the time between the intercept of the first loop and the second loop. Dividing the loop spacing in feet by the elapsed time of travel of the vehicle between the two loops, in seconds, gives the speed in feet per second, which is then converted to miles per hour.

Measurement of loop intercept time is subject to variations depending on the type of vehicle, height above the road of the major metal components and vehicle speed. Both speed and axle spacing measurements are subject to errors which are vehicle sensitive. Checks on the systems using a gun type radar show errors in speed measurements up to plus or minus 3 mph which were not system dependent.

### 3.2 Random Traffic Check.

Two sessions using random traffic were run at Sidney for the final verification of the ability of the six systems to accurately handle high volume traffic at the higher speeds. Trucks were selected randomly at the Augusta ( Northbound ) rest area on I-95, by the State Police traffic enforcement group. The rest area is approximately seven miles from the Sidney site. There is only one possible escape turn off for trucks between the Augusta weighing site and Sidney. It was not used by more than a small percentage of vehicles.

The first run was conducted on August 12th. A total of 125 trucks were weighed, 92 of which were captured by the test scale system. For this run the passing lane was blocked through the system so that all traffic was forced to use the travel lane. Apparently the presence of the barriers caused the more cautious automobile drivers to drive more slowly than was their usual custom. Thus the truck traffic also was forced to drive more slowly and as a result the truck speed was below their normal speed on this highway, running about 50-55 mph instead of the usual 65 or more. In order to obtain a run in which the truck speeds were more nearly at the speed used in the initial calibration, a second run was made with both lanes open. This run was made on August 20th and consisted of 203 vehicles of which 163 were captured by the scales in the travel lane. The passing lane was not equipped with scales.

The weighing at Augusta was done using low profile Electronic Lodec Scales. An observer at Augusta recorded each vehicle weighed, assigned a sequence number to it and recorded identifying details. A second observer also recorded the front axle weight, each set of tandem weights and the total weight for each truck he weighed. Two axle trucks up through 3S3's were weighed. The sequence number and identifying details were radioed to Sidney where another observer passed this information by "Walkie Talkie" to observers at each scale. Here the sequence number was recorded on the print-out for the data of the applicable vehicle. Final weights were not known at Sidney until after completion of the test runs. Correlation of the weigh with the truck numbers was completed at a session the next day.

The data sets, 80 in all, showing total weight, front axle weight, and both tandem weights compared to the Lodec weight were prepared using scatter plot technique and are shown complete in the final report published on December 31, 1987. Copies of the final report are available from the F.H.W.A. in Washington. One set, showing gross weight for all trucks through each scale for both days run are included in this report for reference.

### 3.3 Scatter Plot Calculations.

It is reported that California is using an interesting approach to evaluating the accuracy of WIM scales. The data on the Sidney runs was processed using this technique The percent error, positive or negative of the WIM value for each of the random vehicles with respect to the Static weight was calculated. The mean of these percent errors is calculated along with the deviation. The deviation of the mean from 0, or from a one to one relationship between the static weight and the WIM force reading represents the systematic error of the scale. That is the amount the scale calibration is in error. The standard deviation of the percent errors represents the random errors of the system due to other factors such as speed, vehicle type, road surface conditions and other random variables. The results of such an analysis of the random truck data were obtained on August 12 and 20. The total for both days run is shown for each scale system in Figure 1.

Figure 1- Mean and Standard Deviation for Random Traffic Sessions.

Mean and Standard Deviation of Errors for all trucks on 12 and 20 Aug. 1987

| | Mean | STD |
|---|---|---|
| CMI-IRD | -0.37% | 12.96% |
| PAT | -4.31% | 11.98% |
| S/R Plate | 5.05% | 9.50% |
| S/R Cap.Mat | 5.32% | 16.32% |
| Golden R.Cap Mat | 22.79% | 19.80% |

Minimum, Mean, Standard Dev., and Maximum Values in % error of difference between WIM and Static Gross Weight divided by Static Gross Weight for 3S2 and 3S3 Semis at Sidney on 20 August 1987.

| | CMI-IRD | PAT | S/R Plate | S/R Cap | G/R Cap | BWIM |
|---|---|---|---|---|---|---|
| Min | -46.55% | -31.83% | -28.49% | -26.23% | -45.25% | -43.34% |
| Mean | -3.05% | -6.00% | 4.46% | 5.47% | 16.58% | 4.17% |
| STD | 13.62% | 13.02% | 10.77% | 20.09% | 17.13% | 11.05% |
| Max | 23.56% | 22.85% | 41.30% | 89.09% | 100.68% | 26.60% |

Minimum, Mean Standard Dev., and Maximum Values, in % error, of difference between WIM and Static Gross Weight Divided by Static Gross Weight for 3S2 and 3S3 Semis at Sidney on 12 August, 1987.

| | CMI-IRD | PAT | S/R Plate | S/R Cap | G/R Cap | BWIM |
|---|---|---|---|---|---|---|
| Min | -24.23% | -31.83% | -15.40% | -23.30% | -4.40% | -7.03% |
| Mean | -2.36% | -0.54% | 3.38% | 3.58% | 35.42% | 5.89% |
| STD | 9.13% | 11.14% | 7.21% | 13.78% | 16.45% | 5.66% |
| Max | 19.65% | 27.20% | 19.56% | 33.44% | 73.61% | 16.64% |

Several conclusions can be drawn from these data.

The calibration error for all scales except the Golden River Capacitance Pad was under 5.32 percent.

The standard deviation or random error except for the Golden River ranged between 9.5 and 12.96 percent.

Since the Golden River mat calibration error was so high, 22.79 percent, plots were made of the percent calibration error versus speed for the various systems. All systems had some speed dependence but the Golden River pad system showed a large speed dependent error when plotted. The apparent weight varied from the static by approximately 10 percent at 65 mph and climbed to approximately 70 percent at 35 mph. The manufacturers of the capacitance pad systems know that this type of system has a large speed dependent error. Therefore they have built-in software corrections in the equipment.

Investigation revealed that the Golden River Weighman and the Retriever Elite, which had been supplied to the Maine Facility for this test program inadvertently, had not been upgraded with the latest EPROMS to provide the correction necessary to correct the speed error. Golden River supplied new EPROMS which were installed. A 3S2 loaded to weigh approximately 75,000 pounds was run through the PAST, Streeter Richardson plate and mat system and the Golden River system. Multiple runs were made at 25,35,45,55 and 65 mph.

The large speed dependent error of the Golden River system was reduced. The calibration error is now + 18.12% with a random error of 6.12 percent. The mean and the standard deviation for the four systems is shown below. The Golden River System is now more in line with the other systems. The systematic error is still high but the random error has been reduced. The calibration error could have been reduced nearer to normal by entering a revised calibration into the software via the Retriever, but time did not permit making this change and repeating the run with the 3S2.

| SCALE | MEAN | STD |
|---|---|---|
| PAT Plate | - 3.01% | 6.82% |
| S-R Plate | - 3.77% | 3.74% |
| S-R Cap Pad | -10.47% | 3.36% |
| Golden River Cap Pad | 18.12% | 6.17% |

Based on 3S2 Cal. Runs through the four systems after Golden River Seed Compensating EPROMS were installed.

## 4.0 SYSTEM TRADE-OFF

### 4.1 Capacitance Pad Systems.

The capacitance pad systems which are available from Streeter Richardson, Golden River and PAT are the only truly portable systems. A single lane system costs approximately $25,000 to $30,000 depending on options. Installation is simple as the pad is placed flat on the pavement and fastened down with Parker-Kalon nails with mastic tape placed around the edge. Lag bolts can be used in place of the nails if desired. Either permanent or temporary loops can be used. If temporary loops are used the installation can be completed in approximately two to three hours by four people; two for flagging and two to perform the installation of the pad. The systems are speed sensitive as mentioned and the accuracy not as good as other types of systems.

For collecting 24 to 48 hour data these systems are suitable. The Golden River unit is battery operated and is contained in a small waterproof case that may be chained to a post or guard rail. Maintenance is minimal over a short session. Heavy traffic, or long sessions may result in some movement of the capacitance pad. 4.2 Bending Plate System.

The Bending Plate Systems are semi permanent. Although the plate itself can be moved a frame must be installed in the roadway wherever it is desired to use the scale. Estimated cost is $ 35,000 per lane installed. Installation was done in Maine with a crew of eight including two flagmen. Barriers between the installation and the still operating lane were of course installed. These systems in general have abetter accuracy than the capacitance pad systems. Maintenance was minimal.

### 4.3 Load Cell System

The CMI-IRD system scale is a load cell system within a heavy steel platform weighing approximately 2000 pounds. Two are used per lane, one in each wheel path. A four lane system was installed by the Maine D.O.T. Planning Department in 1985. The cost of the CMI system for two lanes was approximately $ 113,000 and for four lanes $ 220,000. These figures include scales, electronics, software, computer, modem and printer. The cost of making the installation was quite high because of the need to construct the concrete housing vault, which was approximately three feet deep and extended across the passing and travel lanes. In addition, extensive drainage had to be provided. Signing crews and construction costs amounted to about $ 100,000 for a four lane interstate system.

The accuracy was the best of the systems tested.

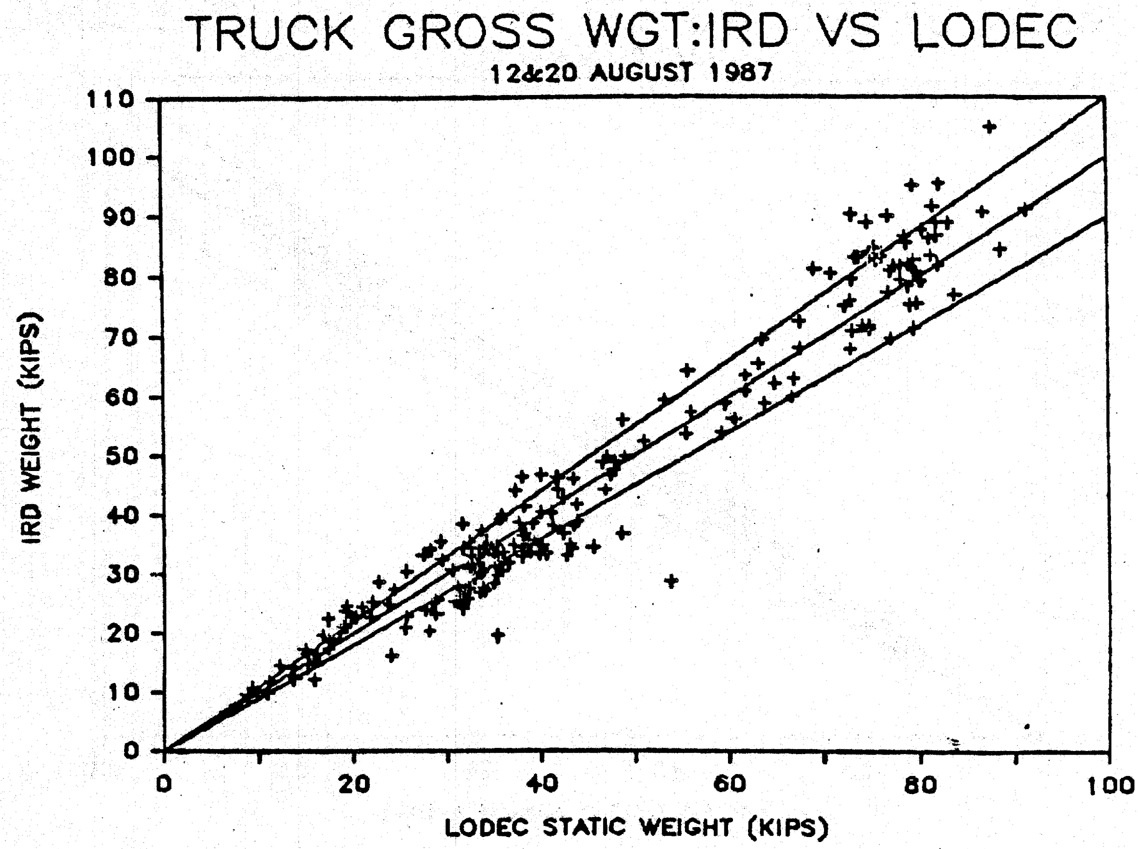
### 4.4 Bridge Weighing Systems, Inc.

The Bridge Weighing System which was tested was one of the first developmental systems supplied to the FHWA by the contractor, Bridge Weighing Systems, Inc. and later modified by Lehigh University. It was loaned to us for testing by the FHWA Fairbanks Laboratory.

The system consists of clamp on strain gauges, two tape switches, a road interface unit, a signal conditioner, a Digital MINC II computer with a terminal and a printer. Power was furnished by a 3KW 120 volt AC generator. Vehicle data can be viewed at the site on the terminal and hard copies printed if so desired, or the data can be stored on discs and processed later. The cost of the bridge Weighing System Inc. unit, including a van and as described above, is approximately $ 100,000. Installation of the clamp on gauges and the two tape switches required on a bridge takes about one hour. Two people can perform the installation and operate the system to take vehicle data. Accuracy of this system was quite good.

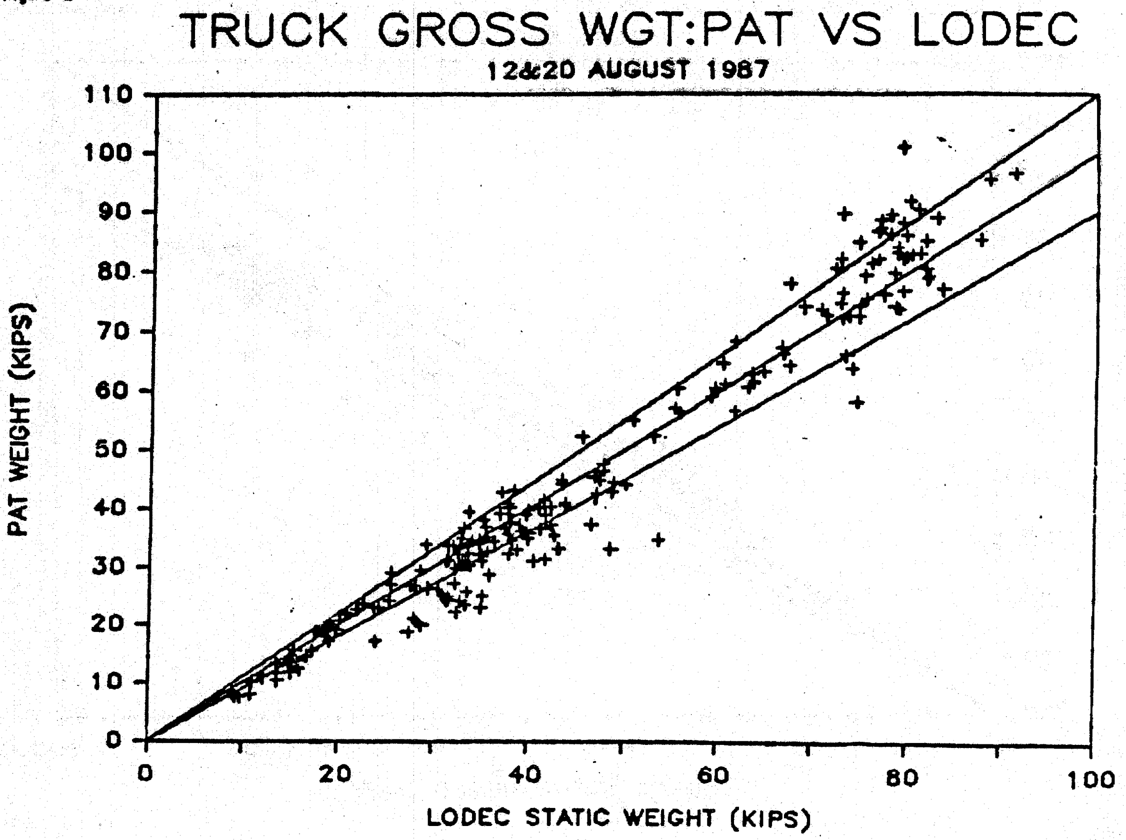
## 5.0 FUTURE NEEDS

One future WIM need, especially for programs like SHRP, are a lower cost portable unit. A calibration technique that more realistically simulates the force to which the transducer is subjected, is needed. More comprehensive documentation would help the training of the technicians who operate the existing field data gathering devices, in becoming more at home with the WIM systems.


TRUCK GROSS WGT:IRD VS LODEC

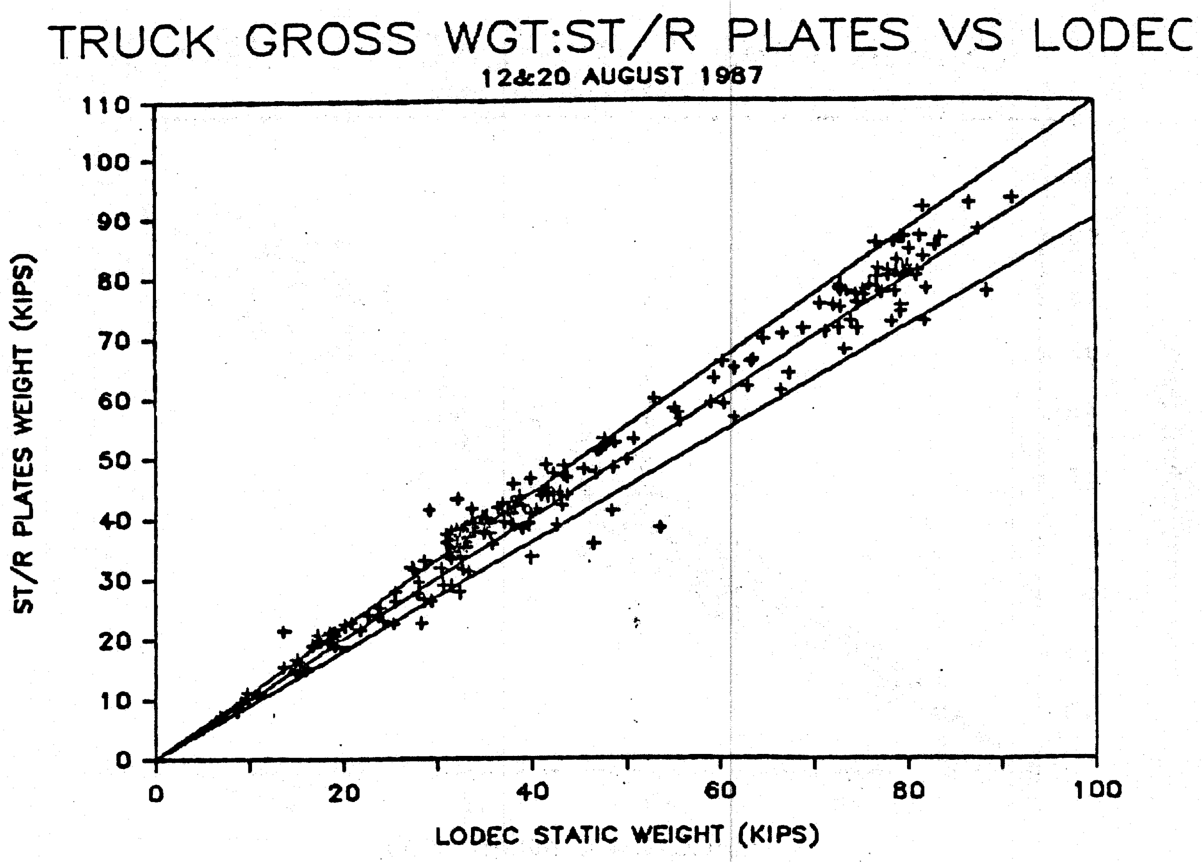
12&20 AUGUST 1987

Figure 2


TRUCK GROSS WGT:PAT VS LODEC

12&20 AUGUST 1987

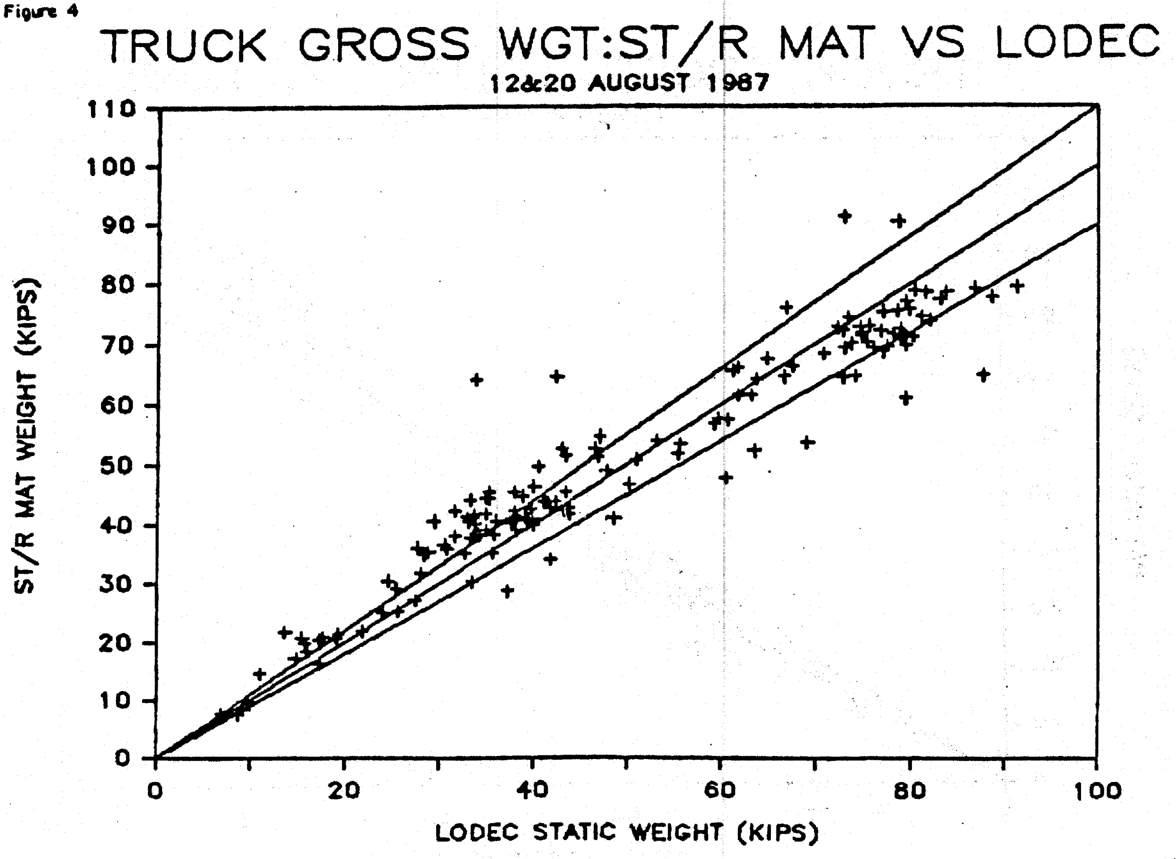
Figure 3



TRUCK GROSS WGT:ST/R PLATES VS LODEC

12&20 AUGUST 1987

Figure 4



TRUCK GROSS WGT:ST/R MAT VS LODEC

12&20 AUGUST 1987

Figure 5

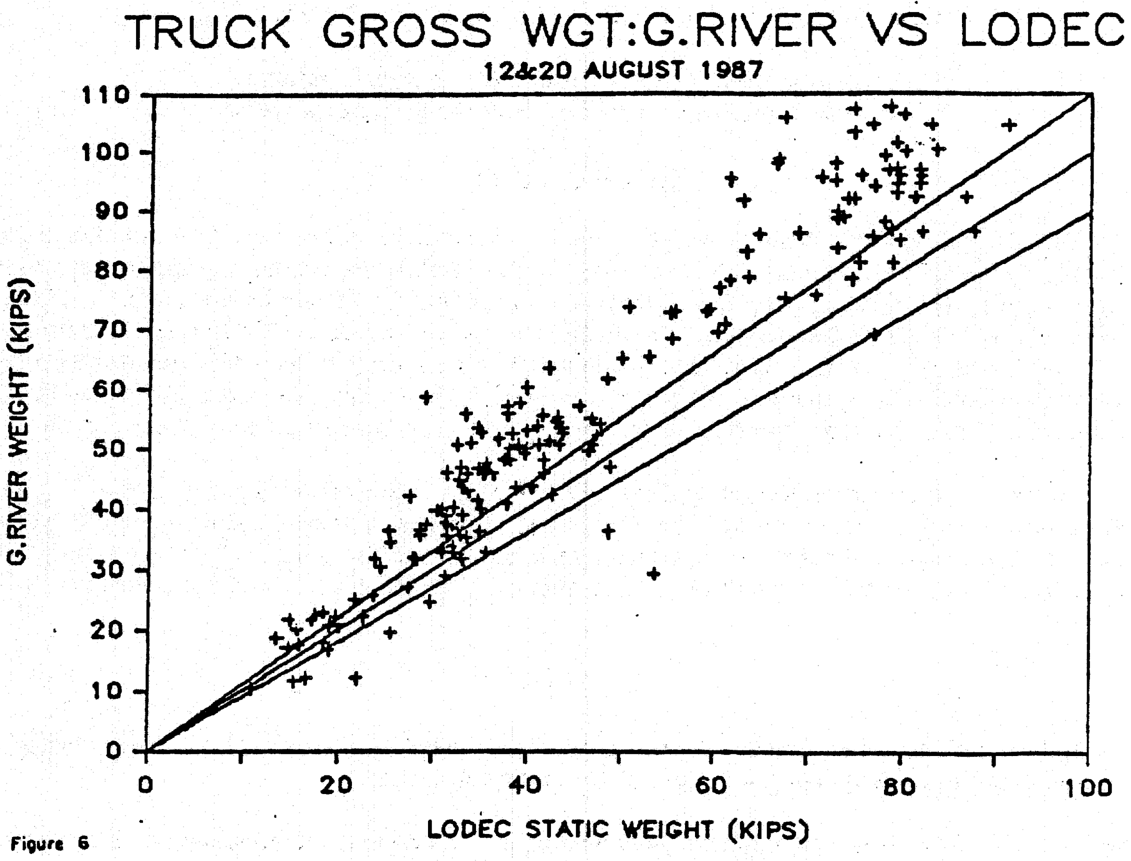


Figure 6

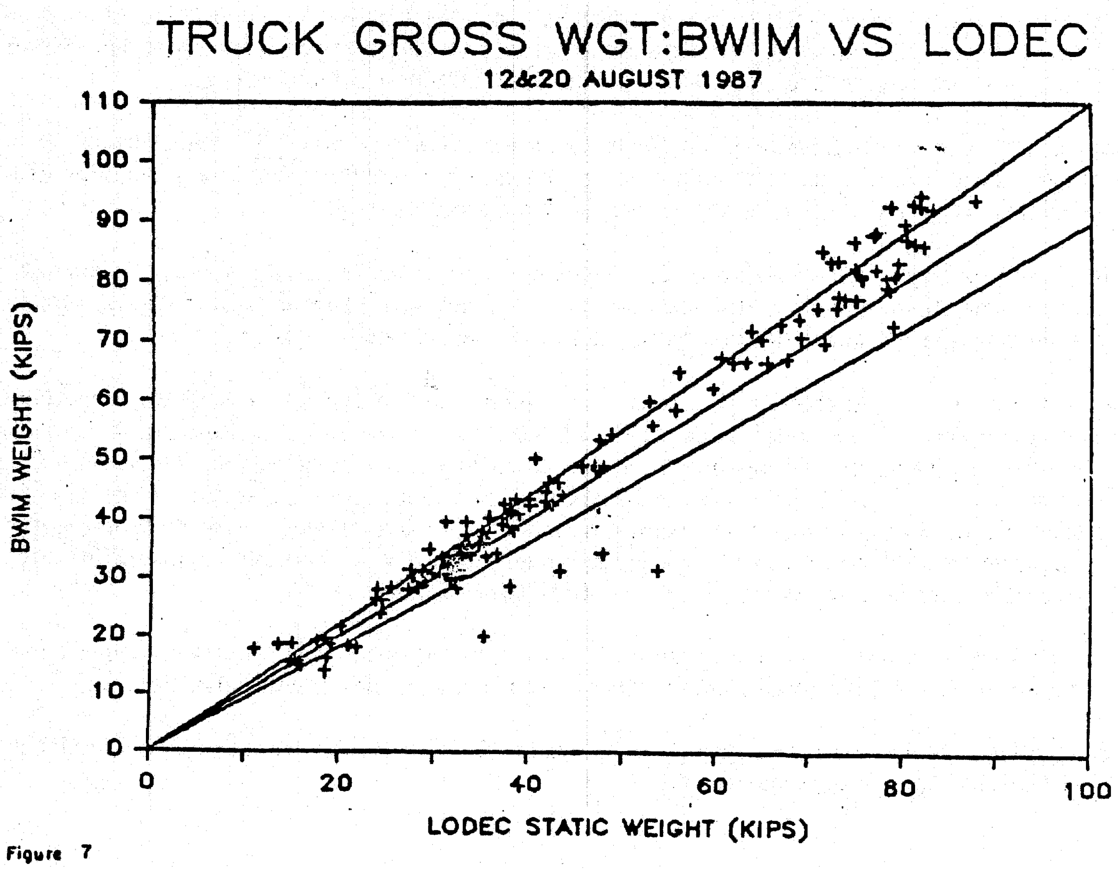


Figure 7

# FACTORS THAT AFFECT THE ACCURACY OF WIM SYSTEMS

*Clyde E. Lee, The Nasser I. Al-Rashid Centennial Professor*
*in Transportation Engineering The University of Texas at Austin*

## INTRODUCTION

A number of different systems for weighing highway vehicles in motion have been developed during the past three decades. These systems, called weigh-in-motion (WIM) systems, have generally been used by public agencies for (1) collecting statistical traffic data, (2) aiding traffic law enforcement, or (3) actual enforcement. There has always been concern about the accuracy with which a WIM system can estimate the weight of a vehicle as well as about the accuracy with which weight needs to be determined for each of the applications mentioned. The purpose of this paper is to identify the factors that potentially act and interact to cause inaccuracy and to discuss the relative importance and magnitude of some of these factors.

In order to communicate accurately about the complex pattern of physical forces which occurs as a vehicle moves over the road surface and thereby affects the weight estimates made by a WIM system, it is necessary to understand the definition of selected technical terms. The glossary below gives the specific meaning of several such terms which will be used in discussing the factors that affect the accuracy of WIM systems.

## GLOSSARY

**Weigh-in-Motion (WIM)** - the *process* of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding weight(s) of the static vehicle [1]

**WIM system** - a set of sensors and supporting instruments which measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates vehicle weights, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information [1]

**accuracy** - 1. the degree of conformity of a measure to a standard or truevalue [2] 2. the closeness or degree of agreement (within a stated tolerance and probability of conformity) between a quantity measured or estimated by a WIM system and an accepted reference value [1]

**accurate** - 1. conforming exactly to truth or to a standard [2] 2. A piece of equipment is "accurate" when its performance or value -...., as determined by tests made with suitable standards - conforms to the standard within the applicable tolerances and other performance requirements. [3]

**tolerance** - 1. The official tolerances prescribed by a weights and measures jurisdiction for commercial equipment are the limits of inaccuracy officially permissible within that jurisdiction. It is recognized that errorless value or performance of mechanical equipment is unattainable. Tolerance values are so fixed that the permissible errors are sufficiently small that there is no serious injury to either the buyer or the seller of commodities, yet not so small as to make manufacturing or maintenance costs of equipment disproportionately high. [3] 2. the defined limit of allowable departure from the true value of a quantity measured or estimated by a WIM system [1]

**mass** - the property of a body that is a measure of its inertia, that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field [2]

**standard of mass** - the United States Prototype Kilogram 20, which is a platinum-iridium cylinder kept at the National Bureau of Standards [3]

**avoirdupois pound** - defined in terms of the kilogram by the relation:
1 avoirdupois pound = 0.453 592 37 kilogram [3]

**inertia** - a property of matter by which it remains at rest or in uniform motion in the same straight line unless acted upon by some external force [2]

**velocity** - time rate of linear motion in a given direction [2]

**acceleration** - the time rate of change of velocity

**force** - an agency or influence that if applied to a free body results chiefly in an acceleration of the body and sometimes in elastic deformation and other effects [2]; has both magnitude and direction

**force of gravity** - the force of earth's gravitation, which when applied to a body in free fall will cause the body to accelerate downward toward the approximate center of the earth; the value of such acceleration at sea level in latitude 45 degrees being 980.1018 centimeters per second per second [2]; varies from location to location on the earth's surface

**weight** - 1. a measure of the inertia of a body, especially in terms of the force of gravity 2. synonymous with mass

**vehicle scale** - A scale adapted to weighing highway, farm, or other large industrial vehicles (except railroad freight cars), loaded or unloaded. [3]

**axle-load scale** - A scale permanently installed in a fixed location, having a load-receiving element specially adapted to determine the combined load of all wheels (1) on a single axle or (2) on a tandem axle of a highway vehicle. [3]

**portable axle-load weigher** - portable weighing elements specially adapted to determining the axle loads of highway vehicles

**wheel-load weighers** - compact, self-contained portable weighing elements specially adapted to determining the wheel loads or axle loads of vehicles on highways for the enforcement of highway weight laws only [3]

## THE WEIGH-IN-MOTION PROCESS

The *process* in which the dynamic tire forces of a moving highway vehicle are measured and used as the basis for estimating the corresponding weight of the static vehicle is called Weigh-in Motion, or WIM. A WIM system consists of a set of sensors and supporting instruments which measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates vehicle weights, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information.

The overall accuracy with which a WIM-system estimates weight is a function of (1) the actual difference in the dynamic tire force of the moving vehicle and the corresponding constant tire force of the static vehicle at the respective times of measurement, (2) accuracy of dynamic tire-force measurements, (3) adequacy of the estimation procedure, and (4) accuracy of weight measurements for the static vehicle. Several factors which affect accuracy are involved at every stage of the process.

## ACCURACY

In this discussion, *accuracy* is the degree of agreement (e.g., within a stated tolerance and probability of conformity) between vehicle weight estimated by a WIM system and an accepted reference value the corresponding weight of the static vehicle measured by a scale or weigher. No measurement process which involves mechanical and electrical devices yields errorless values; therefore, a *tolerance value* is established to define the allowable departure of a measured value from its true value.

Tolerance values for scales and weighers are given in NBS Handbook 44 [3]. These devices, when tested with approved standard test weights, are said to be accurate if *all* indications of weight are within the applicable tolerance value and other performance requirements are met. These tolerance values do not recognize adequately error associated with the manner in which these devices may be used to weigh a truck. For example, user requirements are not definitive concerning whether brakes can be applied during weighing, and the user is required only to have the vehicle "in a reasonably level position" when either an axle-load determination or a gross-load determination is being made utilizing wheel-load weighers or portable axle-load weighers. Accurate equipment can be used in a way that produces erroneous results. Nevertheless, weight values determined under such conditions are generally accepted as the true or reference values to which WIM-system weight estimates are compared.

Tolerance values for WIM systems are discussed by Davies and Sommerville [5] and by Izadmehr and Lee [4], and are included in a draft ASTM standard specification [1]. For high-speed and intermediate-speed WIM systems, the test loads used for evaluation of system accuracy cannot be standard test weights (metal blocks) set on the force sensors. Moving vehicles are required, and the vehicles must also be stopped and weighed statically. Test methods which utilize moving-vehicle loading are incorporated into the draft ASTM standard specification. The intent is to establish tolerances that can be met and that satisfy the needs of WIM-system users without making the manufacturing and maintenance costs of WIM systems excessive.

## FACTORS THAT AFFECT ACCURACY

There are many factors that potentially act and interact to cause inaccuracy in WIM- system estimates of vehicle weights. Some of these factors are listed below and discussed briefly. They are divided into four categories according to the stage in the WIM process at which they might occur.

### *Factors Which May Cause the Tire Forces Produced by a Moving Vehicle and by a Static Vehicle to Differ*

### VEHICLE FACTORS

- **Gross-Vehicle Weight** - The vehicle being weighed may be empty, partially-loaded, or loaded. The dynamic forces associated with the motion of a particular vehicle in earth's gravity are related directly to the *total weight* (mass) of the vehicle. Force is the product of mass times acceleration.

- **Distribution of Gross-Vehicle Weight** - Gross-vehicle weight is made up of the combined weight of several connected (via hinges, springs, and motion-dampers) components. Force may be transmitted through the connections to the components, but each vehicle component, with its own weight, responds independently to the external forces applied to it. The gross weight of the vehicle does not change as the vehicle moves on the road surface nor as the various components experience differential movement; the weight is simply redistributed among the axles and wheels through the connections. When no component of the vehicle is *accelerating vertically* (e.g., when the vehicle is static or moving at constant speed on a smooth, level surface), the sum of all vertical components of force applied at the tire-roadway interface equals the force of gravity at that location on the earth's surface, and is proportional to the gross-vehicle weight. At any instant, the portion of the gross-vehicle weight carried by a given wheel, axle, or axle group is a function of the *relative vertical position* of each component with respect to all others on the vehicle. *Torque* applied to the wheels of the vehicle via the drive train or by the brakes can cause *differential vertical movement* of vehicle components and thereby effect a redistribution of gross-vehicle weight. On tractor-semitrailer combination vehicles, the longitudinal location of the semitrailer connection (fifth wheel) on the tractor also affects the distribution of gross-vehicle weight among the axles.

- **Suspension** - A vehicle suspension system consists of a number of mechanical parts which connect the so-called sprung mass (body) to the unsprung masses (axles and wheels). The spring configurations typically include metal springs, rubber blocks, and air bags. As the vehicle moves, factors such as *stiffness, hysteresis, friction, alignment,* and *wear* in the suspension system affect the dynamic behavior of each individual vehicle component that is connected by the suspension system. Damping of the relative motion between vehicle components is effected in the suspension system mostly by friction between moving parts, by fluid flowing through a restriction, or by other more-complex means.

- **Tires** - Tires are a major component of the wheel assembly at the end of each axle on a vehicle. The tire is the force-transfer medium at the vehicle-road interface. Forces both normal (perpendicular) to and tangential (parallel) to the road surface act on the tires. When the vehicle is in motion, the rotating wheel assembly (including the tires) responds to the complex combination of forces that is applied at the tire-road contact area as well as at the suspension-system connections. Tire-related factors that affect dynamic forces on a moving vehicle include *mass, materials, inflation pressure, temperature, tread pattern, roundness, dynamic balance,* and *wear.* The magnitude of the dynamic force component in the vertical direction that is generated by the high-speed rotation of an out-of-balance or out-of-round tire/wheel assembly is surprisingly large. Such force is often large enough to overcome the applied downward spring force plus the inertial force of the mass and cause the assembly to bounce off a smooth road surface several thousand pounds of force are involved.

- **Aerodynamic Characteristics** - The forces which act on a vehicle as the result of air flowing around the vehicle are a function of the size and shape of the vehicle as well as the speed of the vehicle as it moves through the air. The factors which affect the magnitude and direction of the air-induced forces on a moving vehicle include the *frontal and side areas and their respective shapes as well as the speed* of the vehicle. Air forces acting on the frontal area of the vehicle affect the required tractive effort and thus, through torque applied to the drive axle(s), cause a redistribution of the gross-vehicle weight among the axles of the moving vehicle. A cross-wind (air in motion) similarly applies an external force to the side area of the vehicle (moving or static) and causes a side-to-side redistribution of the gross-vehicle weight among the wheels of the vehicle. Most large highway vehicles are poor airfoils; therefore, at normal highway speeds, lift forces are probably not a matter of serious concern to WIM accuracy.

## ROADWAY FACTORS

- **Alignment** - The *vertical and horizontal alignment* of the roadway, as well as the *transverse slope* of each lane, affect the magnitude and direction of the forces which act on a moving vehicle. The force of gravity acts vertically downward on the various connected components of a vehicle. Any other external vertical force, such as that needed to lift the vehicle on an uphill grade, applied to the moving vehicle through the tires will accelerate the vehicle mass in the vertical direction and will be different in magnitude than the tire forces needed to effect equilibrium of the static vehicle. Also, external force in the horizontal direction, such as centrifugal force developed when the vehicle moves around a horizontal curve, changes the position of the vehicle's overall center-of-oscillation relative to the tire-pavement interface and redistributes the gross-vehicle weight among the wheels of the vehicle. Transverse slope of the roadway surface (crown or cross-slope) likewise causes a change in the relative location of the vehicle's center-of-oscillation. To minimize these effects, WIM-system force sensors should be located on straight, level sections of roadway with minimum transverse slope, or perhaps on a slight downgrade to reduce the effects of drive-train torque. Desirable maximum values for grade and cross-slope are about 2 percent and for horizontal curvature about 1 degree (arc definition).

- **Road Surface** - The road/vehicle interface through which force is transmitted is the tire-contact area a few square inches in size for each tire. If the vertical force at this interface is to be the same for a moving vehicle and for a static vehicle as is desired in in-motion weighing the roadway surface over which these small tire-contact areas pass must be *perfectly smooth and level.* Any *deviation* from this condition will result in *vertical displacement* of the tires on the moving vehicle and *dynamic forces* that are different (either larger or smaller) than corresponding forces for the static vehicle. In practice, such an ideal surface cannot be realized; only approximated. Road-surface roughness is generally manifested as waves of varying length and amplitude or as step irregularities such as potholes, faulted joints, and bumps at the pavement/bridge interface. The effect of different roughness patterns on the dynamic behavior of a moving vehicle is a function of the particular pattern of roughness, characteristics of the vehicle, and speed of the vehicle; each combination is unique. It is known that the dynamic force at the roadway/tire interface resulting from a moving wheel mounting a small bump can be more than double the corresponding force for the static wheel and that this force goes to zero magnitude when the wheel bounces off the road surface. *Surface roughness* is a critical factor that affects the accuracy of a WIM system. Studies and experience indicate that a very smooth roadway surface is necessary for approximately 150 feet in advance of and beyond the WIM-system force sensors if maximum performance is to be achieved by the system. A systematic study of the relationship between various practicably-definable roughness patterns and WIM-system performance is needed so that improved roughness specifications can be developed.

## ENVIRONMENTAL FACTORS

- **Wind** - The effects of a cross-wind acting on the side of a vehicle are discussed above in relation to aerodynamic vehicle characteristics. It should be noted that wind forces acting on the vehicle from any direction must be balanced by tractive forces at the tire-road interface for equilibrium and that wind force, therefore, causes some redistribution of the gross-vehicle weight among the wheels.

- **Ice** - Ice can accumulate on a vehicle component and add to the normal weight of the component. Since the dynamic behavior of each component is a direct function of its weight (mass), such an accumulation of ice can affect the accuracy of WIM-system estimates of weight. Ice formations on the road surface can also introduce patterns of road-surface roughness which affect the dynamic forces experienced by a moving vehicle.

## WIM - SYSTEM FACTORS

- **Road-Surface Roughness Caused by Force Sensor** - Any roughness of the roadway surface at or near the WIM-system force sensors will affect the dynamic forces on the moving vehicle and, therefore, the accuracy of weight estimates made by the system. The force sensors themselves should not introduce roughness - neither a bump nor a depression - to the road surface for best accuracy from the system.

- **Stiffness of the Force Sensor** - Deformation of the WIM-system sensors should approximate the deformation of the surrounding pavement under the moving vehicle forces in order that the vehicle not experience an apparent bump or depression as it passes over the sensors.

- **Oscillation and Damping of Force Sensor** - The applied force from the tires of a moving vehicle typically displaces a WIM-system force sensor downward and stores energy in its spring element. When the force is removed, the sensor will rebound upward under the force from the spring and continue upward until the force of gravity reverses the movement. This sequence of unbalanced forces acting on the sensor will cause it to *oscillate* until some form of *damping* dissipates the energy stored in the elastic system. If another set of tires applies a downward force to the sensor before it comes to rest, the force indicated by the sensor (a function of its displacement) will be the resultant of the applied force and the inertial force of the oscillating sensor. This indicated force can be greater than, equal to, or less than the applied force. The magnitude of the displacement and the period of oscillation of the sensor are functions of its stiffness and its mass. To prevent the interaction of forces from the sensor with the applied tire forces, the mass and deformation of the sensor should be small, and damping should bring the sensor to rest quickly after each tire force has been removed.

## *Factors Which May Cause Error in Measurements of Dynamic Tire Force*

### FORCE SENSOR LOCATION

- **Above Road Surface** - A tire-force sensor above the road surface creates a *bump* which must be mounted by the moving tire. For the tire/wheel assembly to pass over the bump, a force sufficient to displace the mass of the assembly upward and deform the tire by an amount equal to the height of the bump must be applied. The force applied to the sensor will normally be greater than the corresponding tire force when the vehicle is static. It is impossible to adjust the force-sensor output to compensate consistently for the *additional force imparted by the bump* because the magnitude of the additional force is unknown and varies with the unique vehicle characteristics and speed involved with every measurement.

- **Flush With Road Surface** - The best location for a tire-force sensor is with the force-receiving surface of the sensor flush with the road surface. The moving tire experiences no change in vertical force as it traverses the surface of the sensor.

- **On Structure** - In some WIM systems, gages which sense the deformation of selected elements in a massive elastic structure, such as a bridge or a culvert, are used as the basis for estimating the tire forces from a moving vehicle which cause the measured deformations. The entire structure serves as a force sensor, and the gages are located at considerable distances from the tire/road-surface interface where the forces of interest are applied. Errors in dynamic force measurement related to such location of the sensing elements can be attributed to factors such as *mass* of the structure, *complex dynamic behavior* of the structure, *deformations caused by wind and temperature, multiple vehicles* on the structure simultaneously, *speed change* as the vehicle crosses the sensor, road-surface *roughness,* and the always-present "*bump at the end of the bridge*".

### FORCE SENSOR CHARACTERISTICS

- **Sensitivity to Direction of Force Application** - The tire-force component of primary interest for in-motion weighing is the vertical component . If tire-force sensors are affected by force components acting tangential to the road surface, errors in weight estimates may result.

- **Sensitivity to Temperature** - WIM systems must operate reliably over a wide range of ambient temperatures. The output signal from the tire-force sensor must be consistent throughout this range in order to avoid error in weight estimates.

- **Tire Inflation-Pressure Effects** - The inflation pressure of every tire is different; therefore, the tire-force sensor must be insensitive to inflation pressure in order to estimate with minimum error the total force applied to its force-receiving surface by the tire of a moving vehicle. Tire inflation pressure affects both the tire-contact area and the distribution of force over this area.

- **Tire Contact-Area Effects** - Errors in force measurement can result if the output from the sensor is affected by the size of the tire- contact area or by the distribution of the total force over this area. The output of the sensor must be the same regardless of where and how the tire applies force to the force-receiving area to minimize measurement error.

- **Sensitivity and Linearity** - The sensitivity of the sensor must be adequate to prevent measurement error due to insufficient resolution. A defined linear relationship between applied force and output signal from the sensor is necessary; a straight line is not necessary, however.

- **Mass, Stiffness, and Damping** - These sensor characteristics are discussed in the previous section in relation to WIM-system factors which may cause the tire forces produced by a moving vehicle and by a static vehicle to differ. The desirable sensor characteristics to minimize error are low mass, high stiffness, and critical damping.

- **Durability** - WIM-system force sensors operate in an extremely hostile environment where they must withstand millions of applications of force of various magnitudes. Undetected degradation of performance over time can result in errors in weight estimates.

### INSTRUMENT SYSTEM CHARACTERISTICS

- **Sensitivity and Linearity** - The overall quality of performance by a WIM system depends upon the sensitivity and linearity of the instrument system which processes the signals from the force sensors. Errors can be introduced into the measurement process if these factors are inadequate in the instrument system.

- **Stability** - Output from the instrument system must be consistent with respect to time. Automatic compensation for drift and other time-dependent measurement inconsistencies can be provided by the instrument system to minimize error in weight estimates.

## *Factors Related to Interpretation of Dynamic-Force Signals and Weight Estimates*

### SIGNAL INTERPRETATION

- **Analog-to-Digital Conversion** - Most force sensors used in WIM systems produce analog signals. Significant errors can be introduced into the interpretation of these signals unless proper sampling rates and precision in conversion to digital form are used.

- **Filtering** - Most electrical signals contain some "noise". Error can be introduced if improper filtering techniques are used in attempting to eliminate or minimize the noise in a WIM-system force signal.

- **Averaging** - Simple averaging of the dynamic force signal while the tire of a moving vehicle is fully supported by the force sensor is frequently used. Error in this process can result from using an improper technique for determining when the tire is fully supported by the sensor as well as from including excessive force variations in the averaging process.

- **Peak Detection** - Detection of peak values in a dynamic force signal is a relatively simple process. Considerable error in interpreting WIM-system force signals can result from using this technique unless the shape of the force vs. time signal from the sensors and the instrument system is ideal.

- **Integration** - Some WIM-system force sensors do not fully support the entire tire-contact area simultaneously; therefore, it is necessary to integrate, or sum, instantaneous measurements of tire force to determine the total force supported by the tire. Unless the signal from the sensor exhibits a straight-line relationship with respect to force, has no hysteresis, is unaffected by deformations which occur in the sensor outside the tire-contact area, and there is no bridging effect of the tire as it passes from the relatively-rigid pavement surrounding the sensor to the less-rigid sensor, error will occur when the entire force signal is integrated with respect to time.

- **Backward Calculation** - The accuracy of the results obtained by using an algorithm to back-calculate the forces which caused the measured deformation in selected structural members of a bridge or culvert depends very strongly upon how nearly the dynamic behavior of the complex, composite real-world structure agrees with the behavior of a simplified equivalent structure under static forces. The measured deformations are very small; therefore, it is difficult to isolate the forces associated with individual tires with acceptable accuracy.

### CALIBRATION AND ESTIMATION OF WEIGHT

- **Calibration** - The objective of calibration is to make the weights estimated by a WIM system agree as closely as possible with the corresponding weights that would be measured by static scales [4]. Calibration involves adjusting the WIM-system output so that for a representative sample of vehicles, there is zero difference in the mean value of WIM-estimated weights and the mean value of corresponding weights measured with the vehicle static. By proper calibration, virtually all bias, or systematic error, can be eliminated from WIM-system weight estimates at a particular site. Considerations necessary for achieving such calibration are described by Davies and Sommerville [5]. Even after calibration, randomly-occurring error in the weight estimates remains.

- **Estimation of Weight** - As mentioned above, a number of different techniques are used to interpret the signals from WIM-system sensors and thus measure dynamic tire force. Error is involved in this process as well as in system calibration. The overall accuracy of estimated weight is a function of how well the WIM system handles these errors. Additional error is introduced into the WIM-estimated weights if dynamic tire forces on only one side of the vehicle are measured and doubled to yield axle-weight estimates.

## *Factors Which Affect the Accuracy of Static-Vehicle Weight Measurements*

### TYPE OF WEIGHING DEVICE

- **Vehicle Scale** - The vehicle scale is described in the Glossary (p.2). NBS Handbook 44 [3] classes vehicle scales as Class III L and gives acceptance and maintenance tolerances in terms of scale divisions. For normal test loads, these tolerances amount to ±0.1 and ±0.2 percent of the test load, respectively.

- **Axle-Load Scale** - This type of scale is also described in the Glossary (p.2). NBS Handbook 44 classes it as Class III L and gives acceptance and maintenance tolerances which are the same as for vehicle scales.

- **Portable Axle-Load Weigher** - See the Glossary (p.2) for a description of this type of weighing device. NBS Handbook 44 acceptance and maintenance tolerances are ±1 and ±2 percent, respectively [3 (p.

2-23)] for devices not marked with a class. Tolerances for weighers marked Class III, appear to be somewhat different (as percentages) for devices with various numbers of scale divisions and when subjected to different test loads, but they are probably intended to be of the same order of magnitude.

- **Wheel-Load Weigher** - This type of device is described in the Glossary (p.2). NBS Handbook 44 tolerances are the same as for portable axle-load weighers.

USE OF WEIGHING DEVICE

- **Single-Draft Weighing** - This is the most accurate way to determine gross-vehicle weight. All tires of the static vehicle are supported simultaneously on vehicle scales. The vehicle scale may have a single platform, or it may have multiple platforms. Normally, the scale is adjusted to read the *mass* of standard test weights (traceable to the standard of mass at NBS); therefore, the weight measured is actually mass (neglecting the buoyancy of the atmosphere) and is expressed in avoirdupois pounds or in kilograms.

- **Successive Stops** - Gross-vehicle weight or axle-group weight can be determined by successively stopping the axles of the vehicle on axle-load scales, portable axle-load weighers, or wheel-load weighers. This yields less-accurate weights because the gross-vehicle weight is redistributed whenever the vehicle moves and stops on the scales. Torque in the drive train and in the brakes causes vertical displacement of the vehicle components, thereby redistributing the weight among the axles. Several thousands of pounds of force can be transferred in extreme cases.

- **Level Surface** - The distribution of gross-vehicle weight among the wheels and axles of a vehicle is a function of their relative vertical positions. Since WIM systems, of necessity, measure tire forces when all wheels on the vehicle are nearly in the same plane, it is important that this same juxtaposition be present when the vehicle is weighed statically so that corresponding weight values are being compared. Again, several thousands of pounds of force can be transferred among wheels on a vehicle when one or more wheels is displaced vertically (either up or down). The same is true for axles or axle groups on the same vehicle or vehicle combination. Differences in WIM-system estimates of weight and weight measured on static scales can be, and frequently are, attributable to the fact that the portion of the gross-vehicle weight on the tire at the time each measurement is made is actually different. To minimize error in static weighing, the tire-road contact area of all tires on the vehicle being weighed should be approximately in the same horizontal plane when *every* measurement is made.

- **Inertial Forces** - Inertial forces related to a moving mass, such as a load of liquid cargo, can cause components of a stopped vehicle to oscillate. No weight measurement should be taken until such inertially-induced oscillations have subsided to a point that indicated weight is changing only slightly.

## CONCLUSION

Many of the factors that can affect the accuracy of a WIM system are identified above; no doubt, there are others. The magnitude of the effect of each of these factors is variable, and complex interactions among the factors can occur. As mentioned in the previous discussion, steps can be taken in the design and application of a WIM system to control the effects of certain factors, but others (e.g., an out-of-round tire) cannot be controlled. The net effect of all factors at any given time is the matter of concern to a WIM system user.

Each user must decide what level of accuracy - in terms of a tolerance value and a probability of conformity - is required for every WIM system application. In making this decision, consideration must be given to the levels of accuracy that can be attained by available WIM systems under actual field conditions. Then, an appropriate system can be chosen.

A standard specification for four different highway WIM-system configurations, along with appropriate user requirements and test methods for evaluating the performance of each type of system, are being developed by a committee of the American Society for Testing and Materials (ASTM). The purpose for this development is to give potential WIM-system users a convenient means of identifying the performance characteristics of various system configurations, including accuracy, and of specifying a system that will be adequate for the intended application.

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# WIM SYSTEM ACCURACY

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This paper addresses the measurement and expression of the accuracy of WIM systems. The subject of WIM accuracy is very important yet frequently misunderstood by both the vendors and users of WIM systems. As a result, it has often been difficult to compare the specifications published by vendors or to determine which WIM system is most appropriate to a specific application. Consequently, recent studies have addressed the need for better defined measures of accuracy and methods of applying then to WIM systems. These are presented in this paper along with a discussion of the problems associated with measuring the accuracies of WIM systems.

## ACCURACY MEASURES

Accuracy is the quality of conformity of a measured value to an accepted standard value. It can be expressed as either an absolute difference or as the ratio of the error of the indicated value versus the true value, usually a percent.

A related quantity, precision, is the quality of repeatability of measurement data. It is usually expressed in terms of the standard deviation of the errors of a sample set of measurements of the same quantity.

### Weight Data Accuracy

For truck weight estimates, the absolute difference is normally expressed as follows:

$$AD = \text{WIM Weight - Static Reference Weight} \qquad (1)$$

The percent difference is normally expressed as follows:

$$PD = \frac{\text{Wim Weight - Static Reference Weight}}{\text{Static Reference Weight}} \text{ X } 100 \qquad (2)$$

There are two methods that have been commonly used in the U.S. to express the accuracy of weight data produced by WIM systems. Both use differences in truck weights obtained by a WIM system versus weights obtained using static scales. These differences in the weights are normally expressed as a percentage of the static weight as defined in Equation 2. For the first method, the mean (systematic error) and standard deviation (random error) of these percent errors are calculated. Figure 1 illustrates the systematic and random errors on a histogram of a typical distribution of errors from a WIM system.

The systematic error indicates whether there exists a bias in the WIM system. This type of error can usually be reduced by improved calibration procedures. The random error has a zero mean by definition and indicates the spread (or scatter) of the data about the systematic error value. The random error is strongly influenced by the pavement profile. It can be reduced by controlling the smoothness of the approach to the WIM transducer. There is also recent evidence that more complex calibration procedures could be adopted to offset the effects of pavement roughness. These take into account vehicle type and position of the axle/axle group in a nonlinear relationship.

The second method for expressing the accuracy of WIM systems is based on the cumulative distribution function (cdf) of the errors. Under this approach, the following steps are followed:

1. The error is calculated for each observation

2. The observations are then placed in order from lowest to highest
3. The percent of values that are less than or equal to each value of error is then plotted as illustrated in Figure 2.

Possible bias i the WIM system can be assessed from the cdf by examining the median (50th percentile) value shown in Figure 2. The random error can be determined from the 15th and 85th percentile values, which correspond roughly to the mean plus or minus one standard deviation from the median error.

The principal differences in the two methods is the treatment of extreme outliers - the cases where the WIM results are greatly different from the static scale results. With the first method (systematic and random error), all data are included in the calculations so that a few extreme outliers can result in values of the systematic and random error that make the overall result unacceptable even when most of the WIM scale estimates are very close to the static scale values. Using the second (cdf) method, the effects of the most extreme deviations are ignored. This latter approach is beneficial if account is to be taken of the fact that a portion of the heavy trucks in the traffic stream at any location have poor suspension systems and/or out-of-round tires that make it impossible to weigh them accurately with any WIM system.

## Speed Data Accuracy

The ability of WIM systems to accurately measure the speeds of vehicles is another important item to be considered in WIM accuracy. Accurate speed measurements are important not only for their own significance but also for the fact that they are used in other calculations, including the calculation of axle weights from transducer readings and the computation of axle spacings.

## Axle Spacing Accuracy

The accuracy of WIm system axle spacing computations depends on both the speed accuracy and the precision of the recording of the time that each axle strikes an axle sensor. Accurate axle spacings are also important t the classification of vehicles within FHWA Scheme F.

## Vehicle Classification

With the publication of the FHWA Traffic Monitoring Guide, the Scheme F Vehicle Classification schedule shown in Table 1 is now generally accepted as standard. The question of accuracy in vehicle classification in WIM systems is then one of how accurately the correct vehicle type for each vehicle that is weighed is identified.

In addition to evaluating the accuracy of each vehicle, it may also be useful to consider whether compensating error occur. That is, whether the number of vehicles of Type X misclassified as Type Y are offset by the number of vehicles of Type Y misclassified as Type X. This is particularly true with automatic vehicle classification (AVC) equipment, which is not addressed in this paper.

**Table 1. FHWA Scheme F Vehicle Types**

| Type | Description |
|---|---|
| 1. | Motorcycles (optional) |
| 2. | Passenger Cars |
| 3. | Other 2-Axle, 4-tire Single Unit Vehicles |
| 4. | Buses |
| 5 | 2-Axle, 6- tire Single Unit Trucks |
| 6. | 3-Axle Single Unit Trucks |

7. 4 or More Axle Single Unit Trucks
8. 4 or Less Axle Single Trailer Trucks
9. 5-Axle Single Trailer Trucks
10. 6 or More Axle Single Trailer Trucks
11. 5 or Less Axle Multi-Trailer Trucks
12. 6-Axle Multi-Trailer Trucks
13. 7 or More Axle Multi-Trailer Trucks

## THE PROBLEM OF MEASURING WIM SYSTEM ACCURACY

As indicated in the previous paragraphs, the determination of WIM system accuracy requires the availability of an accepted standard value. In fact, a directly measurable standard value does not exist. Instead, we must use measurements of the static weights of the vehicle as the reference. However, the forces applied by the tires of a truck to a static scale are not the same as those applied to the WIM transducer. The differences between the forces occur due to several reasons. First, the wheels and axles of moving vehicles oscillate in a complex manner as they travel down the highway. This is due, in part, to the dynamic response of the trucks when perturbed by pavements roughness. The pattern of oscillation varies from vehicle to vehicle although there appear to be similarities in the behavior of axles at the same position and of the same approximate weight on trucks of the same type. Second, the internal shifting of the gross vehicle weight among axles is significant under actual highway conditions. Third, wind and other environmental effects cannot be ignored.

Since the WIM system-produced axle, axle group and gross vehicle weights are normally compared to results for the same vehicle obtained from a static scale, it is clear that there can be significant errors even if the WIM system accurately measures the forces (weight) applied to it. In fact, laboratory tests have shown that WIM transducers generally do accurately measure the forces applied to them when those forces are measured with independent measurement systems.

Another problem of measuring WIM system accuracy lies in the accuracy of the static weighing devices that are used to establish the standard reference values against which the WIM results are compared. It was shown in an extensive study by Dr. Clyde Lee of the University of Texas that the process of weighing trucks using available static scales in the highway environment is not very accurate when certain types of static devices are used (1). In that study, Dr. Lee examined the accuracy of several types of WIM systems, static scales, and static weighing procedures, including the following:

1. HSWIM - High Speed WIM: Radian-type load cell WIM transducers installed flush with the pavement surface in the main highway lanes.

2. ISWM - Intermediate Speed WIM: Radian-type load cell WIM transducers installed flush with the pavement in the ramp to a truck weight enforcement area.

3. LSWIM - Low Speed WIM: Radian-type load cell WIM transducers installed flush with the pavement in the ramp to a truck weight enforcement area.

4. AX/WHL - Axle and Wheel Scale: Two static scale platforms, each 4 x 6 feet in plan dimensions, arranged side-by-side and mounted flush with the pavement.

5. AX/GRP - Axle Group Scale: Two static scale platforms, each 30 inches by 8 feet in plan dimensions, arranged side-by-side and mounted flush with the pavement surface.

6. AX/GRP (RAM) - Axle Group Scale: Two static scale platforms, each 30 inches by 8 feet in plan dimensions, arranged side-by-side and mounted so that truck tires being weighed first

had to roll up an approach ramp. The height of the platform was approximately 4 inches above the pavement surface.

7. WLW/M300 - Wheel Load Weigher Model 300: A hydraulic portable rollover wheel load weigher 20 x 10 inches in plan and 3 1/4 inches high.

8. WLW/M400 - Wheel Load Weigher Model 400: A hydraulic portable rollover wheel load weigher 20 x 10 inches in plan and 3 1/4 inches high without the rollover option found in the Model 300.

9. WL/100 - Wheel Load Scale WL100: A low profile hydraulic wheel load weigher approximately 18 x 27 inches in plan dimensions and 0.79 inches high.

Table 2 shows the range in variability of the results for each static scale for 60 trucks sampled in the study.

**Table 2. Variability of Static Scales.**

**Range in variability (% Standard Deviation) by weight Estimate**

| TYPE OF SCALE | WHEEL | AXLE | AXLE GROUP | GROSS VEHICLE |
|---|---|---|---|---|
| AX/WHL (reference) | --- | ---- | ---- | ---- |
| AX/GRP | --- | ---- | -1.9 to 3.2 | -0.8 to 2.25 |
| AX/GRP (RAM) | --- | ---- | -1.7 to 5.1 | -1.2 to 4.3 |
| WLW/M300 | -16.9 to 19.25 | -12.25 to 13.5 | -7.95 to 8.25 | -4.95 to 5.6 |
| WLW/M400 | -13.2 to 18.95 | -11.55 to 17.1 | -2.95 to 7.35 | -1.6 to 5.55 |
| WL/100 | -12.7 to 12.35 | -6.6 to 8.45 | -4.25 to 5.55 | -2.45 to 3.8 |

The values in Table 2 represent the lower and upper bounds of the error values that include approximately 68% of all of the observations. If these values shown in Table 2 were doubled, they would include approximately 95% of all of the values observed.

It is clear from Table 2 that even accurate, calibrated, and well-maintained static scales do not weigh trucks without error. Since these devices are used as the reference against which WIM system weight estimates are compared, it is important this understanding into procedures for evaluating and calibrating WIM systems.

## CONCLUSION

It is important that users and vendors of WIM systems use a common basis in terminology and methods for selecting and evaluating the performance of WIM systems. The terms and methods described in this paper have gained wide acceptance and can provide this basis.

# WEIGH-IN-MOTION (WIM) STANDARDIZATION: STIMULATION, DEVELOPMENT & MORE STIMULATION

*by Lawrence E. Hart*[1]

Standards emerge through nurturing and experience. The American Society for Testing and Materials (ASTM) is an excellent case in point. Over 30,000 members through 140 specific committees were voluntarily responsible for over 8500 ASTM standards at the beginning of 1988. The mission of ASTM Committee E-17 on Pavement Management Technologies is the *stimulation* of research, the *dissemination* of knowledge and the *development* of principles, techniques and standards for pavement management technologies. The scope of Subcommittee E17.42 on Traffic Characteristics is, "The Subcommittee shall *investigate* and *develop* the principles, techniques and standards related to the collection, analysis and application of traffic data, such as weight, classification, speed and volume."

ASTM Subcommittee E17.42 began as an ad hoc task group on WIM standards. The first exploratory meeting was held June 3, 1986, in San Antonio, Texas. 22 participants represented state highway departments, the Federal Highway Administration, state enforcement activities, university research programs and manufacturers. It turned out to be an extremely productive planning session. Three semiannual meetings later, the group became a full-fledged subcommittee and had a draft standard ready for the formal ASTM consensus process.

The 6/14/88 proposed Standard Specification for Highway Weigh-in-motion (WIM) Systems with User Requirements and Test Method is being balloted concurrently by Main Committee E-17 and Subcommittee E17.42 (receipt deadline Oct. 27, 1988). The document has a caveat about reproducing or quoting outside ASTM committee activities. In general though, it:

1. Groups WIM systems according to intended applications.
2. Establishes performance levels for each group.
3. Lists requirements for users providing adequate environments.
4. Provides a method for type testing and for in-place calibration.

Anyone requesting the complete document is entitled to receive one, but in receiving it they must adhere to the caveat.[2]

Significant stimulation and development is occurring outside ASTM. As part of the Heavy Vehicle Electronic License Plate (HELP) Project, the Arizona Department of Transportation (DOT) sponsored the study "Development of Weigh-in-motion Performance Specification." The objective was a specification which could be used nation-wide. Texas A&M Research Foundation is responsible for this study, and Dr. Wiley D. Cunagin authored the final report. The study focused on WIM systems suitable for 55-65 mph traffic. Accuracy, durability and life-cycle costs were primary criteria. One recommendation is to consider using the best 75% of each performance sample. A specification is appended to the final report.[3]

The National Cooperative Highway Research Program (NCHRP) has three correlated projects. One is Project 3-34, The Feasibility of a National Heavy-vehicle Monitoring System, by Arthur D. Little, Inc. (final report soon). The second is Project 3-36, Development of a Low-cost Bridge Weigh-in-motion System,

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[1] President, Rainhart Co., Austin, Texas, USA.

[2] ASTM, 1916 Race St., Philadelphia, PA 19103-1187, Re: Committee Letter Ballot E1702(88-2), Issue Date Sept. 15, 1988, Item No. 6.

[3] Arizona DOT, Transportation Planning Division, 206 S. 17th Ave., Phoenix, AZ 85007.

by Bridge Weighing Systems, Inc. (2/3 complete, final report late 1989). These first two studies are stimulating but, in the strict sense, do not have standardization as part of their tasks.[4]

The third NCHRP Project is 3-39, Evaluation and Calibration Procedures for Weigh-in-motion Systems, by Texas A&M University. The stated objective "is to develop a procedure(s), covering all WIM system applications, for (1) acceptance testing, (2) on-site calibration, and (3) periodic verification of systems performance." Because of commonality, Dr. Wiley D. Cunagin, Principal Investigator, and Mr. Frank N. Lisle, Senior Program Officer, started a technical dialogue with ASTM Subcommittee E17.42 at its June 6, 1988, meeting. Dr. Cunagin's work has progressed through an interim report, including a detailed set of evaluation and calibration procedures. A final report should be available early 1990.[4]

The Federal Highway Administration contracted with SPARTA, Inc., to measure WIM accuracies relative to various pavement roughness and to determine approach length and smoothness required to achieve stipulated accuracies. The results included the development of an empirical relationship and procedures to calculate smoothness necessary for given accuracy. Full particulars are in "Calibration of Weigh-in-motion (WIM) Systems, Volume I: Summary and Recommendations, and Volume II: Final Report."[5]

The Transportation Research Board (TRB) A2B08 Committee on Traffic Characteristics is the most focused WIM activity outside ASTM. TRB does not promulgate standards, but A2B08 consistently stimulates research and has steadfastly sponsored an informative WIM session at each TRB annual meeting every January. One concern of A2B08 is law enforcement persons not knowing much about WIM potentials nor what various states are doing with these potentials. Responsible officials in every state need to understand and plan for WIM, without re-inventing the wheel state by state. On January 14, 1988, in their then task force meeting, A2B08 voted to promote a WIM enforcement symposium.[6]

In conclusion, questions seem most appropriate. On June 8-9, 1988, ASTM and the Permanent International Association of Road Congresses (PIARC) co-sponsored the First International Symposium on Surface Characteristics at State College, Pennsylvania. There were many excellent presentations on topics ranging from texture through rolling resistance to pavement management. Singularly lacking, though, was significant consideration of real traffic, the primary *cause* of lower skid resistance, greater roughness and increased distress. Is simple average daily traffic (ADT) good enough? Or does the highway industry need to know the distribution of axle weights and spacings by time of the week and season? What do you think about the possibility of a WIM symposium for legislative, legal and enforcement officials? Should there be a separate symposium on traffic characteristics: measurement and application? ASTM Subcommittee E17.42 is interested in your viewpoint.[7]

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[4] Transportation Research Board, 2101 Constitution Ave., N.W., Washington, DC 20418.

[5] FHWA, RD&T Report Center (HNR-11), 6300 Georgetown Pike, McLean, VA 22101-2296, Re: Publication Nos. FHWA-RD-88-128 and 129 respectively.

[6] Mr. Perry M. Kent, Chairman, FHWA (HPM-30), 400 Seventh St., S.W., Washington, DC 20590.

[7] Mr. Lawrence E. Hart, Chairman, Rainhart Co., P.O. Box 4533, Austin, TX 78765.

# COLORADO'S APPLICATIONS OF WEIGH-IN-MOTION DATA FOR HIGHWAY PLANNING

*Tom Talmadge, P.E., Branch Manager*
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Like most states, until recently the only avenue for vehicle weight data was from information which was gathered at the Port of Entry stations or through "loadometer" surveys. We all know the problems inherent with the "loadometer" surveys such as seasonal bias, location bias, a limited amount of information and the always present scale evasion problem. Although the Port of Entry information eliminates the seasonal bias at some particular locations, the problems associated with limited locations and scale evasion still exists.

Because of these limitations, vehicle classification and weight data has been limited and somewhat inadequate for planning and design purposes. With the advancements in Weigh-In-Motion (WIM) technology over the past few years these problems are being eliminated in Colorado.

Colorado first moved into the world of WIM in 1983, when we sponsored the first National WIM Conference in Denver. The success of that conference coupled with the knowledge gained allowed Colorado to acquire their first set of WIM equipment and implement a pilot program. Since that time we have purchased 4 complete sets of Golden River WIM equipment which we utilize for all our planning needs.

The acquisition of this equipment was only the first step in the development of an overall vehicle size and weight program for Colorado. The second major step was the implementation of a program which utilizes this technology in the development of integrated planning and design programs.

The objective of the first phase of this program was to identify the procedures required to have the most cost-effective vehicle size and weight program possible while providing the necessary planning data for decision makers to allocate our declining financial resources in a cost effective manner to maintain that the integrity of the highway system.

It should be noted that the intent of this program, at this point, was not to address needs for data on specific road segments, i.e. design data, but rather to provide statewide averages on specific functional classifications of roadways which in turn may be used to supplement site specific data.

The basis of this program is the Federal Highway Highway Administration's (FHWA) Traffic Monitoring Guide (TMG). Using this in coordination with our existing traffic counting program, our Highway Performance Monitoring System (HPMS) program and the criteria of the Strategic Highway Research Program (SHRP) we have created a Traffic Monitoring Program for Colorado which will meet all the traffic data needs at the local, State and Federal level including any data needs concerning vehicle size and weight.

Initially, Colorado basically followed the guidelines set forth in the TMG. We have identified 230 sites which we will collect vehicle classification data only. At 90 of these 230 sites, we will also collect weight data using our WIM equipment. Although the TMG stratifies these sites into only two groups, Interstates and other roads, Colorado opted for an expanded stratification so as to increase reliability. Currently these sites are distributed over eight functional classifications which include the following:

|  |  |  |  |
|---|---|---|---|
| Urban Interstate | 16 | Rural Interstate | 14 |
| Urban Other Freeway | 6 | Urban Other Prin. Atr. | 14 |
| Rural Other Prin. Art. | 10 | Urban Minor Art. | 2 |
| Rural Minor Arterial | 18 | Rural Major Collectors | 10 |
| Rural Minor Collector | 0 | Urban Collectors | 0 |
| Sub-Collectors (locals) | 0 |  |  |

Our initial site selection was concentrated on the State Highway system. Given that Colorado does not have any State Highways which are functionally classified as Rural Minor Collectors, Urban Collectors or Sub-Collectors, no size and weight data was scheduled to be collected on these functional classifications at this time.

This was done primarily because the vast majority of heavy vehicle traffic is on the State Highway system and the first priority for Colorado was to address the needs for the State Highway system. In addition, prior to the acquisition of WIM equipment, Colorado's size and weight program ignored our urbanized areas of which we currently have 7. It was decided that one of the top priorities of the new size and weight program was to establish a database for these urbanized areas starting with the State Highway system. Prior to WIM this was virtually impossible.

Colorado, like many states only conducted their loadometer studies during the summer, at a very limited number of sites and for a short period of time. Specifically in Colorado, our study was always conducted during August, every two years, at 12 sites and for only 6 hours at each site.

An example of some of the information we were missing is illustrated in a test site we monitored with WIM equipment to determine if there were any changes during harvest season in eastern Colorado. During the non-harvest season most of the vehicles were of legal weight of 85,000 pounds. However, during harvest season it was noted that a significant number of vehicles were running overweight at approximately 100,000 pounds. In fact one vehicle observed during this period weighed in excess of 140,000 pounds.

One can easily see that this program was not adequate enough to address the questions of seasonal variation or even daily variation not to mention the inadequacies of the program when it was utilized to develop information for 9,200 miles of State Highway.

Today, Colorado's size and weight program has resolved these inadequacies since we now collect size and weight data all year round, excluding the winter months due to snow and freezing conditions, for a minimum of 48 hours at each site and in some instances we will collect data for 7 days straight to investigate if there are any variations during the week.

Even though Colorado has only had this initial WIM program in place for approximately a year, it has already proven to be invaluable in many planning decisions which have recently been made.

The most notable use of this WIM data was in the update of the Colorado Highway Cost Allocation Study. Utilizing data which was derived for our new size and weight program, travel characteristics for all 13 of the vehicle classifications on each of the functional classifications was derived. In addition, weight data was available, for each vehicle classification and functional classification, which ultimately lead to the allocation of highway user cost responsibilities. The results of this study indicated that heavier vehicles were responsible for 35% of the user cost responsibility but only accounted for 21% of the user tax payments. This has now allowed the decision makers to better understand who is causing the damage to our highways and affords them the opportunity to develop strategies which will mitigate these impacts. Without the WIM equipment the level of data available would be drastically reduced and the cost for data collection would be significantly increased and in the end the validity of the study would be in jeopardy

As with any new program, you must learn to crawl before you walk and walk before you run. And with each new step comes new challenges which were not present before. As I noted earlier, our initial program concentrated only on the State Highway system. This did not mean to indicate that Non-State Highways are not critical, but in the past we had always assumed whatever occurred on the State Highway system could easily be applied to the Non-State Highway system.

With the advantage of WIM, we can now afford to monitor heavy vehicle traffic on the Non-State Highway system, and develop programs which will also address the needs on these roadways.

The first need for this came when we presented the Cost Allocation Study to our Legislature which was to be a basis for determining a roadway funding package, including a review of the diesel differential and gasoline taxes of Colorado, which has been noted as being some of the highest in the nation. One of the first questions asked was how does this study relate to Non-State Highway roads, which was obviously a valid question since any funding package being reviewed would apply to all roadways and not just State Highways. With the capabilities of WIM we are now conducting a similar study on Non-State Highways. Without the WIM data this would not have been feasible.

This has also led Colorado into another area of use for WIM data and that is the development of roadway management systems. A pilot project in which the Department of Highways is involve in is with one particular county within Colorado currently who feels that a large number of overweight vehicles are utilizing the local roadway system for short term projects such as oil drilling, and are responsible for the rapid deterioration of many of their roads.

However, due to limited resources they have been unable to prove this. In coordination with the Department of Highways WIM data will be utilized to first determine if indeed an excessive number of heavy vehicles are using these roads and if they are overweight. If this proves to be the case, additional WIM data will be utilized to establish an "impact assessment and permit" process which will help mitigate the damages being caused by these vehicles. In addition, if this program proves to be successful, the county has expressed an interest to collect additional WIM data which will aid them in the establishment of a roadway planning and management system.

The Department of Highways has also received a request from another county requesting our assistance in developing a roadway monitoring system in which they can more accurately monitor the travel on their roadways using WIM and thus be able to plan for future road development as well as better maintenance of their current roadway system.

Both of these pilot projects along with several other requests for this type of information has led the Department of Highways to the determination that it is absolutely essential that our size and weight program be expanded to include all public roadways for all functional classifications, including sub-collectors. This goes beyond the TMG and the HPMS program as currently defined by the FHWA, but Colorado feels that in order to make the decisions which must be made in today's economic environment this is absolutely necessary.

Two new areas in which Colorado is exploring the use of WIM data is in the monitoring of vehicles which are not required to clear our Ports of Entry. Two such groups are military vehicles and recreational vehicles.

In Colorado, using WIM data, it has been noted that on several occasions military vehicles are carrying excessive weights. Such an instance was recorded recently which monitored a convoy of flat-bed trucks with two tanks or armored personnel carriers which weighed in excess of 100,000 pounds. Regardless of whether or not these vehicles are legal, in order for the State to plan an adequate transportation system which can sustain these weights it is essential that we know how many of the vehicles are travelling our highways such that the necessary adjustments can be made. Without WIM data this would not be possible.

As for the recreational vehicles, the question was raised during the review of our Cost Allocation study as to how much damage do these type of vehicles cause in Colorado. Since Colorado is a high recreation State, it is felt that these vehicles, which can get quite heavy, are causing a significant amount of damage, especially on the lower functionally classified roads, but the trucking industry is getting the blame and expected to carry the burden. It is the intention of the Department of Highways to develop a program, using WIM data, which can be utilized to monitor these types of vehicles for the development of planning policies which will properly assess these vehicles the damage they are causing to the roadways.

This basically describes Colorado's current utilization of WIM technology and data for planning purposes. In addition, WIM data is also being utilized in other areas within Colorado, including design and enforcement however, I will reserve discussions concerning Colorado's activities in these areas for another time.

Although we feel Colorado has come a long way since our first exposure to WIM at the 1983 Conference, we feel that we are still in our infant stages. We know how to walk but we fall a lot. There are many areas yet to be explored before we feel that our program is stable and able to walk on its own. I look forward to learning many new ideas at the Minnesota WIM Conference which we will utilize in Colorado to move us ahead to the point we will be able to run.

# DYNAMIC FORCES VERSUS STATIC WEIGHTS - - HIGHWAY DESIGN

*Herbert F. Southgate, P.E., Kentucky Transportation Center*

The contents of this paper reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the University of Kentucky, of the Kentucky Transportation Cabinet, or of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation. The inclusion of manufacturer names and trade names are for identification purposes and are not to be considered as endorsements.

## INTRODUCTION

A Golden River weigh-in-motion (WIM) system has been purchased by the Division of Planning, Kentucky Transportation Cabinet. Among the questions asked at the time of purchase were:

- What calibration number should be used?
- Will the number change as a function:
    - Individual weigh mat,
    - Pavement type, and/or
    - Different highways.
- How are WIM data to be converted to equivalent static truck scale values?

A research study was initiated in an attempt to answer as many of the above questions as possible.

## CALIBRATION FACTORS

The manufacturer's literature suggested calibration factors for each of the two weigh mats based on vehicle gross weight. The predominant vehicle on Kentucky interstate pavements is the Class 9 truck -- a 5-axle semitrailer truck. A WIM site was selected so that the permanent truck scale could not be seen. The permanent truck scale was located approximately 1 mile past the WIM site. Data were collected for Class 9 trucks using both WIM and permanent truck scales in sufficient quantities to provide a matching of approximately 200 to 300 trucks from both sets of scale data. The range of calibration factors extended 20 units above and below the recommended value. Data were collected at intervals of 10 units (for example, 167, 177, 187 (recommended value), 197, and 207).

Comparison of WIM versus static scale data for the steering axle (Figure 1) indicated such differences that data were analyzed by axle location on the vehicle rather than by gross vehicle weight. Scatter in the data suggested that the ratio of static to WIM axleloads might prove to be more meaningful. Figures 2 and 3 illustrate variations in the ratios of static axleload/wim axleload as a function of WIM trailer tandem axleload and calibration factor. Figure 4 shows data for drive tandems using the same calibration factor value as for Figure 3. Note the reduced scatter in ratio values in Figure 4 compared to Figure 3. An average ratio was calculated for the drive tandem and trailer tandem for each calibration factor value. A regression between average ratio and calibration factor was calculated for each mat and the calibration factor calculated for a ratio of 1.00 as shown in Figure 5 for mat A. Figure 6 illustrates the same analyses based on gross weight. Similar comparisons were made for the second mat with similar results.

Figures 1-4 suggested that investigations for converting WIM data to equivalent static data should be based on axle group and by location on the vehicle rather than by gross load. For verification of the assumption, data were collected at a site on an asphaltic concrete pavement section of I-64 in Shelby County, Kentucky. After setting the calibration factor value for mat A, data were collected by both WIM and permanent truck scales until approximately 1600 trucks in Classes 4 through 12 had been correlated. This group of data formed the basis for the analyses contained in this paper.

## WIM VERSUS STATIC

Figure 7 illustrates the relationship between WIM and static axleload data for the steering axle. The heavier axleloads are known to be associated with large dump trucks (Classes 5 and 6) operating out of limestone quarries and which have wide flotation tires on that axle. Note that the WIM axleload is approximately 70 percent of the static axleload. This relationship was noted during an earlier effort at a WIM site located just past the top of a vertical curve on a rigid pavement and the WIM site was within view of the permanent truck scale. Often there was sufficient truck traffic at the permanent truck scale to cause a backup of trucks to form on the shoulder of the mainline pavement. As the trucks came over the top of the hill, drivers would see the backlog of trucks and take their foot of the gas pedal and the front of the truck could be seen to drop in elevation.

Comparison of static to WIM axleloads for four-tired single axles are shown in Figures 8 and 9 for drive and trailer axles respectively. Similarly, the relationships for drive and trailer tandems are shown in Figures 10 and 11 respectively. In Figures 8-11, there is a grouping of data for relatively low WIM axleloads corresponding to much higher static axleloads. These data groups suggest the possibility of axles bouncing over the capacitance pad because they are relatively unloaded while the static scales would capture the total load. In Figure 8, there is the possibility that the torque between the tire and pavement surface is causing a resultant force located at a different angle compared to single axles not subjected to torque such as on trailers. Torque involves a horizontal force vector such that the total force vector is not in the vertical direction. In Figure 10, the slope of the data for drive tandems is flatter than the slope shown in Figure 11 which suggests again that torque is reducing the vertical component (Figure 10) compared to tandems on trailers. Figures 12 and 13 contain data for drive and trailer tridems respectively, but the scarcity of data does not warrant definitive conclusions.

Regression analyses were performed using data shown in each of Figures 8 through 13. Table 1 contains the constant and coefficients and other statistical data for each type of axle assembly and by location on the truck.

## ANALYSES OF WIM DATA

Figures 14 and 15 contain the same data sets shown in Figures 10 and 11 respectively except the difference in the WIM recorded data for each axle is expressed as a percentage difference. The data groupings suggest the possibility of the effects of various suspension systems, but there is no data to confirm such suspicions. Gillespie determined the dynamic effects of three suspension systems as shown in Figure 16 (1). For the torsion bar suspension, there are approximately 2.5 cycles of dynamic force per second. The number of cycles per second increased to 3.5 and 10 for four-leaf and walking-beam suspensions respectively. In addition, the range of dynamic force appears to be approximately the same for the torsion bar and four-leaf suspensions, but a much larger variation for the walking-beam suspension. Unfortunately, the capacitance pad weigh systems did not provide any data output of dynamic force variations for each axle.

The data were separated into sets for the first and second axles for both the drive and trailer tandems as shown in Figures 17-20 respectively. Figure 17 shows that the data tend to separate into small groups that might be a function of type of axle suspension. Regression analyses were made for each axle location within the tandem. Equations for each axle were evaluated on 1,000-lb increments and the resulting data points are shown in Figures 21 and 22 for drive and trailer tandems respectively.

Figures 23-25 present WIM axleload data for the first, middle, and last axle within the drive tridem versus total WIM tridem load. The majority of vehicles were in Class 7. For these vehicles, the air-lift suspension axle is the leading axle in the tridem and is reflected by the wider scatter in data. Similarly, Figures 26-28 are for tridems on trailers, but the scarcity of data precludes any definitive conclusions for trailer tridems. Figures 29 and 30 illustrate the evaluated regression equations for individual axle locations in the same manner as Figures 21 and 22 for tandems.

## VEHICLE VELOCITY

less load, higher speed

Figures 31-39 present the relationship between vehicle velocity and vehicle gross load for Vehicle Classes 4 through 12 respectively. Data for Vehicle Classes 5, and 8 through 11 (Figures 32, 35 through 38) suggest the possibility of a relationship between gross load and vehicle velocity.

The ratios of static gross load to WIM gross load for all vehicle classes were combined and sorted into ranges of gross load. The ratio versus vehicle velocity was plotted for each vehicle in its load range as shown in Figures 40-45. Regression analyses performed for each of Figures 40-45. The middle line is the mean fit to the data and the upper and lower lines correspond to plus and minus one standard error respectively. Figures 40-45 show that as the load increases, the relationship between ratio of gross loads becomes a constant regardless of vehicle velocity.

## WIM DATA AND AASHTO PAVEMENT DESIGN

The 1974 and 1986 AASHTO Pavement Design Guides contain load-equivalency relationships developed from fatigue analyses of pavements at the AASHO Road Test. These relationships are applicable to a four-tired single axle and an eight-tired tandem axle. The effects of the steering axle (a two-tired axle) were included as a part of the rear loaded axles as implied by the statement, "During the 25 months of regular traffic operation, a total of 556,880 vehicle trips (1,113,760 applications) was made in each traffic lane, and thus over each surviving test section." (2). The load per tire for the steering axle of the five-axle semitrailer truck carrying a nominal 32,000-pound tandem load exceeded the load per tire of the tandem, ie., 4,400 pounds per tire on the steering and approximately 4,100 per tire for the tandem (see Table 4, page 14, ref. 2). The 1986 AASHTO Guide provides load equivalencies for tridem axles by substituting "3" for "L2" in the AASHTO equation C-15 (3):

$$\log(Wt) = 5.93 + 9.36\log(SN+1) - 4.79\log(Lx+L2) + 4.33\log(L2) + Gt/B \quad (1)$$

Neither the 1974 or 1986 AASHTO Guides provide a method to account for uneven load distribution between axles within the same group, or the effects of tire contact pressure on the surface of the pavement.

## WIM AND KENTUCKY PAVEMENT DESIGN

The 1981 Kentucky Pavement Design procedure provides load equivalency relationships for:

- two-tired steering axle,
- four-tired single axle,
- eight-tired tandem axle with 54-inch spacing between axles, and
- twelve-tired tridem axle with 54-inch spacing between axles.

Kentucky research efforts since 1981 have resulted in a mechanistic method to account for uneven load distribution within tandem and tridem axle assemblies and tire contact pressures for these various axle arrangements (4). It is recognized that some researchers do not agree necessarily with the Kentucky load equivalencies. The Kentucky procedure is the only known mechanistic method that is based on the same criterion throughout and can account for these variations that do exist. The real importance for using the Kentucky factors in these analyses is not for the values themselves, but for illustrating the relative effects of using load-equivalency factors appropriate to the number of tires and axles involved in the group, inclusion of the effects of uneven loading, and effects of tire contact pressure.

## FATIGUE CALCULATIONS

Fatigue calculations using AASHTO and Kentucky load equivalency relationships were made for the same 1,600 trucks weighed by both WIM and static truck scales and analyzed earlier. Analyses were made for the static truck scale axleloads, WIM recorded axleloads, and WIM recorded axleloads adjusted to an equivalent static value using the regression equations given in Table 1. Tridem axleloads have been eliminated from the calculations for both methods because of insufficient data. Calculated EALs using the AASHTO load equivalency factors are given in Table 2. Calculated EALs using the Kentucky load equivalency factors and adjustments for uneven load distributions and tire contact pressures are given in Table 3. Totals given in Tables 2 and 3 are expressed as percentages in Table 4. At the AASHO Road Test, tires were inflated to 75 psi and the contact pressure with the pavement was calculated to be 67.5 psi. Accounting for uneven load distributions and increased tire contact pressure may cause as much as a 90 percent increase in fatigue compared to the assumption that all loads are divided equally between the axles within that group and at a tire contact pressure of 67.5 psi.

## DISCUSSION

FHWA transmitted a synopsis of Report FHWA-RD-88-128 & 129 titled, "How Smooth for WIM?" The synopsis discusses the need for smoothness and length of "smooth" pavement ahead of the WIM site to determine "level of acceptable error". The immediate reaction is to ask "for what purpose?" If weight and law enforcement is the objective, then the approach should be as smooth as possible. However, if the purpose of collecting WIM data is for determining fatigue for that pavement as may be the case for SHRP long-term pavement performance test sections, then it is suggested that the pavement should not be modified in any way ahead of the WIM site. No two pavements will be identical. Pavement roughness will affect the dynamics and suspension behavior on trucks which also will be reflected in the rate of deterioration of the pavement. If the purpose of the WIM site is to collect data for long- term monitoring as a part of the SHRP program, this author suggests that the approach should not be modified. Thus, the purpose for collecting WIM data should be considered before decisions are made to modify the approach.

## FUTURE RESEARCH

WIM data will provide evidence needed to better understand the resulting dynamic loadings by the various suspension systems now in use. Also, such data should help in designing new suspension systems to reduce dynamic forces on pavements.

The current load-equivalency factor relationships must be revised. Steering axles on today's trucks substantially exceed steering axleloads used at the AASHO Road Test and can no longer be considered as insignificant. For example, using the Kentucky relationship for the steering axle, a steering axleload of 5,400 pounds has a corresponding load-equivalency factor of approximately 0.05. However, an 11,000-pound axleload, typical of steering axles for today's "cab-over" trucks, is approximately 0.43 -- nearly a 10-fold increase. It is noted that the five-axle semitrailer truck used on Loop 6, Lane 2, at the AASHO Road Test had a steering axleload of 10,800 pounds (Table 4, ref. 2) -- 5,400 pounds per tire. The "loaded axles" carried approximately 48,200 pounds -- 6,025 pounds per tire.

Additional research is needed to better define the effects of uneven load distribution, higher tire contact pressures, and the lateral distribution of vehicles in the lane. Uneven load distribution includes distribution of the load between axles within the same group (tandem, tridem, etc.) and uneven tire inflation, and/or contact pressures between dual tires or compared to any tire in the group (including flat tires). The effects of single tires, regular width or wide flotation, on load distribution requires investigation. This combination is being used in many sections of the United States and Europe. It is suspected that higher tire contact pressures are the cause of the "double rutting" in a given wheel track now being observed on some pavements. It is possible that the primary mode of pavement failure may change from fatigue to a punching shear failure because the contact area decreases as tire inflation pressure increases. Thus, the pavement-behavior research picture becomes more complicated rather than simplified. WIM data will help to define some of these problems and should help to solve some of the mysteries seen today.

## LIST OF REFERENCES

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2. The AASHO Road Test Report 3, Traffic Operations and Pavement Maintenance, Highway Research Board, Special Report 61C, Washington, D.C., 1962.

3. AASHTO Interim Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, D.C., 1974 Printing.

4. H. F. Southgate and R. C. Deen, "Effects of Load Distributions and Axle and Tire Configurations on Pavement Fatigue", Proceedings of Sixth International Conference Structural Design of Asphalt Pavements, Ann Arbor, Michigan, July 13 through 17, 1987.

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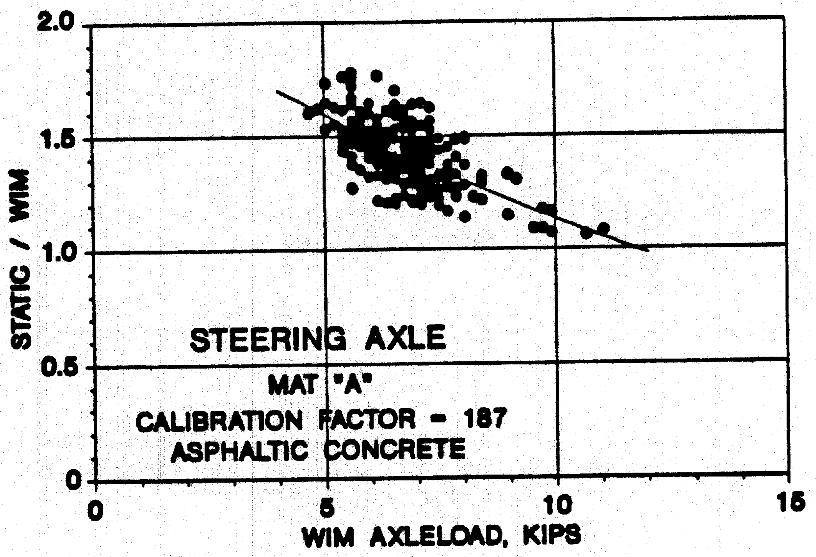
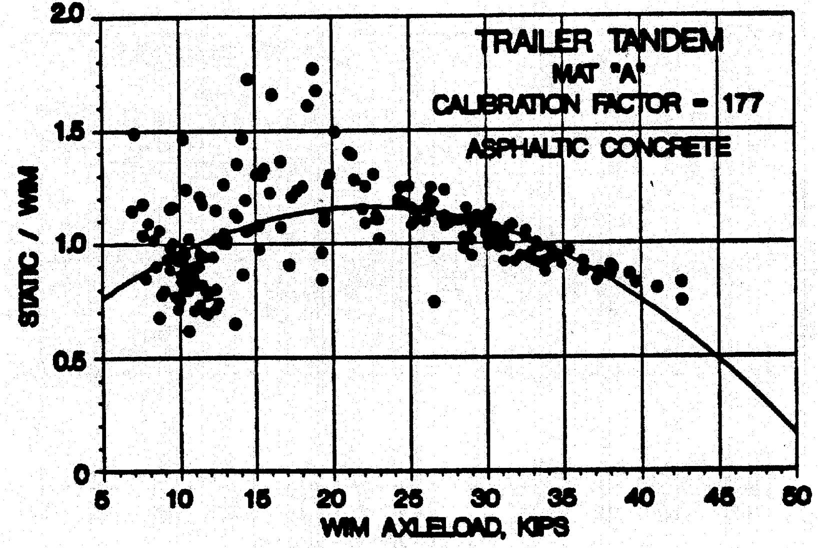


FIGURE 1. WIM AXLELOAD VERSUS RATIO OF STATIC AXLELOAD TO WIM AXLELOAD FOR STEERING AXLES.



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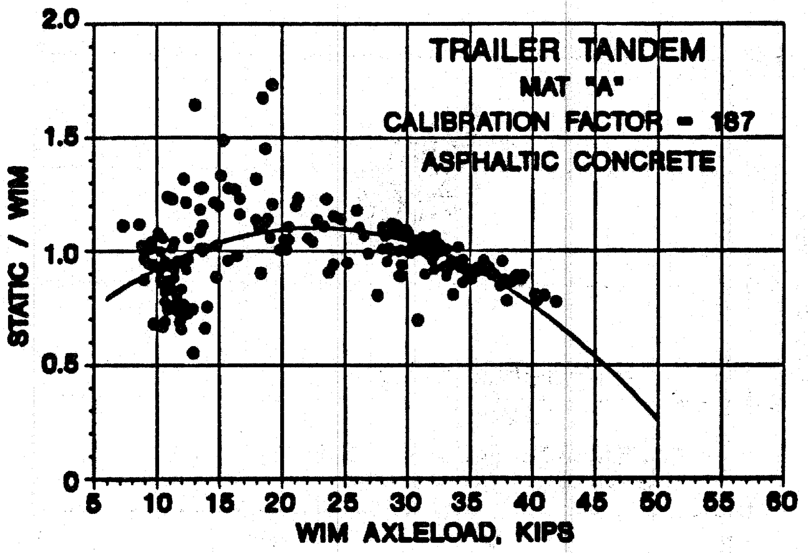

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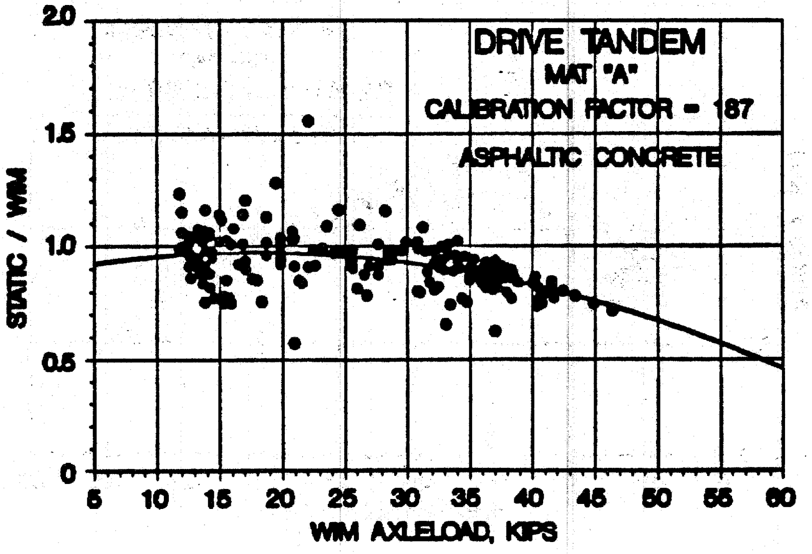

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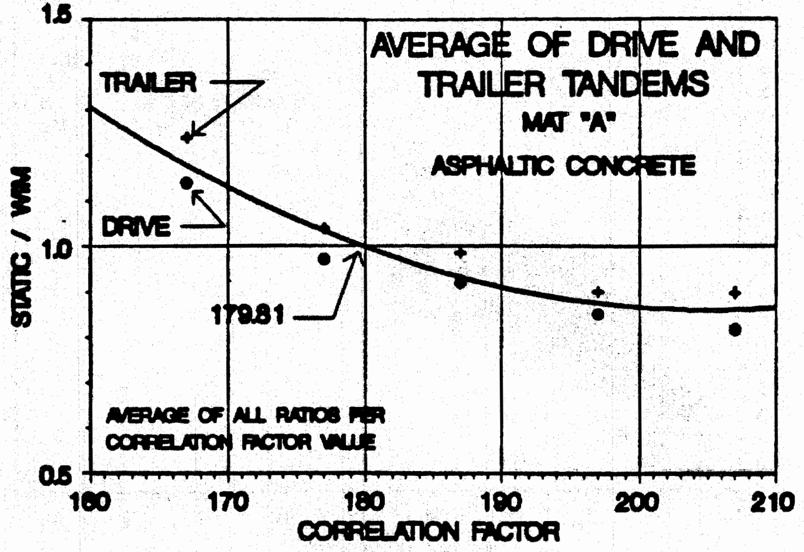

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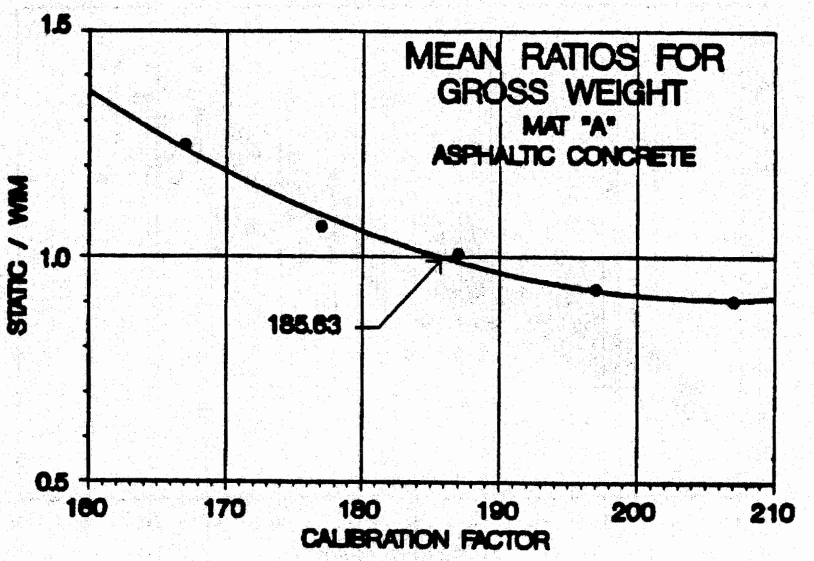

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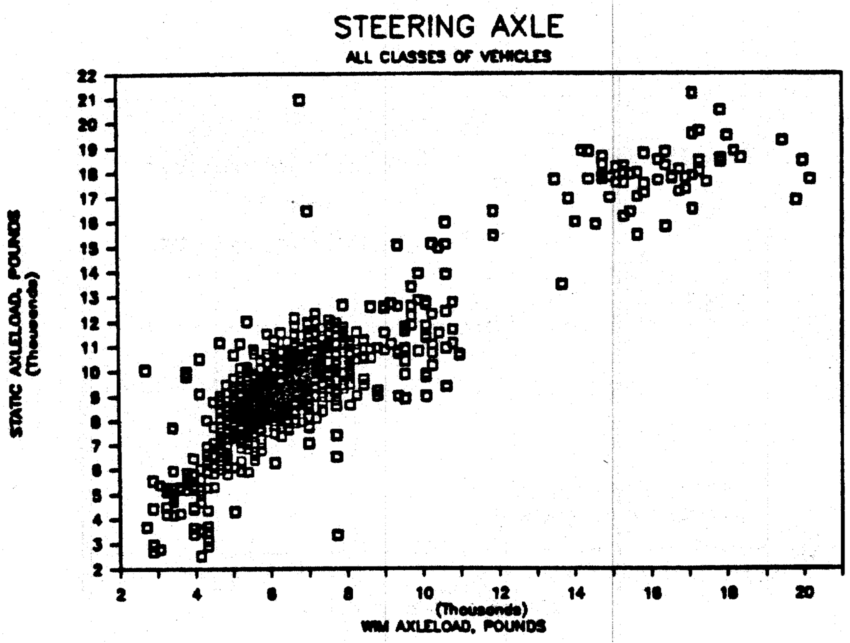

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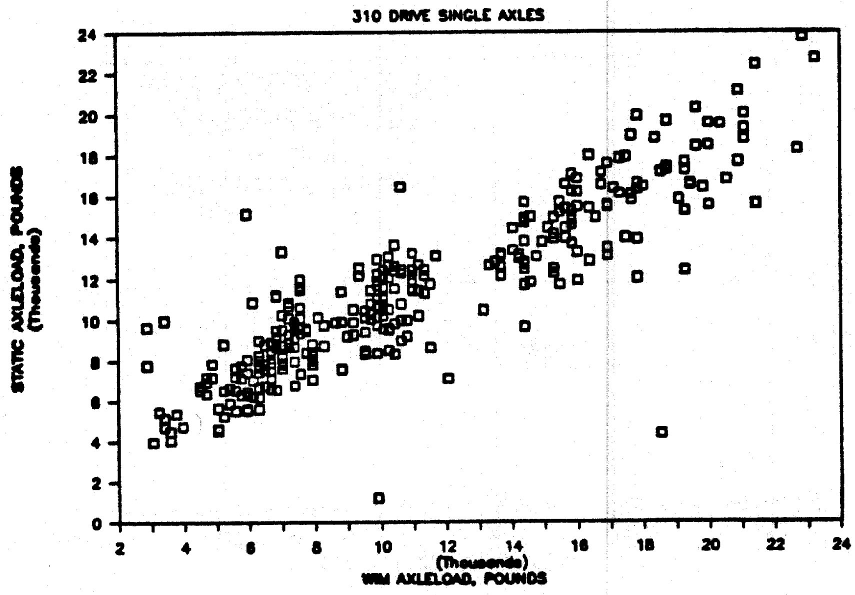

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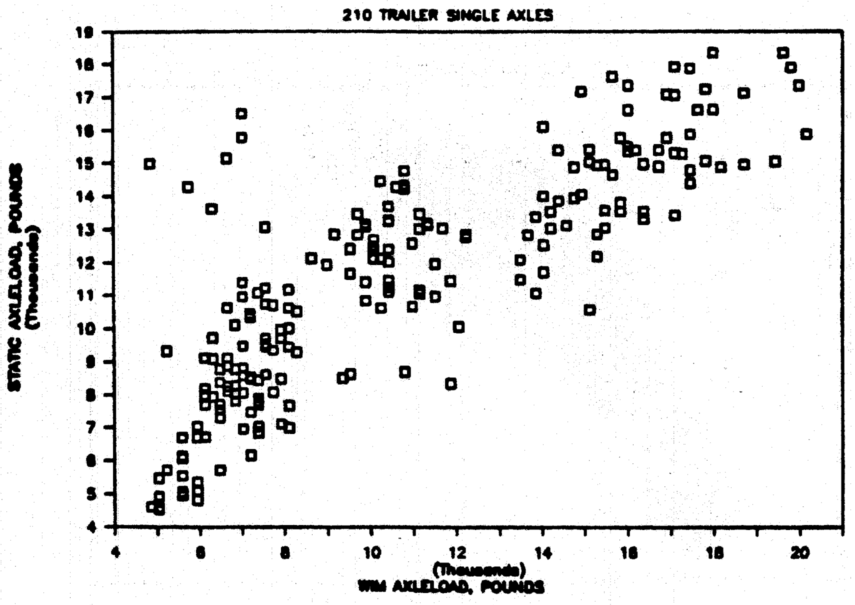

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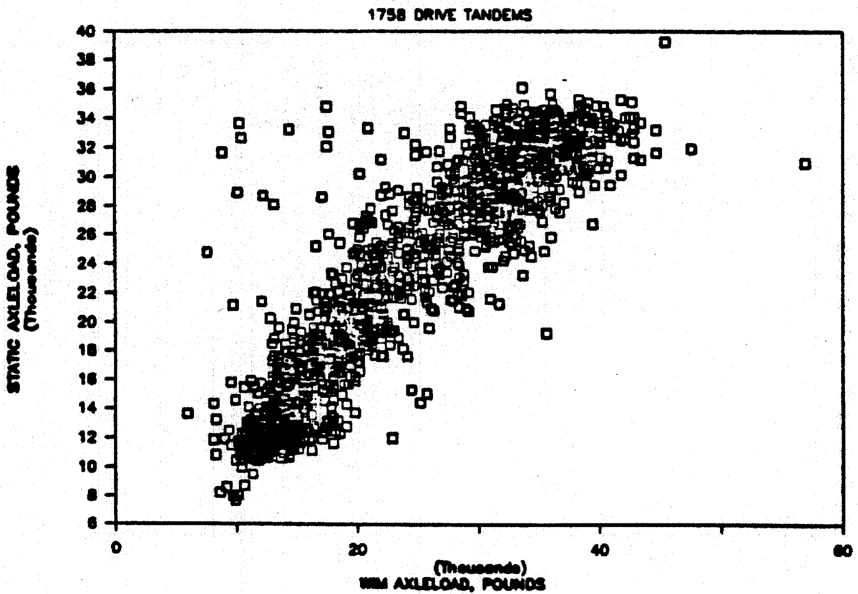

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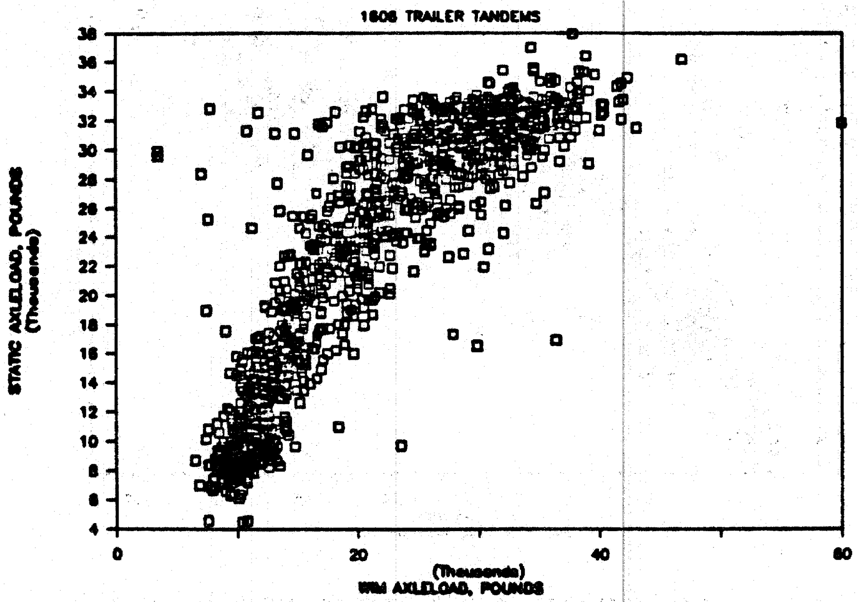

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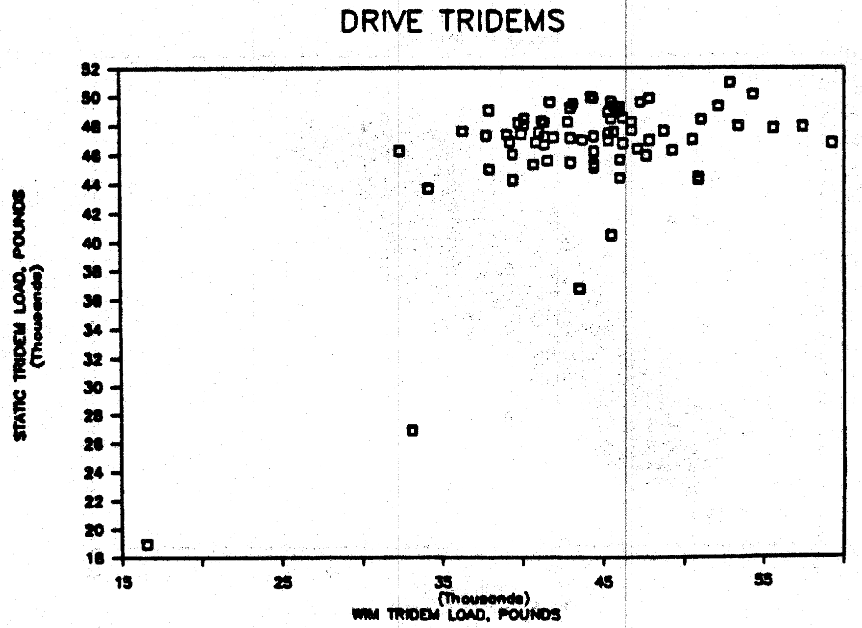

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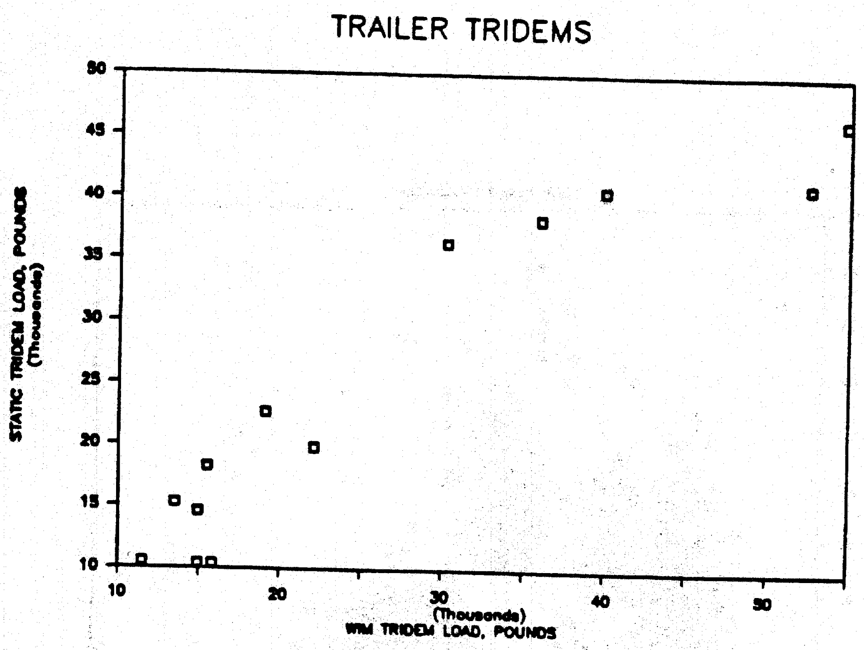

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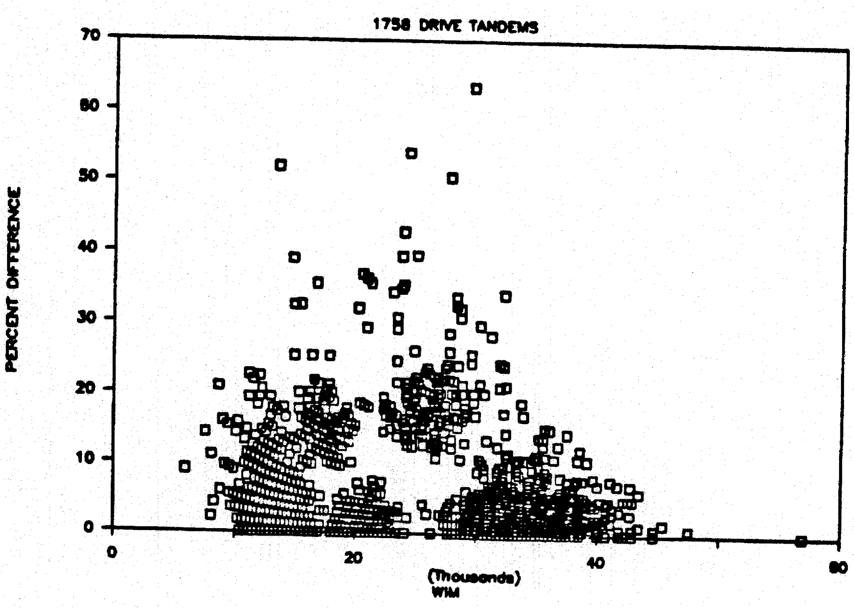

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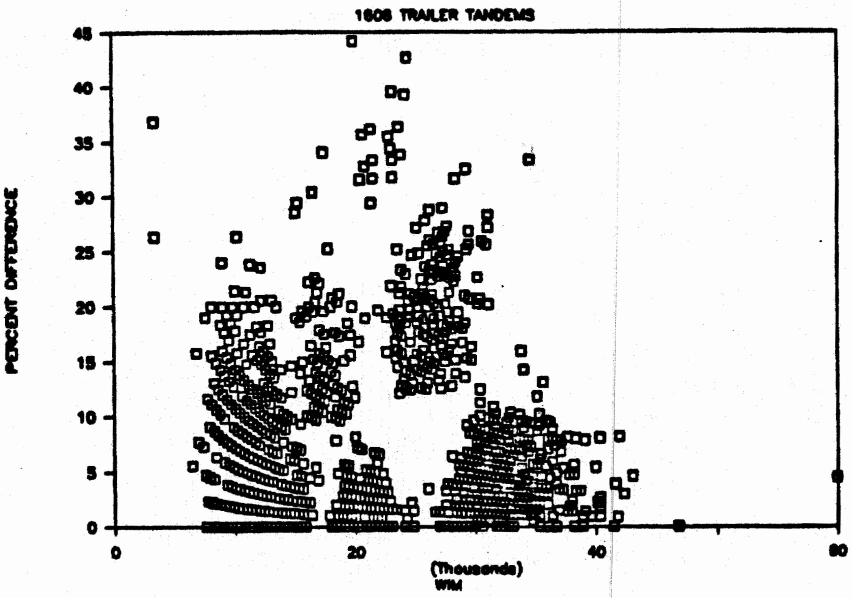

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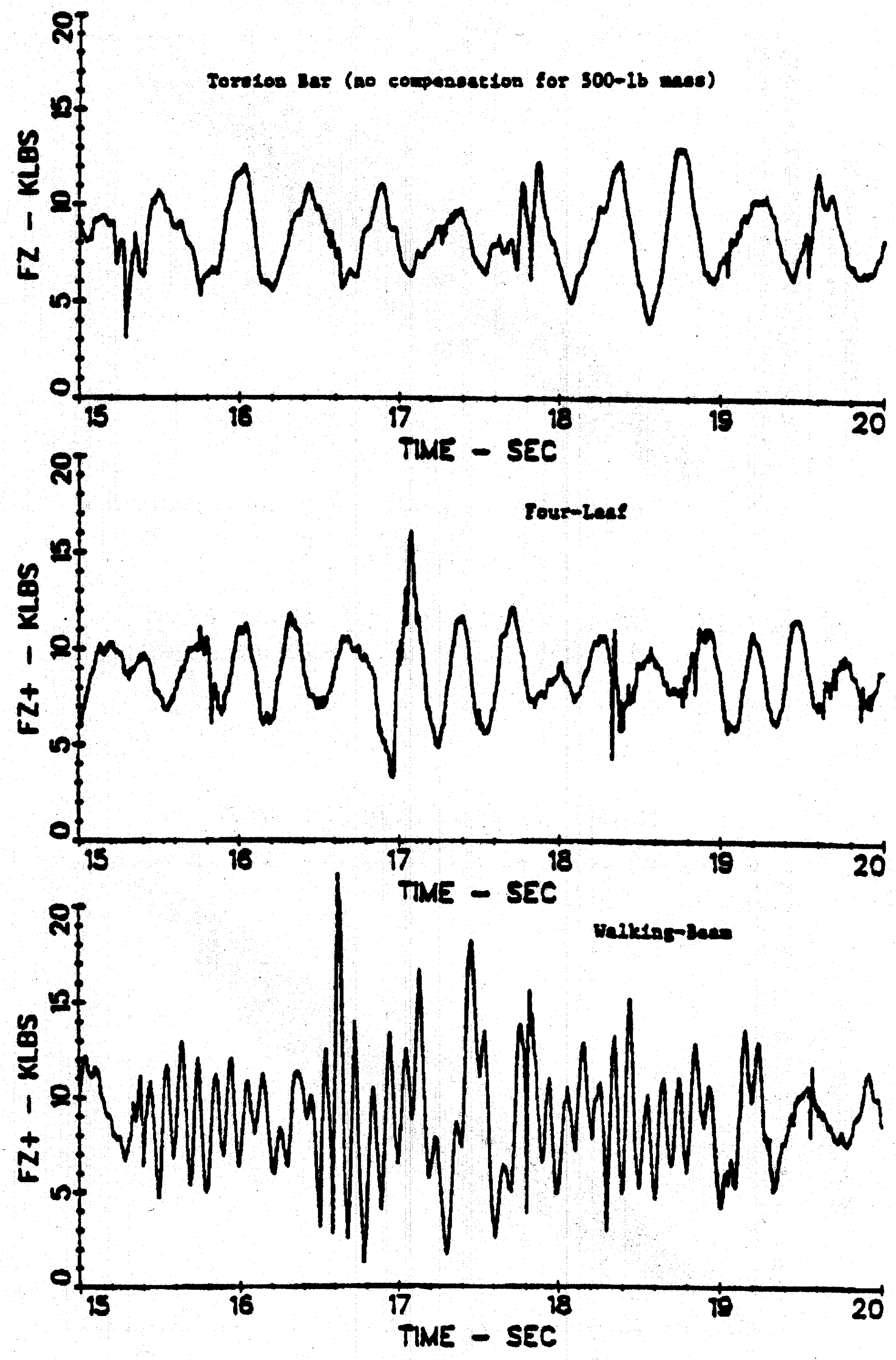


Torsion Bar (no compensation for 500-lb mass)

Four-Leaf

Walking-Beam

FIGURE 16. COMPARISON OF THREE VEHICLE RESPONSES TO THE SAME ROAD INPUT, REF. GILLESPIE'S FIGURE 57.

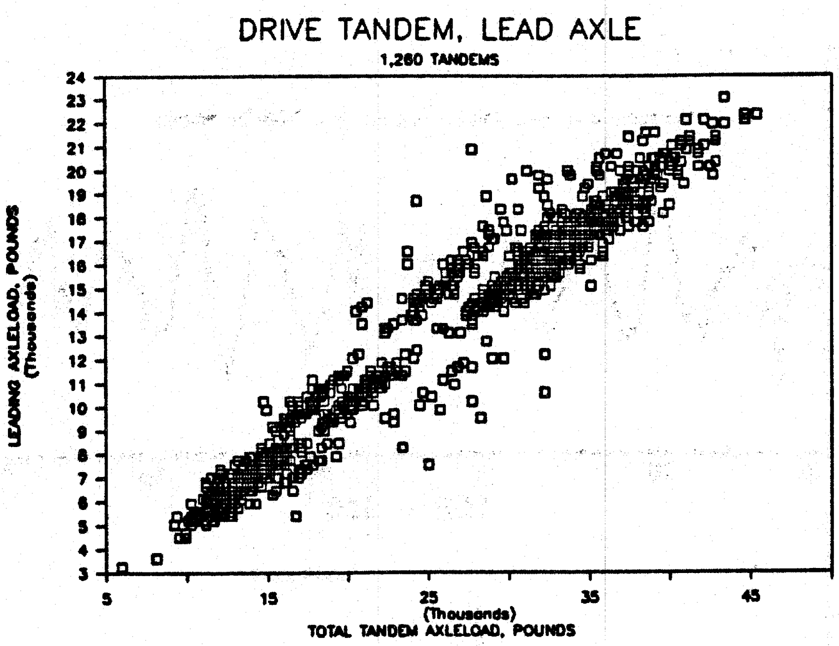
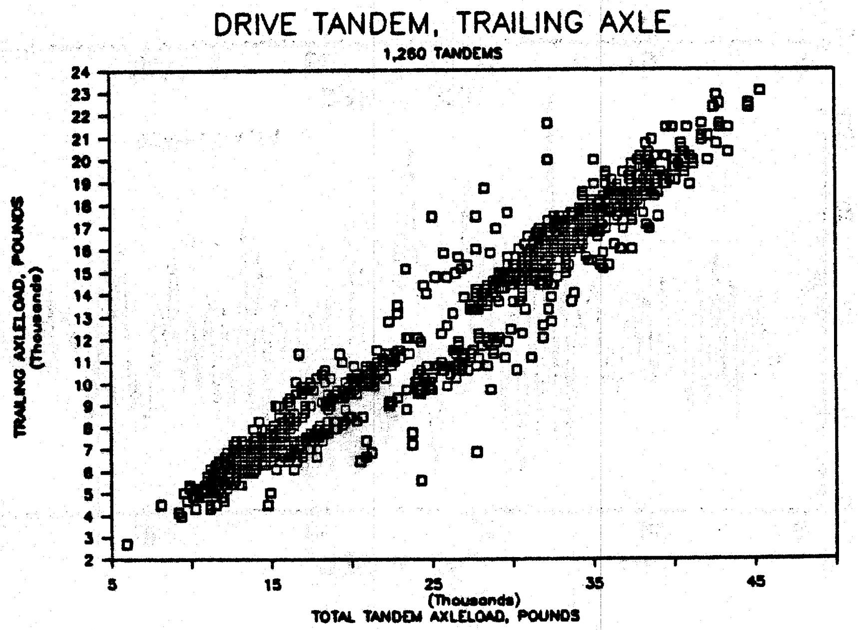


FIGURE 17. TOTAL TANDEM AXLELOAD VERSUS FIRST AXLELOAD FOR DRIVE TANDEM AXLE GROUP.



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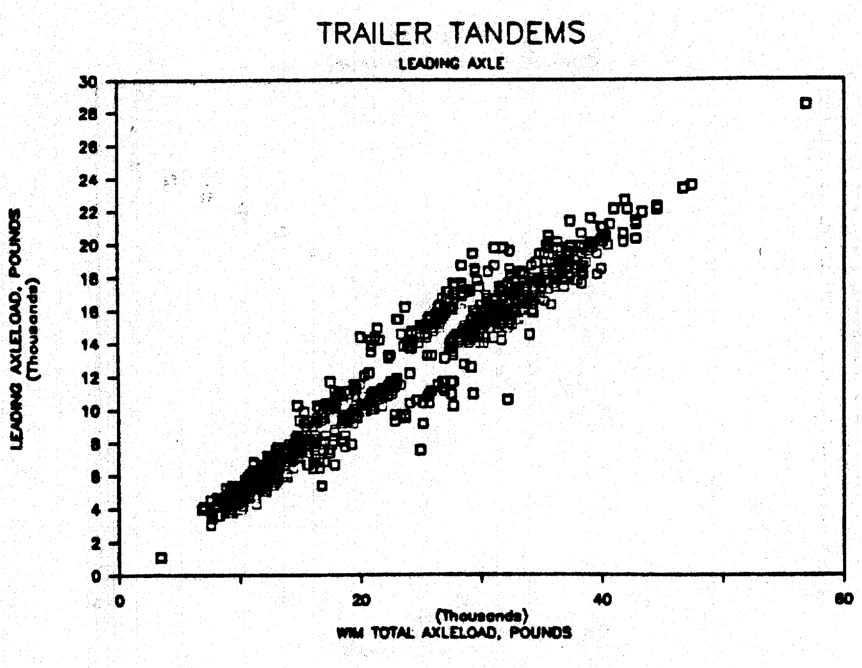

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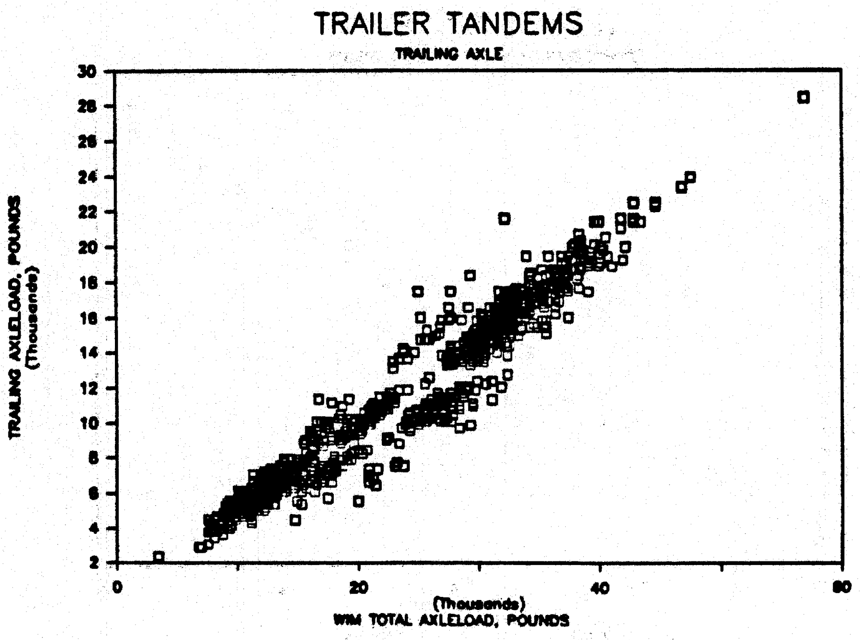

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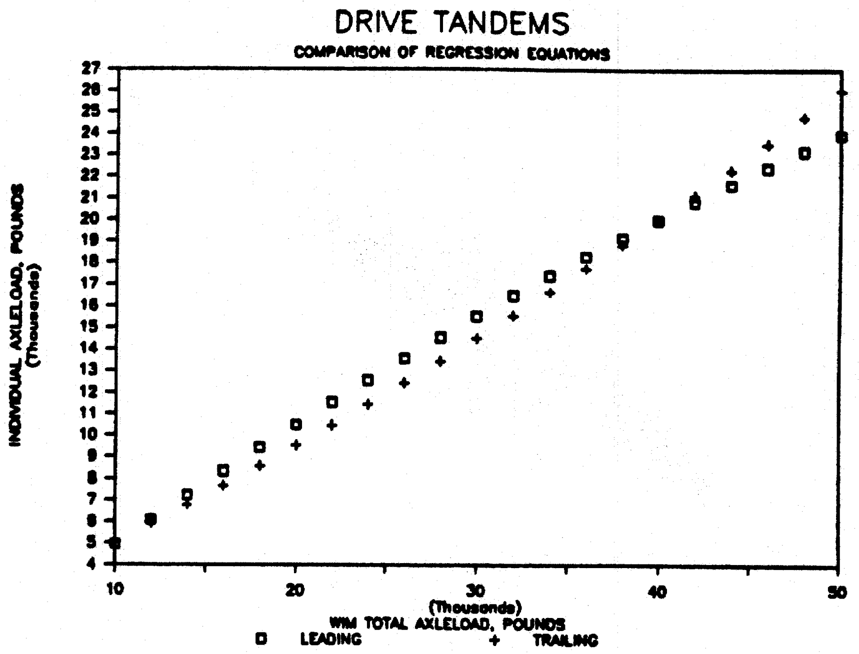

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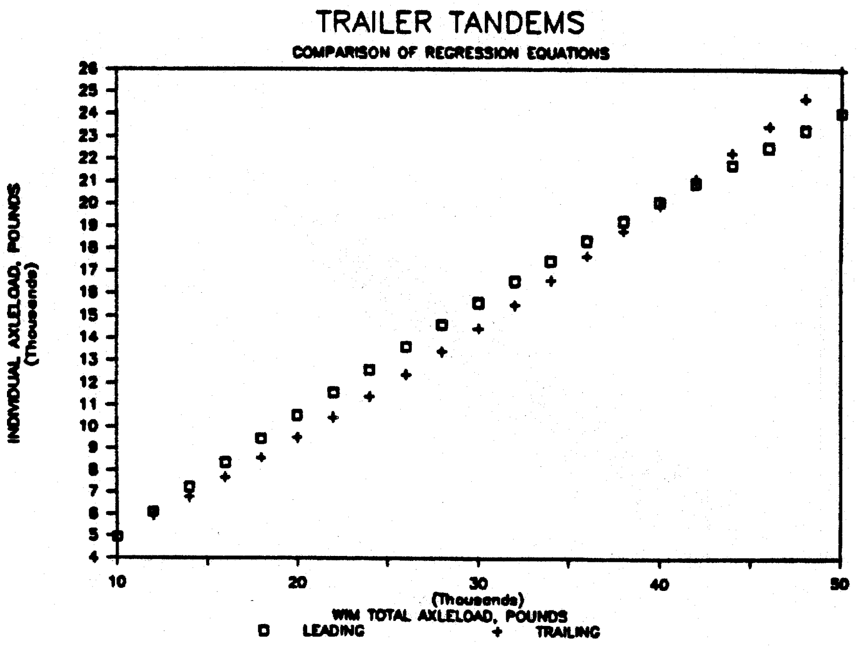

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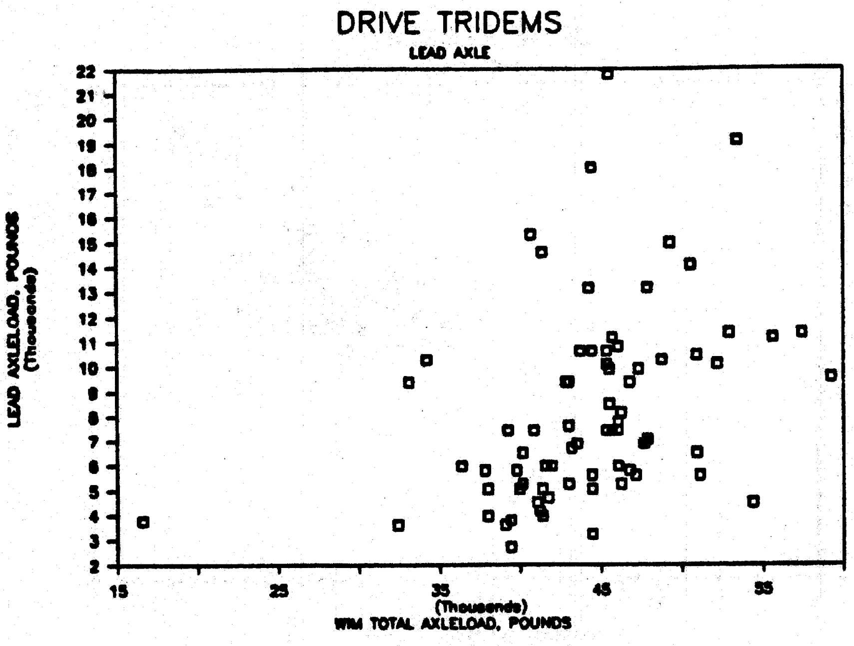

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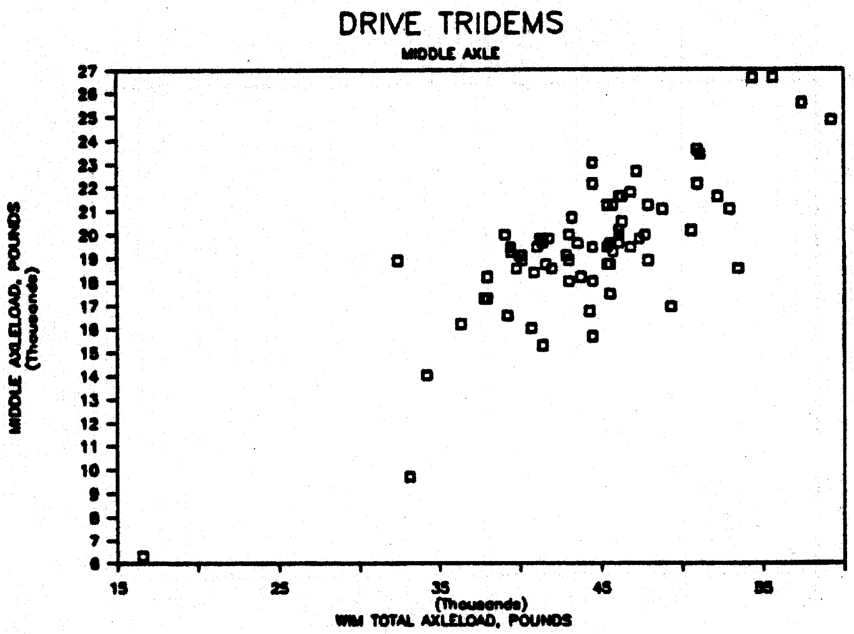

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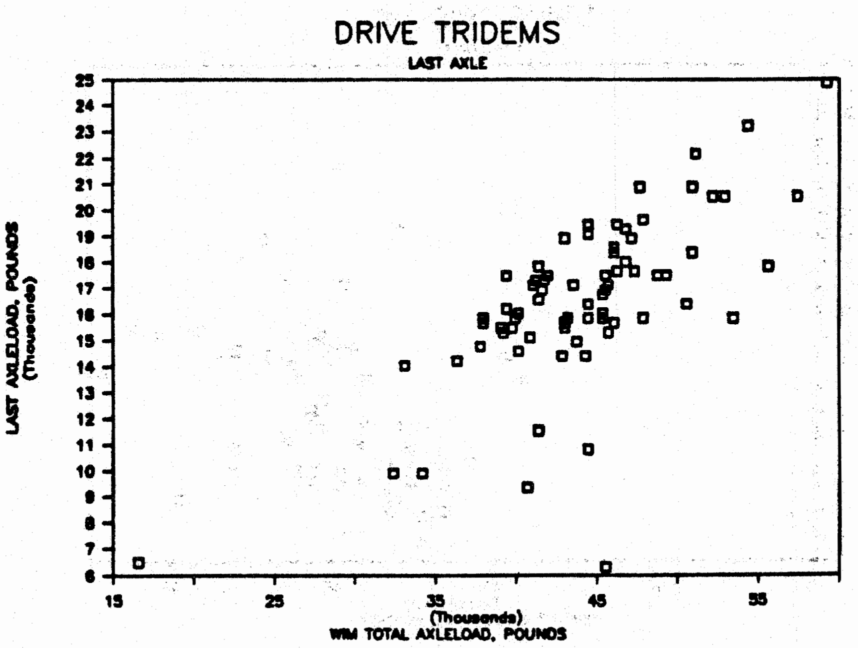

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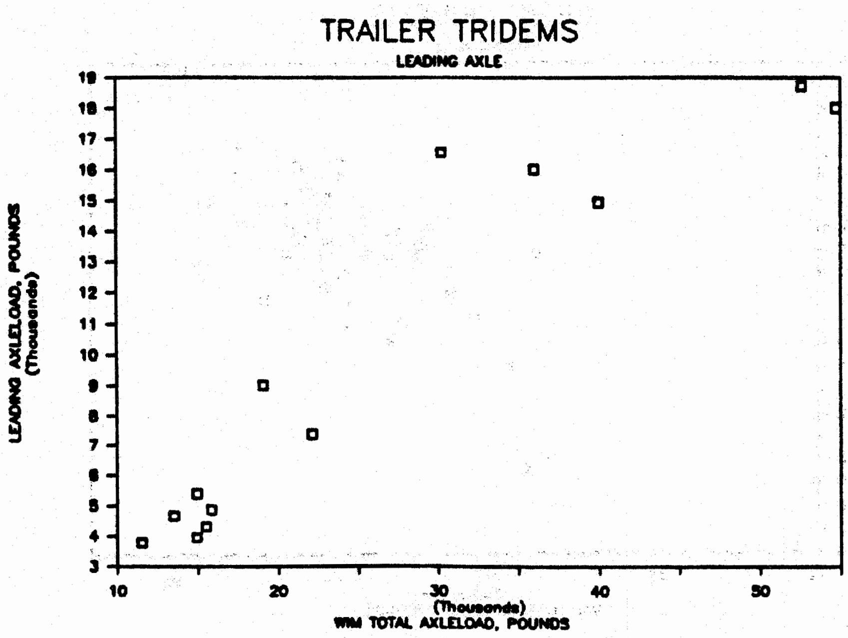

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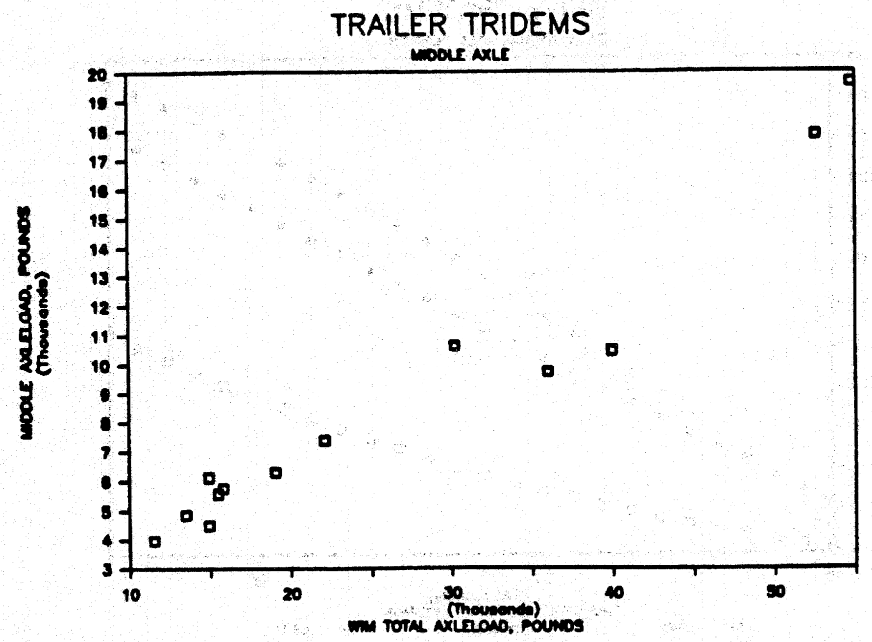

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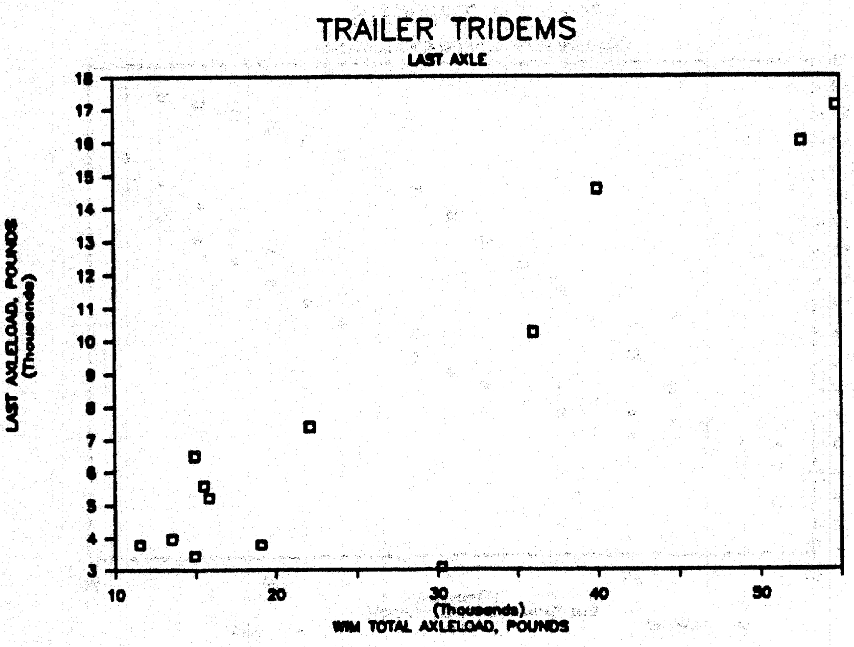

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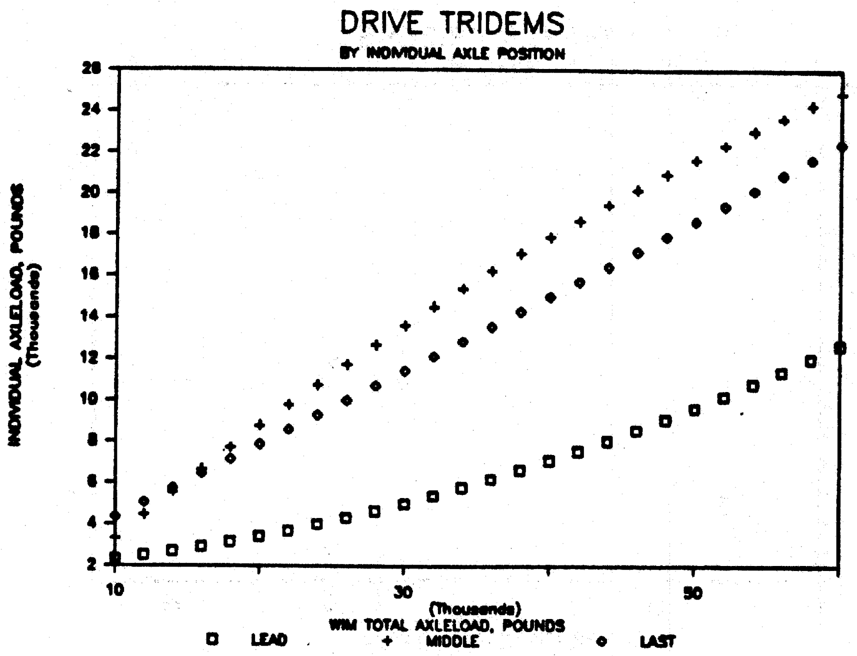

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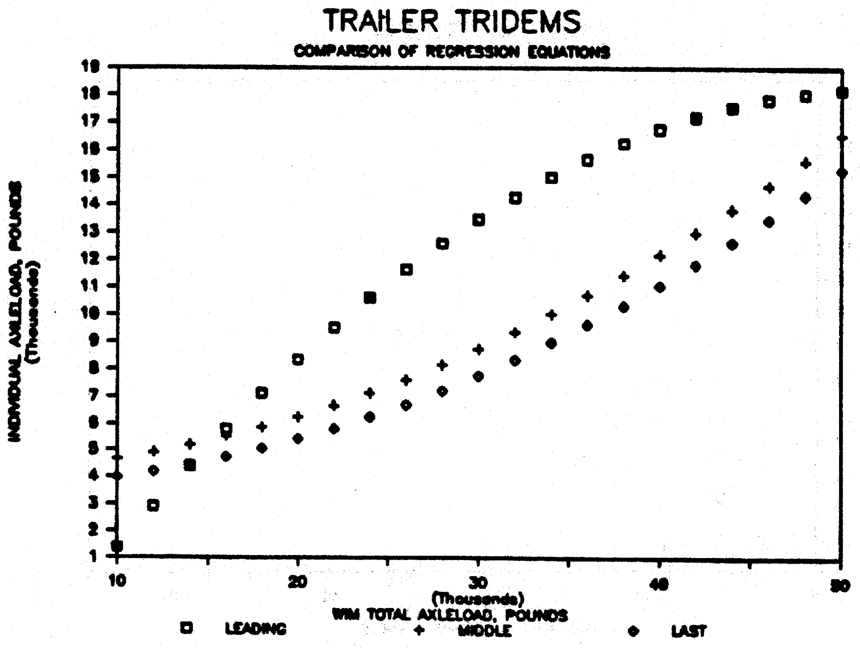

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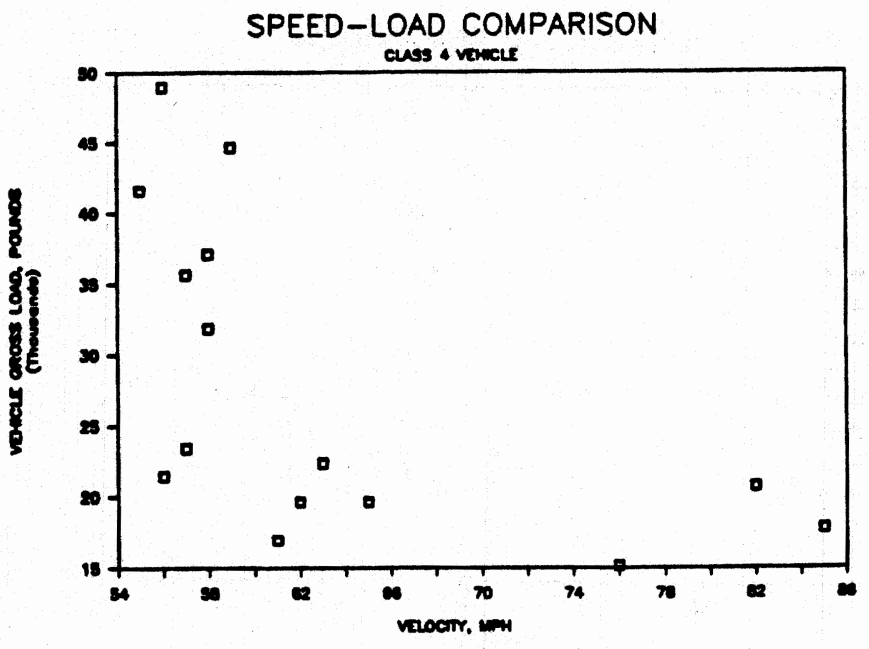

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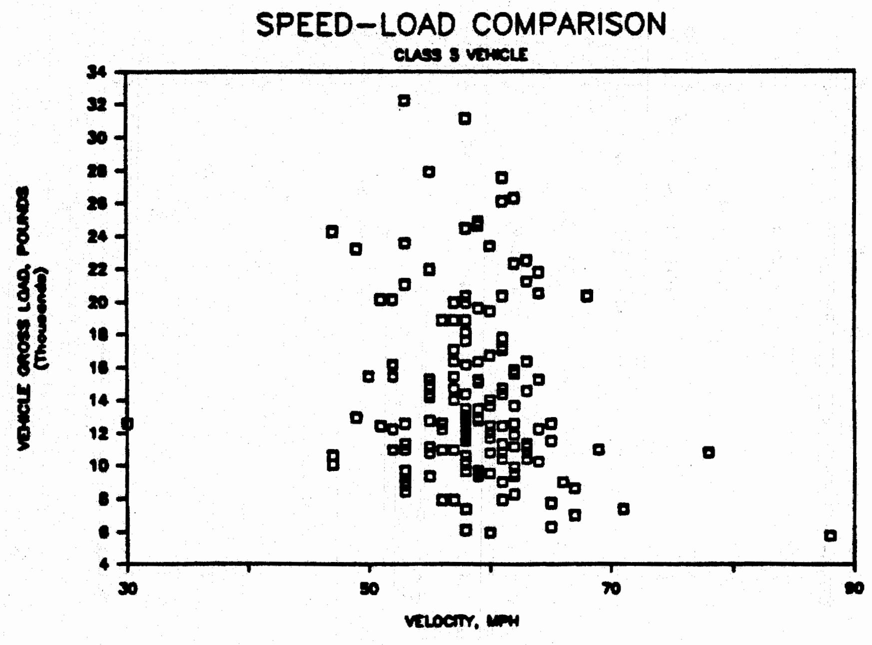

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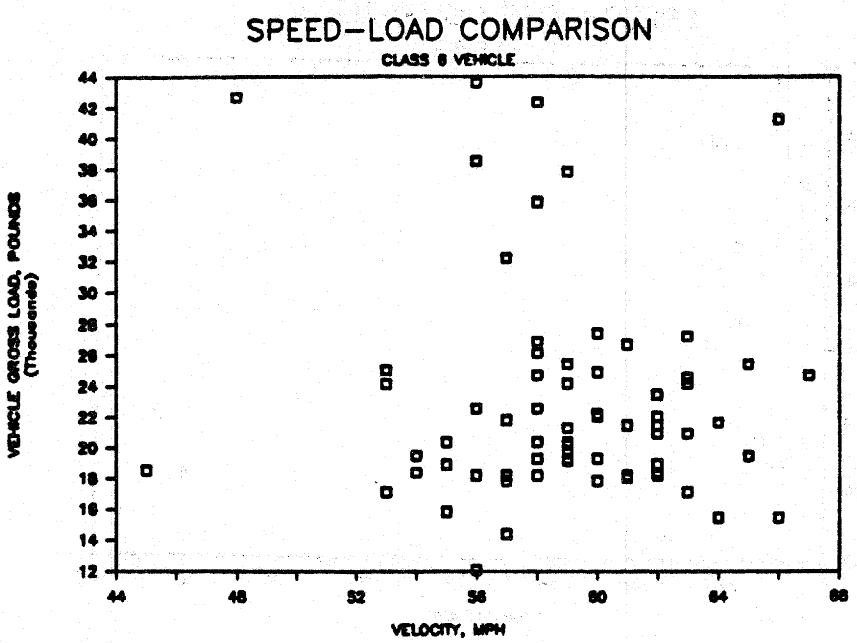

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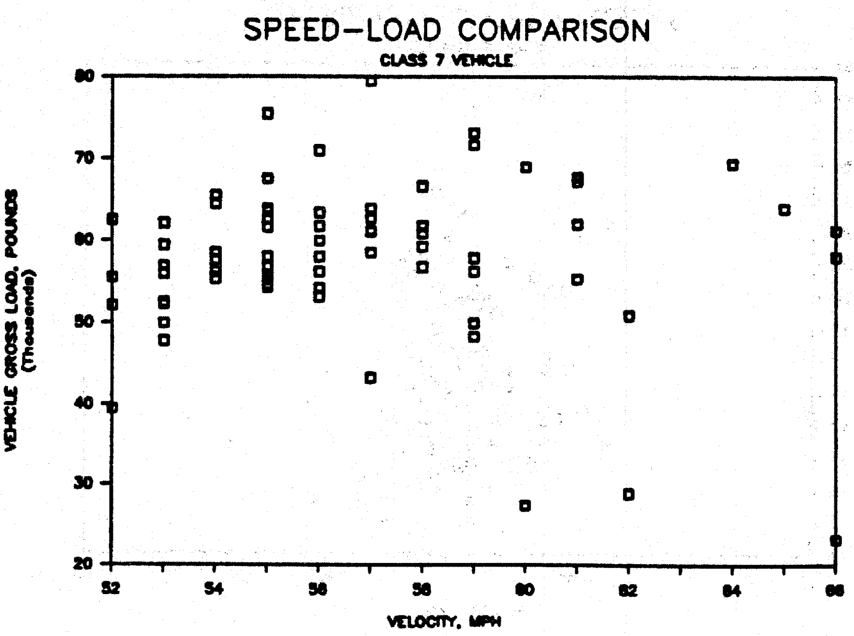

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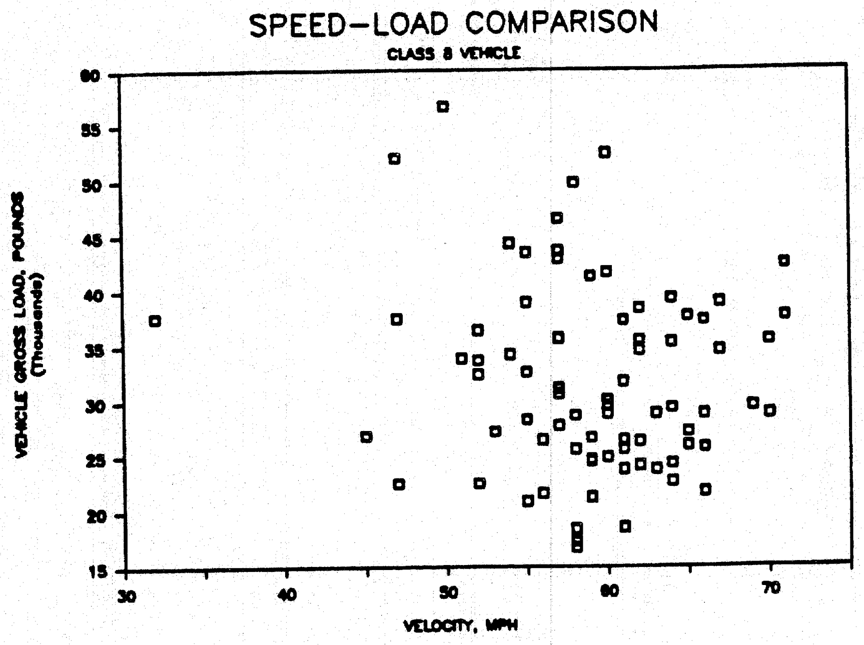

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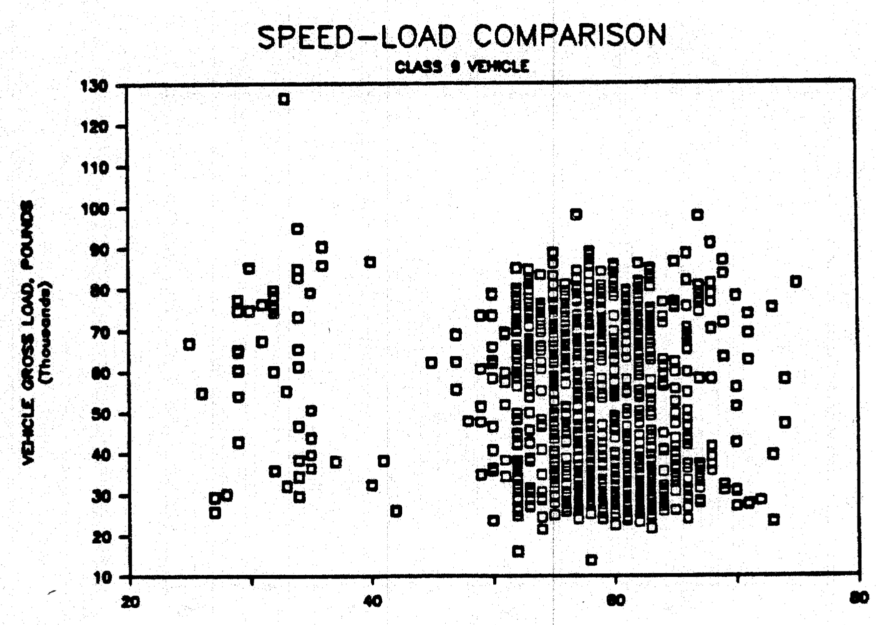

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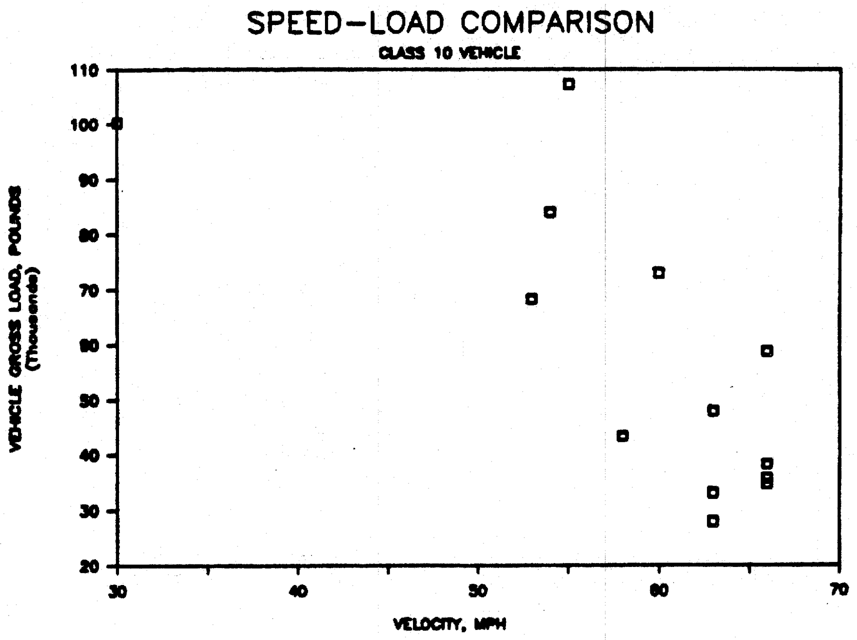

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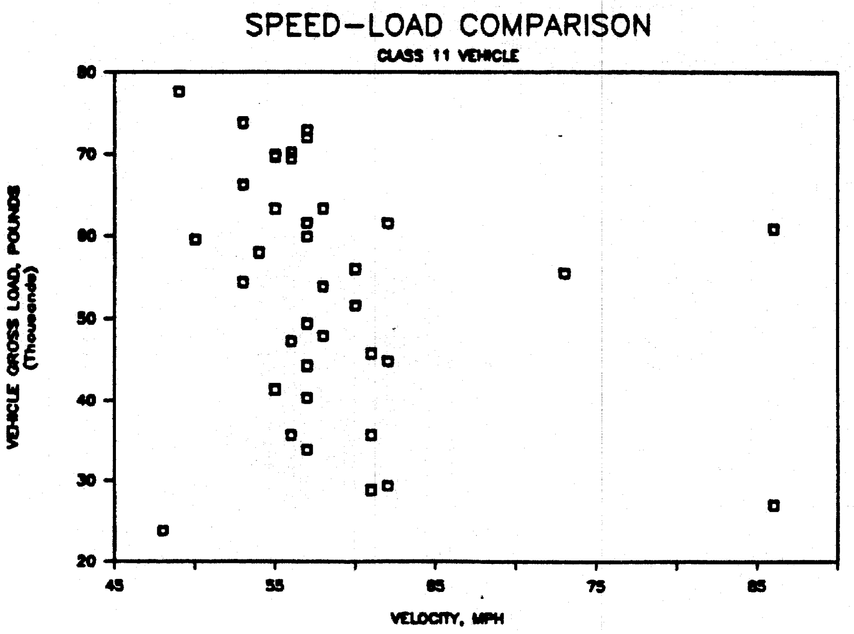

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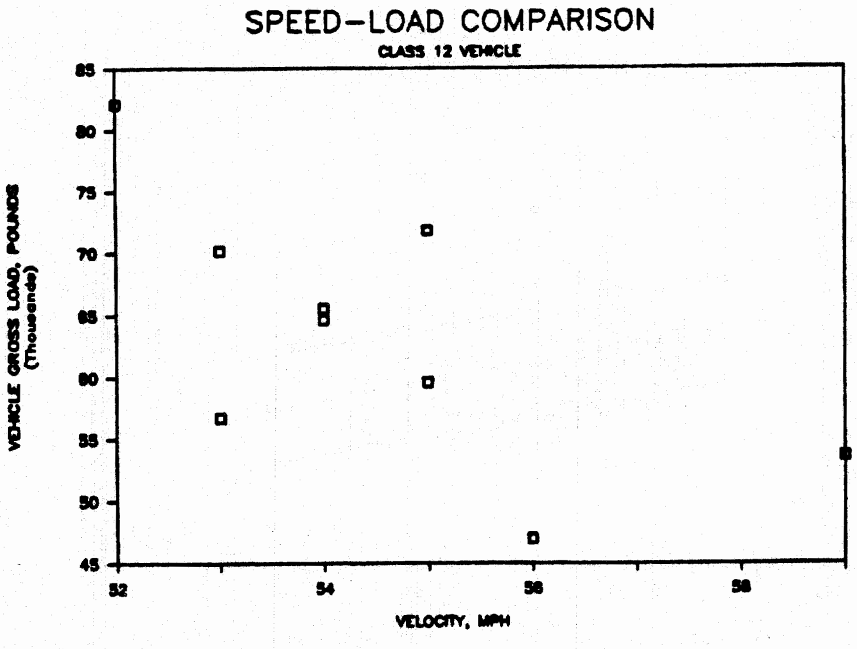

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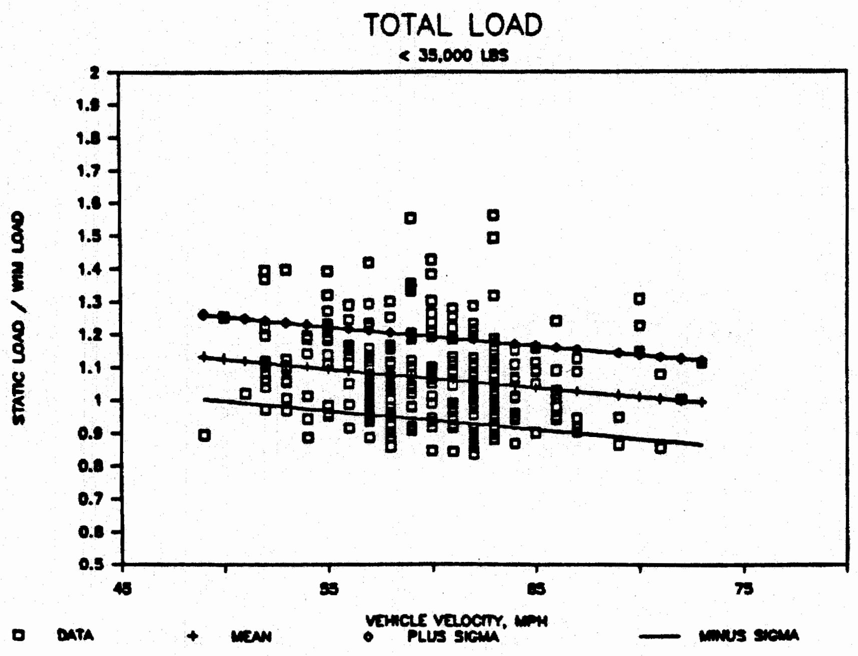

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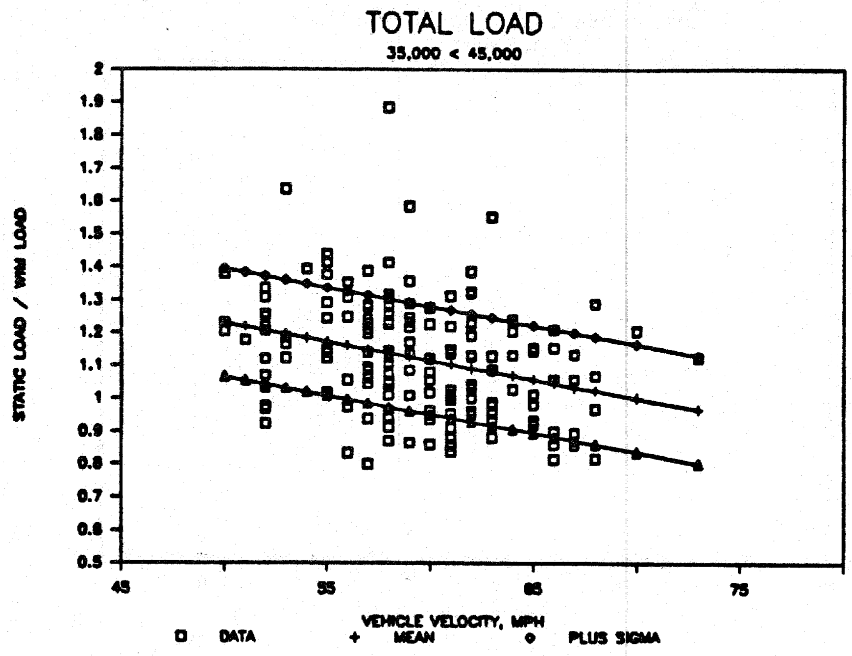

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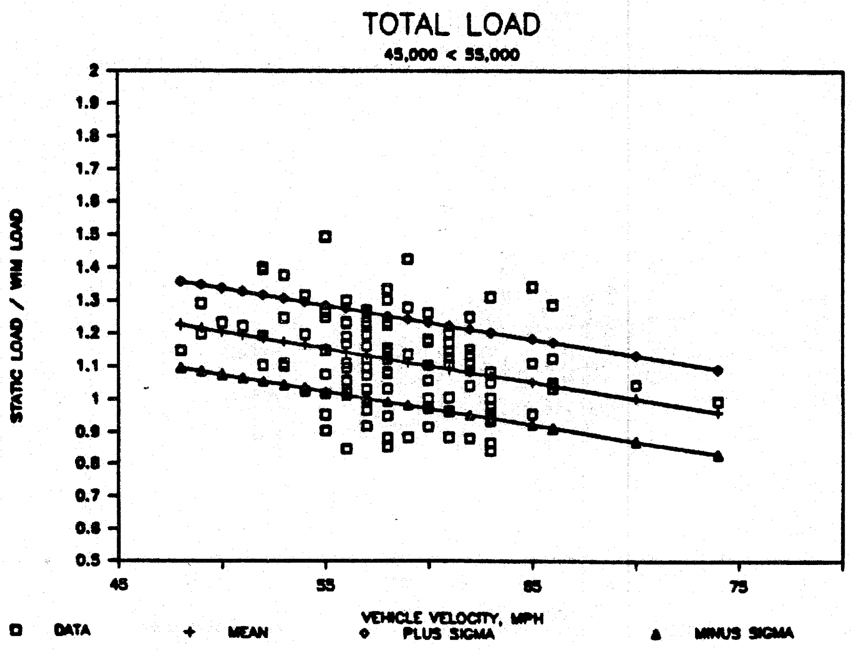

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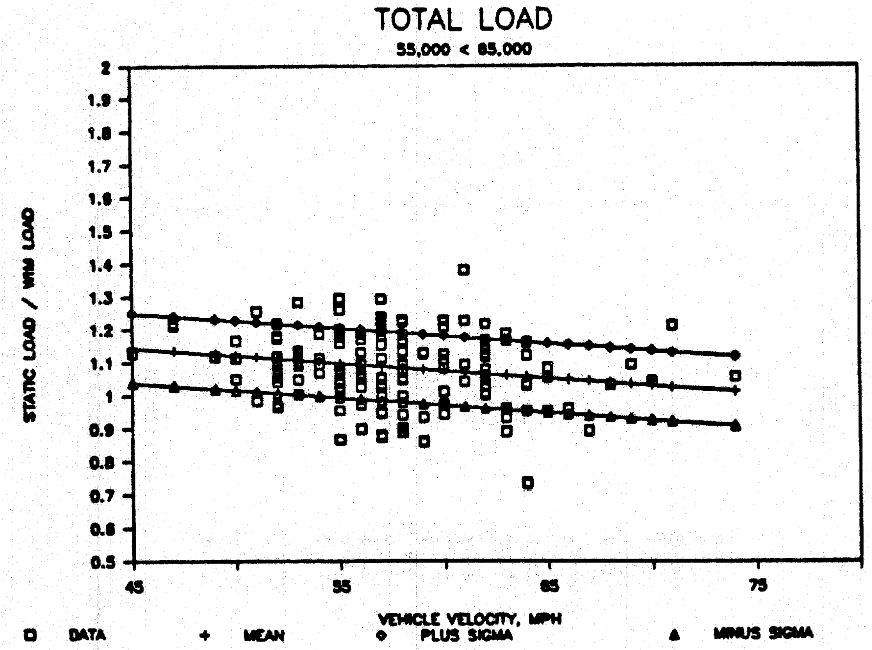

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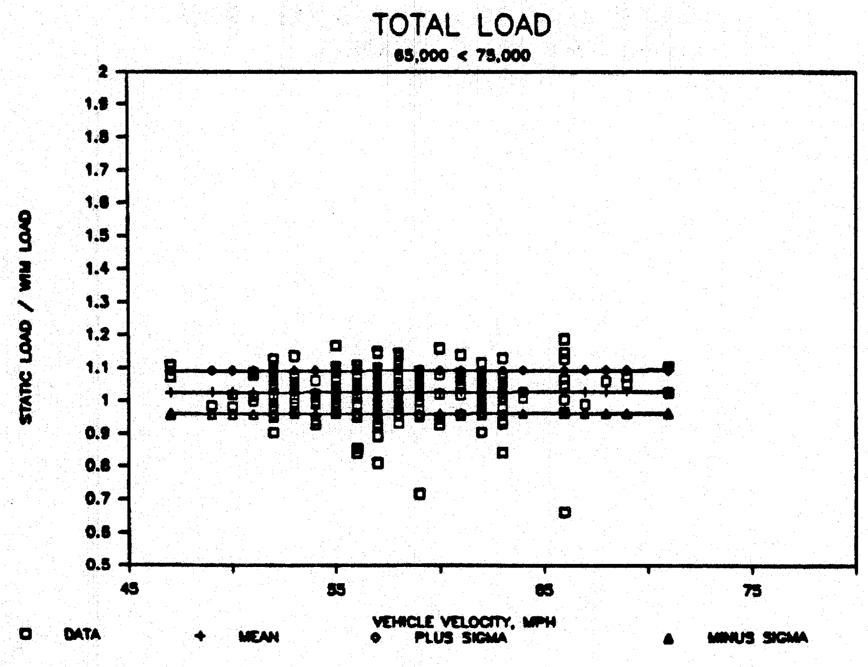

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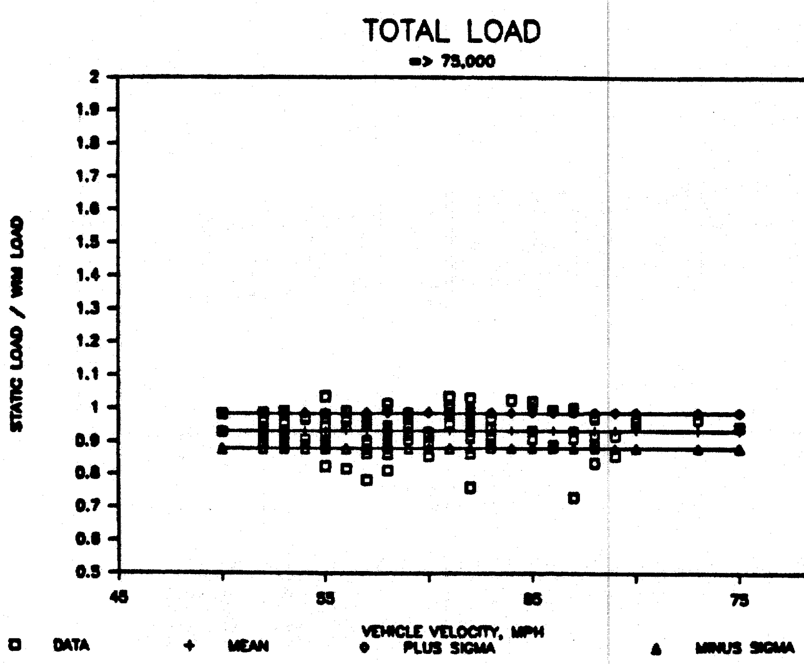


FIGURE 45. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OVER 75,000 POUNDS.

## TABLE 1. POLYNOMIAL COEFFICIENTS TO ADJUST WEIGH-IN-MOTION DATA TO EQUIVALENT STATIC SCALE VALUE BY AXLE LOCATION ON VEHICLE

EQUATION FORMAT: $Y = a + bX + cX^2$

| | | DRIVE AXLE | | | |
|---|---|---|---|---|---|
| | STEERING | SINGLE | TANDEM | TRIDEM | |
| c | -0.000021689 | 0.0000061306 | -0.0000141751 | -0.0000306725 | near 0 |
| b | 1.3313494303 | 0.5710284024 | 1.5035340031 | 3.0087359324 | |
| a | 1641.3641617 | 4135.5077939 | -3930.5004888 | -25467.820407 | |
| STANDARD ERROR | 1051.6604504 | 1903.6409725 | 2548.9995497 | 3064.8081838 | |
| R^2 | 0.7808836423 | 0.7777160252 | 0.9006533335 | 0.7505157055 | |
| F RATIO | 2872.4109067 | 435.59435727 | 5697.8320442 | 108.297660387 | |
| NUMBER OF OBSERVATIONS | 1615 | 252 | 1260 | 75 | |

| | TRAILER AXLE | | |
|---|---|---|---|
| | SINGLE | TANDEM | TRIDEM |
| c | -0.0000359639 | -0.0000243245 | -0.0000195474 |
| b | 1.577666216 | 2.0031561485 | 2.114225245 |
| a | -1067.2289242 | -8415.7658813 | -12941.477115 |
| STANDARD ERROR | 1513.6248287 | 2687.908828 | 3414.8376245 |
| R^2 | 0.8307419998 | 0.910573402 | 0.9466890612 |
| F RATIO | 346.02388608 | 6068.683808 | 88.789381854 |
| NUMBER OF OBSERVATIONS | 144 | 1195 | 13 |

TABLE 2. CALCULATED EAL USING RECORDED WEIGH-IN-MOTION DATA, STATIC SCALE DATA, AND WEIGH-IN-MOTION DATA ADJUSTED TO AN EQUIVALENT STATIC VALUE USING LOAD EQUIVALENCY FACTORS BY AASHTO LOAD EQUIVALENCIES

| KENTUCKY WEIGH-IN-MOTION USING AASHTO LOAD EQUIVALENCIES | STRUCTURAL NUMBER | |
|---|---|---|
| | 4 | 5 |
| STEERING AXLE | 110.77 | 103.78 |
| 4-TIRED SINGLE AXLE, DRIVE | 87.15 | 85.60 |
| 4-TIRED SINGLE AXLE, TRAILER | 44.31 | 42.64 |
| 8-TIRED TANDEM AXLES, DRIVE | 939.30 | 908.42 |
| 8-TIRED TANDEM AXLES, TRAILER | 714.47 | 699.99 |
| TOTAL BY AASHTO LOAD EQUIVALENCIES | 1895.99 | 1840.43 |
| **KENTUCKY STATIC SCALE WEIGHTS USING AASHTO LOAD EQUIVALENCIES** | | |
| STEERING AXLE | | |
| 4-TIRED SINGLE AXLE, DRIVE | 75.77 | 72.86 |
| 4-TIRED SINGLE AXLE, TRAILER | 38.54 | 36.13 |
| 8-TIRED TANDEM AXLES, DRIVE | 983.83 | 948.76 |
| 8-TIRED TANDEM AXLES, TRAILER | 510.97 | 486.41 |
| TOTAL AASHTO | 1768.97 | 1690.07 |
| **WEIGH-IN-MOTION RECORDED WEIGHTS ADJUSTED TO EQUIVALENT STATIC WEIGHTS AND USING AASHTO LOAD EQUIVALENCIES** | | |
| STEERING AXLE | 252.40 | 229.65 |
| 4-TIRED SINGLE AXLE, DRIVE | 68.61 | 65.22 |
| 4-TIRED SINGLE AXLE, TRAILER | 36.13 | 33.74 |
| 8-TIRED TANDEM AXLES, DRIVE | 523.04 | 494.11 |
| 8-TIRED TANDEM AXLES, TRAILER | 479.79 | 453.32 |
| TOTAL EQUIVALENT STATIC | 1359.96 | 1276.05 |

| | STRUCTURAL NUMBER | |
|---|---|---|
| SUMMARY | 4 | 5 |
| TOTAL BY AASHTO LOAD EQUIVALENCIES | 1895.99 | 1840.43 |
| TOTAL STATIC AASHTO | 1768.97 | 1690.07 |
| TOTAL EQUIVALENT STATIC | 1359.96 | 1276.05 |

## TABLE 3. CALCULATED EAL USING RECORDED WEIGH-IN-MOTION DATA, STATIC SCALE DATA, AND WEIGH-IN-MOTION DATA ADJUSTED TO AN EQUIVALENT STATIC VALUE USING LOAD EQUIVALENCY FACTORS BY KENTUCKY METHOD

| | EVEN LOAD DISTRIBUTION | | | UNEVEN LOAD DISTRIBUTION | | |
|---|---|---|---|---|---|---|
| | LOAD | TIRE PRESSURE | | LOAD | TIRE PRESSURE | |
| RECORDED WEIGH-IN-MOTION DATA AND KENTUCKY LOAD EQUIVALENCY FACTORS | EQUIVALENCY | 75 PSI | 105 PSI | EQUIVALENCY | 75 PSI | 105 PSI |
| STEERING AXLE | 211.03 | 265.65 | 517.24 | | | |
| 4-TIRED SINGLE AXLE, DRIVE | 87.77 | 94.56 | 120.26 | | | |
| 4-TIRED SINGLE AXLE, TRAILER | 39.85 | 42.93 | 54.60 | | | |
| 8-TIRED TANDEM AXLES, DRIVE | 358.31 | 387.09 | 497.88 | 474.40 | 512.51 | 659.19 |
| 8-TIRED TANDEM AXLES, TRAILER | 349.15 | 377.20 | 485.16 | 472.36 | 510.30 | 656.36 |
| | ------- | ------- | ------- | ------- | ------- | ------- |
| RECORDED WIM TOTAL | 1046.11 | 1167.42 | 1675.14 | 1285.41 | 1425.95 | 2007.66 |
| RECORDED STATIC WEIGHTS AND KENTUCKY LOAD EQUIVALENCY FACTORS | | | | | | |
| STEERING AXLE | 511.18 | 643.47 | 1252.92 | | | |
| 4-TIRED SINGLE AXLE, DRIVE | 87.77 | 94.56 | 120.26 | | | |
| 4-TIRED SINGLE AXLE, TRAILER | 31.35 | 33.77 | 42.95 | | | |
| 8-TIRED TANDEM AXLES, DRIVE | 231.57 | 250.17 | 321.78 | 321.96 | 347.82 | 447.37 |
| 8-TIRED TANDEM AXLES, TRAILER | 269.15 | 290.78 | 374.00 | 399.91 | 432.03 | 555.68 |
| | ------- | ------- | ------- | ------- | ------- | ------- |
| RECORDED STATIC TOTAL | 1131.02 | 1312.75 | 2111.90 | 1352.16 | 1551.65 | 2419.18 |
| KENTUCKY WEIGH-IN-MOTION DATA ADJUSTED TO EQUIVALENT STATIC WEIGHT AND KENTUCKY LOAD EQUIVALENCY FACTORS | | | | | | |
| STEERING AXLE | 489.82 | 616.59 | 1200.58 | | | |
| 4-TIRED SINGLE AXLE, DRIVE | 59.62 | 64.23 | 81.69 | | | |
| 4-TIRED SINGLE AXLE, TRAILER | 28.44 | 30.64 | 38.97 | | | |
| 8-TIRED TANDEM AXLES, DRIVE | 285.35 | 308.27 | 396.50 | 389.60 | 420.90 | 541.37 |
| 8-TIRED TANDEM AXLES, TRAILER | 238.18 | 257.31 | 330.96 | 353.41 | 381.80 | 491.07 |
| | ------- | ------- | ------- | ------- | ------- | ------- |
| WIM-EQUATED TOTAL | 1101.41 | 1277.05 | 2048.70 | 1320.90 | 1514.16 | 2353.68 |

| | EVEN LOAD DISTRIBUTION | | | UNEVEN LOAD DISTRIBUTION | | |
|---|---|---|---|---|---|---|
| | LOAD | TIRE PRESSURE | | LOAD | TIRE PRESSURE | |
| SUMMARY | EQUIVALENCY | 75 PSI | 105 PSI | EQUIVALENCY | 75 PSI | 105 PSI |
| RECORDED WIM TOTAL | 1046.11 | 1167.42 | 1675.14 | 1285.41 | 1425.95 | 2007.66 |
| RECORDED STATIC TOTAL | 1131.02 | 1312.75 | 2111.90 | 1352.16 | 1551.65 | 2419.18 |
| WIM-EQUATED TOTAL | 1101.41 | 1277.05 | 2048.70 | 1320.90 | 1514.16 | 2353.68 |

## TABLE 4. TOTALS IN TABLES 2 AND 3 EXPRESSED AS PERCENTAGES

### EAL USING AASHTO LOAD EQUIVALENCIES

| | SN = 5 | |
|---|---|---|
| | EAL | PERCENT |
| RECORDED WIM | 1,840 | 100 |
| RECORDED STATIC | 1,690 | 92 |
| WIM EQUATED TO STATIC | 1,276 | 69 |

### EAL USING KENTUCKY FACTORS

| | EAL | | | | | |
|---|---|---|---|---|---|---|
| | TIRE CONTACT PRESSURE, PSI | | | TIRE CONTACT PRESSURE, PSI | | |
| | 67.5 | 75 | 105 | 67.5 | 75 | 105 |
| | ASSUMING EVEN LOAD DISTRIBUTION | | | ACCOUNTING FOR UNEVEN LOAD DISTRIBUTION | | |
| RECORDED WIM | 1,046 | 1,167 | 1,075 | 1,285 | 1,426 | 2,008 |
| RECORDED STATIC | 1,131 | 1,313 | 2,112 | 1,352 | 1,552 | 2,419 |
| WIM EQUATED TO STATIC | 1,101 | 1,277 | 2,049 | 1,321 | 1,514 | 2,354 |

| | PERCENT | | | | | |
|---|---|---|---|---|---|---|
| | TIRE CONTACT PRESSURE, PSI | | | TIRE CONTACT PRESSURE, PSI | | |
| | 67.5 | 75 | 105 | 67.5 | 75 | 105 |
| | ASSUMING EVEN LOAD DISTRIBUTION | | | ACCOUNTING FOR UNEVEN LOAD DISTRIBUTION | | |
| RECORDED WIM | 100 | 112 | 160 | 123 | 136 | 192 |
| RECORDED STATIC | 108 | 126 | 202 | 129 | 148 | 231 |
| WIM EQUATED TO STATIC | 105 | 122 | 196 | 126 | 145 | 225 |

# PAVEMENT MANAGEMENT AND THE PAVEMENT POLICY

*William A. Nostrand, Jr., Chief, Pavement Management Branch*
*Federal Highway Administration Office of Highway Operations*
*Pavement Division*

## Pavement Management Policy

A notice of Proposed Rule Making (NPRM) was published in the Federal Register on January 26, 1988. It allowed the usual 90 days for comment, but because the AASHTO sub-committee on Pavements was meeting in early May, they requested an extension of the comment period so that the committee could present its official position. Everyone therefore had a full 120 days to comment.

There were 70± responses to the NPRM and it has taken all summer to resolve all the comments and prepare a final rule. That rule now has the approval of our Executive Director, Dick Morgan, but still needs the endorsement of the Office of Management and Budget (OMB). We are expecting the publishing of a final rule before the end of the year.

Probably the most significant element of the Pavement Policy is the mandate that all State highway agencies must have a pavement management system (PMS) in operation and acceptable to FHWA within reasonable time but not later than 4 years after the date of issuance of the final rule.

A principal capability of any acceptable PMS is it's data analysis unit. This unit of the PMS takes the inventory data, the condition survey data, and the traffic (load) data and in its analysis is able to recommend to the decision- maker what projects need to be done, the strategy alternatives available for those projects, and their cost. The bottom line of a good PMS is to be able to predict performance over time which will lead to future needs and ultimately to the anticipated budgets for the State Highway Program.

The most significant part of this discussion is the necessity for load information. The equivalent single axle loads (ESAL's) being applied to the pavement are absolutely essential to the entire process.

I am afraid that highway engineers in the past have been remiss in that they designed pavement structures and even predicted performance of the pavement on the basis of a percent of trucks in the average daily traffic (ADT). Highway engineers are fully aware today that we not only have to know how many trucks are using our pavements but we need to know axle loads.

How do we get that information?

The best way is by weighing each and every truck axle load and measuring distance between axles. To do that using the old static scale installations is of curse virtually impossible. Moreover, we also know that 5 minutes after the static scale installation is open, the word is out over the CB radios and many of the heaviest trucks find a way to avoid being weighed making the information obtained totally inadequate.

The answer of course is WIM!

In addition to the mandate on Pavement Management included in the Pavement Policy, is the requirement that the States have a pavement type selection process and a design process on new and reconstructed pavements. It also requires a design process and consideration of alternative strategies on the rehabilitated projects. (Incidentally, the term rehabilitation as used in the Pavement Policy includes the other two "Rs" - Resurfacing and Restoration) It goes without saying that a pavement type selection procedure and a pavement design process cannot be accomplished without good load data. There's no question about it, FHWA is advocating WIM both directly and indirectly by the mandates of its new Pavement Policy.

The Policy states that the FHWA has adopted as guides, the AASHTO "Guidelines on Pavement Management" (1985) which is soon to be revised and updated and the "AASHTO Guide for Design of Pavement Structures" (1986). Please note that I said "adopted as guides." It is not mandated that the State use either of these documents but they are put forward as tools acceptable for use if the State needs them. If a State has a proven design process which has been used effectively over the years, then that process will be acceptable to FHWA to fulfill the mandate for design process.

These concepts will be further explained in the FHPM which will be issued, accompanying the Pavement Policy. The policy is only two pages long. The FHPM will be about a dozen pages.

The policy also requires that an engineering and economic analysis be made on every project to assure that the project represents a cost effective solution to the need. This analysis period will include the initial performance period and at least one rehabilitation. It requires that all alternative solutions be considered over this same time period.

Again, in order to be able to do an acceptable engineering and economic analysis, good load data is essential. Good load data cannot be obtained without WIM.

It is important to note here that in the area of truck load data some important statements need to be made.

- Currently the 3-S-2 heavy combination trucks (18 Wheelers) contribute about 92% of the accumulative 18 Kip ESAL's, so you need to know where those trucks are.
- The number of trucks on our highways is growing at twice the rate of the GNP. But more important than that, the ESAL's are growing twice as fast as the number of trucks.

A real boost to WIM in the future will be an automatic reading of the identification of vehicles. The title of a recent article in the August issue of TR News is "HELP Is On The Way." The article gives a summary of the progress of HELP (Heavy Vehicle Electronic License Plate program). Thirteen States and one Port Authority have come together with the trucking industry in their endeavor. This experiment will be very instrumental in bringing about (1) tighter industry control of vehicles and their loads, (2) greater understanding of roadway use and (3) better administration of existing laws and regulations. All of which will provide better data and tend to reduce the impact on our highways. The FHWA in an attempt to encourage the use of automatic data collection and automatic classification equipment is currently in the process of promulgating a demonstration project. The following is a brief description of Demonstration Project No. 76 which should be available after the first of the new year.

# DEMONSTRATION PROJECT NO. 76
# AUTOMATED TRAFFIC/TRUCK WEIGHT MONITORING EQUIPMENT (WEIGH-IN-MOTION)

*William A. Nostrand, Jr., FHwA Office of Highway Operations*
*Demonstration Projects Division*
*and*
*Office of Information*
*Traffic Monitoring Division*

## INTRODUCTION

Truck usage in the United States has led to previously unexpected demands on the highway infrastructure in terms of its structural integrity, need for maintenance, enforcement of size and weight laws, allocation of user costs, and estimation of the impact of such growth on future highway investments. In order to properly deal with these truck related issues, highway administrators and designers have an increasing need for reliable data on truck characteristics. Some of these characteristics include axle loadings applied by various truck types and axle arrangements, proportion of the active truck universe that have various axle arrangements and weights, and numbers of trucks in operation that exceed legal weight limits.

Various technologies have been emerging to obtain the types of data needed to address the truck issues mentioned above. These technologies have been focused under the general terminology of weigh-in-motion (WIM). While each WIM technology may differ in the approach of providing the data, each is directed to obtaining the vehicle's overall weight, individual and grouped axle weights, and spacing between axles while the vehicle is in motion.

The various types of WIM technology have been tried with varying success by State highway agencies (SHA) and research organizations both in the United States and abroad. Weigh-in-motion has the potential of providing large quantities of truck data in a cost-effective manner. WIM can provide valuable information on truck weight and other characteristics over periods of time and under traffic and/or environmental conditions that are impractical using static weighing techniques. Weigh-in-motion can provide this information without the delay inherent in conventional static weighing of trucks, as well as eliminate some of the problem of evasion of known static weighing operations, resulting in a significant bias in the data collected.

## OBJECTIVE

The objective of this project is to provide State Highway Administrators, pavement designers, weight enforcement personnel, and planners with an understanding of the various types of WIM technologies, their accuracies and reliability, installation costs and procedures, the approximate costs of each and their maintenance requirements, the appropriate application of each, limitations to their use, and cost-effective methods of coordinating WIM data collection to support a multitude of users.

## SCOPE

It is proposed to demonstrate the equipment using a workshop presentation format. Approximately 2 to 3 days will be devoted to the technical presentations supplemented with visual aids and references to FHWA's Traffic Monitoring Guide. The technical presentations will be presented to State highway agency planning, pavement management, weight enforcement, data collection, pavement design, and tax policy development personnel. Interest by all SHA's is anticipated.

Initially the project will include discussions on WIM equipment in use by SHA's and recent developments in WIM equipment technology. This discussion will include load cell, capacitance pad, and strain gage based systems. Other equipment such as that using piezo-electric cable and film or fiber optic media will be discussed as some of the emerging WIM technologies.

The availability and justification of Demo funding for the evaluation of various types of automated traffic data collection equipment will be discussed.

To the degree possible, various WIM devices will be operated under field conditions. This aspect of the project will depend on the availability of WIM equipment from nearby SHA's and the willingness of manufacturers to provide equipment and technicians. It is planned that each type of WIM technology would be discussed. Specific equipment will be available for hands-on demonstration at the request of the attending States.

The project will not be promoting any of the equipment or systems as models, but will be illustrating principles and concepts through the examples for both project level and statewide data collection efforts.

The project presentations will be divided into the following modules:

| | |
|---|---|
| MODULE 1 | INTRODUCTION TO THE TECHNOLOGY OF IN-MOTION WEIGHING OF HIGHWAY VEHICLES |
| Audience | SHA Upper Management (Highway Director and Immediate Staff) |
| Length | 1 hour (maximum) |
| Objective | To gain the support of the State highway director for promoting WIM activities, and to inform him/her of the availability and advantages of the latest automated classification and weighing equipment technology for the collection of traffic data. |
| Method | It would be desirable, schedule permitting, for the Division Administrator to introduce the Demonstration project to the highway director and his/her immediate staff. Using handouts and other visual aids, the project manager will then present an overview program dedicated to the importance of the technology of automated data collection. It will include reports on previous work in the technology, as well as updates on related work efforts. A part of this presentation will be devoted to the topic of automatic vehicle classification (AVC) equipment, and its relationships with WIM. |
| MODULE 2 | AUTOMATED HIGHWAY DATA COLLECTION EQUIPMENT |
| Audience | SHA Managers (Pavement and Structural Design, Pavement Management, Planning, Enforcement) |
| Length | 4 hours |
| Objective | Within the context of the overall traffic data gathering efforts, inform the management personnel of the State highway agencies of the various types of automatic data collection equipment for in-motion weighing and for classification of traffic currently available. Discussions will include appropriate uses and proper applications of each technology as well as their relative purchase, installation and operating costs, and relative accuracies. |

| | |
|---|---|
| Method | Using handout materials and other visual aids, the project manager will identify all of the automated equipment available, and explain the uses and applications, sample installations, and State experiences. |

## MODULE 3 APPLICATIONS AND ANALYSES OF HIGHWAY DATA

| | |
|---|---|
| Audience | SHA Managers (Design, Planning, Enforcement) |
| Length | 4 hours |
| Objective | To present a detailed discussion on the potential applications of the data collected by WIM as well as AVC equipment. |
| Method | The project manager will use visual aids as well as a microcomputer to demonstrate and explain the utility of the data for pavement design, highway planning, traffic forecasts, and enforcement strategies. Software will include that developed by FHWA and SHA's. |

## MODULE 4 DEMONSTRATION OF WIM AND AVC EQUIPMENT

| | |
|---|---|
| Audience | SHA Managers (Open to All Levels) |
| Length | 4 to 8 hours |
| Objective | To demonstrate available WIM and AVC technologies for the benefit of the State and local participants. |
| Method | With the cooperation of State personnel, as well as equipment manufactures, the project manager will demonstrate available WIM and AVC equipment. This will make use of operating scale models of both permanent and portable WIM and AVC technologies. The equipment will be displayed in a mobile exhibit, which will be made available to the SHA's on request. |

## MODULE 5 EQUIPMENT EVALUATIONS

| | |
|---|---|
| Audience | SHA Mid Level Management |
| Length | 1 hour |
| Objective | To evaluate innovative techniques and new automated traffic data collection equipment and systems through actual field applications. |
| Method | States would evaluate newly developed and innovative automated data collection equipment and techniques which are not yet widespread in use. Performance results from other systems will also be discussed. |

## ADDITIONAL INFORMATION

- Project Manager - Perry Kent of the Office of Information Management, Traffic Monitoring Division
- Pilot Presentation - Targeted for early December in Washington, D.C.

- Formal project announcement, solicitation of interest from the States, and scheduling of presentations - January 1989

- Workshop presentations - Targeted to begin in February 1989 and expected to continue until we have visited every State that requests the workshop.

- Fourth National WIM Conference - Planned in about 3 years when this project will be closed out.

- For further information - We invite you to visit FHWA's booth in the in the exhibitor's area.

# APPLICATIONS OF WEIGH-IN-MOTION IN SHRP'S LONG TERM PAVEMENT PERFORMANCE STUDY

*Neil Hawks, Strategic Highway Research Program, Washington, D.C.*

The Strategic Highway Research Program (SHRP) is a five year $150 million effort to achieve rapid progress in highway technology. It is one of the largest programs ever funded in highway research, and has drawn the interest of highway researchers from around the world. The SHRP program includes four technical research areas: Asphalt, Pavement Performance, Highway Operations and Concrete/Structures. Practical, cost efficient and innovative results in these areas will bring important savings in highway construction and maintenance costs.

The Long Term Pavement Performance (LTPP) study is planned as a 20 year effort. The specific objectives of the LTPP study are:

1. Evaluate existing design methods
2. Develop improved design methodologies and strategies for the rehabilitation of existing pavements
3. Develop improved design equations for new and reconstructed pavements
4. Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavement distress and performance
5. Determine the effects of specific design features on pavement performance
6. Establish a national long-term pavement data base to support SHRP objectives and future needs

The LTPP program include two types of studies: General Pavement Studies (GPS) and Specific Pavement Studies (SPS). The GPS will include 800-1000 existing pavement sections located throughout the United States and Canada. The following 8 experiments:

Asphalt Concrete over Granular Base
Asphalt Concrete on Stabilized Granular Base
Jointed Plain Concrete Pavement

Jointed Reinforced Concrete Pavement
Continuously Reinforced Concrete Pavement
Asphalt Concrete Overlay of Asphalt Concrete
Asphalt Concrete Overlay of Jointed Concrete Pavement
Unbonded Jointed Concrete Pavement Overlay of Concrete Pavement

For each of the experiments a matrix has been developed to include a number of variables i.e., subgrade type, base type, thickness, traffic and environmental (wet-dry, freeze-no freeze). The complete experimental design would fill each cell in each matrix with 2 projects.

Specific Pavement Studies will a have their own set of more limited goals, construction needs, and experimental approaches; and are generally aimed at more intensive studies of a few independent variables. It is expected that most of the SPS test sections will be specifically designed and constructed pavements having characteristics needed for specific studies. Several plans for implementing the SPS portion of the study are under consideration.

The primary goal of the GPS experiment is to develop a national data base that will provide the needed data to meet the objectives of LTPP. The data that will be collected for each GPS section can be considered in two broad categories. The first is basic inventory data, which includes those items that remain constant over the monitoring period. The second is monitoring data, which includes those items that will change with time and will require periodic measuring or updating during the 20 year period.

Monitoring data includes distress records, deflection testing results, profile measurements, skid resistance, traffic and axle loads. The majority of the data will be collected by SHRP's contractors. However, the traffic data collection is the state's responsibility.

It is important in the LTPP monitoring effort that valid traffic data collection and analysis procedures be developed and carried out. This will allow reliable and accurate estimates to be developed of the total number of equivalent single axle loads (ESALs) that have been and are currently being applied to the selected GPS pavement sections. In order to calculate the total number of ESALs it is necessary to obtain volume of vehicles, vehicle classification counts and truck weight data for the individual vehicle types.

In June 1988 two Expert Task Groups (ETG) were formed to provide SHRP with recommendations for the traffic data collection. One ETG was concerned primarily with WIM equipment, its cost and accuracy, and the second ETG with data collection forms and procedures. Both of these groups included representatives from universities, state highway agencies, and the Federal Highway Administration.

The ideal traffic data for the LTPP study would consist of weigh-in-motion data for all days since each GPS section was opened to traffic. Unfortunately, at no site does such a data base exist. In most cases, a minor amount of traffic volume and classification information has been kept by state agencies for GPS sites and in a few cases, vehicle weights have been taken at sites near GPS locations. Even in future years, few states will be able to deploy and operate WIM permanently at GPS sites, because the cost of WIM equipment and data collection is so high. Thus, SHRP must rely on a sample of traffic volumes and weights to reduce the amount and cost of data collection required to a level which more acceptably matches available funding and resources.

When considering traffic data collection, two time frames are relevant, "historic data" (i.e., that data previously collected on or near GPS sites from the time they were constructed until the present) and "new data" (that data which could be collected after GPS sites are selected and SHRP traffic data collection activities begin).

In the recommended plan, data to be submitted for these two time periods differ. Little choice is available on the type and quantity of historical data that could be submitted. Thus, it is recommended that the states submit what data is available, along with a description of how that data is manipulated to represent average annual traffic and traffic loadings. It is important that states provide their best available data, but that they do not "invent" numbers. Where data is not available states should simply indicate this fact. This will allow the researchers to make necessary decisions on how best to use the available data.

Theoretically ideal data could be collected during the "new" period but funding constraints limit the "new" data that can reasonably be requested from states specifically for SHRP purposes. Thus, the recommended plan described below was developed with the intent of providing sufficient data at a lower total cost.

As indicated above the ideal traffic data collection plan for SHRP LTPP GPS sites would require weigh-in-motion equipment to be located at each site and to operate 365 days a year. This scenario was envisioned by many of the researchers who initially conceived the GPS study. Unfortunately, the low cost WIM equipment required to allow collection of these data has not yet been adequately developed and is not currently usable at many GPS sites. Purchase, installation and operation of traditional WIM equipment for 1000 GPS sites would cost roughly $40 million over the next six years. Even if current low cost equipment were suitable for all GPS locations, the cost of 1000 sites would be $17.5 million. These costs significantly exceed the funding available through SHRP plus the funds most states expect to contribute to the SHRP effort.

The Expert Task Groups (ETG) considered a number of alternative data collection plans. After reviewing these alternatives and the WIM equipment limitations, the combined expert task groups developed the plan outlined below. This plan provides the minimum level of data collection that SHRP believes is necessary for the success of the LTPP project. The estimated cost of this minimum plan as roughly $11.7 million for the purchase, installation and operation of automatic vehicle classification (AVC) equipment and another $13 million of the purchase and operation of weigh-in-motion equipment. However, for this recommended plan, much of this WIM cost could be reduced by using existing portable equipment already owned and operated by the states.

Continuous WIM data at each GPS site should be collected by states, if possible. Where such data collection is not realistic the following data collection plan is recommended:

A. Automatic Vehicle Classification Counts at each GPS test section

| Minimum | Desirable |
|---|---|
| 1-365 day count completed by June 1992 | Continuous 365 days per year operating by June 1991 |

B. Axle weights at each GPS test section

| Minimum | Desirable |
|---|---|
| 48 continuous hours during weekdays and 48 continuous hours during weekend for each truck season* | 1-7 day continuous count per truck season* |

Collection of axle weights at each GPS site should be completed by June 1992. It may be necessary to make additional axle weight counts in later years.

*A truck season is defined as a period of time during a calendar year when a significant change in expected truck weights occurs. For example in agricultural areas truck weights for specific vehicle types may change several times during the calendar year as different crops are harvested.

C. Regional Weigh-in-Motion Sites
A limited number of WIM sites will be installed and operated 365 days a year for measuring the temporal variation in weight data. These sites do not necessarily have to be at GPS test sites.

The intent of the data collection program recommended above is to provide sufficient (but cost-effective) data to SHRP. The data to be collected for each GPS site must pertain to that GPS site and can not be a "system average." This is because the actual loadings experienced by each GPS site are expected to vary significantly from site to site due to variations in the number of trucks, the types of trucks and the weight of trucks. Because the LTPP project is concerned with site specific pavement deterioration, the pavement performance of respective sites must be well matched with the actual loadings impacting that pavement.

To understand existing variations in traffic, measurements must be taken to determine the fluctuation of traffic characteristics across hours of the day, days of the week, and seasons of the year. Traffic characteristics vary from site to site, depending on such factors as

- local economic development,
- the amount of "through" traffic,
- levels of weight enforcement,
- a variety of other variables.

While it is probable that some traffic trends are fairly constant between similar sites, local changes in economic or enforcement activity may cause significant changes (both long and short term) at some sites while not impacting others. Consequently, data collected at one location may or may not be applicable to other locations. Thus, a reasonable amount of data collection must take place at each site. This need for site specific data collection must be balanced against the cost of collecting data at those sites. Sampling traffic characteristics at each site reduces the amount of traffic data that needs to be collected and processed, but a good sampling plan requires prior knowledge of the population being sampled in order to adequately match the sample size to the expected sample accuracy. In most cases, the available traffic data at each GPS sites is considerably less than what is necessary to perform a valid sample design. Furthermore, in order to collect adequate amounts of traffic data to develop a sampling plan, equipment would need to be placed on a long term basis (e.g., one-year minimum) at these sites.

Once this data base existed, a good sample design could be made to reduce the amount of data collection required to adequately measure the traffic characteristics. However, once the data collection equipment is in place, it is less costly to let the equipment run continuously, than it is to send traffic counting staff to the site to perform short duration sampling counts. Thus, the concept of sampling has only limited applications for the LTPP effort.

To address the needs for site specific information while limiting the cost of data collection, a plan which features both short and long duration on-site data collection and some regional long term data collection was developed. This plan is structured so that sufficient site specific data can be collected at each site to allow the identification and application of "pattern" information determined at regional sites to individual GPS locations.

Two types of site specific traffic data collection are requested in the recommended plan, vehicle classifications and truck weights. Vehicle classification data will be collected from 365-day per year traffic recorders. Truck weights at each site will come from short duration measurements in most locations.

The collection of vehicle classification data provides SHRP with the total traffic volume on GPS sections by vehicle category. Thus traffic volumes are a "free" output of the classification counts.

Because vehicle class information also provides volume data, the use of continuous automatic vehicle classification (AVC) counters at each site eliminates the need for "traditional" ATR stations. The permanent AVC stations will provide the same data on traffic fluctuations by time of day, day of week and season as an ATR station, while at the same time providing information on the number and type of vehicles passing those points.

The need for 365 day counts at each site comes from two areas. In the first, it is important to understand how truck volumes at each site vary over the year. Truck volumes at some sites will vary considerably as a result of the activities in the surrounding region, while other sites will have relatively minor seasonal impacts. Without a measure of seasonality at each site, it would be likely that short duration counts would provide misleading information concerning annual volumes at that site. (For example, if the short count was taken during a high truck volume period, the total number of axles impacting the road would be over-estimated.) 365 day AVC will provide seasonal fluctuation data for all truck types throughout the year.

This information is also important when looking at historical traffic data. While traffic volumes change continuously, changes from year to year are fairly small. (For example, a high growth rate for a site is above 5 percent per year, whereas, the difference between January and June traffic levels are often as large as 50%). Thus, a single year of 365 day AVC counts will not only provide invaluable information on the fluctuation of traffic from January to June, it should significantly improve the estimates of total traffic loadings on GPS sections since the section was opened by providing a baseline against which historic short count data can be compared and evaluated.

Thus, knowledge of the yearly patterns of traffic at each GPS location, and a "true" measure of annual traffic (not relying on seasonal factors off any kind) will markedly increase the accuracy with which SHRP can estimate total traffic volumes experienced by a section of pavement.

Truck weight data has the same problem with variability as vehicle classification data. However, the cost of permanent WIM systems tend to be much higher than AVC. Research to-date has not shown that piezo WIM can be confidently installed in U.S. asphalt pavements, and only one portland cement concrete pavement installation is currently functioning in the U.S. Until piezo-electric WIM has been proven, or another low cost WIM system developed, SHRP will need to limit the amount of weight data it collects to reduce the resource requirements of the project.

An acceptable method of weight data collection requires at least a limited number of weighing sessions at each GPS site. These weighing sessions would then be supported by a limited number of WIM locations at which weights would be measured year-round.

The recommended plan calls for WIM at each GPS site at least once every truck season during the initial SHRP funding period. This data collection is intended to calibrate the WIM data for each GPS location. That is, it will determine what trucks of a specific axle configuration weigh at a specific GPS site. How these weights change over time will be measured in two ways. First, since truck weights will be measured for each truck season at each site, the site specific weighings will provide a measure of how weights change over time at a specific location.

Second, the long term weighings will provide a look at the seasonal trends occurring during the year. It is believed that the combination of seasonality from the AVC counts at each GPS site, the site specific weighings at each GPS site during each truck season and the variation of weights at the regional 365-day WIM sites will provide sufficient data to adequately measure the seasonal variation of weights and axle loadings at each of the GPS sites.

To further enhance the site specific nature of the data, it is recommended that a minimum of 48 hours of continuous weighing take place during both weekdays and weekends for each of the truck s This data is important in order to measure the site specific fluctuations of weights between weekdays and weekends, and to help compare site specific weight variation with 365-day weight variation. 48-hour counts were selected as a compromise between:

- the desire for week long measurements, and
- the high staffing costs of collecting WIM data with portable equipment

It is preferred that weighing take place for one-week at a time at each GPS site, but the staffing requirements for such an effort seem to make this impractical for some states. Still, the collection of week long data by the states is encouraged.

Site specific WIM data will not only serve to measure current vehicle weights at each GPS site. They may also be useful in "calibrating" the old truck weight data collected previously and submitted to FHWA. Because of the nature of static weighing, the existing FHWA truck weight estimates under-represent the number of heavy vehicles using U.S. highways. The WIM data should include a more representative sample of trucks. The collection of WIM data at each site provides an opportunity to factor the historical data to better represent the number of overweight vehicles actually on the road, as compared to the number of overweight vehicles actually measured using static scales. In this manner it may be possible to more accurately estimate the historical weights of vehicles using GPS pavements.

Regional data collection takes the form of long term weight measurements at a limited number of WIM sites. These regional 365-day data will be used in conjunction with the site specific weight classification data to help estimate the actual annual wheel loadings for each section of pavement. These "master" locations will be used to adjust the site specific weights to represent average annual conditions, much as "master" traffic count locations are used for converting short duration volume counts into estimates of AADT. For example, if weights in July are consistently lower than the annual average, a factor may be developed to adjust short duration measurements made in July, to better represent the annual average.

Since very little continuous weight data exists at this time, it is difficult to estimate the impact trade offs between site specific, short duration weighing sessions and regional long term counts will have on the accuracy of the weight data. Therefore it will be necessary to compare the 48 hour data against the patterns shown in the 365-day counts. If the 48 hour measurements, combined with the pattern information collected at the long term stations are insufficient to provide accurate estimates of annual site specific weights (i.e., because axle weights are too variable to be measured with 48 hour counts) then additional weight data will have to be collected at each site during the second 5-year period.

The use of continuous automatic vehicle classification counters at each site will provide excellent information on traffic patterns experienced by the site as well as provide a necessary baseline for estimating historical traffic loadings. The availability of these should significantly improve the estimates of total traffic loadings on GPS sites.

The states will not be required to edit or reduce the traffic data collected by their automated equipment. Truck weight data should be submitted on computer readable tape. SHRP's regional offices will transform the data into the format for storage in the data base.

This is not only a minimum plan but is also an interim plan for the remaining duration of SHRP's currently budgeted time frame. SHRP will evaluate the short term weight data against the long term data to determine the need for additional WIM sessions in the next five year period.

# PENNSYLVANIA'S USE OF WEIGH-IN-MOTION IN ITS WEIGHT ENFORCEMENT PROGRAM

*Frederick R. Juba, Chief, Pennsylvania Department of Transportation*
*Bureau of Maintenance and Operations,Motor Carrier Enforcement Division*

Pennsylvania has actively utilized weigh-in-motion (WIM) in its weight enforcement program for the past 10 years. Since the inception of Pennsylvania's weight laws in 1929, weight enforcement was limited to the use of portable wheel load weighers and static platform scales. These scales were used by the Pennsylvania State Police and municipal police.

In 1976 FHWA mandated that stronger weight enforcement measures be implemented. In 1977 the Pennsylvania Department of Transportation joined forces with the Pennsylvania State Police to bolster weight enforcement efforts. Today, in addition to municipal police, Pennsylvania has 29 dedicated State Police/Department teams, each assigned specific geographic areas (Exhibit A). Each team is equipped with a set of 12 Haenni wheel load weighers. The Department's Motor Carrier Enforcement Officers are responsible for weighing, inspecting vehicles, determining infractions and citing for safety infractions. The State Police direct traffic and cite weight infractions, inspect and cite for safety infractions. Both agencies mutually arrange schedules, locations and select vehicles to be screened based on past experience and tips.

The Department purchased 5 portable PAT 2 pad portable WIM systems in 1979. These bending plate systems are used in roadside rest areas on the interstate system to screen out violators. Violations must be documented by weighing on static scales - wheel load weighers. The WIM system screens vehicles at a maximum speed of 3 miles per hour. It identifies axle weights and gross weights. Accuracy has been found to be ± 6% of static weights in 90% of samples.

Initially 16 permanent weigh stations were planned to be constructed along the interstate highways. The Department constructed the first interstate weigh station in 1979. This station utilizes a Streeter Richardson Roll Weigh WIM system, automatic overhead lane control, with a single axle and gross weight thresholds. This mid speed WIM screens vehicles up to 35 miles per hour and automatically directs potential overweight vehicles to a three section platform scale for documentation of violation. This WIM system has had an accuracy of ± 5% for 90% of samples.

In 1985 a new concept of weigh system/operation was initiated in Pennsylvania. A sophisticated WIM system is used in a semi-portable mode. Siemens PAT computers are housed in 3 mobile command centers (motor homes) that circulate randomly daily to various rest areas. Upon arrival at a site, the command center's umbilical cord is connected to the site's service panel. Each site is permanently instrumented with 4 weigh pads, 2 induction loops and a preamplifier. In addition, permanent signing, electrically activated from the site is installed. The computer has been programmed to weigh axles and gross weights, measure axle spacings and classify vehicles. The computer applies both State mandated axle weights to single vehicles and combination vehicles of up to 73,280 pounds gross weight and applies the Federal Bridge Formula to combination vehicles over 73,280 pounds. The infractions - axle(s) and/or gross weight violations are highlighted for the operator on the video display screen and a print out of the vehicle's characteristics is printed for reweigh personnel to identify violations by statically reweighing the vehicle. The system is capable of screening vehicles at highway speeds but is limited to an average speed of 18 miles per hour due to geometrics of rest areas. Weighing accuracy has been found to be ± 4% of statically measured weight. Axle measurements in 90% of samples are within 2 inches ± 2 inches in 90% of measurements. The $180,000 cost of instrumenting and signing rest area sites has made it possible to instrument 17 locations for little more than the cost of 1 permanent weigh station. A total network of 34 sites is planned over the next 5 years (Exhibit B). Pennsylvania's plan to construct 15 additional permanent weigh stations has been cancelled due to the benefits of the semi-permanent weigh stations (SPWS).

In order to optimize the accuracy of the SPWS, a data file of samples of WIM weights vs. static weights has been entered into a personal computer where the accuracy of each site is monitored. Graphics display errors at various speed ranges (examples in Exhibits C, D, E, F and G). Correction factors are calculated, relayed to the team's supervisor and input into the terminal (Exhibit H). This new procedure should enable maximizing system accuracy. It is anticipated that historic performance data will enable a correlation of accuracy of each site to equipment and environmental characteristics. It is believed that this will enable prediction of system performance at anticipated sites and indicate required pavement improvements for maximizing accuracy of systems.

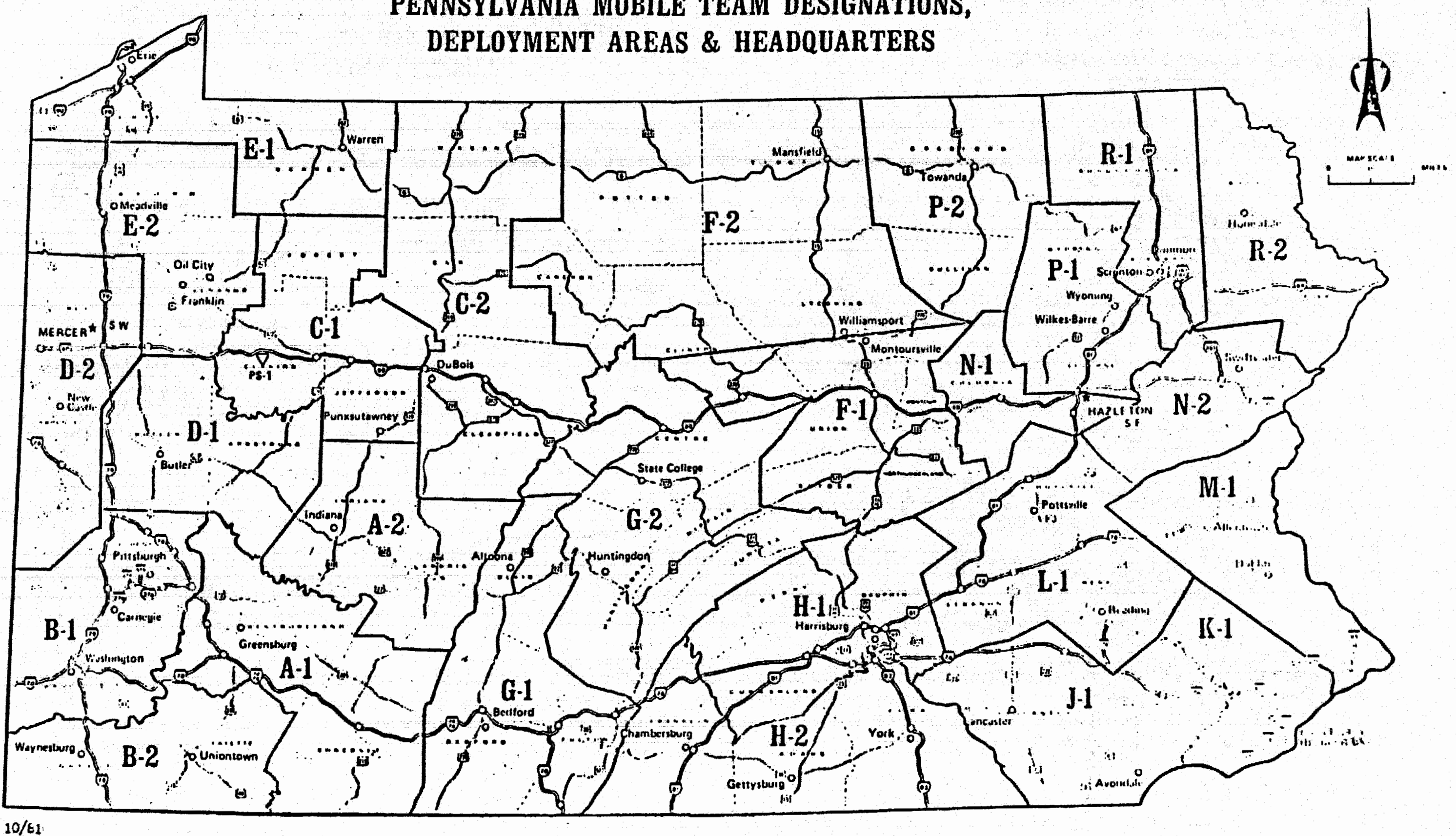
Currently, all present sites utilize existing pavement. The effects of the 4 inch cutting, milling and chipping required for weigh pad installation has not been observed to affect the integrity of concrete slabs. Experimentation is underway to install frames by molding recess into new pavement. System performance of equipment in these installations will be compared to those in previous sites.

Currently the Department's Bureau of Strategic Planning and Bureau of Bridge and Roadway Technology is evaluating the WIM data generated for effects of biasing. Should data be determined acceptable, it may be utilized in these program areas in the future.

The newest challenge for the weight enforcement program is to objectively analyze the program's performance. Through effects of highway deterioration and planning studies, Pennsylvania will attempt to determine the program's effectiveness. In addition, it is hoped this evaluation will assist in maximizing effectiveness through selective scheduling, time and location, and methods of operation. It is believed that analysis will also help correlate the program's cost savings to the degree of emphasis placed in the program.

# EXHIBIT A

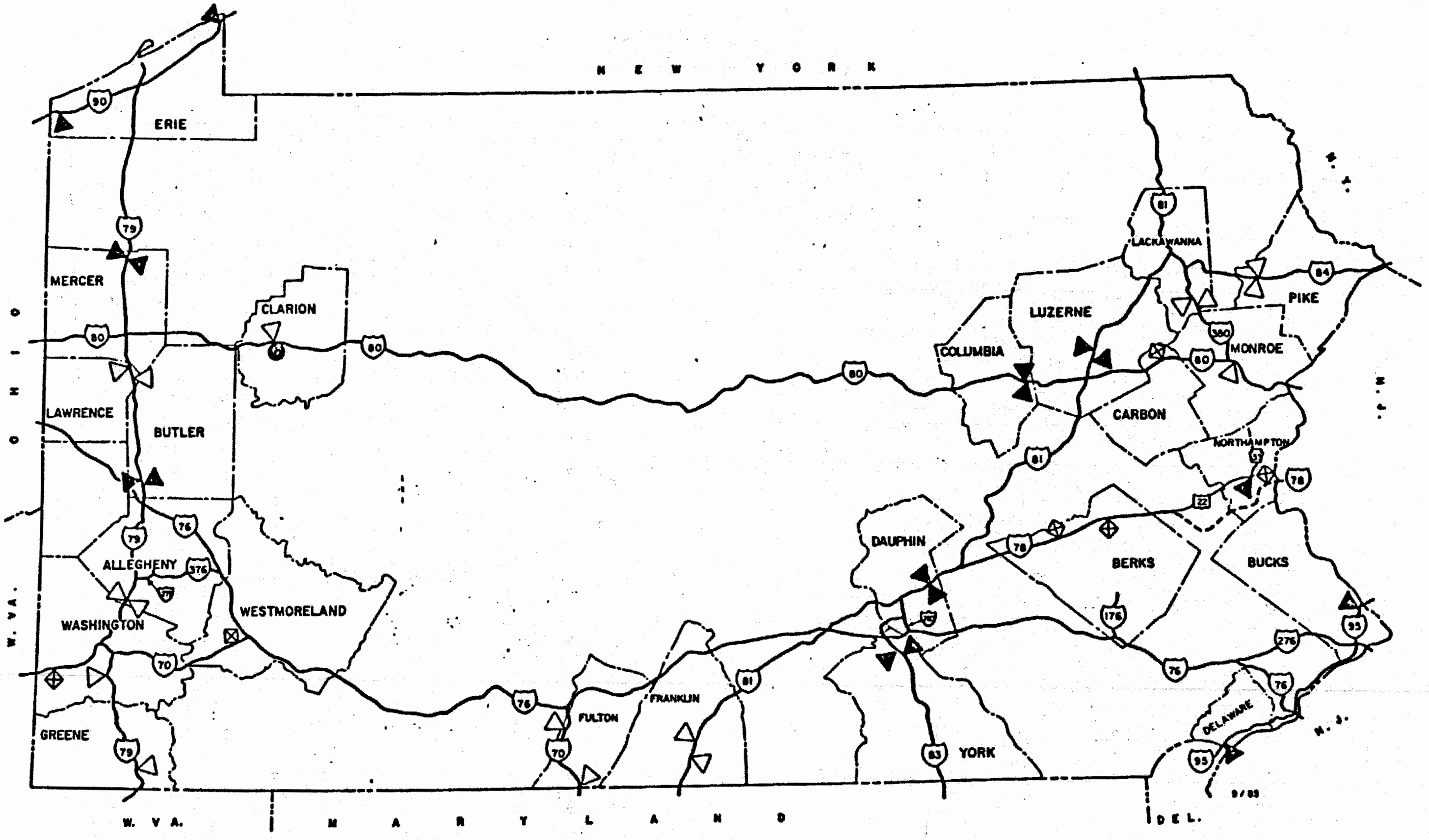
## PENNSYLVANIA MOBILE TEAM DESIGNATIONS, DEPLOYMENT AREAS & HEADQUARTERS



10/61

★ HAZLETON-INTERSTATE TEAM "S"-EAST
★ MERCER-INTERSTATE TEAM "S"-WEST
▽ PERMANENT WEIGH STATION

EXHIBIT B



# PENNSYLVANIA PERMANENT & SEMI-PERMANENT WEIGH STATION LOCATIONS

**LOCATION LEGEND**

- ▲ EXISTING SEMI-PERMANENT WEIGH STATION (SPWS)
- △ PROPOSED SPWS IN EXISTING REST AREA
- ☒ PROPOSED NEW LOCATION FOR SPWS INSTALLATION
- ● EXISTING PERMANENT WEIGH STATION

## EXHIBIT C

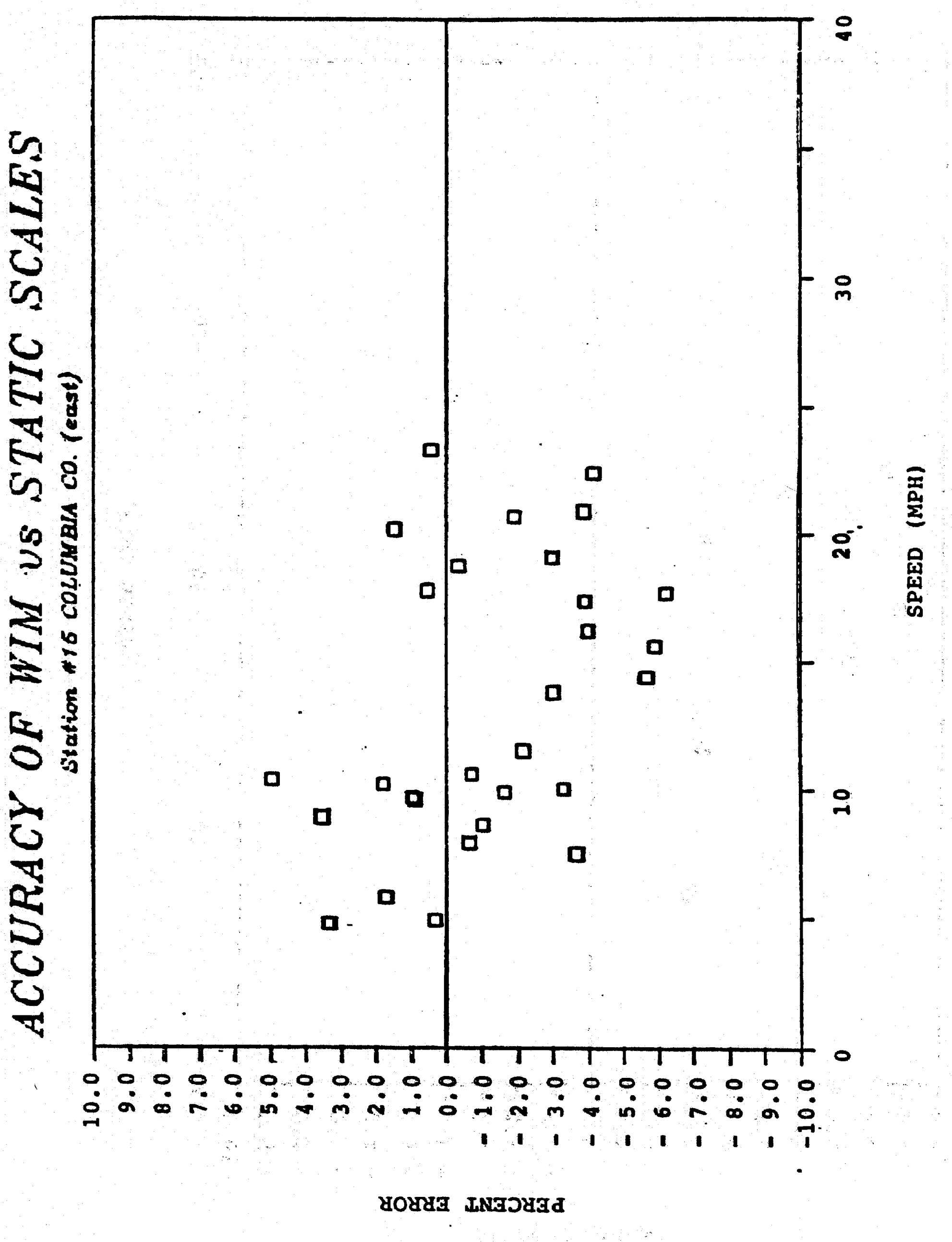

ACCURACY OF WIM vs STATIC SCALES
Station #15 COLUMBIA CO. (east)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
-10.0
PERCENT ERROR
0
10
20
30
40
SPEED (MPH)

**EXHIBIT D**

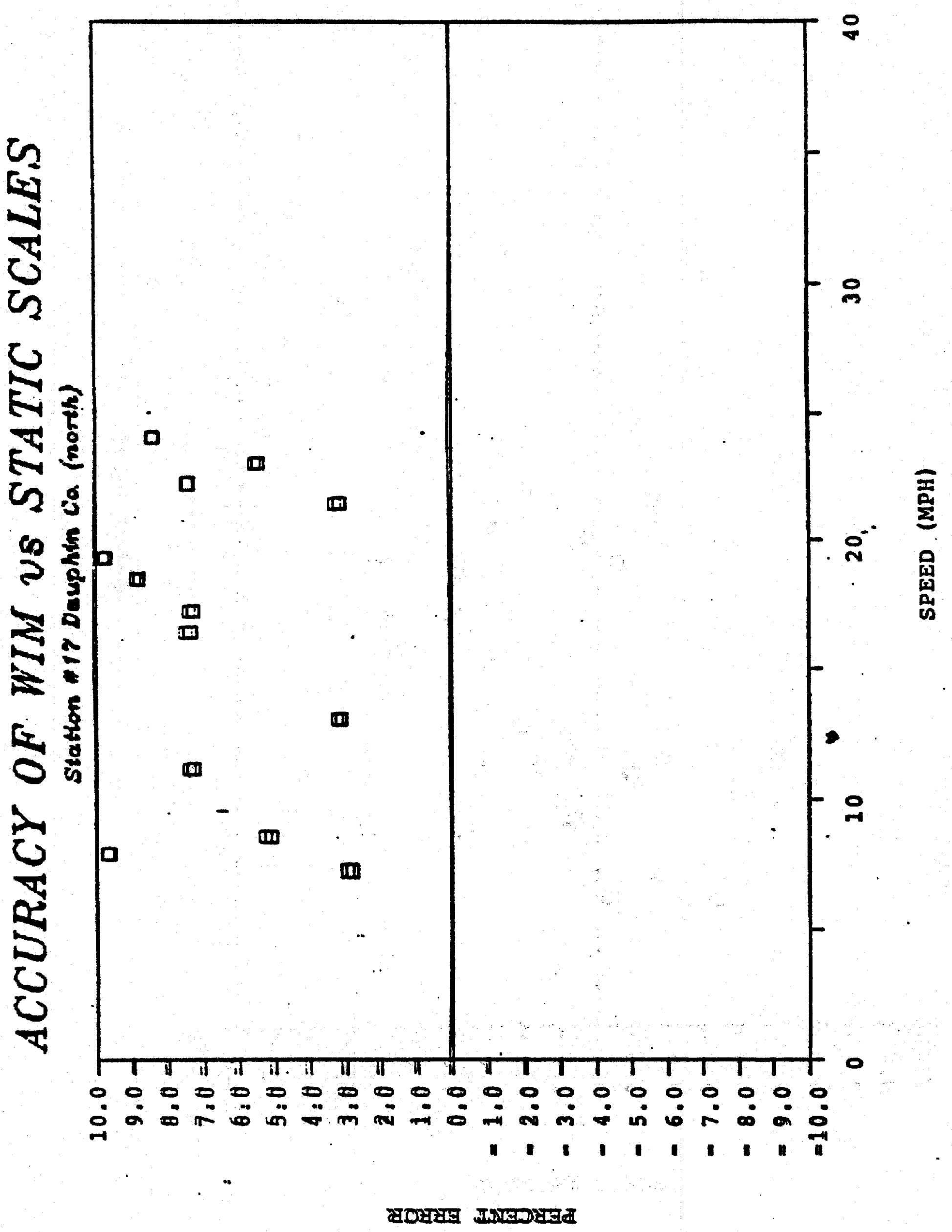
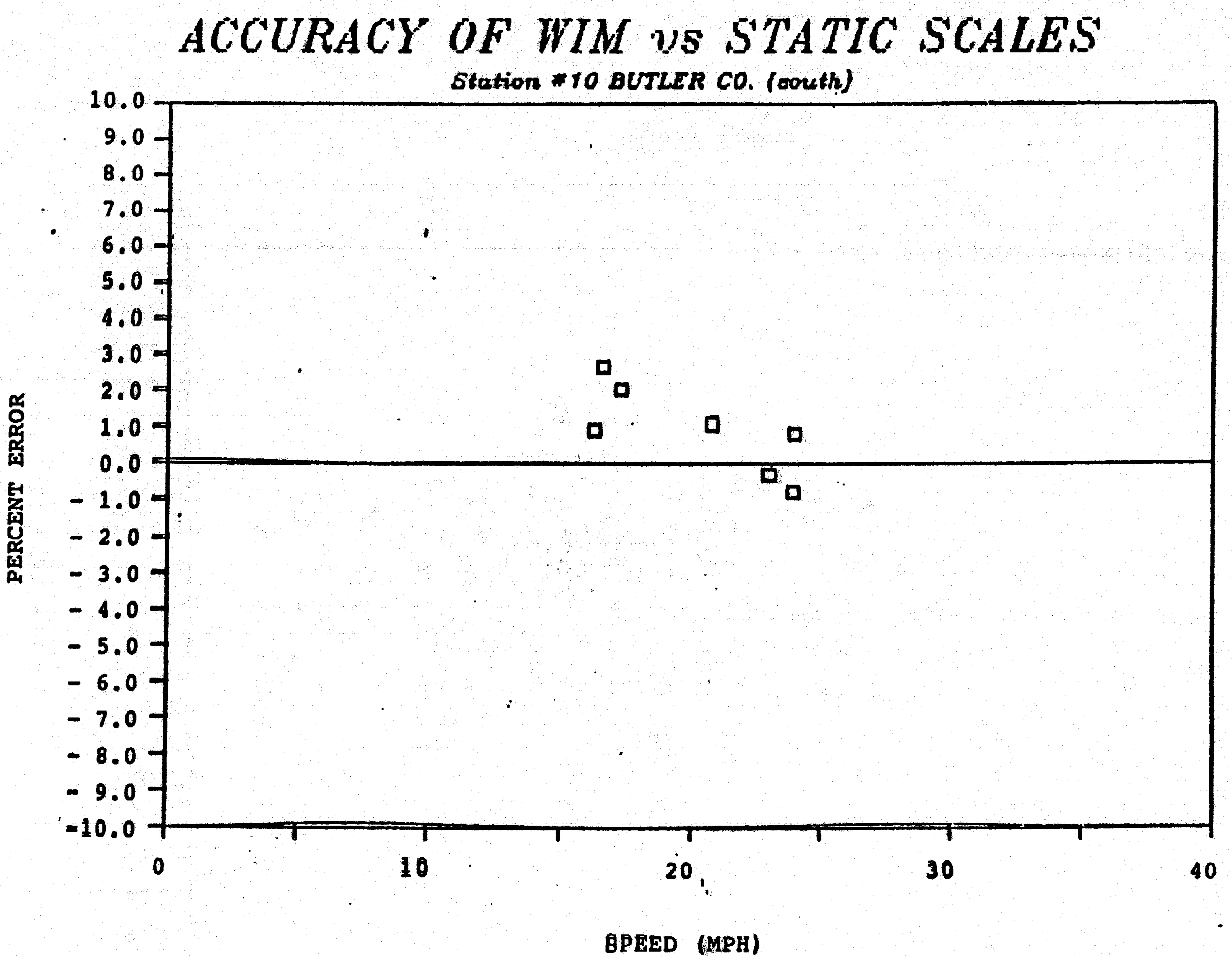
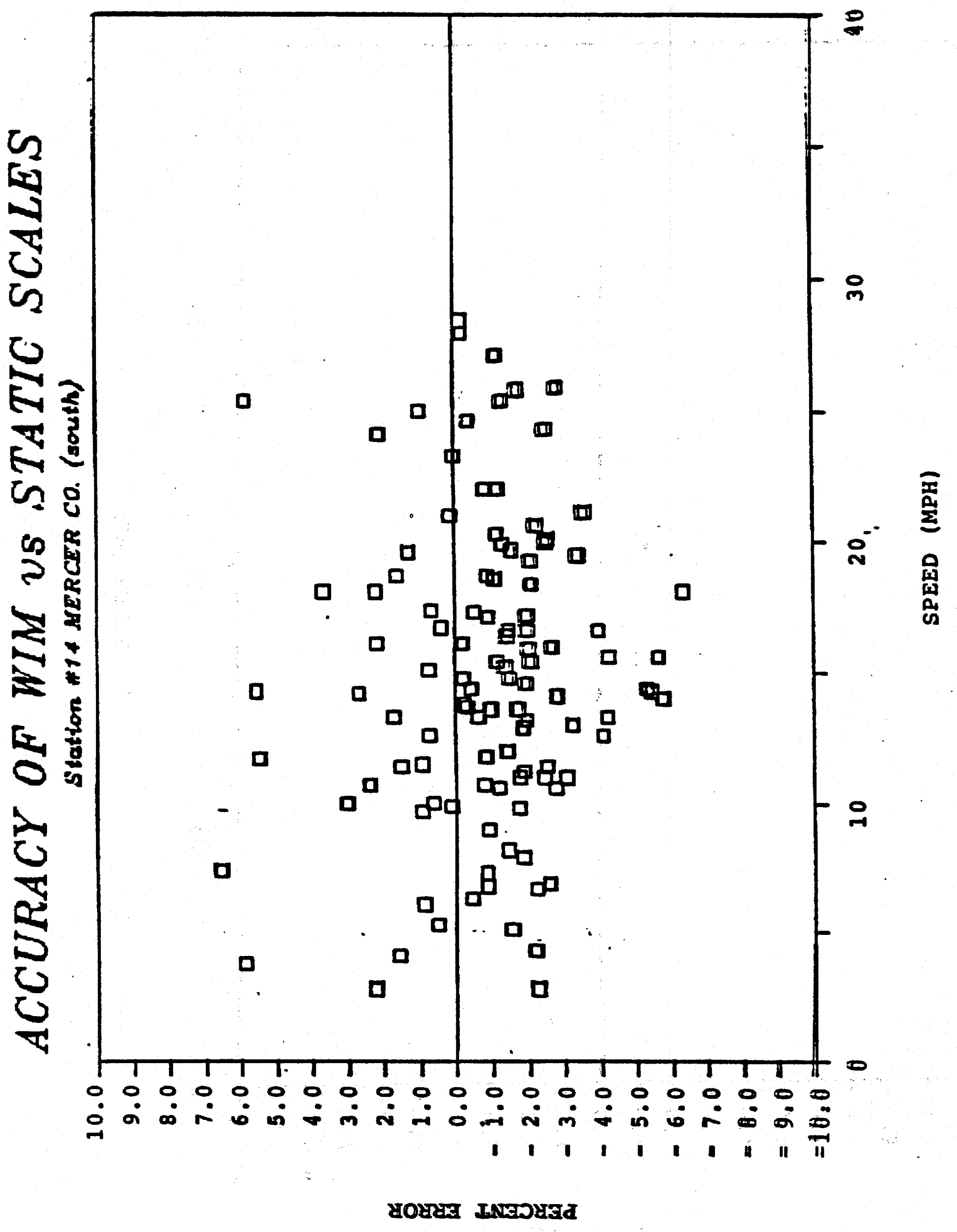

ACCURACY OF WIM vs STATIC SCALES
Station #17 Dauphin Co. (north)
PERCENT ERROR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
-10.0
0
10
20
30
40
SPEED (MPH)

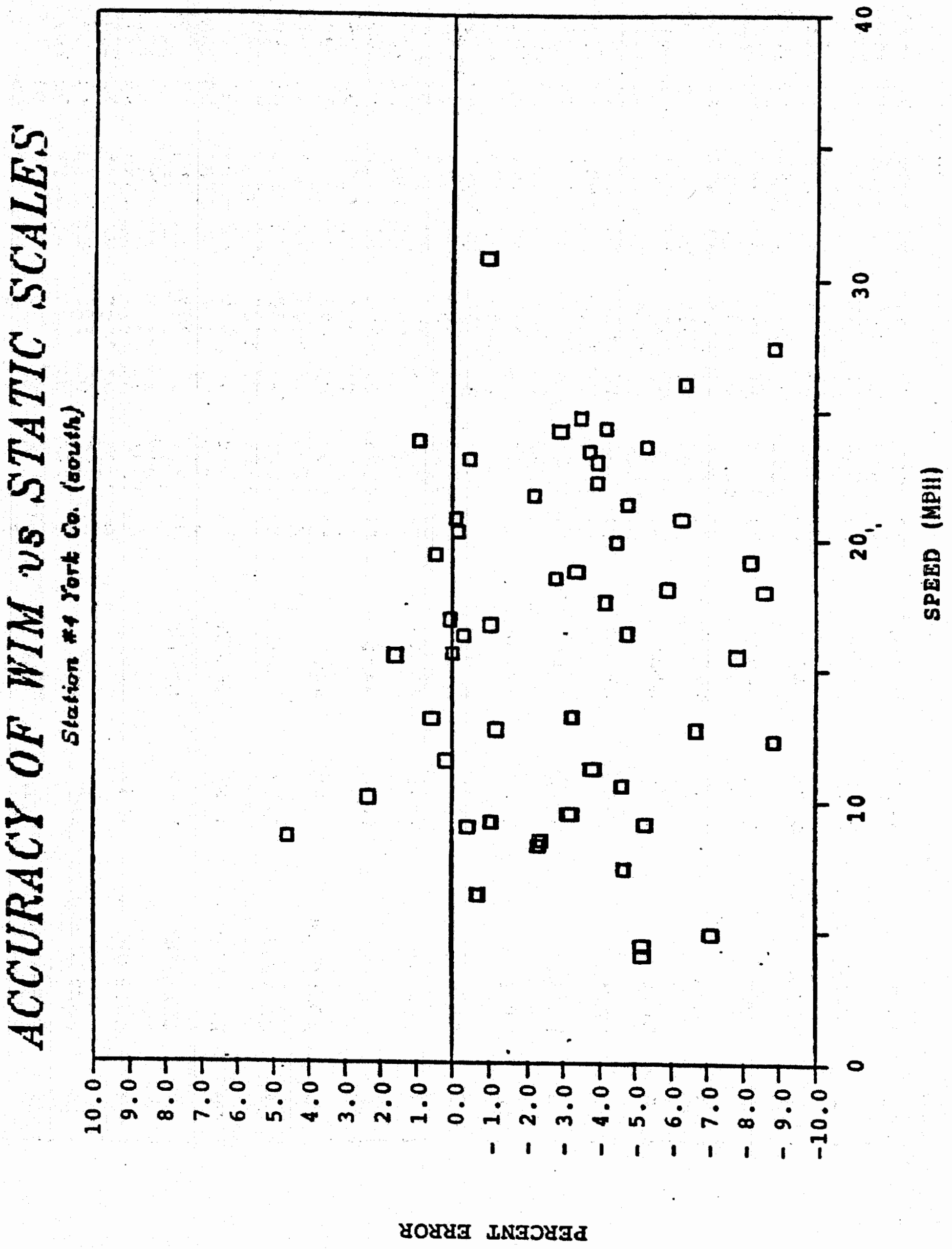
**EXHIBIT E**


ACCURACY OF WIM vs STATIC SCALES
Station #10 BUTLER CO. (south)
PERCENT ERROR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
-10.0
0
10
20
30
40
SPEED (MPH)

## EXHIBIT F


ACCURACY OF WIM vs STATIC SCALES
Station #14 MERCER CO. (south)
PERCENT ERROR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
-10.0
0
10
20
30
40
SPEED (MPH)

## EXHIBIT G


ACCURACY OF WIM vs STATIC SCALES
Station #4 York Co. (south)
PERCENT ERROR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
-10.0
SPEED (MPH)
0
10
20
30
40

# W.I.M. STATION DATA

Truck Weight Enforcement Division

08/24/88

| Sta. | County | Route | Dir. | Calibration Factors | | | |
|---|---|---|---|---|---|---|---|
| 1 | BUCKS | I-95 | south | S1 992 | S2 987 | S3 1004 | S4 995 |
| | | | | S 993 | V1 1000 | V2 1035 | V3 1000 |
| 2 | DELAWARE | I-95 | north | S1 1009 | S2 1008 | S3 1000 | S4 1002 |
| | | | | S 1006 | VI 1072 | V2 1140 | V3 1100 |
| 3 | NORTHAMPTON | US22 | east | S1 989 | S2 981 | S3 971 | S4 991 |
| | | | | S 1022 | V1 1050 | V2 1095 | V3 1025 |
| 4 | YORK | I-83 | south | S1 1032 | S2 996 | S3 987 | S4 978 |
| | | | | S 1037 | V1 1000 | V2 1000 | V3 1000 |
| 5 | YORK | I-83 | north | S1 997 | S2 1005 | S3 993 | S4 986 |
| | | | | S 993 | V1 1053 | V2 1105 | V3 1105 |
| 7 | ERIE | I-90 | west | S1 1002 | S2 1005 | S3 996 | S4 991 |
| | | | | S 1016 | V1 1044 | V2 1111 | V3 1080 |
| 8 | ERIE | I-90 | east | S1 1004 | S2 1012 | S3 1000 | S4 1008 |
| | | | | S 1039 | V1 1010 | V2 1087 | V3 1100 |
| 9 | BUTLER | I-79 | north | S1 1003 | S2 998 | S3 994 | S4 992 |
| | | | | S 1037 | V1 1031 | V2 1010 | V3 1054 |
| 10 | BUTLER | I-79 | south | S1 992 | S2 997 | S3 991 | S4 1011 |
| | | | | S 1015 | V1 1033 | V2 1075 | V3 1124 |
| 13 | MERCER | I-79 | north | S1 980 | S2 998 | S3 995 | S4 993 |
| | | | | S 1019 | V1 990 | V2 1072 | V3 1066 |
| 14 | MERCER | I-79 | south | S1 994 | S2 993 | S3 992 | S4 1006 |
| | | | | S 1037 | V1 1010 | V2 1060 | V3 1013 |
| 15 | COLUMBIA | I-80 | east | S1 1005 | S2 1008 | S3 1011 | S4 1002 |
| | | | | S 1024 | V1 989 | V2 1056 | V3 1099 |
| 16 | COLUMBIA | I-80 | west | S1 1008 | S2 998 | S3 1004 | S4 998 |
| | | | | S 1008 | V1 1009 | V2 1045 | V3 1070 |
| 17 | DAUPHIN | I-81 | north | S1 1003 | S2 990 | S3 993 | S4 990 |
| | | | | S 1108 | V1 1035 | V2 1100 | V3 1108 |
| 18 | DAUPHIN | I-81 | south | S1 994 | S2 994 | S3 1002 | S4 980 |
| | | | | S 1089 | V1 1018 | V2 1061 | V3 1061 |
| 19 | LUZERNE | I-81 | north | S1 993 | S2 977 | S3 998 | S4 999 |
| | | | | S 1070 | V1 1028 | V2 1035 | V3 1084 |
| 20 | LUZERNE | I-81 | south | S1 1004 | S2 1007 | S3 1001 | S4 1007 |
| | | | | S 1056 | V1 1030 | V2 1045 | V3 1052 |
| 29 | PORTABLE WIM | any | any | S1 555 | S2 555 | S3 555 | S4 555 |
| | | | | S 980 | V1 1000 | V2 1000 | V3 1000 |
| 30 | TEST BOX | N/A | N/A | S1 0 | S2 0 | S3 0 | S4 0 |
| | | | | S 0 | V1 0 | V2 0 | V3 0 |

EXHIBIT H

# GEORGIA'S EXPERIENCE WITH WEIGH-IN-MOTION AS A SCREENING DEVICE

*Jack Williams, Georgia D. O. T.*

## BACKGROUND

Ten years ago last June, Georgia took a major step in its Weight Enforcement Program. Two permanent Weigh Stations were constructed on I-75 south of Atlanta in Monroe County. These stations utilize weigh-in-motion scales. Prior to this time, portable teams consisting of four to six individuals operating from a carryall were the backbone of Georgia's Weight Enforcement Program. The team concept program at this time had increased to 16 teams and weighed approximately 412,000 vehicles. The increase teams were brought about by reducing the number of personnel to two in each team and purchasing additional equipment.

In 1979, the number of trucks weighed increased to nearly 1.6 million. By 1984, we had constructed 11 permanent weigh stations along the Interstates and the total number of trucks weighed had increased to 6.5 million. In 1987, we opened our last permanent weigh station giving a total of 18. Each of these stations utilized weigh-in-motion equipment. The number of portable two Officer teams had increased to 42. The total number of vehicles weighed was in excess of 11.8 million. From January through June 1988, over 6.2 million trucks have been weighed. This would have been totally impossible had Georgia not made the commitment to the weigh-in-motion sorting concept.

## EQUIPMENT

Two weigh-in-motion manufacturers were the successful low bidders in Georgia. Radian weigh-in-motion scale systems are used at Catoosa, Columbia, Franklin, McIntosh and Monroe county stations. This system utilizes transducers for weight detection. Each lane of traffic has two plates with the load cells being an integral part.

Streeter Richardson weigh-in-motion scale systems are used at the remainder of the stations. They include Bryan, Carroll, Douglas, Lowndes, and Troup county stations. Unlike Radian, the Streeter Richardson equipment uses load cells for weight detection. Six load cells are placed along the edge of the scale plates. These load cells are independent of the plates and may be replaced individually.

## TYPICAL STATION OPERATION

A typical station layout includes the approach signing along the Interstate at a sufficient distance away from the station entrance to allow all trucks a safe transition to the curbside lane. Immediately before the station entrance, a lighted sign indicates whether the station is "open" or "closed". Signing along the entrance ramp instructs the trucker of the proper interval and procedure while moving through the weigh station. Using an interval of 100 feet, the truck can pass over the weigh-in-motion scales with sufficient distance to correctly determine the axle spacing. This distance also allows for a constant speed.

After the truck has passed over the weigh-in-motion scales and before it reaches the intersection with the static scale entrance, weight data collected is analyzed. All of the systems determine possible axle or gross weight violations. The newer stations, in addition to determining possible axle or gross weight violations, compute possible bridge formula violations. The weigh-in-motion scales are normally accurate within five percent plus or minus.

Once the weights are checked by the weigh-in-motion system, it actuates the directional signal on the ramp. When a truck is traveling within the legal weight limits, the signal indicates a green arrow straight ahead. The truck then re-enters the Interstate. All of this occurs in a matter of minutes and the delay is minimal.

If weights are found to be greater than allowed, the signal system will direct the vehicle in question to static scales. The vehicle is then weighed statically on platform axle scales. When measurement is taken to determine the exact weight assessment. If a vehicle has a weight violation, certain options are available to the violator according to Georgia Laws. With an overweight axle or tandem, the driver at his option, may shift the load by hand to make it legal or accept the citation. If the gross weight is greater than 6,000 pounds, the load must be reduced before it is allowed to move.

## EQUIPMENT OPERATION

The weigh-in-motion equipment installed at each of our stations allows the station operator the flexibility to set the threshold for determining the weights that will be allowed to by-pass the static scales. Normally, vehicles that exceed the following weights are required to be weighed on static scales.

| | |
|---|---|
| Gross Weight | 74,000 pounds |
| Tandem Weight | 34,000 pounds |
| Axle Weight | 20,000 pounds |

The Radian scales' software is set in 100 pound increments to the desired weight. The Streeter Richardson scales are set as a percentage of the legal limits. Normally, 93 to 95 percent is used on the gross weight and specific weights are entered for axle and tandem weight allowances.

Static scales are calibrated every 90 days. The weigh-in-motion scales are not required to be calibrated by Law or Departmental Policy on a set schedule. Therefore, they are checked and recalibrated by comparision weighing on an as needed basis. Normally, they are checked by each shift and adjusted as needed.

## MAINTENANCE

We have a Scale Maintenance Section staffed with trained Scale Technicians to service all our scales. These people, maintaining complete sets of spare parts, have greatly reduced our downtime. The major problem is the transducers and load cells which are subjected to the stormy weather in our State. Both lightning and heavy rains are major factors in scale outages.

The next most susceptible component is the power supply unit. This unit can be damaged by lightning or a power surge. This type of problem has been minimized by the installation of surge protection devices and taking extra precautions during thunderstorms. In most instances, we just shut off and disconnect the weigh-in-motion equipment when lightning is in the area.

Other maintenance problems have been very minor and practically none existent. As a normal routine, preventive maintenance is performed monthly. Each time, the terminal keyboard is thoroughly cleaned and all contacts and connections are checked. This preventive maintenance has been very beneficial in keeping our system operational. Many potential problems that could shut the system down have been detected and repaired. The controlled environment of the weigh stations have also proven to be advantageous in holding downtime to a minimum. This area not only has constant temperature but personnel traffic is held to a minimum which reduces accidents. This also has kept the area relatively clean and dust free.

## FUTURE ENHANCEMENT

Although the weigh-in-motion system has the capability to store weights of all vehicles passing through the station, we have not routinely stored this data. With the increased need for weight statistics for planning and research, efforts to compile and report this valuable data is being reviewed. We also are looking at portable weigh-in-motion scales to be used in a similar manner as at the weigh stations in high traffic areas.

## CONCLUSION

Georgia has made a commitment to use weigh-in-motion as a screening device. This commitment was made ten years ago and has proven to be very successful. We are pleased with our Weight Enforcement Program in Georgia and by comments I hear from the trucking industry we are meeting today's challenges of increased truck traffic by holding delay time in the stations to a minimum.

If you have any questions, I will attempt to answer them at this time. Thank you for the opportunity to share with you Georgia's Weigh-In-Motion Experience.

## LEGAL ASPECTS OF OVERWEIGHT ASSESSMENTS IN GEORGIA

*Jack Williams, Georgia D. O. T.*

According to the Georgia Code "any person who violates the weight limitation provisions of Code Section 32-6-20 shall be conclusively presumed to have damaged the public roads, including bridges, of this State by reason of such overloading". In 1982, this Section of the Code was upheld in a court decision of Department of Transportation vs Del Cook Timber Company. In the Judge's ruling, he stated "it is constitutionally permissable for the State to enact a statute providing that any person who operates an overweight motor vehicle on public roads shall be conclusively presumed to have damaged the roads."

The fines assessed are as follows:

| | |
|---|---|
| lst 1000 | 0.8 cents per pound |
| Next 2000 | 1.5 cents per pound |
| Next 2000 | 3.0 cents per pound |
| Next 3000 | 4.0 cents per pound |
| Excess of 8000 | 5.0 cents per pound |

Once a citation is issued, within ten working days it is keyed into the computer system. The majority of this time is spent transmitting to the general office by the postal service or Officers bringing them in. After the citation is on the system, it is audited for the proper charge and correct citation amount. If this is in error, a letter noting the corrected amount is generated and mailed to the violator.

The violator has fifteen days to either request a hearing or make payment. If there has been no response, a notice that the appeal time has expired and payment is due. Ten days after the initial letter is sent and there is no response, a second letter is sent stating that failure to respond immediately will result in documents being sent to the Collection Unit for legal action to be taken in ten days if no payment is received.

Failure, by the violator, to pay within this ten day period prompts a third letter. This letter is generated in duplicate. The second copy going to the Investigation/Collection Unit. These letters or accounts as they have become at this point are assigned to an Investigator based on area of the State where the violator lives. Violators outside the State are assigned to the Officers in a similar manner with each Officer having certain States. These Officers then make contact with the owner of the truck and if collection is not made, a pickup order is issued. The vehicle, when observed by a team or weigh station personnel, is then held for payment. This process has been tested and all legal requirements have been satisfied.

If, within the first fifteen days, an Administrative Review is requested, the hearing date is established by the Hearing Officer. The citation is coded on the computer system as being in hearing status and no action is taken by the Department to collect the citation until the final ruling is issued. The Hearing Officer's ruling can be appealed to the Deputy Commissioner. These Departmental rulings can and have been appealed in Superior Court. This unique approach to collecting damages has been very satisfactory in Georgia. It assesses all violators with the same rules and the funds collected are used to offset a portion of the damage cost.

I appreciate the opportunity to tell you about Georgia's procedure for handling assessments generated by our Weigh-In-Motion Program.

# USE OF CIVIL PROCEDURES AS A TOOL IN WEIGHT ENFORCEMENT

*Jeff Bilcik, Assistant Attorney General, Minnesota Attorney General's Office*

For detailed information see Minnesota Statutes Chapter 169 subsections 825 through 872

# TRAFFIC DATA COLLECTION PROCEDURES NORTH DAKOTA HIGHWAY DEPARTMENT

*Dennis E. Jacobson, P.E.*

North Dakota is a sparsely populated rural midwestern state. Our annual vehicle miles traveled is approximately 5.6 billion. This is generated on a 106,472 mile system. It's important to note that the state highway system accounts for 59% of the total travel in North Dakota. More importantly, the Interstate and principal arterial system account for over 72% of the states rural esal's.

Many of our rural routes have very low ADT's in comparison to other more urbanized states. Over 60% of the total state highway system has an ADT of less than or equal to 750. 43% of the state system is less than or equal to 500. We have low traffic volumes, but our allowable axle weights are as high as most in the United States.

North Dakota is extremely dependent on the trucking industry to get our crops to market. Many elevators are on branchlines which are being abandoned. Many small country elevators have been replaced with high volume regional grain subterminals. These subterminals can concentrate even light regional truck volumes into significant truck volumes at the subterminal. These heavy concentrations of trucks can also happen in a very short time frame. We also have energy development and related industries to contend with in North Dakota, although this impact has been reduced dramatically in the last few years.

Off of the interstate system, we allow up to 105,500 lbs GVW on all of our system except during spring load restrictions. We allow 20,000 lbs on singles, 34,000 lbs on tandems and 42,000 lbs on triple axles. This puts extreme pressure on our paved system. We adopted a paving policy years ago called stage construction.

The state needed to get out of the mud in the 50's. We paved all of our system but very little of it was to a full depth design. The idea was to get back and add additional strength later. In North Dakota, later never came. We ran into the energy crunch and high oil prices. We now have a fragile system being subjected to very heavy axle weights. We knew we had to get a better handle on where the trucks were and that's how we got started back in 1983. Recent legislation has allowed even longer vehicle combinations. No one knows where it will end. However, we finally have the means to monitor where they are at and what they weigh.

## Data Collection Procedures

Starting in 1982, the highway department began a reduction in state forces effort. The highway department was decreased in size from over 1200 employees to less than 1000. All of the major traffic data collection programs were scrutinized and many were severely curtailed. The department used to volume count half of the state each year. Classification counting was a minimal effort of around 50 sessions. There was an informal directive put out to cut the field work travel budget so the division eliminated all coverage counting on the state system. We replaced it with a vehicle classification effort on all highway links between major intersections.

We lost 50% of our full time data collection force during the RIF so we had to cut back on our state system counting cycle from two years to three. Luckily, we have a fairly stratified economy in the state. We have ranching and energy development in the west. We have sugar beets, potatoes and predominantly small grain and row crops in the east.

Following that idea we divided the state into three east-west zones. The zones were balanced so that we could get all of the work done with our existing forces in a counting season. It really had little to do with statistics, mainly it was based on work load. In the counting season of 1986 we started our procedure of classifying each highway link by zone and all of the hpms sample sections within that zone.

## HPMS Data Requirements

North Dakota has an HPMS universe of approximately 6800 sections. According to the TMG we must sample 964 sections. The TMG requires that we randomly count a third each year so our annual data collection effort is a minimum of 320 sites. Of this total, we are required to randomly classify 70 and weigh/classify 30 locations per year. We actually classify much more than this but not in accordance with the guide.

In each zone, we classify all of the samples and paved highway segments on both the county and state systems. As I said, we do not classify randomly statewide. We do a 100% sample of the state highway and paved county systems in each zone. We only volume count those sections where we are unable to set a classifier. This is usually on gravel roads. The WIM procedure is different.

The major highway in North Dakota is Interstate 94. It runs down the middle of the center zone. If we weighed on a strict zone basis, we would only hit I-94 once every three years. We therefore weigh randomly according to the TMG. Our WIM/classification season is only about 20 to 22 weeks long so we have a very difficult time picking up all of the necessary wim sessions each year.

The duration of our sessions is also different than the TMG recommends. We classify all locations for 48 hours in both directions. The guide only requires 48 hours in one direction. We weigh 24 hours in both directions. The guide again requires 48 hours in only one direction. We feel we are getting a reasonable representation with our data collection procedure. With our manpower crunch, it is about as good as we can do. If we increase our time requirements at each location, we will not be able to collect all of the required sample sessions each year.

The department wants to collect as much classification data as possible for our pavement management system and our highway needs studies. We need to have reliable estimates of truck volumes and classification mixes for remaining pavement life calculations and for our analytical software default tables. If we randomly sample according to the guide we will be unable to collect the amount of classification data that the department needs each year.

The department is in the process developing this data collection proposal as I have presented it. We have submitted a draft outline for review and will be preparing the final this winter for submittal to FHWA for approval. It has been reviewed informally by the FHWA division office but until we formally submit our justification for the plan, they will not act on our data collection proposal.

## Processing the Data

Like most departments, we have automated much of the processing of our traffic data. We have now established permanent count locations throughout the state on all systems. They all have reference numbers like a milepoint when they're available. We now can track our counts over time. We also have finger tip access to our historical count data. This was a manual process before this year. We expect significant time savings in data retrieval and reporting because of the new set up.

In the urban areas the volume count locations are all plotted by the computer. The field person then sets the counters according to his plotted zone map and records the junior count data on the computer generated coding form. When the forms are brought in, it only takes a few hours to input the few numbers which are collected in the field each week. The computer automatically adjusts the counts based on seasonal adjustment and axle factors and updates the traffic database. The count zone maps are still prepared manually but next year we intend to have all of our count locations digitized using autocad. The data collection zones will then be plotted. This will save the counting secion hundreds of man hours each year.

The traffic-comp classifiers require even less handling because they are all electronic. The TC II data is collected by the readers and input into a standard PC at the counter shop. The TC III's collect their data on modules which are then brought to the central office. The data is downloaded from the modules via a reader attached directly to the central office computer.

The wim is collected and stored on a portable PC. The processing and storage time is as fast as a floppy can load data into a computer.

The traffic data is now collected, processed and stored in usable form within one week of collection. In the past, this has taken up to six months to accomplish. Through automation and the full time use of a programmer, we have cut down our administrative processing times tremendously. We can now devote much more time to equipment maintenance and preparations for the next counting season.

## Traffic Counting Equipment

The department has standardized on Streeter-Richardson equipment.

ATR System:

We started with a Streeter-Amet ATR system back in 1978. We upgraded it to do classification by vehicle length in 1984. We have ATR's currently operating at 39 locations statewide. We can classify or do speed monitoring at 30 locations. We did a study of the predominant lengths of the various truck classifications and picked the following length bins:

| | | |
|---|---|---|
| Bin 1 - | all vehicles< 22 feet long | Cl 1-3 & 5 |
| Bin 2 - | vehicles from 22 to 40 feet long | Cl 4,6-8 |
| Bin 3 - | vehicles from 41 to 75 feet long | Cl 9-12 |
| Bin 4 - | all vehicles> 75 feet long | Cl 13 |

The following charts show some examples of the types of statistics and data that we can now generate from the ATR database. Our preliminary data shows significant seasonal variations on the non-interstate routes. The interstate traffic doesn't vary significantly except for beet and potato hauling in the eastern part of the state. The day of week statistics indicate that we are weighing at the proper time to catch the majority of the vehicles.

Automatic Vehicle Classifiers:

We purchased four Traffic-Comp's in 1980 and 8 more in 1981. We doubled that amount by purchasing 12 more classifiers in 1985. We just purchased 36 TC III's last winter. We now have 60 classifiers in inventory. We have had problems with the three dozen machines we bought this year. Our calibration checks show that the new Traffic Comp III's are very accurate but they locked up on us once in a while. This normally happened when trying to load the program from the module into the machine in the field. This can be avoided by pre-programming the machines in the office but we want them to work as they were intended.

The manufacturer has replaced the original prom's twice. We are now using a C7a prom. They seem to be working fine now but we haven't had time to check them out completely yet. We are generally happy with the machines and the relationship with the supplier has been excellent. When we've had problems, they have always responded quickly and they have been very good to us. I'm confident we now have the problems licked.

WIM equipment:

We purchased the Streeter-Richardson WIM unit in 1984 in conjunction with an RTAP project on the impacts of a grain subterminal on the surrounding roadway network. We just completed the report and it will be published this fall. It's almost 200 pages long so there's plenty to study and digest.

We have had very few problems with our WIM unit. We perform weigh scale calibration checks in the spring and fall. Our procedure is to calibrate the unit to class 9 vehicles and then weigh 100 to 200 vehicles at highway speeds. We have been getting accuracies of within 5% of actual weights with the exception of the steering axle which has been between 5 and 10% off.

Even though we have been weighing since 1986, there still is a lot of controversy in the department about WIM data. Many don't feel that it is an actual representation of what's out there. We have been sampling the port of entry scales and the esal's per vehicle figures are higher at the scale houses for just about all classes of vehicles. We suspect that the majority of those vehicles are loaded where intra state trucks would not be.

We have not yet performed an in depth investigation of our WIM database looking for overloads and other statistics. Our main purpose has been to collect esal per vehicle statistics to merge with our classification database. Since we have now completed the third year of our data collection cycle. We will be able to generate accurate esal estimates for all segments of our highway system and many of our county roads.

## Uses of WIM data

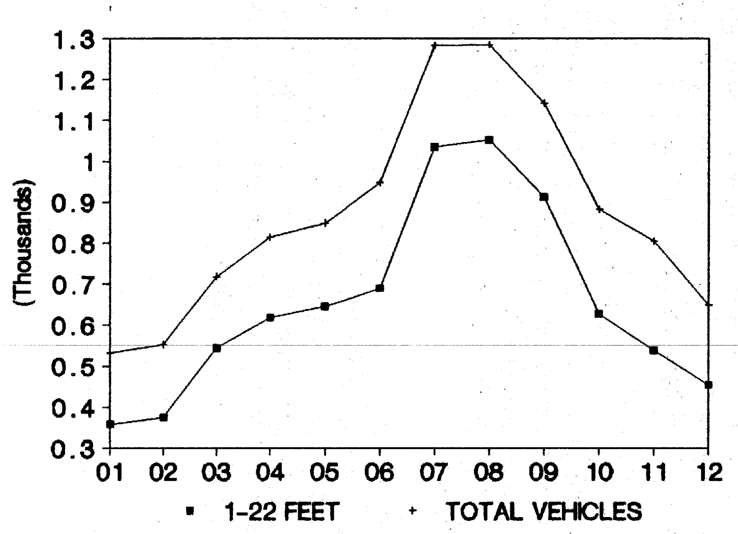
We are starting to use our wim and classification data for our needs studies. Using 1987 data we updated the default tables of the HPMS analytical package to match the traffic characteristics of North Dakota's highways. We also expanded the HPMS sample to include every segment of the rural state highway system. We ran the models and we feel we got a much better representation of our system conditions and highway needs than we would have been able to do without the WIM and classification data.

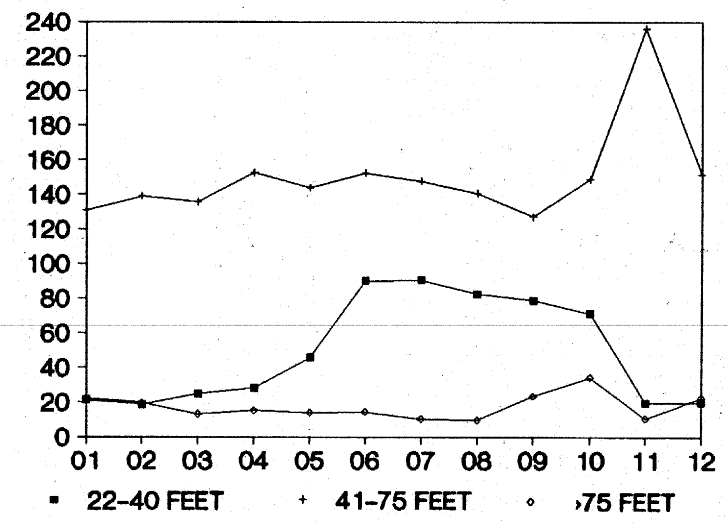
We have just purchased our first "Falling Weight Deflectometer". We will be providing esal information to our pavement management section for their remaining pavement life calculations. We have a pavement serviceability index that combines ride, distress and pavement age. This will be revised in the near future to eliminate age and substitute remaining pavement life. The department feels that this will give us a more meaningful serviceability index. Without the extensive wim and classification data, we wouldn't be able to provide the accurate information.

Our pavement design sections are getting much better traffic information than they used to. We have looked back at many of our early estimates and many are way off. Fortunately, with our low traffic volumes, you can get away with it on some roads. We have had some spectacular failures on our primary system however. Many times after you have checked the new traffic estimates against the actual design, the roads are lasting just as long as they should have. They were just under-designed in the first place. We have been doing a much better job of traffic estimating since 1986 and a lot of it has to do with the increased amounts wim and classification data.

# TRAVEL BY VEHICLE LENGTH GROUP AND MONTH

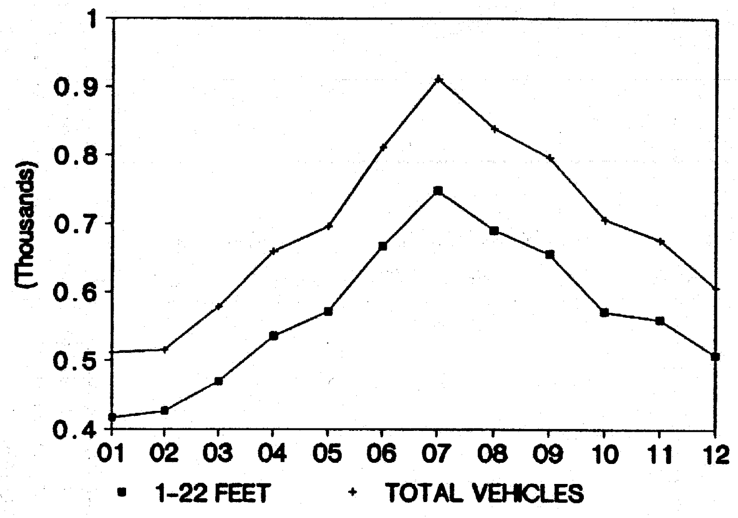
## INTERSTATE (ONE LOCATION)

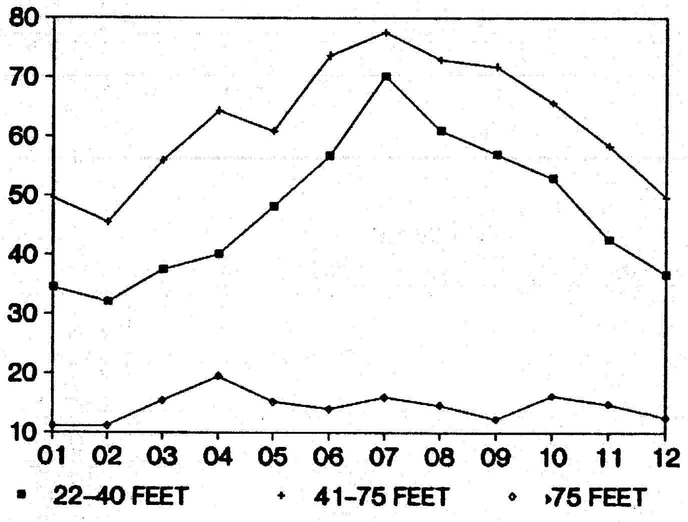




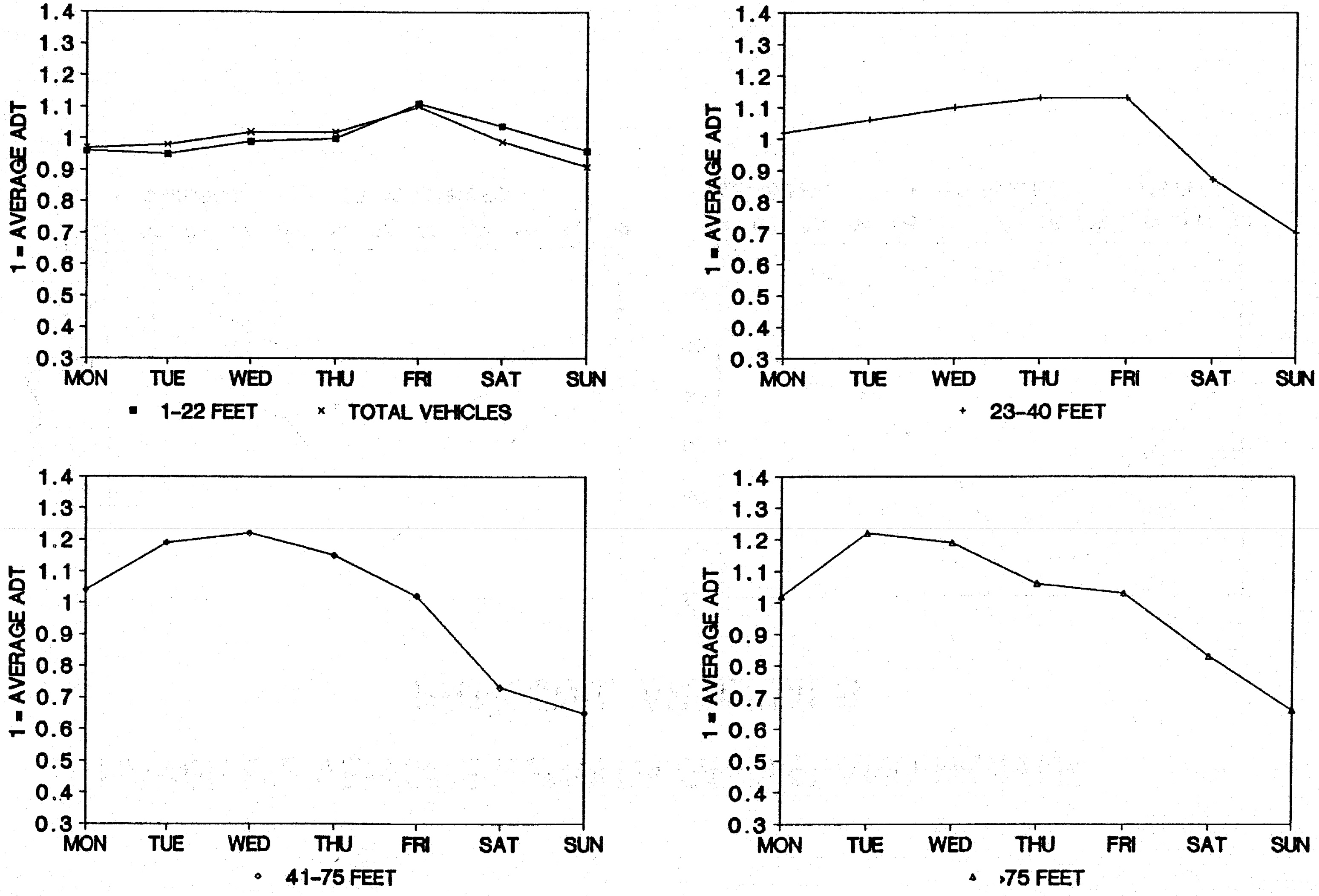
# TRAVEL BY VEHICLE LENGTH GROUP AND MONTH

## PRINCIPAL ARTERIALS

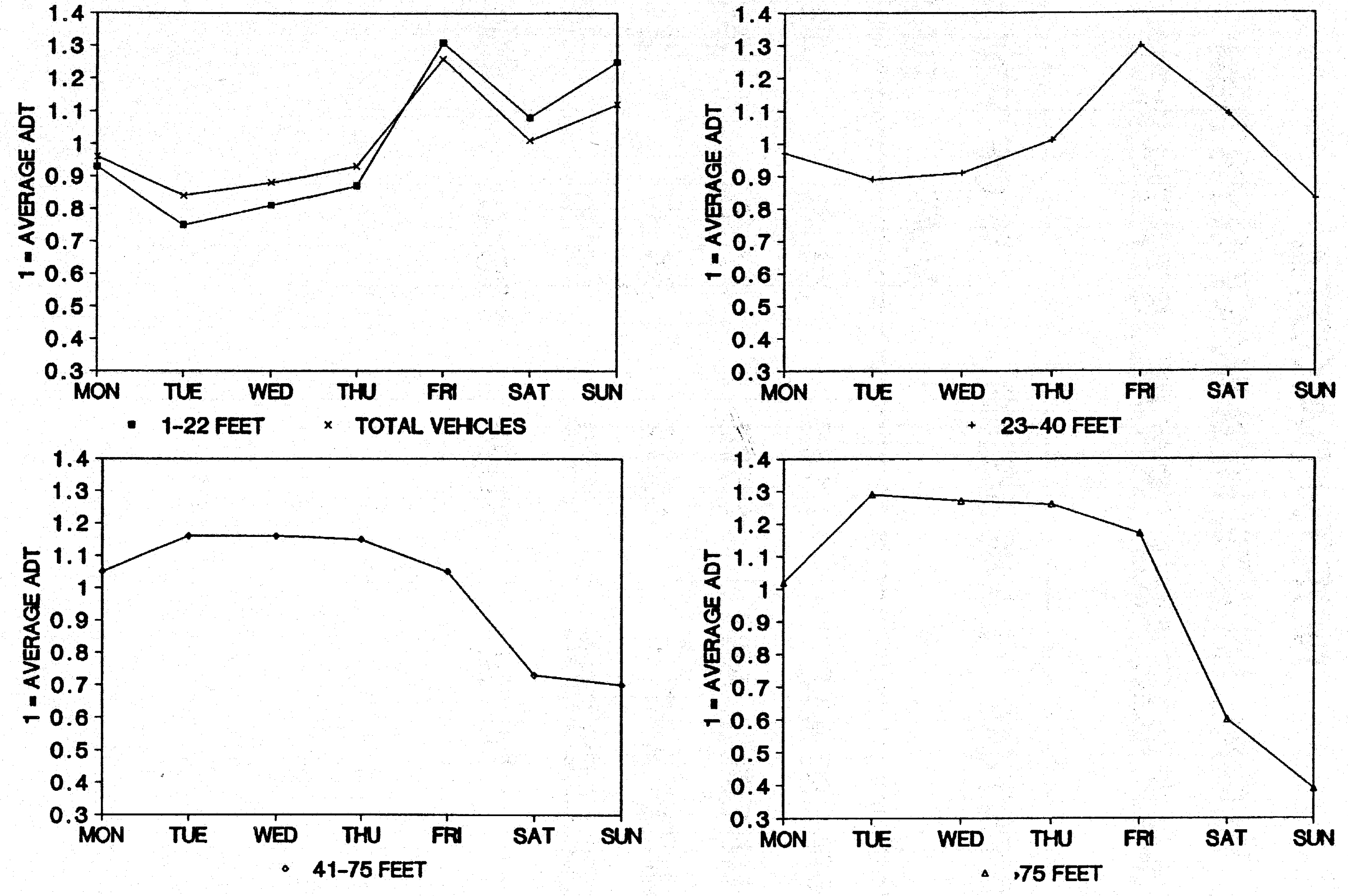




# TRAVEL BY VEHICLE LENGTH GROUP AND DAY OF THE WEEK
# PRINCIPAL ARTERIALS



# TRAVEL BY VEHICLE LENGTH GROUP AND DAY OF WEEK
## INTERSTATE (ONE LOCATION)



# NORTH DAKOTA
# RURAL STATE HIGHWAY SYSTEM
# MILEAGE AND TRAVEL STATISTICS

| SYSTEM | LANE MILES | % OF TOTAL | |
|---|---|---|---|
| | | VMT | ESAL'S |
| INTERSTATE | 1,142 | 33.5 | 48.4 |
| PRINCIPAL ART. | 1,578 | 27.5 | 23.9 |
| MINOR ART. | 4,212 | 34.0 | 24.7 |
| COLLECTORS | 1,163 | 5.0 | 3.0 |
| TOTAL | 8,095 | 100.0 | 100.0 |

# NORTH DAKOTA
# FUNCTIONAL SYSTEM MILEAGE AND VEHICLE MILES TRAVELED

| SYSTEM | MILES | VMT |
|---|---|---|
| INTERSTATE | 571 | 0.893 |
| PRINCIPAL | 1,358 | 1.263 |
| MINOR | 4,456 | 1.334 |
| COLLECTORS | 18,866 | 1.161 |
| LOCALS | 81,221 | 0.980 |
| TOTAL | 106,472 | 5.633 |

# THE BRIDGE WEIGHING SYSTEM AND THE TRAFFIC MONITORING GUIDE
# THE NORTH CAROLINA EXPERIENCE

*E. R. Shuller, NCDOT*

## INTRODUCTION

Since the late 1930's the North Carolina Department of Transportation (NCDOT) has operated a truck weighing program to obtain axle and gross weights, axle spacing, loading practice and related data. In that time there have been years when data collection was suspended and occasionally changes in frequency or length of sample sessions. The most significant change occurred in 1986, however, when the traditional static wheel scales were discarded in favor of weighing-in-motion (WIM).

The focus of this paper is on the goals the NCDOT hoped to achieve with WIM, the selection of equipment, the selection of the sample in compliance with the "Traffic Monitoring Guide" (TMG), and finally a brief comparison of the data collected with the new technology to that collected with the old.

## 1. THE TRADITIONAL WEIGHING PROGRAM

From its inception until 1955 the North Carolina program to determine pavement loadings consisted of weighing a small number of sites repeatedly throughout the year. Each weighing session was 24 hours in length. In that year the procedure was changed to one eight-hour observation per year for each location. Over time the number of locations in the sample fluctuated between 20 and 25 as route changes occurred. The rationale for selection of locations was primarily coverage of major truck routes.

A crew of 8 to 10 people sampled as many trucks as possible with portable wheel scales. At most sites weighing was performed in the travel lanes which required elaborate traffic control. Although providing needed data for planning and design, this procedure was labor intensive, created safety problems and was subject to bias through improper selection of the limited number of trucks that could be weighed. Scale by-passing was thought to be common resulting in design factors of questionable value.

In 1981 economic conditions in North Carolina led to a reduction in funds available to the NCDOT. The truck weighing program was seen as one area in which budget cuts could be made and, with the agreement of the FHWA, it was suspended in that year. In 1983 and again in 1985 the program was not revived. Meanwhile the use by other states of new WIM technology demonstrated that design factors obtained with traditional wheel scales were highly suspect.

## 2. THE PRESENT PROGRAM

In mid-1985 a task force comprised of members of the NCDOT and the FHWA concluded that the need for new weight data in North Carolina must be addressed. One reason for this was encouragement from the FHWA to adopt the data collection program outlined in the "Traffic Monitoring Guide". Perhaps the most important reason was concern by Engineers that some of the premature pavement failures being experienced in the State were the result of inadequate load data for design. It was felt that the problems of static scale weighing, particularly scale bypassing by heavier vehicles, gave a severely low bias to the average weights observed. The task force agreed that weighing in motion with a system that was virtually undetectable by truckers was the only solution to the design load problem.

Four primary uses for truck weight data within the NCDOT were identified:

(1) To comply with Highway Performance Monitoring System (HPMS) guidelines in the "Traffic Monitoring Guide" for reporting 18 kip axle equivalents.

(2) To develop better 18 kip axle equivalent data on the statewide and project levels for pavement design.

(3) To measure stress in bridge members caused by dynamic loading in order to determine if bridges should be posted for weight restrictions.

(4) To supplement the legal load enforcement program.

The purchase of the WIM system and its support equipment was completed by mid-1986 and weighing began in September.

## 2.1 WIM SYSTEM SELECTION

At the time of this study there were three basic types of WIM systems on the market; the load cell mounted in a pit in the pavement, the capacitance pad placed on the pavement, and the instrumented bridge span. The NCDOT's goals for use of WIM were very broad and although each system had unique advantages, no single system was found which was totally satisfactory.

Load cell systems were the most accurate but were expensive, difficult to install, and had limited portability. They were not capable of analyzing stress due to dynamic load in bridge members which was one of the objectives of the NCDOT effort.

Capacitance pad systems were relatively inexpensive and could be installed quickly at almost any point on the highway system. However they also were not capable of determining stress in bridge members. To some degree both of these systems were visible to truckers and could be bypassed by changing lanes unless sensors were installed in all lanes.

Instrumented bridge span systems could weigh vehicles and determine bridge stresses but were expensive and limited to use at bridges only. This could be a problem when attempting to implement a structured sampling procedure such as that in the TMG.

After consideration of these systems it was decided that the instrumented bridge span was the best compromise to meet the NCDOT's needs if it could be shown that a significant number of grade-separated highway bridges existed on HPMS sample sections. A preliminary investigation found nearly 300 bridges that met this criterion. This encouraged the task force to proceed with the bridge weighing system recommendation.

## 2.2 ACQUISITION OF EQUIPMENT

Following the decision on the type of system to be purchased, consideration was given to the support equipment necessary. The experience of the WIM manufacturer and of previous users was drawn upon for ideas on housing and transporting the equipment.

### 2.2.1WEIGHING-IN-MOTION SYSTEM

The WIM system was purchased from Bridge Weighing Systems, Inc. (BWS) of Cleveland, Ohio. The instrumented bridge span system is essentially a custom product. During its development phase certain informational tables emerged with demonstrated value to users. These tables were incorporated into the software supplied to subsequent purchasers. However, the computer software supporting the system can be modified by the manufacturer to present the data in any way the user specifies. The following set of 15 tables was included in the package delivered to North Carolina.

1. Vehicle classification by gross vehicle weight.
2. Vehicle classification by hour of day.
3. Gross vehicle weight by hour of day.
4. Speed distribution by hour of day.
5. Average gross weight of vehicle by hour of day.
6. Weight distribution by axle grouping.
7. Cumulative ESAL values by vehicle classification, gross vehicle weight, and hour of day.
8. Overweight trucks by vehicle classification and hour of day.
9. Overweight trucks by vehicle classification and gross vehicle weight.
10. Overweight trucks by vehicle classification and amount of overweight.
11. Type of axle group violation by vehicle classification.
12. Lane distribution of vehicles by vehicle classification.
13. Lane distribution of vehicle classification and total axle space.
14. Distribution of vehicles by gross vehicle weight and total axle space.
15. Distribution of vehicles by vehicle classification and total axle space.

In the hierarchy of HPMS samples described in the TMG, weight stations are a subset of classification stations. The standard tables printed by the BWS software provide information about equivalent single axle loads and classification counts which satisfies the requirements of the TMG for this data. To complete the data reporting package for FHWA the vendor was also asked to create a record of each weighing observation in the standard Card 7 format which could be submitted to Washington for calculation of the 'W' Tables.

The vendor was also requested to develop new software to take advantage of the stress analysis capability of the system. This software was to evaluate bridge behavior, bridge rating, and bridge loading for the purpose of determining load limits based on actual dynamic observations rather than theoretical calculations.

### 2.2.2TRANSPORT VEHICLE

As already mentioned a decision had been made by the NCDOT to comply with the guidelines in the "Traffic Monitoring Guide" as closely as possible. One of these guidelines was that weighing be conducted for 48 hours.

The version of the BWS which N. C. planned to purchase required AC power for several pieces of electronic equipment. In order to house and transport the equipment, carry an on- board generator, and provide quarters for operators, it was decided that a self-contained van or motor home was needed. Eventually this idea was dropped in favor of a travel trailer towed by a pickup truck. There were two reasons for this decision: (1) the initial cost was lower and (2) the operators would have a separate transportation unit in which to leave the site when necessary.

### 2.2.3TOWING VEHICLE

The towing vehicle had to be capable of pulling a 22 to 24 foot travel trailer of 3500 pounds gross weight and a hitch weight of 400 pounds through terrain ranging from coastal plain to mountainous.

Based on these specifications a dual-tired truck of 1 ton capacity with a pickup body was purchased. To this vehicle was added a Reese-type towing hitch, electric brake hookup, a rack for carrying ladders, and brackets for holding additional 40 pound cylinders of propane which was the fuel used to power the generator. A flashing directional arrow sign was installed over the cab and various safety lights added.

#### 2.2.4CALIBRATION VEHICLE

The bridge weighing system operates on the principal that a given weight causes a repeatable deflection in bridge girders. Because of structural differences, however, the amount of deflection due to the weight will vary from bridge to bridge, Therefore each bridge must be calibrated before it can be used as a scale.

A bridge is calibrated through adjustment of software factors following application of a known weight. This process is repeated until the system gives an approximation of the weight. The vendor recommends a truck loaded to at least 40,000 pounds be used for calibration. The procedure requires driving the truck across the bridge at least 8 times in each lane.

Because of difficulties in borrowing a truck from maintenance or construction operations, a calibration vehicle was assigned full-time to weighing. The vehicle chosen was a combination consisting of a 50,000 GVW tandem axle tractor and a 35 ton low bed trailer. This was a surplus vehicle and did not disrupt normal daily equipment needs for field operations. The permanent assignment of a vehicle to this task also had the advantage of eliminating the need for constant reweighing. The trailer was loaded with concrete barriers and the entire rig weighed. Since the load was a low porosity material, constant reweighing was not required. The one negative aspect of this arrangement was that the driver for the combination had to have a special operators license, therefore it was still necessary to rely on field operations to provide a driver for the calibration truck.

## 3. SAMPLE SELECTION

One of the major objectives of the study was the development of a statewide sampling plan based on the "Traffic Monitoring Guide". In accomplishing this the TMG was adhered to as closely as possible with regard to sample size, sample selection, and length of sample session. The TMG suggests a minimum sample size of 90 HPMS sections. It also recognizes the importance of the Interstate System to nationwide travel by suggesting that states with significant Interstate mileage concentrate one third of their total weighing effort on this system. The remaining samples should be distributed over all other functional classifications higher than local. Further, samples on all functional classifications should be distributed over volume groups.

### 3.1 SAMPLES BY VOLUME GROUP WITHIN FUNCTIONAL CLASS

The application of weighting factors was the method chosen in North Carolina to calculate the number of samples required in each level of stratification. These weighting factors were derived from the proportion of vehicle miles of travel (VMT) in the various strata.

#### 3.1.1DISTRIBUTION BY FUNCTIONAL CLASSIFICATION

Using daily vehicle miles of travel (DVMT) data from the 1984 "Mileage and Inventory Summary" (Table 3-1), 90 sample sessions were distributed. First the number of samples required in each of the broad categories of rural, small urban and urbanized routes was calculated. This was done by applying the percentage of DVMT in each category to the 90 sample sessions. In this calculation the local classification category is not included in the total DVMT.

| Category | Total DVMT | % | Samples |
|---|---|---|---|
| Rural | 63,396,000 | 55.9 | 51 |
| Small Urban | 12,941,000 | 11.4 | 10 |
| Urbanized | 37,080,000 | 32.7 | 29 |
|  | 113,417,000 |  | 90 |

Next the number of samples to be in each functional class in each category was calculated. Since it was predetermined that 30 sample sessions would be on the Interstate system, these 30 were first distributed between the rural, small urban, and urbanized categories.

| Category | Interstate DVMT | % | Samples |
|---|---|---|---|
| Rural | 11,234,000 | 64.3 | 19 |
| Small Urban | 738,000 | 4.2 | 1 |
| Urbanized | 5,511,000 | 31.5 | 0 |
|  | 17,483,000 |  | 30 |

The remaining 60 samples were divided among all other functional classifications higher than local. This procedure is demonstrated in the following example for the rural category. This category had been assigned 51 samples of which 19 were to be on the Interstate system leaving 32 to be distributed.

| Functional Classification | DVMT | % | Samples |
|---|---|---|---|
| Interstate |  |  | 19 |
| Other Principal Arterials | 13,511,000 | 25.9 | 8 |
| Minor Arterials | 8,186,000 | 15.7 | 5 |
| Collectors | 30,465,000 | 58.4 | 19 |
|  | 52,162,000 |  | 51 |

Both the small urban and urbanized categories were treated in the same manner. The entire sample distribution by functional classification is shown in Table 3-2.

### 3.1.2DISTRIBUTION BY VOLUME GROUP

From the HPMS records the total sample mileage in every volume group by functional classification can be calculated. This data is in FHWA report HPN-21 shown in Table 3-3. The only additional information required to determine VMT is average daily traffic (ADT). After some consideration it was decided that the volume groups themselves could be used to represent a reasonable approximation of ADT. By definition each of these groups contains HPMS sections whose ADT's fall within specific ranges. Using the mileage in each group and the midpoint of its volume group range, a satisfactory representation of the VMT was calculated. In Table 3-4 this calculation is demonstrated for volume groups in the rural Interstate and rural Other Principal Arterial classifications. Sample distribution between volume groups was then computed using the proportion of group DVMT to total DVMT as the distributing factor. Because they are calculated the same way, both the classification sample and the truck weight sample are shown in this table. A summary of the entire distribution is shown in Table 3-5.

During the calculation of Table 3-4 it was found to be expedient in some instances to collapse two or more volume groups into one. There were three principal reasons for this:

1. The DVMT in a volume group was too small to justify a sample for the group.

2. The DVMT in a functional class was too small to attract enough samples for each volume group to have one. For example the small urban interstate classification had three volume groups to share one truck weight sample.

3.. There were no suitable bridges in the volume group.

In these cases, rather than biasing the sample further by arbitrarily assigning samples to the larger volume groups and ignoring small ones, group collapsing insures that all HPMS sections have an equal chance of being selected when the sample is drawn.

## 3.2 CHOOSING THE WEIGHT SAMPLE FROM HPMS SECTIONS

The structure of the truck weight monitoring program requires knowledge of the functional classification and volume on each HPMS section before the sample can be drawn. These are standard data items in HPMS records and the sample can be drawn immediately if the WIM system to be used places no restrictions on sampling locations. The BWS, however, depends on bridges for its operation. To effectively choose the sample it is necessary to be able to identify not only suitable bridges within HPMS sections but also those nearby.

### 3.2.1IDENTIFICATION OF HPMS SECTIONS

North Carolina maintains HPMS files and bridge files containing all information necessary to identify, by functional classification and volume group, sections on which bridges are located. All of this data, however, is not in a common data base that can be queried nor can it be visually displayed except in printout form. A visual display is necessary to assist in the selection of the best bridge from several alternatives and also in identifying bridges close to but not on sections. This was felt to be important enough to justify the time required to manually prepare a set of maps showing all HPMS sections and bridges in the State.

A set of county maintenance maps identifying all bridges and major culverts by number has routinely been produced in North Carolina for several years. This provided the base on which to display HPMS sections. The plotting of the HPMS sections presented a more difficult problem. Several years ago when the HPMS system was created, each section was manually plotted and numbered on county maintenance maps. Location descriptions from these maps were coded in the HPMS data base. Two problems made these original visual displays almost useless as overlays on current bridge maps. First, the maps were not updated as the HPMS system changed over time. Second, the original numbering scheme was modified when transferring section descriptions from the maps to the data base to such an extent that the two sources could no longer be easily cross-referenced.

The location descriptions in the 1984 HPMS data base were used to plot each of the sections on the bridge location maps. Because locations are described by county, route, and milepost in this data base and because milepost numbers are not displayed on North Carolina county maintenance maps, this was a tedious exercise in locating beginning and ending points for sections by measuring along the route from a county line reference.

### 3.2.2IDENTIFICATION OF BRIDGE WEIGHING SECTIONS

The choice of the BWS, a compromise to provide the multiple data collection capability desired by the NCDOT, reduced significantly the number of HPMS sample sections that could be used for weighing. Aside from the obvious need of a bridge, additional restrictions were dictated by the nature of the BWS and by the requirement for reasonable access to the bridge girders from below.

Criteria for Bridge Selection

1. Bridge skew less than 45 degrees.
2. Span length less than 100 feet.
3. No traffic signals at ends of bridge.
4. Highway grade separation.
5. Safe parking below bridge for equipment trailer.
6. Reasonable access to bridge girders.

The initial match of the bridge file against the HPMS file found 850 of the more than 2800 sections contained some type of structure. These structures were stream crossings ranging from box culverts to major bridges, railroad crossings, and highway crossings. Most of these were not suitable for use in weighing. Realizing that only highway grade separations would provide easy access to bridge girders and parking out of sight of the traffic being weighed, a listing of these separations was produced from the bridge file. With this list the number of HPMS sections that contained a suitable bridge was further reduced to 194. Because the application of the other five criteria would decrease the number of suitable sections even more, there was concern that insufficient sections would be available from which to draw the sample.

### 3.2.3ADDITIONAL SAMPLES

To enlarge the number of sections from which the sample would be chosen two alternatives were considered. The first was to identify all acceptable bridges on the entire highway system that were within the proper volume groups of the required functional classes and create new HPMS sections. The second was to return to the sample previously excluded sections that were in close proximity to a suitable bridge.

Creating new HPMS sections was found to be a difficult task. Searching for lengths of road which must meet multiple criteria demands a well-designed, unified data base. As a minimum, it must be possible to overlay bridge and volume data on the functionally classified highway system. Such a data base did not exist in North Carolina. This meant a very tedious manual overlay of information from several data files to identify new HPMS sections. For this reason this procedure was only used to locate a few samples which could not be found otherwise.

The method of choice was to return excluded sections to the universe by identifying those sections that had a suitable bridge close by and treating the section as if the bridge were located on it. No restriction was placed on multiple HPMS section references to the same bridge. In fact, 155 bridges were referenced by two or more HPMS sections. By this means the number of sections in the weight universe was increased from 194 to 601 distributed as shown in Table 3-6.

The use of multiple references is an artificial means of expanding the universe and is similar in some respects to the procedure recommended by the FHWA of returning sections to the sample pot after being chosen in order to make them eligible for reselection. Regardless of the method chosen, there will be some cells in the sample for which a suitable bridge on or near an HPMS section cannot be found. In these cases the only choice will be to locate and add new HPMS sections.

### 3.2.4DISTRIBUTION BY YEAR

The final step of this phase of the study was the selection of 30 samples to be monitored in each year of the 3 year cycle. According to the "Traffic Monitoring Guide" the method of choice would be an equal division each year of the samples by functional class. Ultimately, practical considerations determined the final distribution shown in Table 3-7.

Use of the BWS requires compromise not only in sample selection but also in weighing. Ideally samples to be weighed each year should be selected equally from volume groups and functional classes and distributed over days of the week. However the logistics of equipment movement and the arrangement of reasonable work schedules make true random distribution of weighing sessions impractical.

In North Carolina the movement of equipment from site to site was an important issue. Minimizing travel distance for this equipment and for the personnel required to move it was the controlling factor in establishing the annual schedule.

## 4. EVALUATION OF RESULTS

The WIM system has been in operation in North Carolina for nearly two years. In that time 48 of the 90 HPMS weight samples have been completed and sufficient data is now available to make comparisons to the previous weighing technique and to provide improved pavement design information.

### 4.1 ESAL COMPARISON

Equivalent single axle loads was the variable chosen to evaluate differences between data gathered with static wheel scales and that gathered with WIM. It was found, however, that because of tabulation differences, a direct comparison by vehicle type and functional class was very difficult.

The last year data was collected with static scales in North Carolina was in 1979. That data was tabulated using the FHWA 'W' Table software. Only 20% of the WIM data collected in 1986-88 had been processed by that same software when this report was prepared. Therefore the BWS software was relied upon to calculate ESAL information from the WIM data. Unfortunately there are significant differences in the way these two software packages summarize information.

The 1979 North Carolina W-4 Table is tabulated in broad categories of the Interstate Rural System, the Other Rural System, and the All Urban System while the 1986-88 BWS tables are divided into the full range of functional classifications. In order to make a comparison of the ESAL's from these outputs, collapsing of functional classes and of vehicle types was performed using the number of vehicles weighed as a weighting factor. The result is shown in Table 4-1. This illustrates the dramatic rise in 18-kip equivalents found with WIM equipment. The increases are most noticeable in the TTST categories, ranging from roughly two to four times the 1979 ESAL's; a matter of real concern because there are strong indications that not only are the loads carried much heavier but also that the number of these trucks is increasing at a faster rate than other types.

## 5. CONCLUSIONS

The four principal purposes for which the NCDOT planned to use weighing-in-motion were very broad in scope and were not necessarily compatible. Nevertheless an attempt was made to satisfy all data needs with a single system. To date there have been varying degrees of success in meeting these needs.

In collecting and reporting ESAL's in compliance with the "Traffic Monitoring Guide" sampling procedure the restrictive nature of the Bridge Weighing System limited the actual number of HPMS sections that could be monitored to such an extent that there were too few or no possibilities in some cells of the sample. The resulting effort to fill the missing cells was difficult and not completely successful and has raised the question of possible bias being introduced into the HPMS sample. For TMG sampling the BWS was found to have significant limitations.

The development of ESAL's for pavement design produced the expected higher values. This further supports the theory that WIM gives more realistic results by eliminating many of the problems of static weighing, particularly that of scale by-passing by heavier trucks. In this regard the BWS has an advantage over most other WIM systems in being less obvious to truckers when in use.

Measuring stress in bridge members is a worthwhile goal and is possible only with the BWS. At this writing the vendor and bridge engineers in North Carolina have not yet agreed on the final version of the software for this task.

The use of WIM as a supplement to enforcement weighing was attempted using inductive pads as a high speed screening device upstream from a team that stopped and weighed suspected vehicles with static wheel scales. This effort did not prove to be satisfactory. The BWS is even less suited to screening because of the limited number of sites at which it can be used. Its role in enforcement weighing will be largely identification of violation tendencies by route and time of day.

The North Carolina effort has demonstrated that no single system now on the market is capable of fulfilling all possible weighing needs. To achieve its goals the NCDOT must broaden its program in two areas:

1. Continued development of the bridge stress analysis capability of the Bridge Weighing System.
2. The addition of a highly portable system such as the inductive pad or piezoelectric cable for better compliance with the TMG sampling procedure.

Overall the experience of the NCDOT with WIM has been positive. By itself the possible reduction in pavement maintenance costs through better design justifies the program. The future will be a continued effort to provide weight data for a wider spectrum of uses.

# TABLE 3-1
# NORTH CAROLINA MILEAGE AND DAILY TRAVEL SUMMARY
# 1984

## RURAL DATA

| | PRINCIPAL ARTERIALS | | MINOR ARTERIALS | COLLECTORS | | LOCALS | TOTAL |
|---|---|---|---|---|---|---|---|
| | INTERSTATE | OTHER | | MAJOR | MINOR | | |
| MILEAGE | 595 | 2018 | 1985 | 10562 | 9171 | 50771 | 75102 |
| DVMT(000) | 11234 | 13511 | 8186 | 23893 | 6572 | 10417 | 73813 |

## SMALL URBAN DATA

| | PRINCIPAL ARTERIALS | | | MINOR ARTERIALS | COLLECTORS | LOCALS | TOTAL |
|---|---|---|---|---|---|---|---|
| | INTERSTATE | OTH FREEWY | OTHER | | | | |
| MILEAGE | 36 | 69 | 663 | 663 | 494 | 3911 | 5836 |
| DVMT(000) | 738 | 1230 | 7410 | 2957 | 606 | 2275 | 15216 |

## URBANIZED AREA DATA

| | PRINCIPAL ARTERIALS | | | MINOR ARTERIALS | COLLECTORS | LOCALS | TOTAL |
|---|---|---|---|---|---|---|---|
| | INTERSTATE | OTH FREEWY | OTHER | | | | |
| MILEAGE | 165 | 140 | 975 | 1463 | 835 | 8204 | 11782 |
| DVMT(000) | 5511 | 4731 | 15352 | 9580 | 1906 | 5535 | 42615 |

## STATEWIDE TOTALS

| TOTAL PUBLIC ROAD MILEAGE | TOTAL DVMT(000) |
|---|---|
| 92720 | 131644 |

## TABLE 3-2

## STATION DISTRIBUTION BY FUNCTIONAL CLASS

| | 1984* DVMT | Class Station | Weight Station |
|---|---|---|---|
| **RURAL** | | | |
| Interstate | 11,234,000 | 39 | 19 |
| Other Principal Arterials | 13,511,000 | 34 | 8 |
| Minor Arterials | 8,186,000 | 21 | 5 |
| Collectors | 30,465,000 | 76 | 19 |
| | 63,396,000 | 170 | 51 |
| **SMALL URBAN** | | | |
| Interstate | 738,000 | 2 | 1 |
| Other Freeways & Expressways | 1,230,000 | 3 | 1 |
| Other Principal Arterials | 7,410,000 | 18 | 5 |
| Minor Arterials | 2,957,000 | 7 | 2 |
| Collectors | 606,000 | 2 | 1 |
| | 12,941,000 | 32 | 10 |
| **URBANIZED** | | | |
| Interstate | 5,511,000 | 19 | 10 |
| Other Freeways & Expressways | 4,731,000 | 12 | 3 |
| Other Principal Arterials | 15,352,000 | 38 | 9 |
| Minor Arterials | 9,580,000 | 24 | 6 |
| Collectors | 1,906,000 | 5 | 1 |
| | 37,080,000 | 98 | 29 |
| **GRAND TOTAL** | 113,417,000 | 300 | 90 |

*1984 North Carolina "Mileage and Daily Travel Summary"

## TABLE 3-3 (a)

### FHWA-HPN-21
### 1984 HPMS NORTH CAROLINA

RURAL

| | NO. OF SECTIONS | SAMPLE MILEAGE | EXPANSION FACTOR | CALCULATED UNIVERSE MILEAGE |
|---|---|---|---|---|
| INTERSTATE | | | | |
| VOLUME GROUP 01 | 2 | 8.520 | 1.00 | 8.520 |
| VOLUME GROUP 02 | 51 | 302.770 | 1.23 | 372.407 |
| VOLUME GROUP 03 | 23 | 97.450 | 1.77 | 172.487 |
| VOLUME GROUP 04 | 7 | 29.630 | 1.27 | 37.630 |
| VOLUME GROUP 05 | 2 | 3.230 | 1.04 | 3.359 |
| TOTAL | 85 | 441.600 | | 594.403 |
| OTHER PRINCIPAL ARTERIAL | | | | |
| VOLUME GROUP 01 | 179 | 827.030 | 1.07 | 884.922 |
| VOLUME GROUP 02 | 145 | 527.360 | 1.63 | 859.597 |
| VOLUME GROUP 03 | 25 | 81.910 | 2.22 | 181.840 |
| VOLUME GROUP 04 | 9 | 40.130 | 1.44 | 57.787 |
| VOLUME GROUP 05 | 6 | 18.950 | 1.19 | 22.551 |
| VOLUME GROUP 06 | 1 | 2.170 | 3.18 | 6.901 |
| TOTAL | 365 | 1,497.550 | | 2,013.598 |
| MINOR ARTERIAL | | | | |
| VOLUME GROUP 01 | 71 | 411.840 | 1.90 | 782.496 |
| VOLUME GROUP 02 | 40 | 167.490 | 4.02 | 673.310 |
| VOLUME GROUP 03 | 19 | 64.580 | 6.79 | 438.498 |
| VOLUME GROUP 04 | 14 | 31.570 | 2.47 | 77.978 |
| VOLUME GROUP 05 | 6 | 9.720 | 1.50 | 14.580 |
| TOTAL | 150 | 685.200 | | 1,986.862 |
| MAJOR COLLECTOR | | | | |
| VOLUME GROUP 01 | 89 | 338.400 | 22.07 | 7,468.488 |
| VOLUME GROUP 02 | 49 | 130.450 | 16.23 | 2,117.204 |
| VOLUME GROUP 03 | 17 | 38.780 | 22.86 | 886.511 |
| VOLUME GROUP 04 | 11 | 10.090 | 8.76 | 88.388 |
| TOTAL | 166 | 517.720 | | 10,560.591 |
| MINOR COLLECTOR | | | | |
| VOLUME GROUP 01 | 158 | 453.260 | 16.65 | 7,546.779 |
| VOLUME GROUP 02 | 52 | 107.080 | 12.09 | 1,294.597 |
| VOLUME GROUP 03 | 14 | 22.960 | 8.78 | 201.589 |
| VOLUME GROUP 04 | 13 | 21.720 | 4.23 | 91.876 |
| VOLUME GROUP 05 | 6 | 7.180 | 5.26 | 37.767 |
| TOTAL | 243 | 612.200 | | 9,172.608 |
| INTERSTATE 139A | | | | |
| VOLUME GROUP 03 | 1 | 0.340 | 1.00 | 0.340 |
| TOTAL | 1 | 0.340 | | 0.340 |

## TABLE 3-3 (b)

### FHWA-HPN-21
### 1984 HPMS NORTH CAROLINA

| SMALL URBAN | NO. OF SECTIONS | SAMPLE MILEAGE | EXPANSION FACTOR | CALCULATED UNIVERSE MILEAGE |
|---|---|---|---|---|
| INTERSTATE | | | | |
| VOLUME GROUP 02 | 11 | 12.470 | 1.47 | 18.331 |
| VOLUME GROUP 03 | 8 | 8.750 | 1.67 | 14.613 |
| VOLUME GROUP 04 | 1 | 0.860 | 2.98 | 2.563 |
| TOTAL | 20 | 22.080 | | 35.507 |
| OTHER FREEWAY & EXPRESSWAY | | | | |
| VOLUME GROUP 01 | 18 | 12.400 | 1.60 | 19.840 |
| VOLUME GROUP 02 | 32 | 18.540 | 2.06 | 38.192 |
| VOLUME GROUP 03 | 4 | 2.300 | 3.05 | 7.015 |
| VOLUME GROUP 04 | 1 | 0.410 | 8.71 | 3.571 |
| TOTAL | 55 | 33.650 | | 68.618 |
| OTHER PRINCIPAL ARTERIAL | | | | |
| VOLUME GROUP 01 | 106 | 53.430 | 2.28 | 121.820 |
| VOLUME GROUP 02 | 107 | 63.280 | 4.43 | 280.330 |
| VOLUME GROUP 03 | 65 | 39.760 | 4.00 | 159.040 |
| VOLUME GROUP 04 | 16 | 12.700 | 5.72 | 72.644 |
| VOLUME GROUP 05 | 13 | 9.960 | 1.92 | 19.123 |
| VOLUME GROUP 06 | 5 | 4.070 | 1.75 | 7.123 |
| VOLUME GROUP 07 | 2 | 2.020 | 1.13 | 2.283 |
| TOTAL | 314 | 185.220 | | 662.363 |
| MINOR ARTERIAL | | | | |
| VOLUME GROUP 01 | 57 | 25.830 | 10.09 | 260.625 |
| VOLUME GROUP 02 | 28 | 11.160 | 21.37 | 238.489 |
| VOLUME GROUP 03 | 12 | 9.510 | 14.17 | 134.757 |
| VOLUME GROUP 04 | 5 | 2.290 | 9.20 | 21.068 |
| VOLUME GROUP 05 | 5 | 2.690 | 2.77 | 7.451 |
| VOLUME GROUP 06 | 1 | 0.610 | 1.34 | 0.817 |
| TOTAL | 108 | 52.090 | | 663.207 |
| COLLECTOR | | | | |
| VOLUME GROUP 01 | 104 | 49.030 | 6.33 | 310.360 |
| VOLUME GROUP 02 | 32 | 15.270 | 7.07 | 107.959 |
| VOLUME GROUP 03 | 20 | 8.550 | 8.21 | 70.196 |
| VOLUME GROUP 04 | 4 | 1.850 | 3.03 | 5.606 |
| VOLUME GROUP 05 | 1 | 0.050 | 1.00 | 0.050 |
| TOTAL | 161 | 74.750 | | 494.171 |

## TABLE 3-3 (c)

### FHWA-HPN-21
### 1984 HPMS NORTH CAROLINA

| URBANIZED | NO. OF SECTIONS | SAMPLE MILEAGE | EXPANSION FACTOR | CALCULATED UNIVERSE MILEAGE |
|---|---|---|---|---|
| INTERSTATE | | | | |
| VOLUME GROUP 01 | 20 | 36.590 | 1.67 | 61.105 |
| VOLUME GROUP 02 | 31 | 43.550 | 1.64 | 71.422 |
| VOLUME GROUP 03 | 8 | 8.710 | 1.99 | 17.333 |
| VOLUME GROUP 04 | 1 | 0.760 | 1.74 | 1.322 |
| TOTAL | 60 | 89.610 | | 151.182 |
| OTHER FREEWAY & EXPRESSWAY | | | | |
| VOLUME GROUP 01 | 45 | 52.020 | 1.31 | 68.146 |
| VOLUME GROUP 02 | 58 | 46.520 | 1.20 | 55.824 |
| VOLUME GROUP 03 | 12 | 14.790 | 1.13 | 16.713 |
| TOTAL | 115 | 113.330 | | 140.683 |
| OTHER PRINCIPAL ARTERIAL | | | | |
| VOLUME GROUP 01 | 11 | 7.420 | 3.70 | 27.454 |
| VOLUME GROUP 02 | 35 | 20.740 | 2.55 | 52.887 |
| VOLUME GROUP 03 | 130 | 88.570 | 3.37 | 298.481 |
| VOLUME GROUP 04 | 106 | 78.220 | 3.47 | 271.423 |
| VOLUME GROUP 05 | 60 | 38.200 | 3.98 | 152.036 |
| VOLUME GROUP 06 | 38 | 36.310 | 2.60 | 94.406 |
| VOLUME GROUP 07 | 37 | 24.160 | 2.56 | 61.850 |
| VOLUME GROUP 08 | 9 | 5.400 | 2.05 | 11.070 |
| VOLUME GROUP 09 | 7 | 3.170 | 1.87 | 5.928 |
| VOLUME GROUP 10 | 4 | 1.750 | 1.46 | 2.555 |
| TOTAL | 437 | 303.940 | | 978.090 |
| MINOR ARTERIAL | | | | |
| VOLUME GROUP 01 | 89 | 59.970 | 5.17 | 310.045 |
| VOLUME GROUP 02 | 68 | 43.060 | 11.96 | 514.998 |
| VOLUME GROUP 03 | 80 | 53.040 | 8.11 | 430.154 |
| VOLUME GROUP 04 | 50 | 36.330 | 4.32 | 156.946 |
| VOLUME GROUP 05 | 23 | 12.630 | 2.78 | 35.111 |
| VOLUME GROUP 06 | 7 | 5.210 | 2.05 | 10.681 |
| VOLUME GROUP 07 | 4 | 3.510 | 1.03 | 3.615 |
| TOTAL | 321 | 213.750 | | 1,461.550 |
| COLLECTOR | | | | |
| VOLUME GROUP 01 | 52 | 31.610 | 11.23 | 354.980 |
| VOLUME GROUP 02 | 62 | 40.520 | 4.04 | 163.701 |
| VOLUME GROUP 03 | 71 | 53.660 | 4.95 | 265.617 |
| VOLUME GROUP 04 | 32 | 20.000 | 2.28 | 45.600 |
| VOLUME GROUP 05 | 7 | 3.280 | 1.52 | 4.986 |
| VOLUME GROUP 06 | 2 | 0.670 | 1.93 | 1.293 |
| TOTAL | 226 | 149.740 | | 836.177 |
| INTERSTATE 139A | | | | |
| VOLUME GROUP 01 | 1 | 0.520 | 3.29 | 1.711 |
| VOLUME GROUP 02 | 6 | 5.170 | 2.05 | 10.599 |
| VOLUME GROUP 03 | 5 | 1.620 | 1.09 | 1.766 |
| TOTAL | 12 | 7.310 | | 14.076 |

## TABLE 3-4

## STATION DISTRIBUTION
## BY VOLUME GROUP WITHIN FUNCTIONAL CLASS

### RURAL INTERSTATE

| | | | | Classification Sample | | | Weight Sample | | |
|---|---|---|---|---|---|---|---|---|---|
| Volume Group | Mean Volume | HPMS Miles | HPMS DVMT | Combined Groups | Combined DVMT | Station | Combined Groups | Combined DVMT | Station |
| 1 | 5,000 | 8.5 | 42,500 | | | | | | |
| 2 | 15,000 | 302.8 | 4,542,000 | 1,2 | 4,584,500 | 22 | 1,2 | 4,584,500 | 11 |
| 3 | 25,000 | 97.4 | 2,435,000 | 3 | 2,435,000 | 12 | 3 | 2,435,000 | 6 |
| 4 | 35,000 | 29.6 | 1,036,000 | 4,5 | 1,184,500 | 5 | 4,5 | 1,184,500 | 2 |
| 5 | 45,000 | 3.3 | 148,500 | | | | | | |
| | | 441.6 | 8,204,000 | | 8,204,000 | 39 | | 8,204,000 | 19 |

### RURAL OTHER PRINCIPAL ARTERIAL

| | | | | Classification Sample | | | Weight Sample | | |
|---|---|---|---|---|---|---|---|---|---|
| Volume Group | Mean Volume | HPMS Miles | HPMS DVMT | Combined Groups | Combined DVMT | Station | Combined Groups | Combined DVMT | Station |
| 1 | 2,500 | 827.0 | 2,067,500 | 1 | 2,067,500 | 9 | 1 | 2,067,500 | 2 |
| 2 | 7,500 | 527.4 | 3,955,500 | 2 | 3,955,500 | 16 | 2 | 3,955,500 | 4 |
| 3 | 12,500 | 81.9 | 1,023,750 | 3 | 1,023,750 | 4 | 3 | 1,023,750 | 1 |
| 4 | 17,500 | 40.1 | 701,750 | 4 | 701,750 | 3 | 4,5,6 | 1,251,250 | 1 |
| 5 | 25,000 | 18.9 | 472,500 | 5,6 | 549,500 | 2 | | | |
| 6 | 35,000 | 2.2 | 77,000 | | | | | | |
| | | 1497.5 | 8,298,000 | | 8,298,000 | 34 | | 8,298,000 | 8 |

# TABLE 3-5

## STATION DISTRIBUTION SUMMARY BY VOLUME GROUP WITHIN FUNCTIONAL CLASS

| | RURAL | | SMALL URBAN | | URBANIZED | |
|---|---|---|---|---|---|---|
| | Combined Vol Groups | No. Samples | Combined Vol Groups | No. Samples | Combined Vol Groups | No. Samples |
| Interstate | 1,2 | 11 | 2,3,4 | 1 | 1 | 2 |
| | 3 | 6 | | | 2 | 6 |
| | 4,5 | 2 | | | 3,4 | 2 |
| Oth Frw & Exp | | | 1,2,3,4 | 1 | 1 | 1 |
| | | | | | 2 | 1 |
| | | | | | 3 | 1 |
| Oth Prin Art | 1 | 2 | 1 | 1 | 1,2,3 | 2 |
| | 2 | 4 | 2 | 1 | 4 | 2 |
| | 3 | 1 | 3 | 1 | 5 | 1 |
| | 4,5,6 | 1 | 4,5,6,7 | 2 | 6 | 2 |
| | | | | | 7,8,9,10 | 2 |
| Minor Art | 1 | 1 | 1,2,3 | 1 | 1,2 | 1 |
| | 2 | 1 | 4,5,6 | 1 | 3 | 2 |
| | 3 | 1 | | | 4 | 2 |
| | 4,5 | 2 | | | 5,6,7 | 1 |
| Collectors | 1 | 7 | 1,2,3,4 | 1 | 1,2,3,4,5,6 | 1 |
| | 2 | 6 | | | | |
| | 3 | 3 | | | | |
| | 4,5 | 3 | | | | |
| | | ------ | | ------ | | ------ |
| | | 51 | | 10 | | 29 |

## TABLE 3-6

## EXPANDED HPMS UNIVERSE

| Functional Classification | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Volume Group** | | | | | |
| **Rural** | | | | | | | | | | |
| Interstate | 2 | 46 | 17 | 6 | 2 | | 2 | | | 75 |
| Other Principal Arterials | 22 | 38 | 5 | 5 | 3 | 1 | 2 | | | 76 |
| Minor Arterials | 2 | 2 | 3 | 3 | | | | | | 10 |
| Collectors | 17 | 10 | 3 | 2 | | | | | | 32 |
| **Small Urban** | | | | | | | | | | |
| Interstate | | 7 | 7 | 1 | | | | | | 15 |
| Other Freeway & Expressway | 12 | 20 | 2 | | | | | | | 34 |
| Other Principal Arterials | 15 | 18 | 5 | 1 | | 2 | | | | 41 |
| Minor Arterials | 5 | 3 | | | | | | | | 8 |
| Collectors | 2 | 1 | 1 | | | | | | | 4 |
| **Urbanized** | | | | | | | | | | |
| Interstate | 19 | 30 | 12 | 1 | | | | | | 62 |
| Other Freeway & Expressway | 29 | 44 | 12 | | | | | | | 85 |
| Other Principal Arterials | | 4 | 25 | 23 | 9 | 11 | 18 | 3 | 3 | 96 |
| Minor Arterials | 13 | 7 | 12 | 10 | 8 | 3 | | | | 53 |
| Collectors | | | | | | | | | | |
| Total | 144 | 233 | 104 | 52 | 23 | 17 | 22 | 3 | 3 | 601 |

## TABLE 3-7

### ANNUAL SAMPLES BY FUNCTIONAL CLASSIFICATION

| Functional Classification | Year 1 | Year 2 | Year 3 | Total |
|---|---|---|---|---|
| <u>Rural</u> | | | | |
| Interstate | 6 | 7 | 6 | 19 |
| Other Principal Arterials | 5 | 1 | 2 | 8 |
| Minor Arterials | 2 | 1 | 2 | 5 |
| Collectors | 9 | 4 | 6 | 19 |
| <u>Small Urban</u> | | | | |
| Interstate | 0 | 0 | 1 | 1 |
| Other Freeway & Expressway | 1 | 0 | 0 | 1 |
| Other Principal Arterials | 0 | 2 | 3 | 5 |
| Minor Arterials | 2 | 0 | 0 | 2 |
| Collectors | 0 | 1 | 0 | 1 |
| <u>Urbanized</u> | | | | |
| Interstate | 0 | 5 | 5 | 10 |
| Other Freeway & Expressway | 0 | 2 | 1 | 3 |
| Other Principal Arterials | 3 | 4 | 2 | 9 |
| Minor Arterials | 2 | 3 | 1 | 6 |
| Collectors | 0 | 0 | 1 | 1 |
| | 30 | 30 | 30 | 90 |

# TABLE 4-1

## COMPARISON OF EQUIVALENT SINGLE AXLE LOADS
## STATIC WHEEL SCALES VERSUS WIM

| | 2 AXLE-6 TIRE | | 3 OR MORE AXLE SINGLE UNIT | | 3 AND 4 AXLE TTST | | 5 OR MORE AXLE TTST | |
|---|---|---|---|---|---|---|---|---|
| | STATIC | WIM | STATIC | WIM | STATIC | WIM | STATIC | WIM |
| RURAL INTERSTATE | | | | | | | | |
| Rigid | 0.177 | 0.229 | 0.691 | 0.726 | 0.547 | 1.287 | 1.242 | 1.780 |
| Flexible | 0.180 | 0.248 | 0.512 | 0.630 | 0.497 | 1.282 | 0.757 | 1.165 |
| ALL OTHER RURAL | | | | | | | | |
| Rigid | 0.136 | 0.162 | 0.818 | 0.971 | 0.374 | 1.211 | 0.876 | 1.693 |
| Flexible | 0.142 | 0.182 | 0.591 | 0.644 | 0.335 | 1.264 | 0.555 | 1.096 |
| ALL OTHER URBAN* | | | | | | | | |
| Rigid | 0.123 | 0.077 | 0.749 | 1.368 | 0.263 | 1.004 | 0.692 | 1.555 |
| Flexible | 0.125 | 0.066 | 0.519 | 0.915 | 0.265 | 0.956 | 0.447 | 1.015 |

*Does not include Interstate or Other Freeways & Expressways

# WISCONSIN REVISED TRUCK WEIGHT STUDY

*Paul P. Stein, Wisconsin Department of Transportation*

## BACKGROUND

In 1983 the Wisconsin Department of Transportation (WISDOT) implemented a truck weight data collection program utilizing a high speed Bridge Weigh-In-Motion (BWIM) system. This program called for data collection at 21 locations on 7 functional highway systems throughout the state. Duration of site operations was to be determined by attainment of predetermined truck type samples. These goals, and the allocation of sites between highway systems were determined by statistical analysis of Gross Vehicle Weight (GVW) data collected at permanent scales between 1980 and 1981. Additional guidelines were established to collect day, night, and seasonal data at a control station on each highway system.

In 1986 WISDOT began a study of the data collected to determine the adequacy of the program, the validity of the data collected, and to make recommendations for revisions in the program in light of the results of the analysis and the then recently published FHWA Transportation Monitoring Guide (TMG) guidelines. The results of this study were published in December 1987[1]. These results along with a the findings of a companion study on the population of overweight trucks in Wisconsin[2] are the focus of my presentation.

## 1983 - 1986 DATA BASE FINDINGS

While the plan called for collection of a target goal number of trucks for each truck classification for each highway system, the plan did not specify which goals were a priority, or how many goals should be attained. The practicality of time and equipment scheduling became the controlling factor, so in general collection was limited to that which could occur in a 40 hour week which included travel time, site preparation and equipment removal from two bridges or opposing lanes per week. This resulted in the attainment of 95% Confidence with 5% Precision level sampling goals for 3S-2s for most highway systems and 95/10 level goals for common truck types on higher volume systems. Sampling goals were seldom attained at night collection sessions or on weekends.

Based on the variability of GVW a 95/20 C/P level was attained for the overall data base. Individual highway systems ranged from 95/10 to 95/20 with the higher levels on the higher volume systems. For the 3S-2 which accounts for up to 80% of the truck population observed, a 95/10 to 95/20 C/P levels were attained based on ESAL variability. Slightly higher levels are attained if only loaded trucks are considered. These results met the goals of the plan with respect to weekday daytime data for the higher volume systems.

## METHOD OF DETERMINING REVISED PROGRAM

Initially determination of number of sites required for a revised program was attempted following the logic of the 1983 plan design while basing the determination on variability of ESALs as recommended in the TMG. This method based on weighted variability of ESALs between trucks produced a station requirement in excess of 2000 stations. It was then determined to utilize a parallel approach but based on the variability of station averages for GVW and ESALs. This method thus looks at variability between sites and produced the following station requirements based on C/P level noted.

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[1] Stein, Paul P., 1987. Review and Revision of the Wisconsin Department of Transportation Statewide Truck Weight Study Program. Madison, Wisconsin: Wisconsin DOT.

[2] Stein, Paul P., Friedrichs, David A. and Wiley, Marsh M., 1988. The Overweight Truck in Wisconsin - Its Impact on Highway Design, Maintenance and Enforcement Planning. Madison, Wisconsin: Wisconsin DOT.

## ESTIMATED STATION REQUIREMENTS
## BASED ON VARIABILITY OF MEAN ESALS BETWEEN STATIONS

| Highway System | Confidence/Precision Levels<br>95/10 | 95/15 | 95/20 |
|---|---|---|---|
| Urban Interstate (UI) | 1 | 1 | 1 |
| Rural Interstate (RI) | 18 | 8 | 5 |
| Urban Principal Arterial (UPA) | 23 | 10 | 6 |
| Rural Principal Arterial (RPA) | 6 | 3 | 2 |
| Urban Minor Arterial (UMA) | * | * | * |
| Rural Minor Arterial (RMA) | 256 | 114 | 64 |
| Major Collector (MC) | 231 | 103 | 58 |

* Only one station in data base, can not be determined using this method.

## REVISED PROGRAM

Based on the table above and the stated goals in the TMG the revised program will continue to collect data on 7 highway systems statewide at 69 stations over a three year cycle with one-third of the stations on each system sampled annually. Twenty-four stations will be on the Interstate with 6 on Urban segments and 18 on Rural. The urban sites were increased from the 1 needed according to the table to 2 per year to attain wider system coverage. Nine stations were assigned to each of the remaining systems. This should result in attaining TMG goals of ESAL data on 3S-2s at the 95/10 C/P levels or better on the Interstate and 95/20 for other systems, while providing us with expanded data to refine station assignment on systems other than the Interstate.

While sample goals for each truck type for each highway system were determined, they will be used as benchmarks for analysis of future data. Collection will be scheduled to include a minimum of 48 hours of continuous directional data collection at each site. Where ever practical data will be collected for all lanes of traffic. This system is anticipated to produce an expanded data base meeting benchmark goals on higher volume systems and sufficient data on lesser volume systems. To facilitate the expanded collection system the BWIM was replaced with two 2 lane pad W-I-M (PWIM) systems. Collection on 4 lane divided highways is accomplished by operating both systems from a motor home parked in the median.

## CONTROL PROGRAM

A control program for the purpose of collecting day of week and seasonal data was established. Under the old program one station on each system was designated as a control station at which in addition to the normal collection effort, one evening, one weekend, and three additional weekday sessions were scheduled per cycle (2 year). While this data provided some insights, it was not a statistically significant sample for valid analysis of evening and weekend data and the collection of additional weekday sessions did not follow a standard repeatable format.

To improve on the validity of the control program it was decided to focus the program on two systems, the urban and rural interstate. Three control stations were assigned to each system, with one on each to be collected each year. Collection at control stations will begin on monday following travel to site and site preparation and continue through the following week tuesday morning in alternating months from may through october resulting in three full weeks of data collection at each location. It is anticipated that this additional data will allow for the beginning development of factors for factoring 48 hour sample results to average weekly and average annual data. It is anticipated the control program will be useful in providing insights in determination of station needs for continuous truck weight data collection when the systems become affordable for network installation.

## SITE SELECTION

Due to the size of the sampling plan and the need to meet requirements of other data users sites were selected based on a number of criteria including AADT, HPMS sections, proposed SHRP sections, proximity of BWIM collection site, proximity to permanent enforcement scales, and proximity to existing ATR, control or classification count stations. AADT was a major factor in determination of possible segments on the minor arterial and major collector systems. Proposed SHRP sections were given priority over an equally qualified non-SHRP segment. Former BWIM collection sites, with suitable AADT were utilized for the value of historical data comparison. However, BWIM sites that were chosen primarily based on the availability of a bridge were not given priority. Possible sections were given consideration if they were in the proximity of a current ATR station or a count or classification control station. A map depicting possible site segments and enforcement scales was made and proposed sites were prioritized based on the forgoing considerations and the desire for statewide coverage. Where ever possible sites on the same segment or in close proximity to an enforcement scale were avoided. Final site selection was made by staff members inspecting the segments to determine if a specific site meeting PWIM system requirements existed. Two staff members touring the state over a week and a half period were able to field select approximately half of the 69 locations, only three segments had to be dropped due to no suitable site being found. Assignment of proposed sites to collection year was done through the use of random selection with minor alterations to efficiently schedule collection at sites on different systems in close proximity.

Avoidance of enforcement scales was done to maximize the probability of sampling an unbiased universe. An analysis of the data base for the years 1983 - 1986 indicated that overall 14% of the 3S-2s observed had a probable axle load above the legal limit. The average on highway systems ranged from 24% on the Urban Interstate to 6% on the Rural Minor Arterials. It is estimated that only 1% of the trucks weighed at enforcement scales are found to have a weight violation. Through the decision to avoid collecting data near enforcement scales it is hoped that system data will be developed to better assist the State Patrol in future scale site selection and personnel staffing and scheduling.

## DATA ANALYSIS

### MAGNITUDE OF DATA

Under the old program utilizing BWIM the maximum trucks weighed in a season was approximately 12,000. Over 250,000 truck weighing's have been accomplished through the end of September this year under the new program. It becomes imperative that this data be analyzed on a timely basis and the information disseminated to interested parties.

Each state and the Federal Government will be faced with the problem of managing this mountain of data and each analyst will be faced with some surprising and unexpected observations. New formulations for determining daily, weekly, monthly and annual average ESALs will be tried and improved upon. Various systems of data summarization will be designed. Old reports will be updated and new ones created and a multitude questions will need answers. While we are at the threshold of the new age in affordable automated WIM and AVC data collection systems it becomes imperative that findings, surprising observations, and questions be readily shared so that we may move forward efficiently.

## OBSERVATIONS AND QUESTIONS

How should 'Average ESALs' be determined? Since the ESAL curve is geometrical and not a straight line progression, is the 'mean' a valid computation? Using the old analogy which illustrates that you can't average values on the Richter Scale to come up with an average earthquake, the same applies to the earthquake scale of the 18 wheeler, the ESAL.

When analyzing ESALs is it proper to use statistical methods based on standard distribution or should a non-standard distribution method be developed?

Is it valid to use the AASHTO formula for determination of ESALs from dynamic forces? The AASHTO study measured the weight of the test trucks statically and did not measure dynamic effects. Since high and moderate speed WIM system dynamic weights will vary significantly from static weights are we overestimating ESALs when computed from WIM observations?

Which is the best method of determining ESALs; using look-up or semi-look-up table methods that assign one ESAL value to a range of 1,000 KIP for a single axle, 2,000 for a tandem and 3,000 for a Tridem with a table maximum value (similar to the method used in the new W-Table software) or computing ESALs based on formula to 0.1 KIP? WISDOT has computed ESALs using the AASHTO formula to 0.1 KIP. Our vendor software also computes an ESAL value for each truck using the look-up table approach. Based on approximately 150,000 FHWA Class 9 vehicle weighings this year the formula determined the average ESAL to be 1.6361 while the look-up approach resulted in a value of 1.9052, 16 percent greater than the formula method. This finding was some what of a surprise since there is no cap on the maximum ESAL that can be calculated. However, the variability of the ESAL observations when computed is greater than when a look-up method is used. The COV for these observations is 1.15 using the look-up tables and 1.36 following the formula.

An interesting and unexplained observation from the BWIM data showed that GVW on all highwy systems for 3S-2s rose substantially at night. However, Average ESALs per 3S-2 were lower at night on Rural segments and higher on Urban segments than their corresponding daytime average. Many explanations for this are possible. It would be interesting to know if anybody else has noted this phenomena. The 1988 data has yet to be analyzed in this respect.

I thank you for the opportunity to share some observations on how we in Wisconsin are approaching WIM data collection and some of the questions and observations we have seen. It is my hope that this conference will generate further discussion and the sharing of data and analytic approaches among the participants and their jurisdictions.

# NETWORK AND PROJECT DATA COLLECTION

*William E. Barrows ,Illinois Department of Transportation*

## Illinois Highway System

Illinois has 136,928 miles of roads and streets that carry 76 billion vehicle miles of travel (VMT) annually. The state system, 17,242 miles, represents 13% of the total miles but has 65% of the annual VMT. The interstate system of 1,933 miles, just over 1% of the total miles, carries almost one quarter of the annual VMT in the state. In addition to the state system there are three other highway systems in Illinois. Those are the county, township, and municipal systems. There are 102 counties, 1,488 townships, and 1,281 municipalities responsible for almost 120,000 miles of roads or streets or 87% of the total miles, however they only carry about 35% of the annual VMT in the state.

## Pavement Management, Major Data Items

The Department has a data base consisting of administrative data items, physical attributes and operational data items on all the roads and streets in Illinois as well as the 25,000 structures in the state. There is also a pavement feedback system that is being implemented for the interstate system. That system contains detailed information on the materials in the pavement, pavement distress, other construction details, historic information such as loadings and other factors affecting pavement performance. Illinois has nine district highway offices and each of these offices has a planning staff that has the responsibility for collecting the inventory data used to revise the data base as well as obtaining traffic volume and vehicle classification data. The central office is responsible for the policy and procedures for the data collection, processing the data to the data base and providing users with reports and information from the data base.

There are certain data items that are of primary use in pavement management on the state system. The major items listed are all data items included in the data base:

Functional Classification
Annual Average Daily Traffic (AADT)
Truck Traffic
Number of Lanes
Pavement Type
Pavement Width
Pavement Condition
Pavement Distress
Rideability
Shoulder Width and Type

The pavement condition rating survey is conducted on the entire state system on a biennial basis by visual inspection of a trained panel of raters from each district. They collect condition rating, pavement distress, and road ride. Condition rating is on a 1.0 (failed) to 9.0 (excellent) scale. Road ride is based on rider comfort 1 (poor) to 6 (good). Sampling techniques are used to ensure statewide consistency of data among the 9 district offices.

## Traffic Volume Data

Collecting traffic volume data for entry into the data base consists of several activities.

We are just completing a major renovation to our continuous count network. Several stations are being relocated to provide the statistical data needed by functional classification. The continuous count network consists of 45 locations which are solar powered and use telemetry to transmit data to the central office. Twenty-one of the stations classify the vehicles into the standard thirteen vehicle types as outlined in the Traffic Monitoring Guide (TMG) using piezo cable as an axle detector. We also use 35 speed monitoring stations to collect traffic volume data on a continuous basis. This basically provides us with 80 locations where traffic volume data is collected continuously.

There are 36 locations where data is collected for one week in each of the months: April, June, August and October. When seasonally factored, these counts provide reliable interstate anchor point AADT volumes to supplement the continuous count locations. Inductance loops in the pavement are used and the volume data is summarized by hour. There are also approximately 280 locations, many having inductance loops, where one week of volume data is collected each year. The volume data for the week long counts is also collected on a hourly basis.

The continuous count data is used to develop monthly factors to apply to 24 hour or 48 hour weekday machine counts made on Monday through Thursday to obtain an AADT volume. The continuous count stations are also used to develop travel monitoring reports on a monthly basis.

There are about 25,000 machine counts made annually that are mostly 24 hour counts. The State system is counted every two years and a map published along with entry of the volumes into the data base.

Each of the 102 counties are counted on a 5-year cycle. Roads having an AADT of 150 or more are usually counted along with any railroad grade crossings and structures that would not have a count as part of the scheduled count program. These counts are 24-hour machine counts taken on a Monday through Thursday. Traffic flow maps are published for the counties and the traffic volumes are entered to the highway data base by the district offices. Where district offices make comprehensive coverage counts in cities, traffic volume maps are prepared and the volume data is entered into the data base. The volume counts required for the Highway Performance Monitoring System (HPMS) samples are integrated into the overall counting program.

### Vehicle Classification Data

Approximately 1,000 manual counts are made annually by the district offices for intersection design studies or pavement design. These counts are automatically stored in a computer file when they are processed and this data is used to develop estimates of VMT by vehicle type by functional class or federal aid system. A truck map is published every four years showing truck volumes on the state system. Many of the counts for the map are made manually. The 21 continuous count stations that were recently installed that are classifying into the 13 vehicle types will be a major asset in estimating vehicle type VMT by system as well as developing factors to use on manual and portable classification counts. We are also implementing the TMG requirements whereby 48 hours of classification data will be collected at 300 sites, 100 each year.

Lack of portable classification equipment has limited us to about 40 sites per year for the last two years but we anticipate that will improve now that we have acquired additional equipment.

### Truck Weight Data

There are three permanent high speed WIM locations in Illinois. Each of these locations are on rural interstate routes and are capable of weighing in each of the lanes. They are intended to operate in a continuous mode with the data transferred to the central office by telemetry.

We are implementing weighing of the truck weight samples on HPMS sections as outlined in the TMG procedures which requires 30 locations per year, 90 samples in total for the three year period. A portable weigh pad is being used to collect the truck weight data at these locations. There are also several sites where we have collected portable WIM data in conjunction with ongoing research in the Department regarding specific pavement designs and the performance of those pavements.

## Project Data Collection

Project data collection is a responsibility of each of the district offices. Depending on the project it may be necessary to schedule machine volume counts and vehicle classification counts to supplement the data collected for the network. Once the current volume and vehicle classification data are compiled traffic estimates are prepared by the district office for each of three vehicle types, passenger vehicles, single unit trucks and buses, and multiple unit trucks (truck tractor semitrailers, full trailer combinations and other combinations of a similar nature).

Truck weight data is not collected for individual projects for design purposes at the present time. The current procedure entails the department utilizing static truck weight data to calculate 18 kip ESAL's per vehicle for each of the three vehicle types, passenger vehicles, single units, and multiple units. This information is used to calculate a traffic factor which is the number of 18 kip ESAL's anticipated to be carried by the pavement over its design life. This data is then used to determine the pavement thickness required.

At the present time we do not anticipate collecting truck weight data for individual projects. The variability of WIM weights when compared to static weights and the associated problems in using dynamic data to calculate ESAL's to be used for design of a pavement are such that it is our opinion the method currently in use is as good if not better than collecting truck weight data for specific projects. As an example we compared the average gross weight of 76 five-axle single trailer vehicles (class 9) obtained from a weigh pad at highway speeds of 55-60 MPH with the average gross weight of the same trucks at a permanent scale used for enforcement. The average static gross weight was 57,960# and the average WIM gross weight was 58,860# or about 1.6% higher. However, the average ESAL per truck using the static weights was 1.46 while the average ESAL using the WIM weights was 2.33 or 60% higher. We are interested in obtaining better vehicle classification data for specific projects but feel we can use network truck weight data to determine structural design.

We are analyzing the WIM data that has been collected and are making every effort to understand the accuracy and limitations of the data. This information is being compared to the ESAL data by vehicle type presently being used for design purposes and will be the basis whereby revisions to the ESAL data will take place in the future. However, we will probably use WIM data to detect trends in weights rather than using ESAL's from dynamic weights to replace those now in use.

We currently have a study underway with a university consortium to evaluate WIM data we have collected to determine if parameters such as speed, axle spacings, or steering axle weight could be used to edit out questionable truck data. We have also used the average weight of the steering axle on class 9 vehicles as a measure of whether the WIM scales were in calibration during the period truck weights were being obtained.

## Distribution of Truck Weight Samples

Selection of the 300 vehicle classification samples from the 3500 HPMS samples followed TMG guidelines. Selection of the 90 truck weight samples from the 300 vehicle classification samples also followed the suggested procedures. The truck weight samples are causing us some concern primarily because of the split between rural and urban and the relative low volume of trucks at some of the selected samples.

The vehicle classification samples are distributed to urban and rural and volume subgroups proportional to AVMT; therefore, the truck weight samples drawn from the vehicle classification samples have 67% of the samples in urban areas because 69% of the AVMT in urban areas. However, class 9 truck travel is just the reverse, that is, 66% is in rural areas with only 34% in urban areas.

The reason for using class 9 truck travel in this example is because it represents those trucks responsible for the majority of the ESAL's applied to the pavements. As an example, data from our permanent WIM station shows that class 9 vehicles account for 78% all trucks in the traffic stream and almost 90% of the total ESAL's being generated by those trucks.

The 30 selected truck weight samples on the interstate system show a similar pattern, that is, only 40% of the truck weight samples are on the rural interstate system where 69% of the interstate class 9 truck travel occurs. In fact 46% of all class 9 truck travel in Illinois is on the rural interstate system but only 13% or 12 of our truck weight samples are on that system.

The 60 selected truck weight samples on other roads resulted in 70% of the sites in urban areas where 41% of the class 9 truck travel on other roads occurs. Only 14% of all class 9 truck travel is on urban other roads but 47% or 42 of our 90 samples are on this system. We also have several sites that have relative low truck volumes. This is particularly true in urban areas on the lower classification roads.

## Concerns, Problems, and Suggestions

Using the TMG procedures in Illinois resulted in 60 of the 90 truck weight samples in urban areas where only 34% of the class 9 truck VMT is located. Thirty of the samples or 1/3 are not on the state system and do not carry any route markings. The truck volume on many of those samples is very low.

This creates some problems unless we can modify the sample selection somehow. Urban locations with parking lanes basically prohibits us from setting a weigh pad. The cost per truck record of data collected becomes extremely high where there are low truck volumes. We had one sample on a state marked route where the AADT was about 1000 and the results of a 48 hour WIM set out resulted in 25 class 9 vehicles being recorded. The labor alone for driving to the site, setting it out, going back to pick it up plus the flagmen and expendable commodities for the setout was at least $450 so it cost us $18 for each class 9 vehicle weighed.

The resources available to us to operate the portable WIM are less than adequate so we want to make sure that what we collect fulfills FHWA requirements as well as our own needs in the State. I believe our current sample selection using the TMG is inadequate and needs to be improved. One suggestion is that class 9 truck VMT should be part of the sampling procedure. That would result in a shift of the samples to rural roads where the majority of class 9 truck travel is located. It is also suggested that a HPMS sample for a truck weight sample be required to have a minimum number of class 9 trucks or it would be rejected as a sample and replaced with a sample that does have some minimum number of class 9 trucks. This would result in more truck weight data per sample, thereby reducing the cost per truck record.

In the discussion period following the presentations I would be very interested in comments or suggestions you have regarding your experience using the TMG procedures to select the truck weight samples.

# NETWORK AND PROJECT DATA COLLECTION

*Keith E. Longenecker, P.E., Idaho Transportation Department*

Over the past several years, the Idaho Transportation Department has been developing and implementing new management systems to more efficiently carry out millions of dollars in construction and maintenance activities through better information regarding the highway facilities and resources, and targeting of limited construction and maintenance dollars. The programs are computer oriented, thus reducing manpower requirements, while at the same time providing analytical capabilities.

The complexities of developing and implementing these systems have made it necessary for the Department to hire private consultants and purchase equipment. This has resulted in up-front costs which are now completed.

The Planning and Budgeting Cycle of the Idaho Transportation Department forms the hub around which systems' performance and programming activities revolve (Figure 1). In this cycle, roadway inventories are conducted during April to September and the information is analyzed and evaluated and made available for determining system service levels in October and November. In May, alternative construction and maintenance work programs are drafted based on forecasted state user revenue for the budget year and Federal-aid apportionments. A draft legislative budget proposal is developed in June which is evaluated from forecasted required manpower, resources, operation expenses, contract payments and equipment needs. Required legislation and supplemental revenue are considered at this time. After the Bureau of the Budget and legislative adjustments are made, an approved budget is developed and the work program is adjusted by the Idaho Transportation Board. The various forecasts of manpower, etc. are then readjusted and the Department's internal budget is prepared. In a cyclic schedule, the inventories and system service levels are revised for the following year's activities.

The principle roadway inventories that go into the budgeting cycle are: pavement performance, traffic data, accident history, bridge inspections and roadway environment. Systems service levels are established for safety (economic loss/mile and hazard reduction goals), maintenance (performance) and pavement and bridge condition ratings. The above are used to identify system deficiencies and prioritize corrective projects.

The Department has a small staff; therefore, it is essential that all data be processed as automatically as possible. This is accomplished by collecting data on magnetic devices and processing it through microcomputers to the IBM mainframe computer. For this purpose, several automated data collection and processing systems have been developed.

Today, I will confine my remarks to two areas of data collection: traffic surveys and video imaging.

## TRAFFIC SURVEYS

Idaho is presently implementing the Traffic Monitoring Guide including special needs studies. We developed a statewide traffic data collection plan which will be evaluated in three years and again in six years. The traffic volume data collection portion has been implemented and work is being done on equipment needs for drawing the vehicle classification and truck weight samples.

For the past three years we have been building a database of commercial volumes at ATR sites based on vehicle volumes and lengths. These will be used to forecast commercial volumes by vehicle lengths and changes in commercial trends. The ATR's are also used to obtain data for seasonal variation analysis.

Our present traffic data system forecasts Equivalent Single Axle Loads (ESALS) stratified by light, medium and heavy vehicle classifications. The AASHTO formula is used to calculate ESALS per vehicle.

In the future, we will try to establish a correlation between the Gross National Product and truck volume trends and also ESALS. If there are no correlations, we will continue to use truck volume and weight trends.

Vehicle classifications are collected for a minimum of 48 continuous hours. Because of the extended count period we are actively working on upgrading vehicle classification equipment. Our philosophy is that each vehicle is represented by a data record. This gives us the flexibility to calculate volumes, speed and vehicle classes for any time increment by axle arrangement. To accomplish this, we have developed our own vehicle classifier configured to an MS DOS microcomputer. This was done in an effort to write a specification for the type vehicle data recorders we plan to purchase. We have also been testing a vehicle classifier developed by the Diamond Scale Co. of Oregon. These two classifiers have recently been tested and the results are good. Twenty units have been ordered for more intensive study for network evaluation.

We conducted a study in cooperation with the State of Wyoming on traffic recorders from five different manufacturers and the two units that capture individual vehicle records. From the results, we do not believe present commercial data collection equipment does an adequate job of binning truck weight and classification data into thirteen vehicle-type categories.

In combination with the vehicle data recorder efforts, we are testing road tubes for diameter and hardness. We find that lengths, diameter and hardness affect the accuracy of the data collection; and there is also a significant variation in air switches. For these reasons, we are developing our own specifications for road tubes and air switches.

For truck weights, we have been testing Golden River WIM equipment as part of the HELP study. The tests have been made at Bliss, Idaho. Wiley Cunagin of Texas Transportation Institute has been observing the field operations and analyzing the data.

In Idaho, seven, nine and more axles are becoming more commonplace. The thirteen categories in scheme F do not give enough information to monitor these vehicles. This affects the calculation of ESALS. By capturing the time and speed of each axle, we are able to classify up to nine axles with the software we have developed. In the future, this will give us the capability to perform pace, gap and speed studies directly from the vehicle classification data. We will also be able to relate vehicle types to accident records.

Plans and specifications have been prepared for automating the Ports of Entry. The systems will be modular and designed to capture each vehicle. At the present time, load cells are being installed on static scales at the Ports of Entry so they can operate as slow speed weigh-in-motion scales. A data record for each vehicle will be captured. A pilot project will include a vehicle classifier using road tubes or other permanently installed axle sensors. At low volume Ports of Entry the modified static scales will be adequate. At higher volume Ports of Entry we eventually plan to use WIM systems to bypass legal loads. From the truck weight data seasonal variations and forecasting data will be determined. As part of the analysis, we are trying to calculate WIM factors by commercial vehicle classifications. These will be used with actual WIM data to arrive at accurate commercial weight data.

For construction projects we plan to use WIM equipment to collect project specific information. This will be done for major projects. We will have to collect data four times a year where there is seasonal-type activity, i.e., logging, harvesting, etc. This would give us a base for forecasting ESALS and commercial volumes from our network trends. We plan to track changes in trends of truck loadings at SHRP sites and some HPMS sites. I should say, however, that I have some concerns regarding the use of dynamic loads for pavement design at this time.

A memorandum from Dick Morgan, Executive Director, FHWA, to the Regional Administrators, dated March 2, 1988, recommended that "all States immediately move from the use of static weights for non-weight enforcement data gathering to the use of WIM data collection using techniques comparable to those outlined in the FHWA Traffic Monitoring Guide (TMG)." There are several issues that should be resolved before this policy is firmed up.

1. Dynamic loads should be correlated to static loads in the determination of load damage factors for pavement design since the AASHTO equations are based on static loads. The SHRP study should enable us to make the correlations.

2. There are factors that affect dynamic loads which vary from location to location, i.e., roughness, grade, etc. These need to be evaluated.

## VIDEO IMAGING

The pavement distress survey is a component of the Idaho Transportation Department's annual pavement condition inventory. The other components are roughness, deflection and skid. The computer models can be run using any combination of distress, roughness and deflection or singly. The current method of observing and rating the pavement surface distress through the window of a slow moving vehicle is time consuming, inaccurate and incomplete. Therefore, the Department has been involved in the development of an automated pavement surface distress acquisition and analysis system which is capable of providing pavement surface distress data either at the network or project levels in a fast, complete and accurate manner.

The initial work was begun in 1983 and vertical video pictures of the Idaho Interstate system and selected Primary highways were taken at highway speeds in 1985, 1986 and 1987. The work has progressed to the point where project level cracks can be identified by type, quantity and severity. These are automatically calculated and plotted with a Compaq 386 computer. We are presently investigating methods to increase the trough time to digitize the video frames. This includes a 25 MHZ microcomputer and specialized digitizing boards.

The scope of work for 1988 consists of again capturing the pavement surface images of the Idaho Interstate highways and the Principal Arterials in ITD District Three with four video cameras mounted in a trailer and towed at traffic speeds up to 65 MPH.

The Interstate Highways will be surveyed in both directions while the Principal Arterials will be surveyed in one direction only. The total estimated mileage of the pavement surface to be surveyed is 1220 lane miles of Interstate Highways and 380 miles of Principal Arterials.

Three cameras will be positioned so that at least a twelve foot width of the pavement surface is covered. A fourth camera will use a wide angle lens to shoot the entire twelve foot width for visual synchronization purposes. The name of the highway, milepoint and segment code, direction of travel and survey date will be recorded on the video tape at the beginning and ending of each tape. Milepoints to the thousandth of a mile will be shown on the monitor at all times during tape playback. The tapes will be in VHS format to allow the automated data extraction program to extract cracking data from the tapes.

The objectives of the Distress Index development procedures are as follows:

1. Utilize the video images captured in pixel by a CCD video camera at highway speed as the primary basis and source of the Pavement Distress Survey.

2. Develop a process whereby gray-scale resolution of video images can distinguish and classify various pavement crack types on pavements of the State High;way System.

3. Develop a process whereby pavement distress can be measured as to its approximate crack length and width and develop a program algorithm to calculate the surface crack impact area.

4. Study and analyze procedures and hardware that will facilitate mass storage of inventoried historical data for evaluating crack indices and performance of pavement maintenance and rehabilitation needs.

5. Develop an indexing procedure based upon the various distress and severity classifications, and density of affected crack areas; and identify the stages of pavement crack deterioration and the implication of the pavement distress in relation to performance.

In conclusion, technological developments are changing the way we do things in the highway business. With the data collection and processing power available to us today and tomorrow, we will do things impossible only a short time ago. In the future, I believe we will see deflection and pavement thickness measuring devices traveling at highway speeds. The motto for tomorrow is: "Think Digital."

# REMARKS ON THE FEASIBILITY OF A NATIONAL HEAVY VEHICLE MONITORING SYSTEM

*Lance Grenzeback*

For details on this presentation see:

Lance R. Grenzeback, Joseph R. Stowers, Ashok B. Boghani; *Feasibility of a National Heavy Vehicle Monitoring System*. NCHRP Report Series, Forthcoming, Jan. or Feb. 1989.

## PAVEMENT MANAGEMENT WORKSHOP, DATA ANALYSIS AND USE

*Presiding: Dave McElhaney*

In the next few minutes, I'm going to summarize the second part of the Pavement Management Workshop, which dealt with Data Analysis and Use. For those of you who were not in attendance at the workshop, the seven presentations that were delivered will be reprinted in the Final Report to this conference which will be distributed to attendees. I certainly encourage all of you to read these excellent papers, but for now, I'm going to briefly outline the workshop for you by reemphasizing some of the highlights of each presentation.

Bonnie Brothers, from the Tennessee Department of Transportation, began the workshop by offering an overview of Tennessee's experience in implementing the Traffic Monitoring Guide. She showed how they have progressed from the labor-intensive, static loadometer studies, to weigh-in-motion (WIM) equipment, with which abundant data on truck weights can be obtained much more cost-effectively. She summarized how WIM data has been analyzed and used as a planning tool by establishing trends in highway usage in Tennessee.

Barna Juhasz, Chief of the FHWA's Planning Analysis Division in Washington, D.C., showed that historically, truck travel, as well as the number of Equivalent Single Axle Loads (ESAL's) applied to our pavements, have been increasing at a more rapid rate than originally anticipated. His comments emphasized the importance of WIM information to generate more reliable future estimates of truck volumes and weights to predict and design for future pavement performance.

Our third speaker was David Huft, from the South Dakota Department of Transportation. He discussed South Dakota's use of bridge WIM equipment since 1983, and their recent attempts to use capacitance pads since 1986. They have tried to estimate static weights based on the dynamic forces produced by WIM equipment, since static weights are the basis for the AASHTO pavement design procedures. This work has observed a slight increase in overall truck traffic damage to pavements from 1983 to 1985. Dave noted that South Dakota plans to expand its program to include more WIM sites in the immediate future.

Mark Hallenbeck of TRAC discussed the design implications of the difference between weight data obtained statically versus data obtained via WIM equipment. He explained the theory behind his suggestion that WIM actually overestimates ESAL's and concluded by suggesting a method to bring WIM estimates down to more closely parallel static determination of ESAL's.

Curtis Dahlin from the Minnesota Department of Transportation described the experiences Minnesota has had since 1981, when it installed its first continuously operating WIM system. He reviewed Minnesota's process for converting WIM data and vehicle classification information to arrive at an Annual Average Daily Traffic (AADT). He also noted that the weight on a tandem axle should not necessarily be interpreted as being equally divided between the front and rear axles. His research showed that on rough pavements especially, the weight imbalance between the front and rear axles on a tandem axle can be nearly as much as 20%. Echoing Mark Hallenbeck's discussion, Curtis also touched on the potential overestimation of ESAL factors and suggested that further research be done to provide for a correction factor.

Wisconsin's Bruce Aunet pointed out that ESAL forecasting procedures are relatively primitive, due, in part, to the limitations of current data, and then referred to Wisconsin's present procedures, and how they plan to improve the quality of data collected in the future. After a State has taken the step toward collecting more accurate data, he discussed how a State needs to fully interpret that data into a meaningful and useful format. Next, he explained the factors that should be considered when forecasting total ESAL's, and showed how pavement thickness design is not particularly sensitive to total ESAL forecasts. He concluded that we may do better to concentrate our efforts on improving current estimates, rather than to spend time developing a sophisticated model designed to forecast total ESAL's.

FHWA's Perry Kent was our final speaker who demonstrated how to use the new Traffic Monitoring Guide software to analyze Truck Weight Study data. He emphasized that the software was developed with flexibility in mind, so that each State could adapt the software to its own specific needs. Distribution of this software is expected by the end of the year.

In summary, I think we have all seen during this past week that a shift has taken place from the earlier conferences which focused on WIM equipment, to this conference, which concentrated more on data accuracy and uses of data. Although there is some concern that we may be systematically slightly overestimating ESAL's with WIM, most agree that WIM data is much superior to older static weight studies in representing the traffic using our highway systems. We were rightfully cautioned to pay closer attention to forecasting of ESAL data to provide a more accurate assessment of pavement needs in the future.

Finally, I would like to acknowledge the States of Wisconsin, Iowa, and Minnesota, on behalf of the FHWA on the fantastic job they did in preparing and presenting what I think has been a most successful weigh-in-motion conference. I'm sure that, in addition to speaking for myself and FHWA, the salute also represents the feeling of the rest of the attendees towards our gracious hosts.

# TENNESSEE WEIGH-IN-MOTION

*Bonnie H. Brothers, Civil Engineer Manager 1, Tennessee DOT*

Tennessee did the necessary analysis to meet the requirements of the Traffic Monitoring Guide for HPMS data collection. We colored coded a State map for all 84,000 miles of roadway by each functional system, county by county. We calculated the percent of DVMT for each functional system (Table 1). From the TMG we determined that about 300 stations were required for Tennessee but we knew we needed more because of our TRIMS file. TRIMS stands for Tennessee Roadway Information Management System. We have all 26,000 miles of functional class routes on TRIMS. The TRIMS personnel calculate ADT, DHV, peak hour and three types of vehicle class by sections for the 26,000. From TRIMS we obtain the vehicle class changes across the State. We have Knoxville, Chattanooga, Nashville, and Memphis plus five other urbanized areas with the remaining areas being small urban and rural.

The Traffic Section does forecasting for the Department's Planning, Design, Structures, and Program Divisions for all 95 counties in the State. We make 12,000 annual machine counts and 600 manual turning movement counts annually. On the colored coded map we spotted 300 classification stations required by the TMG by first identifying the 33 continuous ATR locations (Figure 1), (Figure 2). We are doing 600 classifications on three-year cycle which includes the 90 WIM stations (figure 3). Of the 90 WIM stations, 30 are on rural and urban Interstates. (We have 1,062 miles of Interstate highways in Tennessee), 28 are on other rural locations and 32 on other urban locations (Table 2). Each year we weigh at about 30 stations.

As Richard Morgan said the other day, "One can understand how important the WIM is, because FHWA has so many representatives here and they usually don't put this much emphasis on most conferences". We have found this to be true, as Tennessee gets more and more requests concerning truck traffic.

In 1937 through 1976 Tennessee conducted weighing operations each year, then beginning in 1976 Tennessee started weighing every two years. In 1985 Tennessee purchased a Streeter-Richardson WIM system. We have a four-man crew operating the WIM equipment on a four-day shift, collecting data for 24 hours. In 1986 Tennessee compared 14 stations using WIM equipment to the 1984 at ten portable and four pit locations. In 1984, 2,000 trucks were weighed and in 1986, 52,000 trucks were weighed using WIM. Table 3 compares the 1984 portable loadometer static weight scales to the 1986 WIM for total vehicles, trucks, and ADL.

Data for truck axle equivalency factors are taken from the "W-4" Tables and tabulated by vehicle type and functional systems. Charts and Graphs are completed for rural Interstates, rural FAP and urban routes for each vehicle type for Flexible and Rigid pavements. Rural Interstate, five axle or more TTST are shown on Table 4 and Figure 4. The averages are calculated and also a projected 10-year Trend is calculated. These values are used for calculating ADL for pavement design, (Table 5).

Last year the Design Section requested an analysis and evaluation on the percent of trucks in the design lane. Comparisons were made of the ASSHTO Interim Guide Procedures, the NCHR 277 and the Highway CApacity Manual. Graphs were produced and the truck percents on Figure 5 and TAble 6 were recommended for TDOT usage in computing ADL's for pavement design.

Each season for WIM equipment is calibrated using Interstate truck weight enforcement platform scales and section of Interstate with loops installed down stream from the enforcement station. Samples consisting of Dual Rear, 3S1, 3S2, and twin trailers are sued to calibrate the WIM equipment. Throughout the season the fieldmen can usually determine when the scales need to be recalibrated by noting such things as the weight of empty car carriers, if their weight varies they calibrate.

Each time a WIM, a machine or a manual classification is completed, an axle adjustment factor is calculated (Table 7). If a road tube had counted this particular location the machine count would indicate 42,310 vehicles instead of 13,345 vehicles, thus an axle adjustment of 0.63 should be calculated. Each factor obtained is placed on a large map. Tennessee has an axle adjustment factor for each of our 12,000 annual 24-hour machine counts. The TRIMS file is adjusted for axle for all the functional classified routes in Tennessee.

TABLE 1

CLASSIFICATION STATIONS

| | (1000) Miles | DVMT * | % | Number Stations |
|---|---|---|---|---|
| Interstate, Rural | 783 | 13,869 | 15.63 | 47 |
| Principal, Art., Rural | 1,061 | 5,306 | 5.98 | 18 |
| Minor Art., Rural | 4,153 | 12,633 | 14.23 | 43 |
| Major Collector, Rural | 5,345 | 4,843 | 5.46 | 16 |
| Minor Collector, Rural | 11,089 | 7,274 | 8.19 | 24** |
| Local | 49,694 | 4,823 | - | - |
| Sub-Total | 72,125 | 48,248 | 49.49 | 148 |
| | | | | |
| Interstate, Urban | 248 | 10,694 | 12.05 | 36 |
| Principal, Art., Urban | 1,370 | 23,708 | 26.71 | 80 |
| Minor Art., Urban | 959 | 6,379 | 7.18 | 22 |
| Collector, Urban | 1,239 | 4,054 | 4.57 | 14 |
| Local | 8,168 | - | - | - |
| Sub-Total Urban | 11,984 | 44,835 | 50.51 | 152 |
| Total Rural & Urban | 84,109 | 88,760* | | 300 |

| | Non<br>Required | Tk. Wt. | Tk. Wt. | Spotted |
|---|---|---|---|---|
| Interstate, Rural | 47 | 25 | 17 | 42 |
| Prin. Art., Rural | 18 | 39 | 8 | 47 |
| Minor Art., Rural | 43 | 178 | 12 | 190 |
| Major Collector, Rural | 16 | 24 | 11 | 35 |
| Interstate, Urban | 36 | 25 | 17 | 42 |
| Principal Art., Urban | 80 | 106 | 20 | 126 |
| Minor Art., Urban | 22 | 73 | 6 | 79 |
| Collector, Urban | 14 | 12 | 4 | 16 |
| Total Rural & Urban | 276 | 485 | 91 | 576 |

* TRIMS (Local not included)
** too low class.

TABLE 2

## WEIGH-IN-MOTION STATIONS

| | (1000)<br>DVMT | % | #<br>Tk. Wt. Sta. |
|---|---|---|---|
| Interstate, Rural | 13,869 | 56% | 17 |
| Interstate, Urban | 10,694 | 44% | 13 |
| | 24,563 | | 30 |
| | | | |
| Other Rural[1] | 30,056 | 47% | 28 |
| Other Urban[1] | 34,141 | 53% | 32 |
| | 64,197 | | 60 |

[1] Not including Local

| | | | |
|---|---|---|---|
| Principal Arterial, Rural | 5,306 | 18% (28) | = 5 |
| Minor Arterial, Rural | 12,633 | 42% (28) | 12 |
| Collector, Rural | 12,117 | 40% (28) | 11 |
| | 30,056 | | 28 |
| | | | |
| Principal Arterial, Urban | 23,708 | 69% (32) | = 22 |
| Minor Arterial, Urban | 6,379 | 19% (32) | 6 |
| Collector, Urban | 4,054 | 12% (32) | 4 |
| | 34,141 | | 32 |

Interstate, Urban

| | | | |
|---|---|---|---|
| Memphis | 2,627,920 | 27% | 4 |
| Nashville | 4,008,543 | 41% | 5 |
| Chattanooga | 1,135,026 | 12% | 2 |
| Knoxville | 1,931,650 | 20% | 2 |
| | 9,703,139 | | 13 |

Table 3

### TENNESSEE
### TRUCK WEIGHT STATIONS
### 1986 WIM VS 1984 PORTABLE LOADOMETER SCALES

| | TOTAL VEHICLES | | TRUCKS | | ADL FLEX | | RIGID |
|---|---|---|---|---|---|---|---|
| STATION | 1948 | 1986 | 1984 | 1986 | 1984 | 1986 | |
| 2 | 6,815 | 6,351 | 1,449 | 1,312 | 1,238 | 1,105 | |
| 3 | 4,957 | 4,999 | 737 | 668 | 791[1] | 448 | |
| 4 | 4,528 | 4,154 | 629 | 486 | 591 | 428 | |
| 5 | 14,475 | 7,386[2] | 780 | 508 | 423 | 376 | |
| 8 | 9,088 | 8,005 | 770 | 575 | 343 | 191 | |
| 9 | 20,072 | 24,944 | 6,191 | 5,736 | 6,723 | 6,349 | |
| 10 | 3,765 | 2,769 | 366 | 351 | 239 | 236 | |
| 11 | 39,134 | 46,230[3] | 10,046 | 8,797 | 9,074 | 9,813 | |
| 13 | 14,540 | 9,126 | 3,179 | 3,174 | 2,182 | 3,338 | |
| 14 | 14,107 | 12,596 | 5,792 | 5,219 | 4,940 | 3,830 | 8,187 |
| 15 | 15,377 | 13,190[4] | 4,638 | 4,410 | 4,449 | 5,127 | |
| 16 | 8,380 | 7,704 | 504 | 458 | 134 | 353 | |
| 17 | 20,049 | 14,493 | 5,410 | 5,835 | 5,696 | 6,887 | |

1984 Stations weighed 6 AM - 2 PM, using sample of traffic stream.

1986 Stations weighed 24 hours all vehicles.

* These are not factored for day of week or month of year. 1986 and 1985 ADT in Classification Report match cycle counts or TRIMS.

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[1] 1982 ADL = 370, 1980 ADL = 549

[2] Station moved out to two-lane section in 1986, traffic decreases, but tractor trailer trucks remain constant.

[3] This count for truck weight station ramps only, so expanded.

[4] Doubled one side.

TABLE NO. 1
TENNESSEE TRUCK WEIGHT STUDY
18 KIP AXLE EQUIVALENCY FACTORS (RATE PER 1,000 TRUCKS WEIGHED)
PAVEMENT TYPE FLEXIBLE
HIGHWAY SYSTEM INTERSTATE RURAL

| | YEAR | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Type | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1978 | 1980 | 1982 | 1984 | 1986 | Average | Trend |
| Panel and Pickup | 2 | 3 | 2 | 4 | 3 | 2 | 4 | 5 | 6 | 5 | 9 | 9 | 3 | 1 | 0 | 4 2/ | 10 |
| Single Rear Tire | 2 | 7 | 5 | 3 | 3 | 9 | 7 | 8 | 8 | 6 | 5 | 7 | 14* | 10 | 0 | 6 2/ | 10 |
| Dual Rear Tire | 227 | 242 | 214 | 202 | 203 | 207 | 113 | 139 | 147 | 146 | 185 | 155 | 156 | 272* | 138 | 177 | 170 2/ |
| 3-Axle or More | 270 * | 227 * | 802 | 799 | 803 | 920 | 632 | 620 | 596 | 521 | 806 | 407* | 668 | 672 | 449* | 713 2/ | 350 |
| Sub-Total Single Unit Trucks | 92 | 101 | 113 | 107 | 107 | 98 | 62 | 67 | 60 | 56 | 69 | 52 | 57 | 73 | 98 | 81 | 100 |
| 3-Axle Tractor Trailer | 556 | 777 | 701 | 558 | 543 | 556 | 493 | 570 | 517 | 335* | 675 | 770 | 734 | 614 | 357 | 602 | 700 2/ |
| 4-Axle Tractor Trailer | 562 | 634 | 713 | 611 | 677 | 570 | 573 | 660 | 630 | 590 | 617 | 553 | 496 * | 534 | 334* | 610 | 540 |
| 5-Axle or More Tractor Trailer | 632* | 688* | 827 | 888 | 911 | 832 | 902 | 902 | 825 | 877 | 1068 | 868 | 920 | 1020 | 1043 | 914 | 1100 2/ |
| Sub-Total Tractor Trailer Trucks | 605* | 680* | 794 | 816 | 852 | 773 | 833 | 857 | 791 | 817 | 997* | 836 | 878 | 982 | 961 | 849 | 1000 |
| Total All Trucks | 339* | 396* | 486 | 501 | 520 | 434 | 436 | 458 | 401 | 382 * | 471 | 466 | 481 | 561 | 697 | 483 | 600 |

* Not used in averages or trends
1, Used 1973 to present
2/ Factor selected for ADL

Table 4

Table 5

TENNESSEE DEPARTMENT OF TRANSPORTATION
MAPPING AND STATISTICS OFFICE
TRAFFIC AND SAFETY PLANNING SECTION

PROJECT NO. P.E. 19002-1147-44
COUNTY Davidson
PROJECT DESCRIPTION West of Harding Place to East of Bell Road
ROUTE NO. I-24
CITY Nashville

## Interstate

## Pavement Structural Design

## Calculation of Equivalent Daily 18 Kip Single Axle Loads

| | Type Vehicle | 1999 (Mid-pt.)<br>ADT<br>(No. Counted) | Flexible | | Rigid | |
|---|---|---|---|---|---|---|
| | | | 18-kip Factor | ADL | 18-kip Factor | ADL |
| | Pass. cars, and motorcycles | 73814 | 0.001 | 73.8 | 0.001 | 73.8 |
| | Buses | 106 | 0.300 | 31.8 | 0.300 | 31.8 |
| Single-Unit | Panel, and Pick-up Trucks | 12519 | 0.004 | 50.1 | 0.005 | 62.6 |
| | 2-axle, 4-tire | 337 | 0.006 | 2.0 | 0.010 | 3.4 |
| | 2-axle, 6-tire | 2302 | 0.170 | 391.3 | 0.170 | 391.3 |
| | 3-axle or more | 481 | 0.700 | 336.7 | 1.000 | 481.0 |
| Tractor Semi-Trail. | 3-axle | 318 | 0.700 | 222.6 | 0.880 | 279.8 |
| | 4-axle | 645 | 0.700 | 451.5 | 0.780 | 503.1 |
| | 5-axle or more | 5778 | 1.100 | 6355.8 | 1.780 | 10284.8 |
| | Totals | 96300 | | 7915.6 | | 12111.6 |

**Suggested Percentages of Trucks in Design Lane**

| | 4 Lane | 6 Lane | 8 Lane |
|---|---|---|---|
| 5,000 or less ADT | 90% | 75% | 70% |
| 5,000 - 10,000 ADT | 80% | 70% | 65% |
| 10,000 - 15,000 ADT | 75% | 65% | 60% |
| 15,000 - 20,000 ADT | 75% | 65% | 55% |
| 20,000 - 30,000 ADT | 70% | 60%. | 50% |
| 30,000 - 70,000 ADT | 65% | 60% | 50% |

No. of Lanes 6
% Trucks in Design Lane 60%
ADL in Design Lane FLEX 0.5 X .60 X 7915.6 = 2374.7
RIGID 0.5 X .60 X 12111.6 = 3633.5

ADL Calculations By: Johnny R. Smith Date: 7-18-88
Reviewed By: Bonnie H. Brothers Date: 7-18-88

Table 6

## ATTACHMENT 1

## TRUCK PERCENTAGES IN LANE ONE

## FREEWAYS

| ONE-WAY DT (1000) | 4-LANE | | | 6-LANE | | | 8-LANE | | |
|---|---|---|---|---|---|---|---|---|---|
| | INTERIM GUIDE | NCHR 277 | CAP. MAN. | INTERIM GUIDE | NCHR 277 | CAP MAN. | INTERIM GUIDE | NCHR 277 | CAP. MAN. |
| 5 | 90 | 88 | 90 | 90 | 74 | 70 | 90 | 74 | 60 |
| 10 | 85 | 81 | 80 | 85 | 68 | 60 | 85 | 68 | 50 |
| 15 | 80 | 77 | 70 | 80 | 65 | 50 | 80 | 65 | 45 |
| 20 | 75 | 75 | 65 | 75 | 63 | 50 | 75 | 63 | 40 |
| 30 | 70 | 72 | 80 | 70 | 59 | 50 | 70 | 59 | 30 |
| 40 | 60 | 69 | - | 60 | 57 | 50 | 60 | 57 | 30 |
| 50 | 60 | 67 | - | 60 | 55 | 60 | 60 | 55 | 40 |
| 60 | 60 | 66 | - | 60 | 53 | 80 | 60 | 53 | 50 |
| 70 | 60 | 66 | - | 60 | 52 | 100 | 60 | 52 | 65 |

INTERIM GUIDE - Interim Guide Procedures, AASHTO, Appendix D, page D-2.

NCHR 277 - NCHR 277, "Portland Cement Concrete Pavement Evaluation Systems," TRB, NRC, Sept. 1985, Figure 6, page 52.

CAP. MAN. - "Highway Capacity Manual," Special Report 209, TRB, NRC, Dec. 1986, Figure 5-6, page 5-12.

## TRUCK PERCENTAGES IN LANE ONE

## FREEWAYS

| ONE-WAY · ADT (1000) | RECOMMENDED FOR TDOT | | |
|---|---|---|---|
| | 4-LANE | 6-LANE | 8-LANE |
| 5 | 90 | 75 | 70 |
| 10 | 80 | 70 | 65 |
| 15 | 75 | 65 | 60 |
| 20 | 75 | 65 | 55 |
| 30 | 70 | 60 | 50 |
| 40 | 65 | 60 | 50 |
| 50 | 65 | 60 | 50 |
| 60 | 65 | 60 | 50 |
| 70 | 65 | 60 | 50 |

Table 7.

## CLASSIFICATION

STATION: 54 COUNTY: GREENE

DATE: 5/10-12/88 ROUTE: I-81

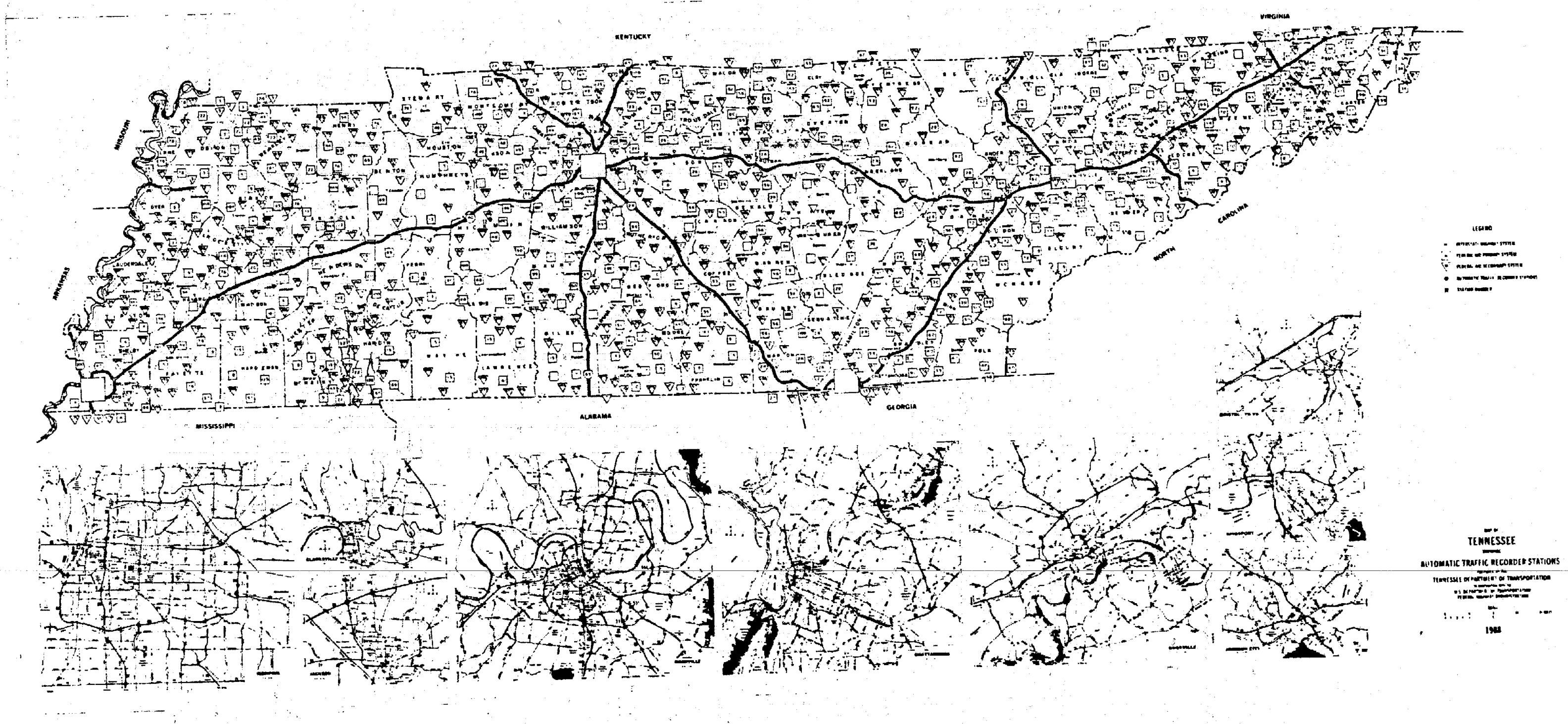
| CLASS | DIRECTION SOUTH | DIRECTION NORTH | TOTAL | % | |
|---|---|---|---|---|---|
| 1. Motorcycles | 9 | 7 | 16 | ,12 | |
| 2. Cars | 3151 | 3020 | 6171 | 46,24 | |
| 3. Pick-up, Panel, Van | 419 | 412 | 831 | 6,23 | |
| Sub-total Passenger Veh. | 3579 | 3439 | 7018 | 52,59 | 14,036 |
| 4. Buses | 12 | 7 | 19 | ,14 | 38 |
| 5. Dual Rear | 206 | 212 | 418 | 3,13 | 836 |
| 6. 3-Axle Tk. | 28 | 40 | 68 | ,51 | 204 |
| 7. 4-Axle Tk. | 6 | 3 | 9 | ,07 | 36 |
| Sub-total S.U. Tks. | 252 | 262 | 514 | 3,85 | |
| 8. 2S-1, 3S-1, 2S-2 | 239 | 242 | 481 | 3,60 | 1924 |
| 9. 3S-2, 2S-3 | 2041 | 2241 | 4282 | 32,09 | 21,410 |
| 10. 3S-3, 3S-4 | 12 | 22 | 34 | ,26 | 204 |
| Sub-total Comb. Tks. | 2292 | 2505 | 4797 | 35,95 | |
| 11. 2S-1-2 | 128 | 104 | 232 | 1,74 | 1160 |
| 12. 2S-2-2, 3S-1-2 | 18 | 12 | 30 | ,23 | 180 |
| 13. Any 7-Axle | 2 | 3 | 5 | ,03 | 35 |
| Sub-total Twin Trailers | 148 | 119 | 267 | 2,00 | |
| Total Combinations | 2440 | 2624 | 5064 | 37,95 | |
| Total Trucks | 2692 | 2886 | 5578 | 41,80 | |
| 14. Other | 338 | 411 | 749 | 5,61 | 2247 |
| Total Vehicles | 6609 | 6736 | 13,345 | 100,00 | 42310 |

1988 A.D.T. 14,150

$\frac{42,310}{2} = 21,155$

13345/21155 = .63

Figure 1



TENNESSEE

AUTOMATIC TRAFFIC RECORDER STATIONS

TENNESSEE DEPARTMENT OF TRANSPORTATION

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

1988

Figure 2

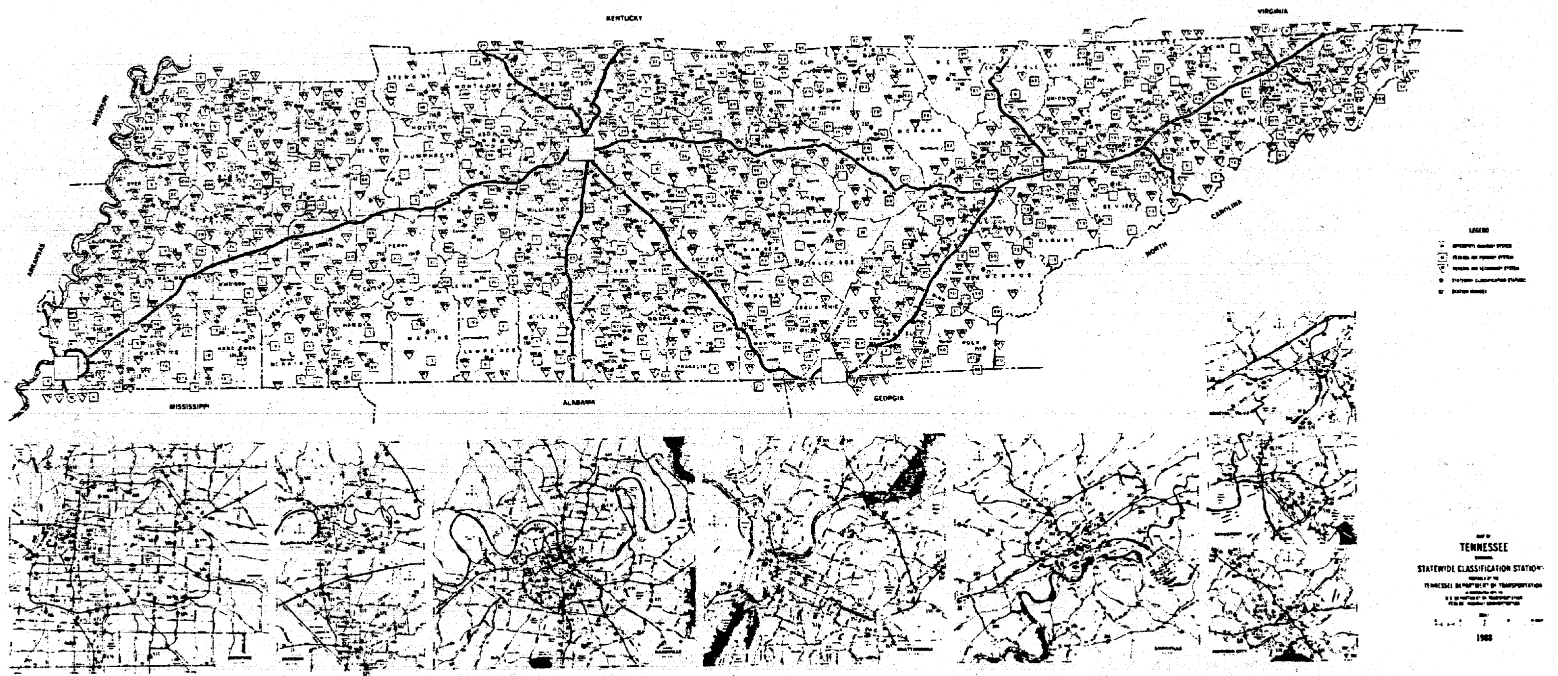
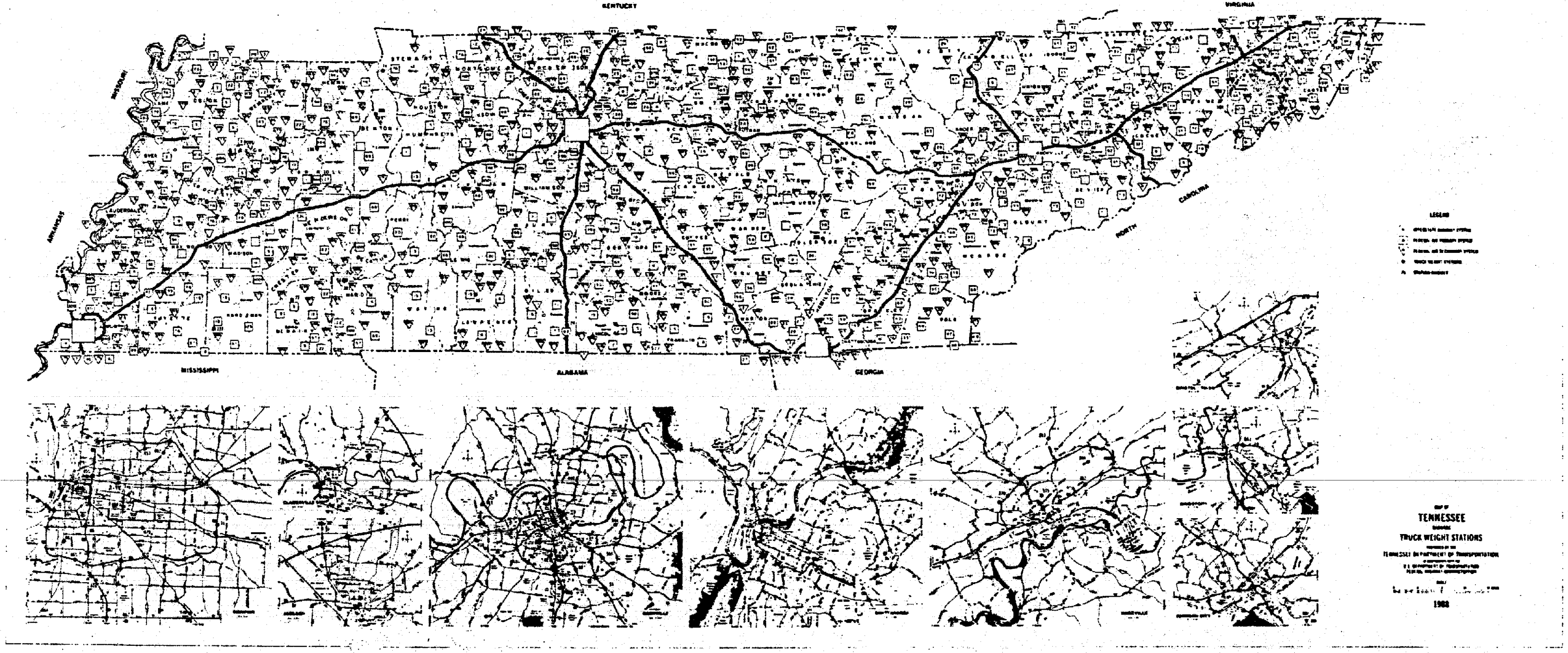

KENTUCKY
VIRGINIA
NORTH
CAROLINA
GEORGIA
ALABAMA
MISSISSIPPI
MISSOURI
ARKANSAS
LEGEND
TENNESSEE
STATEWIDE CLASSIFICATION STATIONS
1988

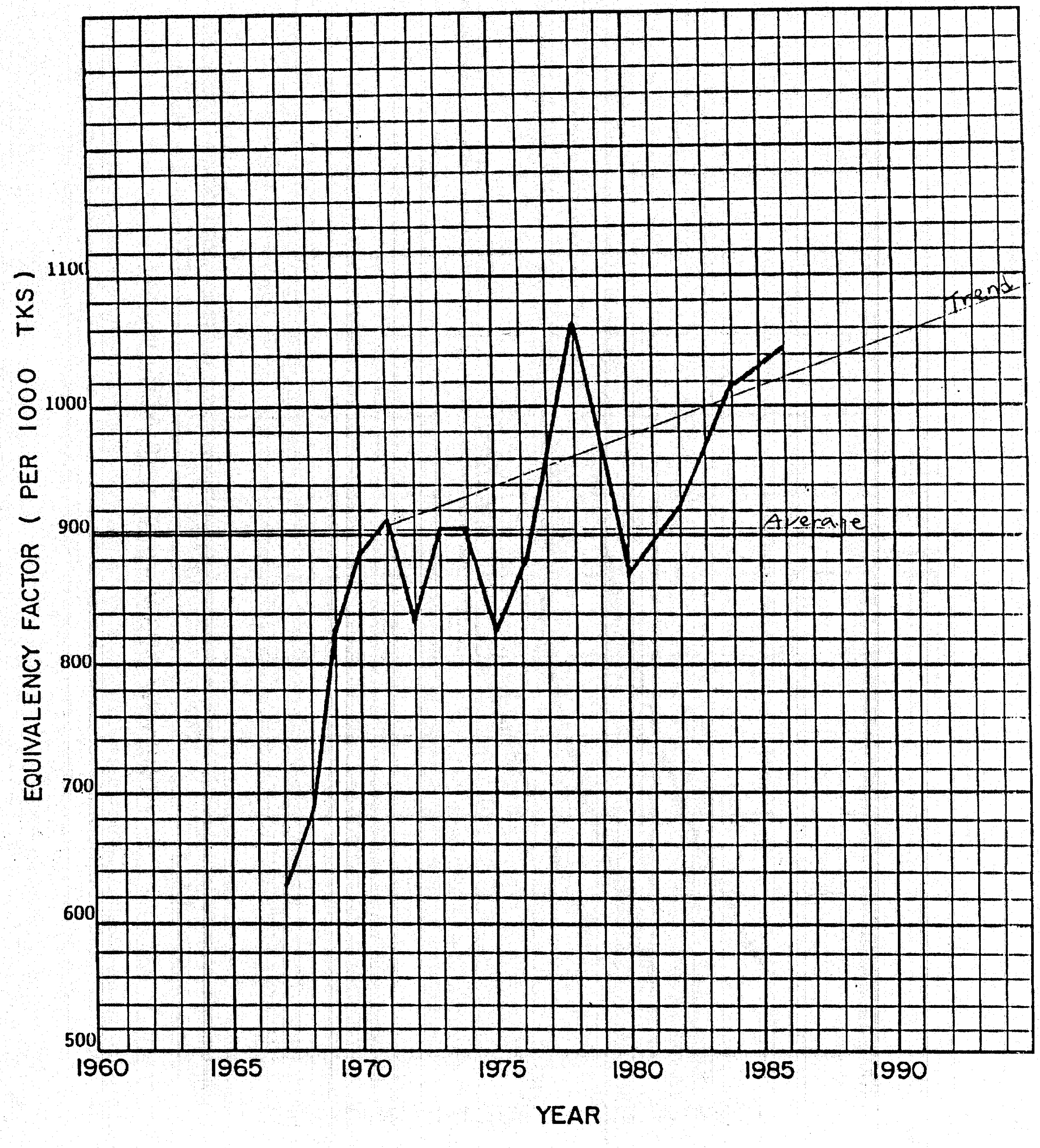
Figure 3


KENTUCKY
VIRGINIA
NORTH CAROLINA
MISSOURI
ARKANSAS
MISSISSIPPI
ALABAMA
GEORGIA
LEGEND
TENNESSEE
TRUCK WEIGHT STATIONS

## 18 KIP AXLE EQUIVALENCY FACTORS

Figure 4

SYSTEM INTERSTATE, RURAL
PAVEMENT TYPE FLEXIBLE
VEHICLE TYPE 5 AXLE OR MORE TTST



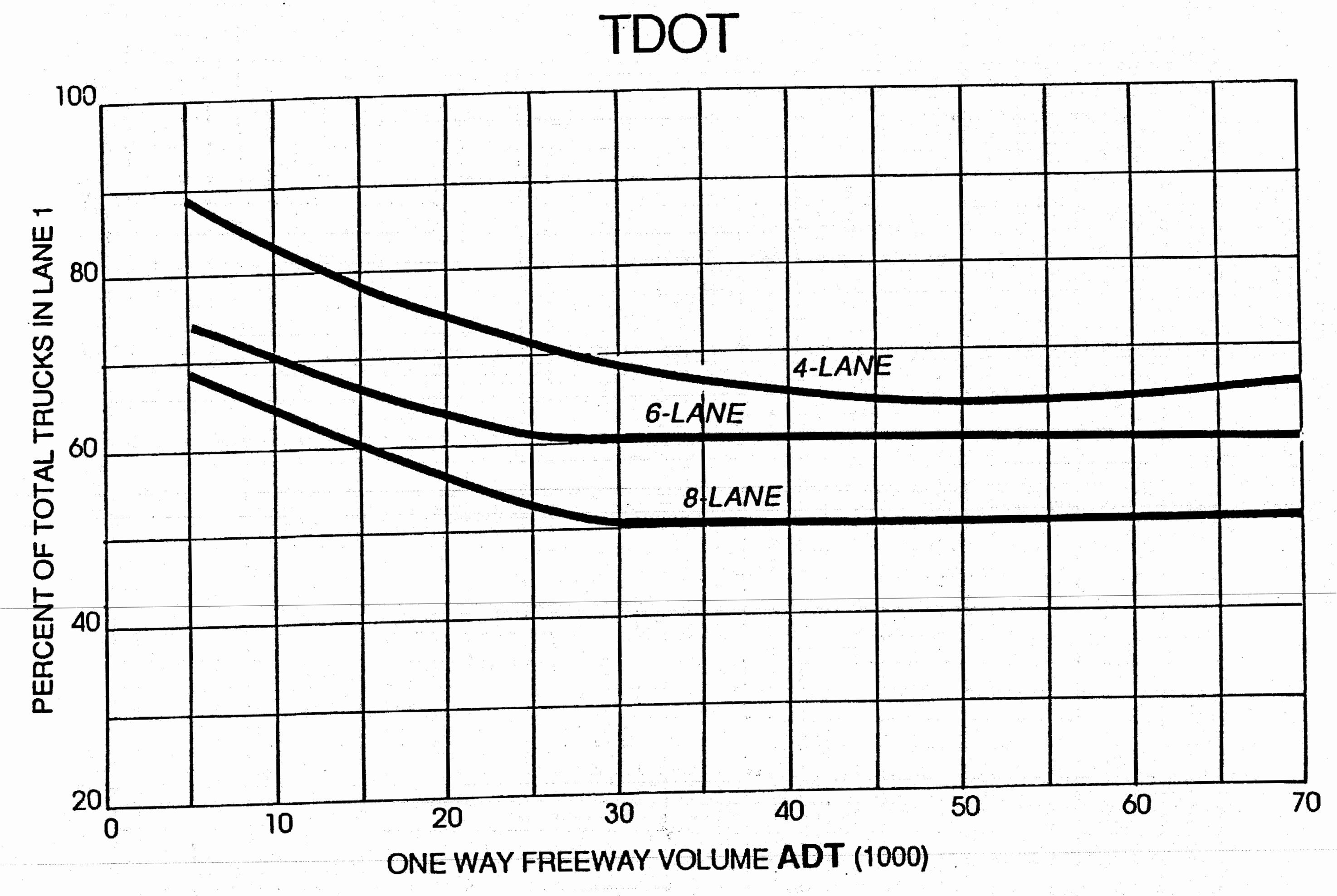

TDOT
PERCENT OF TOTAL TRUCKS IN LANE 1
100
80
60
40
20
0
10
20
30
40
50
60
70
ONE WAY FREEWAY VOLUME **ADT** (1000)
4-LANE
6-LANE
8-LANE

Figure 5

# IMPORTANCE OF TRUCKS IN PAVEMENT MANAGEMENT

*Barna Juhasz, James Gruver, Roger Petzold, Richard Backlund*
*Planning Analysis Division, Office of Planning, Federal Highway Administration*

## INTRODUCTION

The purpose of this paper is to discuss:

1. Why trucks movements on the highway system are important to pavement management.
2. How to determine where trucks are moving on the highway system now and in the future.
3. How to determine the effect of trucks on pavement performance now, in the future, and in the past.

With the completion of the Interstate System, attention has shifted from building a highway network to improving, operating, and maintaining the highway system. Thus, we have moved from construction to management of our highways in a cost-effective manner. Pavement management is an integral part of this overall highway management effort. Pavement management systems are being established to "assist decision makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition." This systematic approach is needed to improve management of this nations large existing investment in pavements and to help make better use of limited funds.

How large an investment do we have in pavements today? We have approximately 4 million miles of public highways with an annual total highway budget for all levels of governments of 63 billion dollars. Approximately 50 percent of these funds are spent on pavements. The conclusion is that management of pavements is a big job and that good management will result in big savings.

Many factors affect pavement performance; these include age, environment, load, drainage, design and construction quality. In this paper only truck related factors are addressed. The major truck related factor of concern is the load the truck imposes on the highway.

A single vehicle travels down the road on a pavement structure. That structure deflects slightly with each pass of an axle load. This deflection fatigues the pavement structure, reducing its strength, thereby causing distress and roughness. Given enough repetitions of load, the pavement structure will fail.

The problem facing pavement management is to determine, under specific conditions, how many loads a pavement structure can carry. To answer this question, the AASHO Road Test was carried out between 1958 and 1960 in Ottawa, Illinois.

## AASHO ROAD TEST

The AASHO Road Test was responsible for the concept of 18,000 pound equivalent single axle loads (ESALs). This concept provides, for any given pavement design, pavement damage caused by single or tandem axles to be expressed in terms of ESALs. The Road Test equation demonstrated for the first time, for conditions at the road test, that pavement performance is associated with specific axle loads and number of repetitions. The ESAL concept relates the pavement design needed for a specific level of pavement performance to a specific load level.

As defined at the AASHO Road Test, the ESAL is a function of:

(1) load on the axle or axle group,
(2) number of axles,
(3) the pavement structure (SN or D)
(4) the serviceability level at which the pavement needs repair.

The ESAL concept makes it possible to represent any mix of cars and trucks on the highway in terms of a group of single axles, all weighing 18,000 pounds. Since the Road Test, the typical axle loadings have increased and new pavement types have been introduced. At the Road Test, single axle loads ranged from 2,000 lbs to 30,000 lbs, and tandem axles loads ranged from 24,000 lbs to 48,000 lbs. No tridem axles were tested. The pavement design types used were limited and tested under one environmental condition and one subgrade condition. Using additional data accumulated since the road test, the ESAL factors contained in Appendix D, "AASHTO Design of Pavement Structures", have been adjusted to cover the wider load range of triple axles. In general, there is little change in ESAL factors for a reasonable range of terminal serviceability and pavement thicknesses, although differences do become significant at greater loadings.

## CURRENT TRENDS IN TRUCKS

Figure 1 shows the relative increase in growth for gross national product (GNP), vehicle miles of travel (VMT), heavy combination truck VMT and ESALs on the rural Interstate System from 1970 to 1985. The chart reveals that VMT and GNP have been growing at about 3.5 percent per year. Combination VMT has been growing at about 5.6 percent per year during this period, while the ESALs on the rural Interstate have been growing at about 9.1% per year. The movement of freight by trucks is increasing at about twice the rate of growth as the VMT or GNP. In addition, the high growth rate in ESALs indicates that there are more trucks on our highways and shows that a larger portion of these trucks are heavy combination trucks. Figure 1 also shows that the number of heavy trucks has increased steadily over time.

Overall the number of heavy combination trucks is growing faster than overall traffic, and the size and weight of these trucks are increasing over time. The result has been more damage to our pavements than anticipated. The key question is what does the future hold?

## FUTURE TRENDS IN TRUCKS

Recent forecasts by Data Resources, Inc., regarding the trucking industry indicate four major trends:

(1) Truck tonnage will grow faster than industry production in most commodity markets.

(2) The share of tonnage hauled by <u>for-hire fleets</u> will increase.

(3) Smaller shipments as corporations try to control inventories.

(4) Continued over capacity and intensified competition within the trucking industry

What this means is that the amount of freight hauled by trucks will continue to increase, more of this freight will be hauled by for-hire fleets, and competition within the trucking industry will intensify. In the future, we can expect more trucks on our highway system. Most of these additional trucks will be heavy combination trucks (i.e., 3S2, 2S2-2) loaded to legal limits. The end result is a continued growth in ESALs at a rate higher than GNP or VMT.

At the Federal level, a variety of changes are possible with regard to size and weight restrictions in the future. Changes being explored are:

Length and Trailer Configuration

- Increase twin trailer lengths up to 30 to 34 feet
- Larger route networks for "Longer Combination Vehicles"

Weight

- Remove 80,000-pound cap and allow bridge formula to govern
- Revise bridge formula
- Reduce axle weights
- Tandem-axle controls
- Tire pressure controls

The potential for change in the future in the types of trucks on our highways, especially on the Interstate, is high. We must carefully monitor changes to be able to accurately predict future loadings on our pavements.

Based on an FHWA study for the year 2020 it is estimated that truck VMT (2 axle, six tire and greater trucks) will grow at approximately the same rate as the gross national product (GNP). The compound growth rate will be 3.4% per year through 2005, and 2.7% per year from 2005 to 2020. This means that trucks will continue to grow faster than cars at a 50% greater rate. Figure 1 has shown that in the past heavy trucks have grown at an even faster rate. Assuming the same relationship between the rate of growth of heavy combination trucks and ESALs as shown in figure 1, the ESAL growth rate on rural Interstate should be approximately 5.7 percent per year through 2005 and 4.4 percent per year from 2005 to 2020. To better understand the growth in heavy combination vehicles and ESALs, we need to move from trend type forecasting procedures to forecasting procedures that reflect changes in truck fleets, gross national product, local economic and other indicators. In the year 2020 our highway structure will probably look much like it does today, but with many improvements in technology, both within the vehicle and along the highway. The future will result in many unexpected changes. We must continue to monitor these changes and improve our ability to forecast the future.

## IMPACT OF SPECIFIC TRUCK TYPES

The pavement manager needs to know the type of trucks moving over the highway system. The same cargo carried by different types of trucks will have very different effects on pavement performance. Table 1 shows 1000 tons of load carried by five different types of heavy commercial trucks and the resulting ESALs. The standard 3S2 results in 134 ESALs for flexible pavement. The western double (2S1-2) results in 175 ESALs, or a 30 percent increase in ESALs over the conventional 3S2. On the other hand, the addition of four extra axles and an increase in load of 20,000 lbs (the Turner truck proposal (3S2-4)) results in a 70 percent decrease in ESALs per 1000 tons of load. The Turner truck greatly decreases pavement damage, with a slight increase in operating cost and bridge deterioration. The pavement manager needs to know the types of heavy vehicles moving over his pavement to be able to predict future performance.

## PERFORMANCE PREDICTION

The maintenance, rehabilitation, reconstruction and construction of pavements is expensive both in terms of construction and user costs. The key to evaluation of alternative management strategies is the ability to accurately predict pavement performance. The AASHO Road Test developed relationships that showed that the loss in serviceability[1] is directly related to truck loadings for both rigid and flexible pavements (See Figure 2). To manage pavements one must know current pavement conditions and must be able to accurately predict the future performance of these pavements.

To accurately predict the performance of new or rehabilitated pavements, we must be able to accurately predict future heavy truck traffic. Without good truck information, we cannot conduct life-cycle-cost analyses that are meaningful, predict future needs, or evaluate alternative design loadings (ESALs).

## TRAFFIC DATA NEEDED IN PMS

In the discussion of traffic data needed for a PMS, we must keep in mind that the final product is the total number of ESALs during the design period for a specific location. To obtain this number, the traffic counting program provides the following data for each section:

- Current year AADT
- Vehicle classification
- ESAL factors by vehicle class
- Directional distribution factor
- Lane distribution factor

A traffic counting program based on the FHWA, "Traffic Monitoring Guide" or similar statistically based traffic program will provide the capability to estimate current AADTs for the State system.

Good vehicle classification data is the key to estimation of current ESALs. Vehicle classification data is highly variable by location. With the heavier vehicles (5 axles and more) responsible for most of the ESALs on our pavements (80 percent of the ESALs for all systems and 92 percent of the ESALs for rural Interstate highways), we should concentrate our efforts on accurately predicting heavy truck movements for percentages of 3S2s.

The FHWA "Traffic Monitoring Guide" (TMG) recommends approximately 300 sites per State be counted during a three year period to obtain representative vehicle classification data, with an approximate precision of 10 percent and a 95 percent confidence level. For estimation of ESALs, a minimum of three vehicle groupings is needed. The three groupings are:

| | |
|---|---|
| Light Vehicles - | Motorcycles<br>Cars<br>Pickups<br>Other 2 axle, 4 tire vehicles. |
| Medium Vehicles - | 2 axle, 6 tire, single unit<br>3 or more axle, single unit<br>3 or 4 axle, single trailer. |
| Heavy Vehicles - | 5 or more axle, single trailer<br>5 or more axle combination. |

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[1] <u>Present Serviceability Index (PSI)</u> - A formula used to estimate the mean of serviceability ratings made by a panel of judges.

<u>Present Serviceability Rating (PSR)</u> - The judgement of an observer as to the current ability of a pavement to serve the traffic it is meant to serve.

The average ESAL factors for these groups are:

| | | |
|---|---|---|
| Light Vehicles | 0.001 | ESALs per vehicle |
| Medium Vehicles | 0.35 | ESALs per vehicle |
| Heavy Vehicles | 1.00 | ESALs per vehicle |

From these ESAL factors it is evident that light vehicles, even in high volumes, contribute little to the total ESALs for any given roadway segment.

Truck weight data is the source of information to calculate ESALs for specific pavement types and vehicles. To obtain accurate weight data, enough random locations are needed to provide the accuracy level desired. The TMG recommends approximately 90 sites per State counted during a three year period to obtain ESAL estimates representative of the highway network for three axle tractor and two axle semi-trailer (3S2) trucks, with an approximate precision of 10 percent (20 percent for non-Interstate) and a 95 percent confidence level. The best way to obtain accurate weight data is with weigh-in-motion (WIM) data collection equipment.

The reason WIM data, rather than static data, is critical for the calculation of ESALs is that studies in Arizona and Maryland have shown that using static weighing for enforcement underestimated the number of overweight trucks by 34 percent during nonenforcement periods. Therefore, static scales (assuming trucks do not distinguish between enforcement and non-enforcement weighing) underestimate the number of heavy trucks which have the greatest effect on ESAL factors. Looking at a flexible pavement with a Structural Number (SN)=5, Terminal serviceability (pt)=2.5 and a 3S2 truck with a gross weight of 80,000 pounds, we see that the 3S2 causes 2.37 ESALs of damage to the pavement.

| **Steering Axle** | **Tandem Axle** | **Tandem Axle** | **Total** |
|---|---|---|---|
| 12,000 lbs | 34,000 lbs | 34,000 lbs | 80,000 lbs |
| 0.19 ESALs | 1.09 ESALs | 1.09 ESALs | 2.37 ESALs |

Now consider the same truck loaded to 100,000 pounds; this vehicle causes 6.19 ESALs of pavement damage.

| **Steering Axle** | **Tandem Axle** | **Tandem Axle** | **Total** |
|---|---|---|---|
| 12,000 lbs | 44,000 lbs | 44,000 lbs | 100,000 lbs |
| 0.19 ESALs | 3.00 ESALs | 3.00 ESALs | 6.19 ESALs |

As this example shows, a 25% increase in gross load results in a minimum increase in pavement damage of 161%. This is due to the 4th power relationship between axle weight and serviceability loss. This relationship indicates that a two unit increase in weight per axle causes a 16 unit increase in pavement damage. By using WIM equipment, we are now measuring the weight of the heavy trucks often missed by static scales. Stated differently, by not using WIM equipment, we could be underestimating pavement life by 25 percent.

## CURRENT HEAVY TRUCK VOLUMES

With heavy vehicle (three axle tractors with two axle semi-trailers, plus larger trucks) accounting for 80 percent of all ESALs on all highways and 92 percent of all ESALs on rural Interstate highways, pavement managers must know where these vehicles are moving on the highway system. One way to do this is to develop a heavy truck flow/load map for heavy vehicles (Figure 3). Heavy truck flow/load maps (i.e.,

Figure 3), if not already available from the Planning/Traffic Section in your State, can be developed from a statistically based traffic counting program which includes traffic, vehicle classification, and weight data.

To develop a truck flow map, one begins by getting either a traffic flow map or an estimate of traffic volumes on each roadway segment from the Planning/Traffic Section. The next step is to estimate the distribution of light, medium and heavy vehicle types on each roadway section using the vehicle classification data available from the Planning/Traffic Section. Heavy truck volumes are then plotted to better define the truck movements on the highway system. A few States have begun to publish heavy vehicle flow maps for either 3S2s or other heavy vehicle combinations.

To build a load map, it is first necessary to establish a load distribution table for each roadway type and for each vehicle classification category. These load distributions are converted to ESAL factors for each vehicle classification and roadway type. These load distributions, wherever possible, should be developed from WIM data that were collected in accordance with the TMG.

The ESAL map is developed by taking the volume of each vehicle type for each roadway section, multiplying the volume by the respective vehicle type ESAL factor, and summing the ESALs. The result is the annual cumulative ESALs for each roadway section. These results displayed on a map form the basis for estimating pavement deterioration rates, growth in ESALs, and forecasting future pavement performance.

Heavy truck flow/ESAL maps are a very useful way to summarize truck data being collected by the Planning/Traffic Section. These maps, produced on a periodic basis (i.e., every few years), would be very useful to many parts of a highway department in areas such as pavement management, bridge management, accident analysis, traffic operations, environmental and other topics.

## FORECASTING

Pavement managers need an estimate of cumulative ESALs for a specific location. We can estimate current year ESALS in an accurate manner; the greater challenge is to accurately predict ESALs over a 10, 20 or 30 year period. Most States today estimate future traffic using trend analysis for rural areas and urban transportation planning projections for urban areas.

### Forecasting Methods

There are four basic types of forecasting procedures that can be used:

- Trend Analysis
- Average Growth Rate
- Compound Growth Rate
- Regression Analysis

Each one of these methods uses past data to analyze trends and project those trends into the future. As discussed earlier, it is best to divide the traffic into three groups: light vehicles, medium vehicles, and heavy vehicles. Forecasting procedures should be developed for each of the three groups. By using separate groups, future growth in heavy trucks will be more accurately predicted. As historic trend data has shown, heavy trucks are growing faster than traffic in general. The next section briefly reviews the five basic forecasting procedures.

Trendline Analysis - Trendline analysis is the most often used forecasting method. This method is based on a review of historical trends and then projecting those trends into the future at an annual growth rate. This forecasting technique is most often used on rural highways, where limited additional information is available and little change in conditions is expected in the future.

Trendline analysis is accomplished by obtaining as many years of historical data as possible. The data is plotted and notations made of any major developments or road improvements that may have affected truck volumes (Figure 4). Also, any inconsistency in count data are noted and checked carefully. After all information has been reviewed, a trendline is established. The trendline should be adjusted if, in future years, higher that expected industrial or population growth is anticipated. Finally, a sensitivity analysis should be conducted on the trendline. For example, in forecasting trucks, by making reasonable assumptions concerning the minimum and maximum growth rates in truck traffic, the best estimates of the range of future truck volumes can be obtained. Such a sensitivity analysis will define the potential impact of errors in the forecasts. Note that trendline analysis should only be used to make projections for up to the number of years for which historical data are available.

Average Growth Rate - The average growth rate is a very common method for forecasting future growth in truck traffic and is very similar to trend analysis. Here a single rate of growth is established for the forecast period and projected into the future.

Forecast value = ((AGR) (N1) (X1)) + X1
AGR = Average growth rate
N1 = Number of years in forecast period
X1 = Initial value

Compound Growth Rate - Often truck growth during a forecast period will not occur in a linear form. Growth may occur very quickly or start off slowly and then accelerate. When the assumption of linear growth does not apply, non-linear methods of forecasting must be considered. The most often used non-linear growth methodology is the compound growth rate approach. As before, a constant rate of growth during the forecast period is assumed, but that rate as a percentage applies every year and results in greater absolute growth in later years.

$$\text{Forecast Value} = X1\,(1 + ACG)^{N1}$$

X1 = Initial value
ACG = Average compounded growth rate
N1 = Forecast period

Care should be taken in using this forecasting method as the compounding effect will create progressively larger increases in growth for longer forecasting periods.

Regression - Linear and non-linear regression have been widely used to establish trends between variables. With the widespread use of computers to make the calculations, regression equations (either linear or non-linear) can be developed very easily. Either equation will predict "y" based on a series of independent variables Xn. Care must be exercised to use those independent variables that have a causal relationship to the dependent variable. The equation that produces the "best fit" of the data being represented is determined by the "R" squared and "student T" statistical significance test. Examples of regression equations follow:

$$Y = a + bx$$
or
$$Y = a + bx + tax2$$
or
$$Y = a + bx + cx2 + dx3$$

Potential for Error

The characteristics of traffic will change over time. The vehicle type composition of the traffic stream will change, as will the total traffic loadings on the pavement. This changing traffic will influence, possibly to a significant degree, the life of existing pavements, as well as the design of new and rehabilitated pavements.

Average truck equivalency factors (ESALs per vehicle) vary widely by route, time of year, and, in the case of tractor-semi-trailers, by trailer type. There also appears to be a significant amount of unexplained year-to-year variability. Characteristics of truck traffic can accelerate pavement damage. These characteristics include the lane distribution of truck traffic; variation in the average weight of each truck type by lane, reflecting the assumption that trucks travelling in the slow lanes are more heavily loaded than those in the fast lanes; ESALs occurring during the freeze-thaw cycle months; truck traffic expected to experience congested speeds during the hot summer months. It is important to determine with some accuracy the mix of the highway traffic by vehicle class and the appropriate ESAL factors.

Judgement about how the project area or corridor is expected to grow is also necessary. Simple extrapolation of past trends most likely will not adequately reflect land use or economic growth expected in the area. Consideration needs to be given to the origin and destination of the trucks. Are the through trips effected by considerations outside the immediate area or State?

Check Reasonableness of Forecast

After the initial forecast is made, assumptions made and other factors that effect truck growth must be carefully checked. Factors affecting future truck growth include:

Urban Areas

- Land uses/economic activity
- Other anticipated highway projects
- Available capacity
- State's economic growth rate
- Commodity growth rates

Rural Areas

By county or State:
  - Vehicle registration
  - Employment
  - Population
  - Households

State

  - Economic growth rate
  - Commodity growth rates

Knowledge of the area and common sense are the final factors in determining that the forecast is reasonable.

### Future Changes in ESAL factors

ESALs vary from year to year, mostly due to changes in size and weight laws. In the calculation of cumulative ESALs, careful consideration should be given to expected changes in trucks during the analysis period. Emphasis should be placed on developing trends for heavier, larger vehicles since they affect pavements more than other vehicle types. If no trend data is available, a 1% average growth rate for heavy vehicle ESAL factors and no change for other vehicle types is a good rule-of-thumb.

### Future Changes in Directional Distribution

The directional distribution factor for pavement design purposes should reflect the distribution of daily load by direction, not the distribution of vehicles. Changes in distribution factors will occur with changes in economic development, such as port or rail facilities. Large manufacturing plants may cause an imbalance of loaded and empty trucks. Very little change in directional distribution would normally be expected during the forecast period.

### Future Changes in Lane Distribution

Lane distribution, as in directional distribution, should reflect the distribution of load, not traffic. In urban areas, more truck lane management strategies are being implemented that will change lane distributions. Therefore, in urban areas, lanes should be designed to carry 100% of the anticipated loads. In rural areas where little change is expected in the future, the initial value should be used.

### Results of Forecasts

No matter what method of forecasting is used the desired result is the same. Cumulative ESALs in the design lane need to be accounted for in a given analysis period. To determine total cumulative ESALs, the following values must be forecast:

(1) Light vehicle volumes
(2) Medium vehicle volumes
(3) Heavy vehicle volumes
(4) ESAL load factors by vehicle type
(5) Directional distribution factor
(6) Lane distribution factor

The importance of forecasting can not be overstated. Estimates of future volumes of traffic are the basis for highway design and are used in estimates of future funding for the highway program. Errors in forecasting have resulted in expensive mistakes, such as premature failure of facilities or reconstruction of facilities soon after initial construction is completed. A well developed accurate traffic forecasting procedure will result in significant future cost savings.

## PAST TRUCK TRAFFIC

To improve forecasting procedures and better understand how pavements are performing, a pavement manager needs to have the ability to determine what truck traffic has passed over a section of pavement. If we can estimate past traffic, we can determine:

(1) Accuracy of past forecasts
(2) Ways to improve forecasting accuracy
(3) Critical factors in past forecasting
(4) Past pavement performance prediction accuracies in relationship to ESALs

(5) New rehabilitation technique performance related to ESALs
(6) How to improve existing pavement performance predictions.

If we can estimate past traffic, we can gain a better understanding of how to improve forecasts of future traffic and determine the remaining life of our pavements.

Estimation of past traffic is a straightforward process. There are nine basic steps:

(1) Gather historic data on:

  a. Traffic volumes
  b. Vehicle classifications
  c Truck weights
  d. Legal load limits

(2) Divide highway system into functional classes or other groupings
(3) Establish vehicle types (A minimum of two types should be used, medium and heavy vehicles)
(4) Establish analysis period - Group the backcasting period into years with similar ESAL factors for the vehicle groupings
(5) Develop table of historic ESAL factors by pavement type, years, and vehicle type
(6) Determine best estimate of vehicle distribution by vehicle type and analysis period
(7) Determine best estimate of vehicle volumes by classification by analysis period
(8) Calculate cumulative ESALs for each analysis period
(9) Result: Cumulative 2-way ESALs.

## CONCLUSION

What we have shown in this paper is that a pavement manager must know what heavy trucks are moving over the highway system in order to manage pavements. A pavement manager needs to know:

- Current heavy vehicle volumes by section
- Future heavy vehicle volumes by section
- ESAL factors by pavement and vehicle types

With good methods to estimate current heavy truck volumes, forecast future vehicle truck volumes and calculate ESAL factors, a pavement manager can accurately predict future pavement performance. To obtain this information, the pavement manager needs to work with his respective Traffic/Planning Section to get access to information from an integrated traffic counting, vehicle classification and weighing program that provides accurate information on the current heavy vehicle population. The Traffic/Planning Section also has forecasting procedures that take into account past trends and the effect of future changes, both in economic activity and changing truck fleets. The pavement manager, working with the Traffic/Planning Section to obtain accurate estimates of current and future truck loadings, can have confidence that he is doing the best possible job in predicting the future performance of his pavements.

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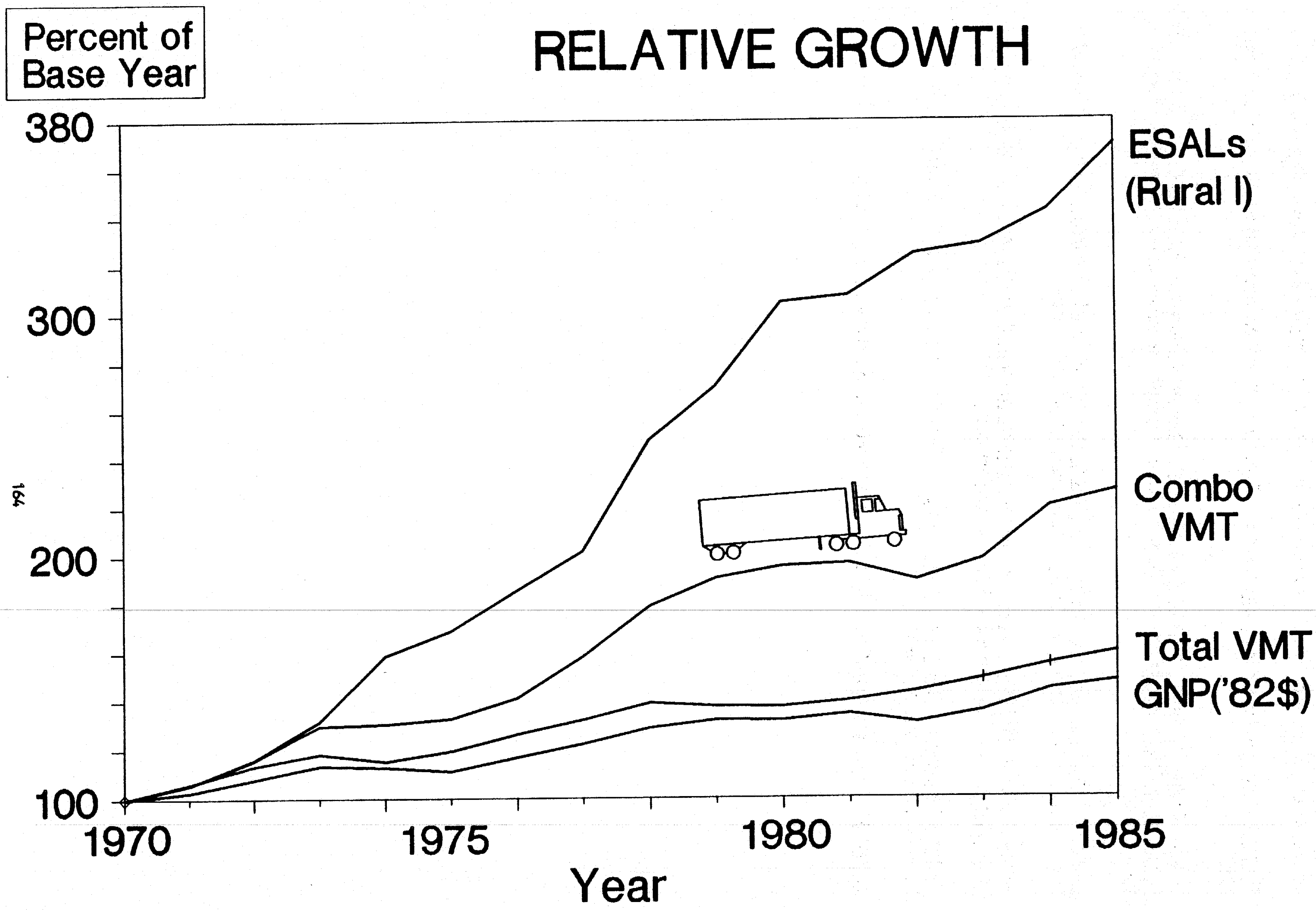

Percent of Base Year
RELATIVE GROWTH
380
300
200
100
1970
1975
1980
1985
Year
ESALs (Rural I)
Combo VMT
Total VMT
GNP('82$)

Figure 1

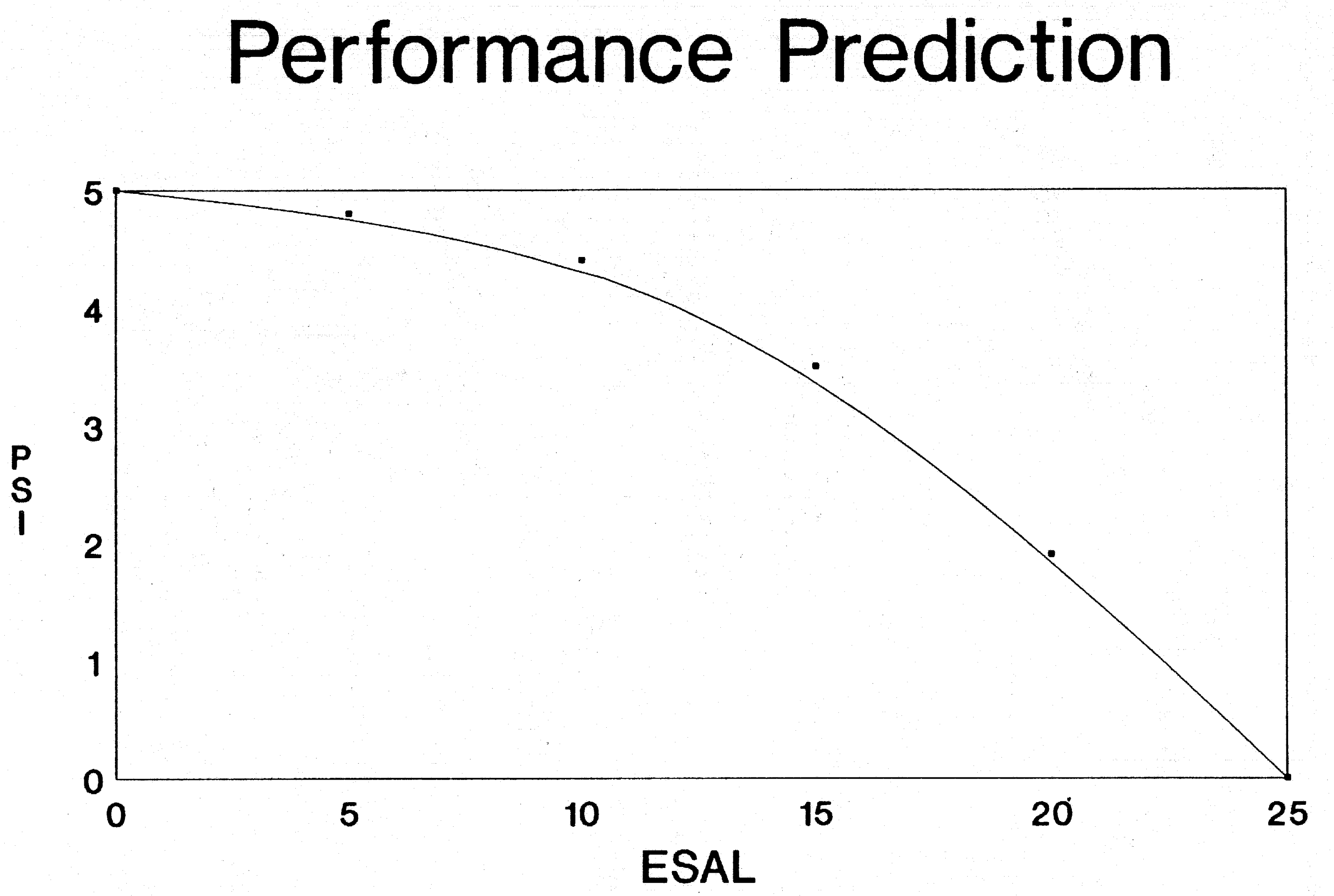
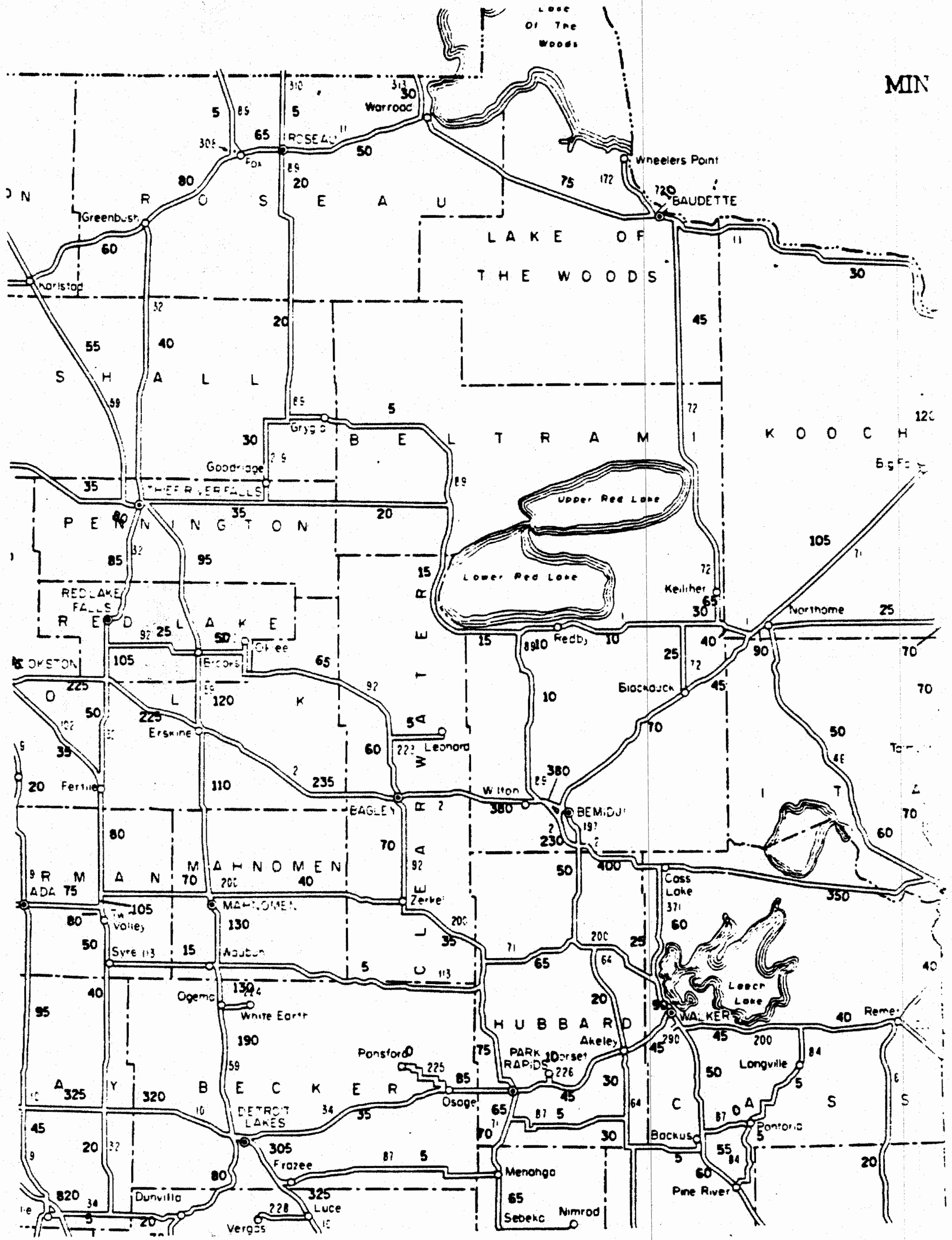


Figure 2



1986
Five Axle
Tractor Semitrailer
Traffic Volumes
(Showing Average Annual Daily Volume)
State of Minnesota
Figure 3

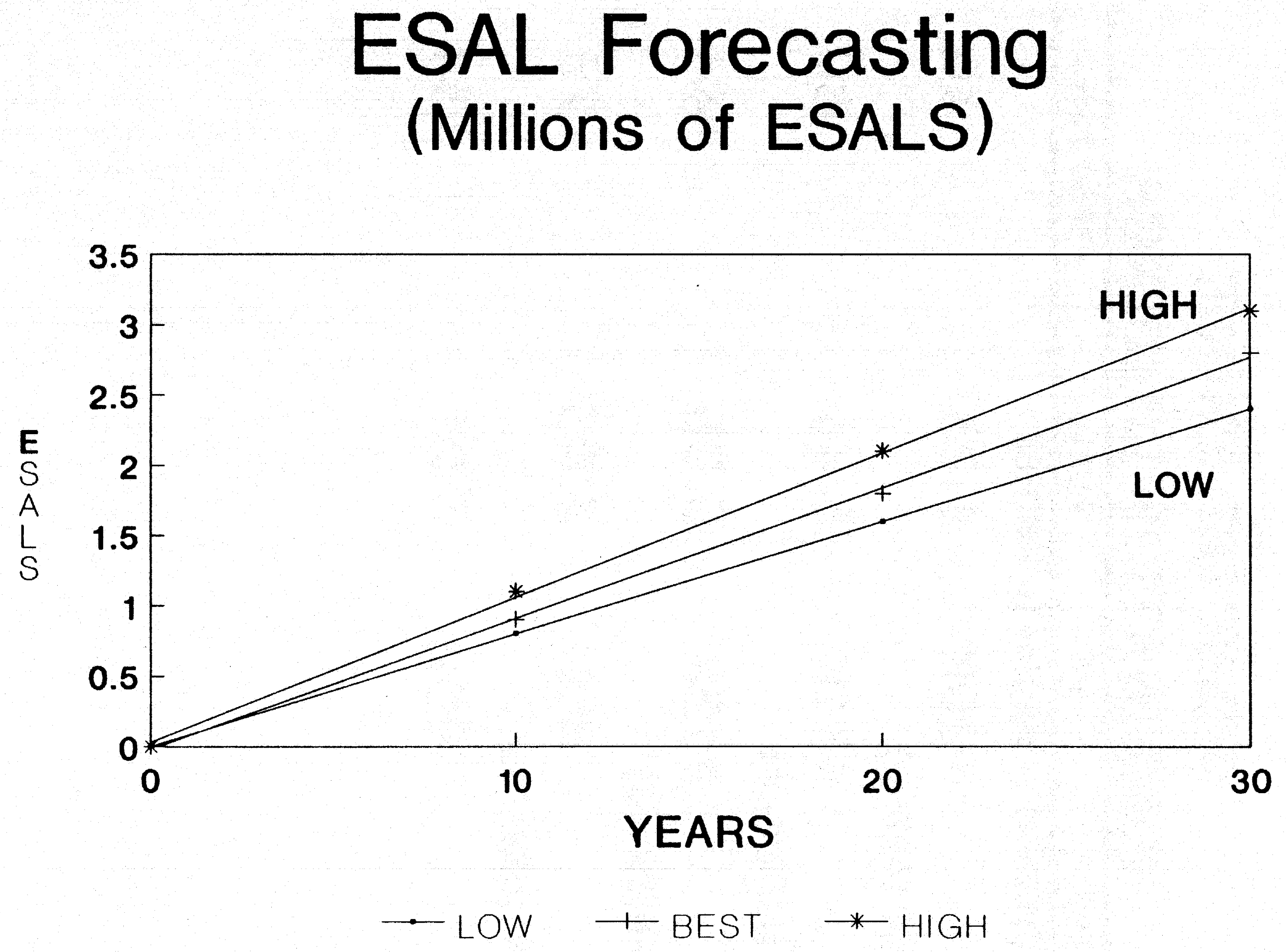

ESAL Forecasting
(Millions of ESALS)
ESALS
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
YEARS
HIGH
LOW
LOW
BEST
HIGH

Figure 4

TABLE 1

# SELECTED TRUCK COMBINATION LOADINGS

| TWINS | WT | ESALs | /1000 TONS |
|---|---|---|---|
| SHORT (3S2—4) — similar to TURNER | | | |
| | 100K | 1.23 | 40 |
| TURNPIKE (3S2—4) | | | |
| | 131K | 3.44 | 80 |
| ROCKY MT(3S2—2) | | | |
| | 112K | 5.05 | 144 |
| WESTERN(2S1—2) | | | |
| | 80K | 4.03 | 175 |
| CONVENTIONAL(3S2) | | | |
| | 80k | 3.21 | 134 |

# USE OF WEIGH-IN-MOTION DATA FOR PAVEMENT DESIGN
# A PRELIMINARY EXAMINATION OF ESAL CALCULATION USING WIM DATA

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## ABSTRACT

This paper examines the use of weigh-in-motion (WIM) data for calculating equivalent standard axle load (ESAL) values, which are an important factor in pavement design. More specifically, it examines the differences to be expected between data collected with WIM and static weights. It then describes how these theoretical differences impact the calculation of ESALs. A methodology is presented to adjust the WIM data for the expected differences between WIM and static values. The preliminary findings of a test of this procedure are examined, conclusions are drawn, and future research is suggested.

Theory indicates that ESAL values calculated from WIM data should exceed ESAL values from static weights. The cause of these differences is vehicle motion, which is a function of vehicle load, vehicle suspension and road characteristics. In theory, the greater the vehicle motion, the greater the over-prediction of ESALs by WIM equipment, provided the WIM equipment is correctly calibrated and functioning.

However, when a limited set of actual WIM and static weight data, was examined the phenomenon of ESAL over-prediction was often overshadowed by inaccurate WIM data produced by poorly calibrated equipment and other problems. That is, ESAL calculations were affected by problems with the data to a greater extent than they were affected by random "dynamic" effects.

## INTRODUCTION

As the U. S. highway system matures, less emphasis is being placed on the construction of new highways, and more emphasis is being placed on the management and maintenance of existing facilities. One of the major concerns of highway maintenance is the design of pavements. The early break-up of some pavements has caused engineers to reconsider the quality of the assumptions and data used to design pavements. Because the expense of rehabilitating pavements (particularly in heavily traveled urban areas) has grown over time, attention has been increasingly focused on providing better information for pavement design.

Ample research has shown that, among other considerations, good pavement design requires accurate data on

- soil conditions,
- environmental factors,
- the number of trucks crossing the pavement section, and
- the weight of those trucks.

Historically, truck volumes and weights have been some of the weakest data used in the pavement design process.

New technologies and microcomputer power have allowed recent advances in the methods and equipment available for collecting truck volume and weight information. In addition, the FHWA and many state agencies have encouraged the collection, manipulation and use of increased volumes of truck weight data to provide a better basis for pavement design and evaluation.

The most significant trend in weighing trucks has been the move towards weigh- in-motion. WIM has many advantages over traditional static vehicle weighing, including

- faster weighing,
- decreased truck delay,
- increased productivity of data collection and enforcement staff,
- increased vehicle safety (through the reduction of queues of trucks waiting to be weighed),
- a greater possible volume of truck weight data, and
- a reduction in the bias inherent in the collected data (because use of inconspicuous data collection equipment without enforcement provides a more representative sample of weights than traditional static scales).

The problem with weigh-in-motion is that WIM weights are intrinsically different from static weights, and these intrinsic differences affect the use of weight data for estimating loads for pavement design. This problem arises because almost all commonly used pavement designs are based on some form of a conversion of static weights to "damage factors." (Most of these design procedures were developed at a time when only static weights were available.)

The most common "damage factor" is the Equivalent Standard Axle Load (ESAL). The ESAL was developed as a result of the ASSHO Road Tests performed in the 1950s. The equations developed for converting weights to ESALs were derived from static weights, and their use with weigh-in-motion data may have some unexpected results. In examining these unexpected results, we must first look at why and how static and dynamic axle weights differ.

## WHY STATIC AND DYNAMIC WEIGHTS DIFFER

A vehicle at rest distributes its load among its axles in a consistent manner (i.e., the weights applied at any one axle or wheel are essentially constant, unless the load is shifted or changed.) In motion, that same vehicle applies a variety of different loads to the individual axles and wheels, depending on the interaction of the vehicle, the load, and external factors such as the road condition.

A number of researchers have shown how various factors influence the weight applied by any given axle or wheel of a vehicle at any given point in time. The paper, "Concepts of Weigh-in-Motion Systems," by Dr. Clyde Lee, given at the National WIM Conference in Denver, Colorado, July 11 through 15, 1983, presents an excellent summary of most of these factors. Among the more important of these factors are the following:

- pavement profile and condition,
- vehicle suspension characteristics,
- vehicle configuration,
- vehicle speed,

- tire pressure, and in some cases,
- environmental conditions.

The above factors interact to produce a series of oscillations in a truck as it proceeds along the highway. As the vehicle oscillates, the measured "weight" of the vehicle (actually the force applied) or any of its axles changes, depending on where the vehicle is in its oscillation cycle (i.e., whether the vehicle is bouncing up or down). Because they vary, WIM weights are called "dynamic" weights.

Because WIM equipment weighs moving vehicles, it is affected by the dynamic action of the axles. The primary affect of vehicle dynamics on the weighing function is that if the vehicle is bouncing up when it crosses the WIM equipment sensors, the "weight" felt by the sensors is less than the "weight" those sensors would experience if the vehicle were stationary. Similarly, if the vehicle is descending as it crosses the WIM sensors, the "weight" on the sensor exceeds the stationary "weight."

Consequently, the greater the motion of the vehicle, the greater is the variation in weight applied by the axles at any given time (although the mean weight applied by the axle is still approximately equal to the static weight.) Conversely, the more smoothly a vehicle is traveling on the highway, the lower the oscillation of the vehicle and the closer the weight applied by any one axle is to the weight applied when the vehicle is at rest. For more information on the importance of smooth roads to the accuracy of WIM, please refer to previously published research such as "Calibration of Weigh-in-Motion Systems," by the SPARTA, Inc., published by FHWA in August 1988.

Because of the dynamic effects described above, the accuracy with which a WIM scale can predict the static weight of an axle is both a function of the design qualities of the scale system and the motion of the vehicle being weighed. That is, the WIM scale must be able to repeatedly measure the same forces applied by vehicles and convert those forces into weight estimates, and the vehicle must also consistently apply the same force to the transducers.

Because the truck population's configurations, suspension systems, tire pressures and loadings vary significantly, it can be safely said that no high speed WIM system will be able to consistently predict static axle weights for all trucks under normal operating conditions in the foreseeable future. Modern equipment designs will continue to reduced the average error for individual axle weights through the use of multiple sensors, large transducers and sophisticated electronics, but some error will continue to exist simply because "dynamic" and "static" weights are different entities.

## HOW WIM DATA DIFFER FROM STATIC DATA

Given that WIM data are different than static data (although for any given axle the measurements may be equal), it must be determined how much WIM weights differ from static weights and what those differences mean when placed in the context of an entire population of trucks.

First, look at what happens when one axle is measured repeatedly in both a static and dynamic fashion. Repeated weighing with an "accurate" static scale will most likely produce a very minor variation in weights (less than a 1 percent standard deviation.) Repeated weighing of that same axle with any existing high speed WIM device will likely result in a standard deviation of between 4 and 15 percent, depending on the factors described above.

In theory, the WIM measurements will form a normal curve around the static weight value, such as shown in Exhibit 1. Half of the time, the WIM scale weighs the axle when it is bouncing upwards, and half the time as the axle is coming down. Exhibit 1 shows that, in theory, the dynamic effects of a vehicle should produce a number of axle measurements that exceed the actual static weight of the axle, and a number of estimates that are below the actual static estimate.

To continue this theoretical reasoning, static and dynamic weighings of a population of trucks (of a variety of weights and configurations) are compared in Exhibit 2. In this exhibit, the differences between the WIM and static estimates are not as pronounced as in Exhibit 1 (since some of the low and high estimates cancel each other out), but the WIM scale still provides slightly more high and low axle weight estimates and correspondingly fewer middle estimates. Note that the mean axle weight of the two populations should be the same if the scale is correctly calibrated. However, if these two distributions are converted into ESALs, the WIM data will produce a higher ESAL value per truck than data from the static scale.

## USING WIM DATA TO CALCULATE ESALS

The WIM data produce a larger ESAL value because they contain a higher number of heavy axles, even though these axles are balanced by a like number of lighter axles. When axle weights are converted to ESALs, heavy weights play a more significant factor than light axles. This is because of the mathematic properties of the fourth order equation used to convert axle loads to ESALs.

The following examples illustrate the impact of heavy axles on the ESAL calculation. The examples assume flexible pavement with a serviceability of 2.5 and a structural number of 3. For two 18 Kip axles, the calculated total ESAL is 2.0. If those two axles were weighed as one 16 Kip axle and one 20 Kip axle (mean of 18 Kips), the total ESAL is calculated as 2.14. In this case, a difference of +11 percent in weight equals a 7 percent increase in ESAL, even though the mean weight of the measured axles is the same (i.e., there is no systematic error in the WIM scale.)

If those same two axles are estimated as 22 Kips and 14 Kips (again an 18 Kip mean), the calculated ESAL increases to 2.51. In this case, the +22 percent error in weight results in a 25.7 percent increase in the ESAL estimate.

These examples show that data from a properly calibrated WIM device (i.e., one that correctly estimates the mean value of the axle population) will over-estimate the ESAL of the truck population, provided the dynamic effects of the trucks occur randomly. The examples also show that this effect will be greater at WIM locations whose data have a high standard deviation (i.e., the standard deviation of the difference between static and dynamic axle weights). The high degree of variability results in a greater number and range of over-estimated axle weights, than will occur at sites with a smaller standard deviation.

The problem with WIM data is not that the WIM sensors are not accurate, but that the motion of the vehicles causes some axles to be measured as being heavier than their "static" weights. Thus, unless the data are adjusted to account for the increased variation caused by in-motion weighing, or the weight-to-ESAL equations are adjusted to account for the collection of weigh-in-motion data, the use of WIM equipment will result in an over-estimation of the ESALs (or damage) inflicted by trucks on a road.

Other than through simple calculations like those above, the size of this over-estimation is not known. What is known is that the error is a function of the number of over-estimated axles and the average size of that over-estimation. It is not known how these errors compare to other errors relating to the calibration and general accuracy of WIM equipment. Still, if the reliability of WIM systems continues to improve and the number of WIM data continues to increase, the conversion of WIM to ESALs will need more thorough examination.

## CONCEPT FOR ADJUSTING WIM DATA

As noted above, a well calibrated WIM system should measure the mean axle weight within desirable limits. Further, the shape of the axle weight distribution curve should be reasonably similar to that of the static weight curve (only slightly lower and flatter.) However, the motion of the vehicles prevents a WIM scale from "accurately" weighing any given truck's axle. This fact has been well understood by the nation's weight enforcement agencies. If the WIM system is well calibrated, the population of trucks as a whole can be reasonably well measured.

The WIM data available for estimating ESALs are therefore an excellent basis for the calculation of ESAL values. The need is to reduce the potential for over-estimation of some axles, not get rid of weigh-in-motion.

The concept presented here for modifying truck weights for ESAL calculations involves using statistics to reshape the curve formed by WIM data. That is, given a measure of a WIM scale's variation, reshape the histogram of the WIM data to more closely resemble the histogram of the static weights.

This approach is possible because the standard deviation of a WIM scale is found when the scale is calibrated and acceptance tested. The suggested methodology for adjusting WIM data is to adjust the truck weight by "repacking" the data into a tighter curve, attempting to better estimate the curve predicted by static weights.

The algorithm tested consists of the following steps:

1 From the scale calibration data, calculate the differences between the WIM and static weights for each axle and tandem.

$$DIF_i = WIM_i - STA_i \qquad (1)$$

where WIM = the weigh-in-motion estimate for that vehicle (either single or tandem axle weight),

STA = the static weight for that same axle or tandem, and

i = the ith vehicle in that data set.

2 Calculate the proportion of difference for each pair of weights.

$$PDIF_i = DIF_i / STA_i \qquad (2)$$

3 Calculate the mean and standard deviation of the proportion of difference.

$$APDIF = \Sigma\ PDIF_i / N, \text{ and} \qquad (3)$$

$$SPDIF = SQRT(\ \Sigma\ PDIF_i * PDIF_i) / N - APDIF * APDIF) \qquad (4)$$

where APDIF = the average proportion of difference

SPDIF = the standard deviation of the proportion of difference

N = the number of observations, and

SQRT = the square root function.

4 Calculate the mean value for the WIM data to be adjusted.

$$MNWIM = \Sigma WIM_j / M \qquad (5)$$

where MNWIM is the mean value of the data set to be adjusted

M = the number of observations in the new data set, and

j = the jth vehicle in that data set.

5 Calculate the adjusted weight for each WIM estimate as follows:

$$WIMADJ_j = (1\text{-}SPDIF) * WIM_j + SPDIF * MNWIM_j \quad (6)$$

One pass through the adjustment process has a fairly small impact on the overall ESAL calculation. Therefore, the adjustment may need to be repeated several times. If the adjustment is to continue, replace $WIM_j$ with $WIMADJ_j$ in Equation 6. Then recalculate a new $WIMADJ_j$. In the tests of the algorithm, the adjustment was repeated as many times as was necessary to make the WIM data's standard deviation equal to that of the static calibration data.

## TEST OF THE ALGORITHM

To test the algorithm and examine the impacts of WIM data on ESAL calculations, a number of data sets were obtained from Washington State Department of Transportation tests of WIM systems and several tests done as part of the HELP project. These data sets contained both static and dynamic (WIM), single and tandem axle weights for a variety of trucks. The HELP data consisted of four separate weighing sessions at a number of sites, while the WSDOT data contained data for only one weigh session at each site.

Washington state data were used to initially develop the algorithm and computer programs. HELP data were then used to examine the effects of the adjustment technique on independent data. To test the algorithm on the HELP data, the standard deviation of the error in single and tandem axle weights for the scale was calculated from the first of the four weighing sessions. This standard deviation was assumed equal to the information available from the calibration of a WIM device and was then applied to the remaining three data sets.

ESALs for individual axles and tandems were then calculated for the static, original dynamic (WIM) and adjusted dynamic single and tandem axle weights. The ESALS were then totaled for each site and compared. Individual axle ESALs were not compared, because the algorithm is not intended to improve the accuracy of any specific axle weight, only the sample as a whole.

When using the HELP information available for this test was evaluated, a number of obvious data errors were encountered. Several other errors in the data were also suspected, but the time frame, resources, and preliminary nature of the project did not allow for extensive data checking. Data containing obvious errors were discarded, and the results of the remaining tests must be treated as preliminary, pending further review and analysis of the data.

Exhibits 3 and 4 show comparisons of static and WIM axle measurements at two of the HELP locations. These histograms show that the axle weights are not normally distributed, but that the WIM data tend to be reasonable replications of the static data. Furthermore, in most cases, the WIM data did exhibit a higher number of extreme weights (low and high). In cases where the WIM weights were less variable than static weights, it was unclear whether the lack of variability in the WIM data was a function of errors in the data, or whether the characteristics of that particular WIM scale actually resulted in less variability in the WIM axle weights than was present in the corresponding static weights. (In several cases, the static and WIM estimates appeared to be switched, but time did not allow the substantiation of some of these suspicions.)

The review of the data also showed that the WIM systems did not always predict the mean value of the axle population well and that the mean values given by the weights included in the data sets did not match the published values from the HELP reports. This made error checking difficult without easy access to the data source. The scope and time frame of this effort did not permit this check.

To help reduce the impact of the data errors, sites with obvious errors were removed from the analysis. Locations with "suspect" data were analyzed. It is important to note that errors in the data may have affected a number of the preliminary conclusions of the tests.

The results of applying the adjustment algorithm can be seen in Exhibit 5. The algorithm reduced the number of extreme weights in the data set and increased the number of weights in the middle weight categories. This had the effect of reducing the total ESAL calculated for the sample. For the data sets examined, the ESAL value was reduced an average of 13.3 percent. The standard deviation of the ESAL reduction was 6.9 percent. The minimum reduction was 3 percent, and the maximum reduction was 35 percent.

In those cases where the WIM data over-estimated the static ESAL, the adjustment process improved the accuracy of the ESAL estimate. However, in several of the test cases, the mean of the WIM data was sufficiently below the static mean that the WIM data under-estimated the ESALs for the site. In these cases, the WIM adjustment increased the error associated with the data conversion.

## CONCLUSIONS

The statistical adjustment tested in this effort does reduce the calculated ESAL value as intended. However, in the tests of the algorithm, errors present in the data sets available and/or in the estimation of axle weights by the WIM systems often far exceeded the random errors caused by random motion of the truck axles. These errors in estimated weight caused considerable error in the calculation of ESALs

In the available data sets, the WIM estimates did not always produce a larger ESAL estimate than the static estimates. This was particularly true when the WIM system under-estimated the mean of the sample. In these situations, the suggested adjustment procedure then accentuated the under-estimation of ESALs.

Therefore, the authors conclude that the weight adjustment process appears to serve its function, although the specific algorithm needs additional testing and refinement. However, problems with the WIM devices (poor calibration, degradation of the scale performance over time, or degradation of the pavement around the scale) may cause data errors that over-shadow the 5 to 20 percent error the traditional ESAL calculation may create.

## FUTURE RESEARCH

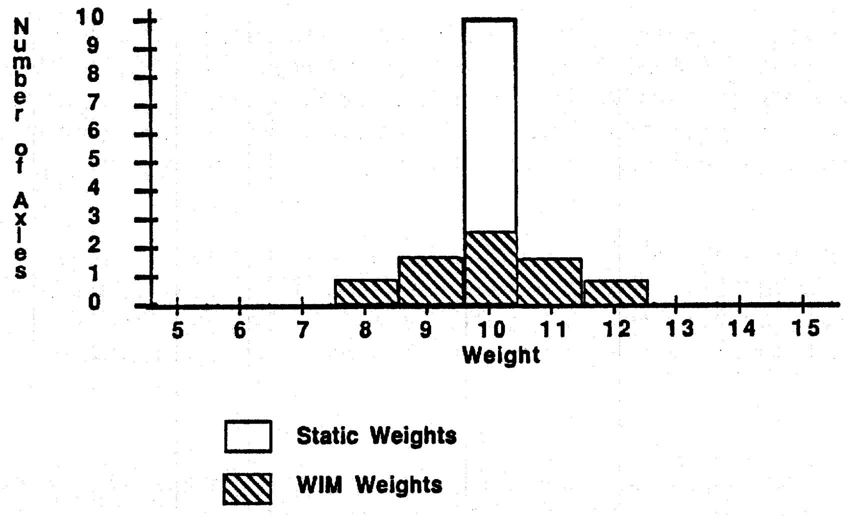
The entire topic of the use of WIM data in place of static weights requires additional research. On the basis of the preliminary findings in this effort, the authors suggest that following items require more study:

- How big are the differences between WIM and static axle weights at most (or the "typical") WIM sites?
- How large is the corresponding error in ESAL estimates? and
- Do we (as state agencies) maintain the calibration of WIM devices (and surrounding pavements) sufficiently well that the errors caused by the conversion of WIM data to ESAL

rather than static data to ESAL are overwhelmed by errors in the performance of the device?

**EXHIBIT 1**

**Static .vs. Dynamic Weights**



## EXHIBIT 2
## Theoretical Comparison of WIM and Static Data

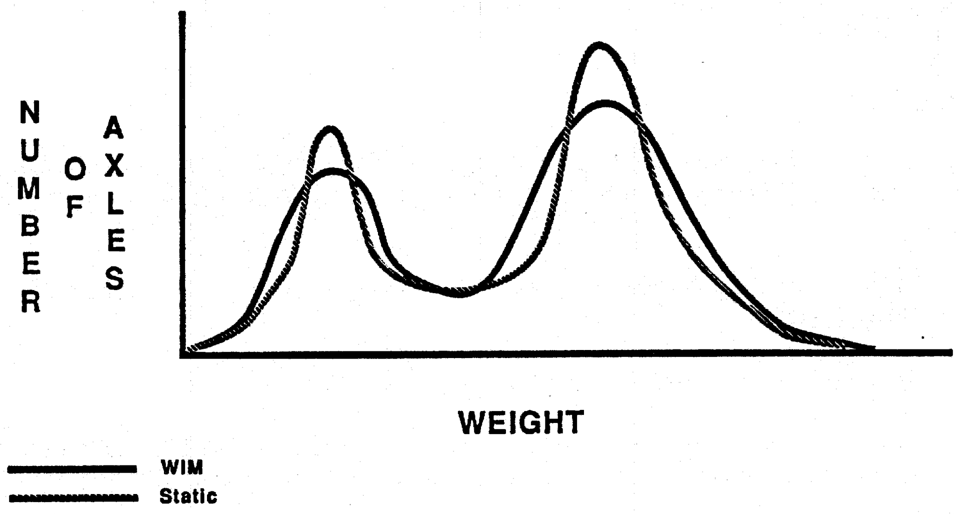


Exhibit 3 - Static .vs. WIM Single Axle Weights

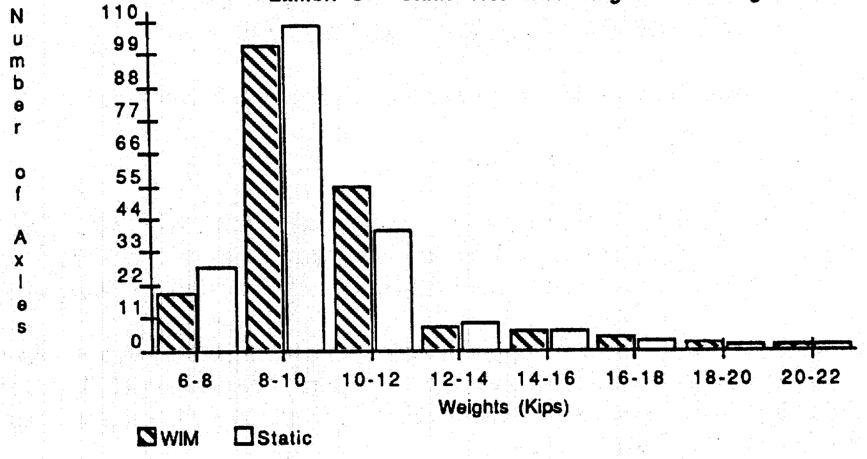


Exhibit 4 - WIM .vs. Static Tandem Weight

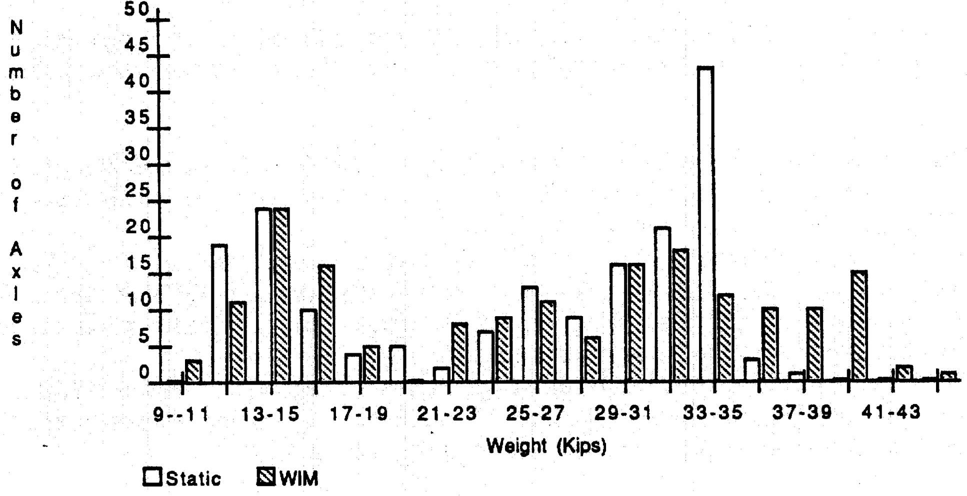
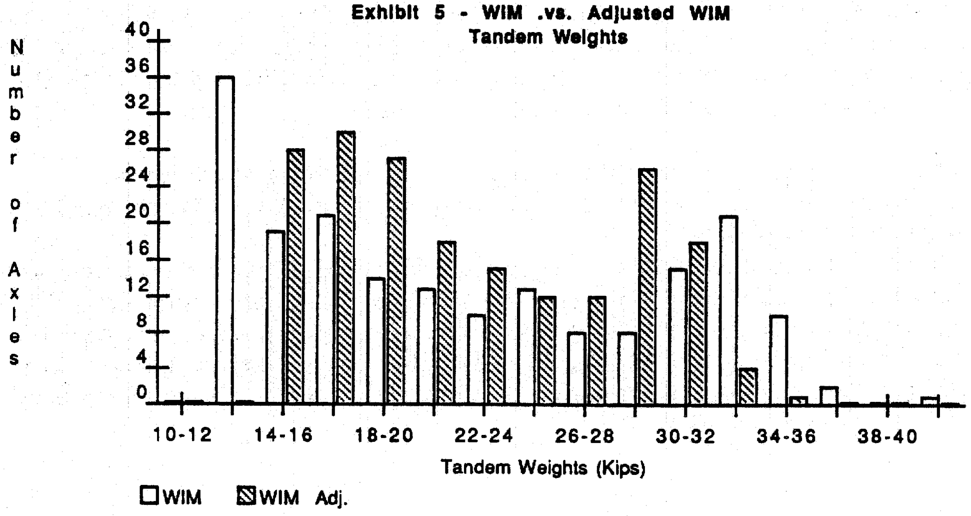


Exhibit 5 - WIM .vs. Adjusted WIM Tandem Weights



# INSIGHTS FROM WEIGHING-IN-MOTION - ADJUSTMENT OF SHORT TERM WIM DATA TO AADT, DYNAMIC WEIGHTS OF TANDEM AXLES, AND OVERESTIMATION OF ESAL FACTORS

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## Introduction

Minnesota's first continuously operating WIM system was installed in 1981. Since that time Mn/DOT has installed them at three other data collection sites. Analysis of the data from three of those four sites has led to several important observations and discoveries I would like to share with you.

The first item I would like to cover is adjusting short term truck traffic data to Annual Average Daily Traffic (AADT). The second item concerns the dynamic weights of tandem axles. The third item deals with overestimation of ESAL factors. Now lets talk about adjusting short term truck traffic data, both weight (ESAL's) and volumes of vehicles to AADT values.

## Adjustment of Short Term WIM Data To AADT -- ESAL's

Minnesota's WIM sites are located on a variety of roads. The following is a brief description of the location and function of the routes. Keep these varying functions in mind as we cover the seasonal variations we have observed.

1) I-494 on the interstate beltline around the Twin Cites in Bloomington. Scales are located in the two eastbound lanes.There is a mixture of rural and urban truck traffic. The two-way AADT is about 80,000.
2) TH 2 on the Bemidji Bypass. Scales are in the two eastbound lanes and the right westbound lane. TH 2 is a principal arterial crossing the northern part of the state. The principal commodity being hauled is grain going to the ports at Duluth-Superior. The two-way AADT is about 4100.
3) TH 99 west of St. Peter. There are scales in both directions in this two-lane highway. TH 99 is a minor arterial which is restricted to 7 tons in the springtime. It is a farm-to-market road. The two-way AADT is about 1600.

This brief analysis will concentrate on the three truck types which have the most impact for us -- the 2 axle 6 tire trucks, the 3 axle single unit and the 5 axle semi. These three vehicles on the average account for approximately 8%, 7% and 67% of the ESAL's respectively, so we have 82% of all ESAL's represented here. One can see that if we can do a good job of estimating ESAL's for the 5 axle semi, we will be 2/3rds of the way there. So much depends on this one vehicle type for us.

The analysis in this portion of the report is based on the following assumptions:

1) Short term WIM data will be collected by an agency on a weekday or weekdays between May and October.
2) This data will be collected for exactly 24, 48 or 72 hours. Because the weights and numbers of trucks vary throughout the day, one must first make sure that representative data is collected during the sampling. For instance, if data were collected for one day and two nights at a site, there would likely be a built in bias because the trucks operating during the night are generally heavier than those operating during the day.

Data collected for the three truck types at the three sites is summarized in Tables 1-3 and also in Figures 1-3. Note that Figure 2 is drawn to a different scale. Table 1 and Figure 1 show few similarities between ESAL data collected for 2 axle 6 tire trucks at the three sites.

Table 1

Factors to Adjust Average Weekday ESAL's
for 2 Axle 6 Tire Trucks to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | .95 | 1.01 | 1.10 | 1.09 | .93 | .90 |
| TH 2 | .91 | .73 | 1.01 | 1.03 | .89 | 1.02 |
| TH 99 | 1.04 | 1.15 | 1.00 | .87 | .94 | .72 |

Perhaps the only general similarity is that TH 2 runs somewhat parallel to I-494 but only on a lower level. July and September show similar results. TH 99 is very different in function from the other two. These trucks are generally local in nature. The seasonal pattern at sites like this vary depending on local industry.

Table 2

Factors to Adjust Average Weekday ESAL's
for 3 Axle Single Unit Trucks to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | .95 | 1.01 | .96 | .97 | .97 | .98 |
| TH 2 | 1.13 | .98 | 1.09 | 1.14 | .89 | .88 |
| TH 99 | .95 | 1.29 | 2.14 | 1.29 | 1.08 | .80 |

Table 2 and Figure 2 again show little similarity in the pattern of ESAL factors for 3 axle single unit trucks at the three sites. I-494 has a flat pattern just below 1.00. TH 2 is erratic. TH 99 has a very pronounced bell-shaped pattern. These high adjustment factors for June through August on TH 99 mean that the weights were very light in those months compared to the rest of the year. It should be noted for June, July, September and October that the values for the individual lanes for TH 99 were far apart. It could be that this high directional difference in not that unusual on a farm to market route. Additional data will give us the answer to that question.

Table 3

Factors to Adjust Average Weekday ESAL's
for 5 axle semi to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | 1.02 | 1.05 | 1.02 | .95 | .98 | 1.00 |
| TH 2 | 1.06 | 1.05 | .98 | .99 | 1.00 | .99 |
| TH 99 | .99 | 1.24 | 1.19 | 1.01 | .86 | .77 |

Table 3 and Figure 3 show that the most important vehicle type has a much more consistent ESAL pattern. I-494 and TH 2 both have flat patterns of the same magnitude, around 1.00. The weights are steady throughout this time period. TH 99 has somewhat of a bell-shaped pattern. This is distinctly different from the other two sites. The weights on TH 99 are heaviest in the fall, so perhaps this route is more sensitive to the movement of grain harvested in the area than the other two sites. The factors on I-494 and

TH 2 probably show such consistency because there are large numbers of these trucks and the inter-city nature of the commodities carried compared to the other two truck types we examined. TH 99 is a comparatively low volume farm to market road so it is heavily influenced by the local situation.

It is interesting to note that for 5 axle semi (at two of our three sites) in particular and 2 axle 6 tire and 3 axle single unit trucks to a lesser degree the ESAL factors are remarkably close to 1.00. This has worked for our benefit in the past as we simply collected weight data on a summer weekday and used it as being representative of the entire year. We had no way of adjusting it until now. Now lets look at volumes of these three types of trucks.

## Adjustment of Short Term WIM or Vehicle Classification Data to AADT--Numbers of Vehicles

Much of the previous discussion about ESAL's also applies to numbers of vehicles. Data collected for these three truck types at the three sites is summarized in Tables 4-6 and also in Figures 4-6.

Table 4

Factors to Adjust Average Weekday Volumes
for 2 Axle 6 Tire Trucks to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | .75 | .69 | .68 | .67 | .75 | .77 |
| TH 2 | .79 | .70 | .79 | .72 | .64 | .69 |
| TH 99 | .73 | .85 | 1.00 | .91 | .68 | .63 |

Table 4 and Figure 4 show the pattern of factors to adjust 2 axle 6 tire trucks to AADT for the three sites. I-494 forms a regular pattern with low factors in the summer months and higher factors in the spring and fall. TH 99 also has a pattern but it is the opposite of I-494 and it is more pronounced. TH 2 is erratic.

Table 5

Factors to Adjust Average Weekday Volumes
for 3 Axle Single Unit Trucks to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | .66 | .66 | .66 | .62 | .70 | .65 |
| TH 2 | .76 | .57 | .71 | .64 | .56 | .56 |
| TH 99 | .78 | .40 | .72 | .69 | .72 | .69 |

Table 5 and Figure 5 show the pattern of factors to adjust 3 axle single unit trucks to AADT. I-494 once again has perhaps the most stable pattern of the three sites. It is pretty flat. TH 99 is fairly stable except for June when the factor dropped dramatically because the volume increased so much. TH 2 is somewhat erratic. Even given the irregularities we see here, there is some pattern with many of the values being generally between .60 and .72. This may be explained by the fact that this truck type is often used in construction activity which predominantly takes place in these months.

## Table 6

### Factors to Adjust Average Weekday Volumes for 5 Axle Semi to AADT

| Site | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|
| I-494 | .74 | .74 | .74 | .71 | .73 | .70 |
| TH 2 | .77 | .65 | .82 | .70 | .72 | .83 |
| TH 99 | .76 | .62 | .77 | .67 | .67 | .71 |

Table 6 and Figure 6 show the pattern of factors to adjust 5 axle semi to AADT. The tightness of the patterns we see here for 5 axle semi are generally the same as we saw for 5 axle semi in the ESAL section. Overall it seems to be the most stable of the three truck types regardless of the type of roadway we have examined. I-494 has a very stable flat pattern. The other two sites have more variation but the values are still generally in the .70 to .80 range.

One thought to keep in mind concerning all of this preceding data is that it is the average weekday for each month which we have examined. This means that there are about 20 individual days in each month which were averaged to compare to the AADT. There of course is variation in the daily data.

In our application of this WIM data at this time, it may be better to average the values from a number of model stations (permanent WIM) and have one set of adjustment factors for each vehicle type. We simply don't have a data base that is broad enough so we can match up individual short term weight locations with individual model stations and have substantial confidence in the results. As WIM becomes cheaper and we develop extensive systems, this may become feasible.

More analysis can be done with this data. For instance, the months can be looked at over successive years to determine which ones seem to be more stable than the others.

We must move toward using continuously collected weight and vehicle classification data to adjust short term data to average annual data. If we are unable to obtain continuously collected data, we should consider building a data base showing seasonal variation by sampling for at least 48 hours once a month during the year, weather permitting. We would not dream of developing estimates of total traffic volumes without using data collected at ATR's to adjust 48 hour machine counts to AADT, but that is what we have been doing with weight and vehicle classification data.

We all spend a considerable amount of time and money collecting this weight and vehicle classification data, but we do not take advantage of what our neighbors are doing. We should be sharing our data much more extensively with each other. This sharing could be done on a regional basis, or at least among states which border one another. Perhaps FHWA can take a leading role in this and set up a pilot project involving a number of states.

### Dynamic Weights of Tandem Axles

Now lets look at the issue of dynamic weights on tandem axles. The manner in which weight distributes on the individual axles of a tandem on a moving vehicle is of great importance to the highway researcher and designer. The amount of damage which should be attributed to tandem axles is a function of the smoothness or roughness of the road surface. The advent of WIM gives us an opportunity to catch glimpses of how the dynamic weight distributes on tandems. There are two interrelated elements which play a role here. One of them is the way the weight is statically distributed and the other is the effect of dynamics. These are difficult to separate.

We have compiled sample data on the weight distribution of tandems on 5 axle semi at each of our permanent WIM data collection sites. We also included data from the screener scale at the St. Croix Weigh station and from Iowa's piezo installation for the AWAC's study. We wish to thank the Iowa DOT and Castle Rock Consultants for supplying us with this data. The Iowa AWAC's site is unique in that we have data from two piezo cables spaced 16 feet apart.

We chose to look at the 5 axle semi because there are two sets of tandems on each vehicle. This afforded us the opportunity to see if the patterns for the first and second tandems were the same. Also, as was mentioned earlier, this is our most important vehicle. We generally included only loaded tandems in this study. Lightly loaded axles tend to bounce more than those that are heavily loaded and we wanted to have a uniform sample.

The weights which are recorded at our WIM sites reflect what is happening only at that precise location. These dynamic weights are profoundly influenced by the profile of the approach to the scales. Other factors are the trucks' speed, suspension system, axle configuration, tires and aerodynamic characteristics. As you will note, the sample was small in some cases as we used what data we had available.

A brief description of the physical characteristics of each site is as follows:

1) I-494 is a fairly rough riding concrete roadway which was constructed about 1962.
2) TH 2 is a smooth bituminous roadway which was constructed in 1982.
3) TH 99 is a fairly smooth older bituminous roadway which had a 500 foot overlay applied prior to the installation of the scales in 1984.
4) I-94 is a smooth concrete roadway which was constructed in 1985.
5) The St. Croix Weigh station ramp is a smooth concrete roadway which was constructed in 1985.
6) The Iowa AWAC's site is on I-35 which is a smooth concrete roadway.

Here is a summary of the data we have compiled.

Table 7

Percent of Weight on Each Axle in a Tandem Group
for Loaded 5 Axle Semi

| | 1st Tandem | | 2nd Tandem | | # of veh. |
|---|---|---|---|---|---|
| | 1st Axle | 2nd Axle | 1st Axle | 2nd Axle | |
| I-494 | | | | | |
| Right Lane EB | | | | | |
| Sept. 30, 1982 | 47.9 | 52.1 | 41.3 | 58.7 | 66 |
| Oct. 11, 1982 | 49.0 | 51.0 | 41.7 | 58.3 | 17 |
| Oct. 25, 1982 | 47.6 | 52.4 | 42.7 | 57.3 | 27 |
| Aug. 4, 1983 | 48.6 | 51.4 | 43.6 | 56.4 | 41 |
| Aug. 28, 1986 | 50.2 | 49.8 | 43.3 | 56.7 | 60 |
| Left Lane EB | | | | | |
| Sept. 30, 1982 | 57.0 | 43.0 | 54.3 | 45.7 | 40 |
| Oct. 11, 1982 | 55.6 | 44.4 | 53.7 | 46.3 | 24 |
| Oct. 25, 1982 | 55.3 | 44.7 | 53.9 | 46.1 | 23 |
| Aug. 4, 1983 | 55.0 | 45.0 | 52.4 | 47.6 | 59 |
| Aug. 28, 1986 | 53.6 | 46.4 | 52.4 | 47.6 | 60 |
| TH 2 | | | | | |
| Right Lane EB | | | | | |
| Nov. 1, 1983 | 50.1 | 49.9 | 48.5 | 51.5 | 17 |
| Nov. 2, 1983 | 50.8 | 49.2 | 47.8 | 52.2 | 49 |
| Nov. 3, 1983 | 50.5 | 49.5 | 47.9 | 52.1 | 52 |
| Feb. 1, 1984 | 50.8 | 49.2 | 47.3 | 52.7 | 29 |
| Oct. 30, 1985 | 50.0 | 50.0 | 48.8 | 51.2 | 17 |
| Sept. 9, 1987 | 50.6 | 49.4 | 48.9 | 51.1 | 22 |
| Right Lane WB | | | | | |
| Nov. 1, 1983 | 51.6 | 48.4 | 50.6 | 49.4 | 7 |
| Nov. 2, 1983 | 52.9 | 47.1 | 50.5 | 49.5 | 15 |
| Nov. 3, 1983 | 52.1 | 47.9 | 51.4 | 48.6 | 17 |
| Feb. 1, 1984 | 50.5 | 49.5 | 50.0 | 50.0 | 18 |
| Oct. 30, 1985 | 52.0 | 48.0 | 51.6 | 48.4 | 7 |
| Sept. 9, 1987 | 51.8 | 48.2 | 54.2 | 45.8 | 4 |

|  |  |  |  |
|---|---|---|---|
| TH 99 |  |  |  |
| EB Lane |  |  |  |
| Oct. 1984, Mar. 1986 & Sept. 1987 | 51.4 - 48.6 | 48.9 - 51.1 | 19 |
| WB Lane |  |  |  |
| Oct. 1984, Mar. 1986 & Sept. 1987 | 49.4 - 50.6 | 47.8 - 52.2 | 15 |
| I-94 |  |  |  |
| Right Lane EB |  |  |  |
| Jan. 26 & Feb. 2, 1987 | 51.5 - 48.5 | 52.5 - 47.5 | 45 |
| Sept. 11 & 29, 1987 | 51.8 - 48.2 | 52.0 - 48.0 | 51 |
| Middle Lane EB |  |  |  |
| Jan. 26 & Feb. 2, 1987 | 50.6 - 49.4 | 50.5 - 49.5 | 45 |
| Sept. 11 & 29, 1987 | 50.2 - 49.8 | 50.9 - 49.1 | 68 |
| Middle Lane WB |  |  |  |
| Jan. 26 & Feb. 2, 1987 | 51.6 - 48.4 | 49.9 - 50.1 | 45 |
| Sept. 11 & 29, 1987 | 49.9 - 50.1 | 49.6 - 50.4 | 17 |
| Right Lane WB |  |  |  |
| Jan. 26 & Feb. 2, 1987 | 53.1 - 46.9 | 53.1 - 46.9 | 45 |
| Sept. 11 & 29, 1987 | 52.2 - 47.8 | 52.2 - 47.8 | 71 |
| St. Croix Weigh Station |  |  |  |
| Incoming Ramp |  |  |  |
| Jan. 13, 1988 | 52.0 - 48.0 | 49.8 - 50.2 | 85 |
| Mar. 10, 1988 | 51.4 - 48.6 | 49.7 - 50.3 | 80 |
| Iowa AWAC's |  |  |  |
| Sensor 1 |  |  |  |
| Sept. 15, 1986 | 50.1 - 49.9 | 46.4 - 53.6 | 66 |
| Sensor 2 |  |  |  |
| Sept. 15, 1986 | 51.0 - 49.0 | 50.8 - 49.2 | 66 |

After studying this data, we can draw the following conclusions:

1) Each lane has a unique profile in the area of the scales.
2) The consistency in the way the weight distributes generally holds steady over an extended period of time.
3) In this brief study we find three basic patterns represented. They are:
   a) The first axle of each tandem is the lighter one.

b) The first axle of each tandem is the heavier one.
c) The first axle of the first tandem is heavier while the first axle of the second tandem is lighter.

We did not find the fourth basic pattern which would show the first axle of the first tandem lighter and the first axle of the second tandem heavier. Our sample was probably not extensive enough to pick it up.

4) As one would expect, the roughest pavement, I-494, has the most pronounced imbalances, nearly approaching 60-40 with one set of tandems.
5) A majority of the readings from the other sites are close to 50-50, but they still have unique patterns. These sites have pretty smooth approaches.
6) The data from the Iowa AWAC's site is particularly interesting. It is our only look at what happens at two places in the same lane. Here we can see that there is a different pattern from one sensor to the other, particularly on the second tandem. The pattern had changed in 16 feet.

It probably is not important which axle of a tandem is heavier since presumably they are constantly switching back and forth. The critical point is the magnitude of the split.

All of these readings were from trucks which were traveling at highway speeds except those from the St. Croix Weigh station which were traveling at 20-30 MPH. Even at these slower speeds, there is an imbalance in the distribution of the weight.

An analysis of the individual vehicles which went into these groups showed that each one of them did not necessarily follow the pattern exhibited by the group as a whole. We have not measured the profile of each approach to attempt an in-depth analysis of the issue. This is one of the things that should be done in future research.

The distribution of weight on tandem axles is important in calculating ESAL's. The assumption is that the weight is distributed evenly or nearly so on the two axles. This means that there should not be large individual or systematic differences in the weight distribution, but that is what we are seeing in some locations. We can see the systematic extremes on I-494 and conclude that this likely causes problems for us in correctly calculating ESAL's. We may not suspect that there would be a problem on TH 2 which seems to be pretty well balanced. When we look at the individual tandems, we see that TH 2 also has a problem but it is not as bad as on I-494.

When we have a situation where the weight is not distributed evenly, the logical question is whether we should calculate the ESAL's in a different manner. One approach is to treat the heaviest axle as a single axle and calculate the ESAL's based on it alone while ignoring the impact of the lighter axle.

In calculating ESAL's for tandem axles, when the weight is evenly distributed between the two axles, the relationship between the factor for the tandem and the factor for an individual axle if that axle is treated as a single axle is 1.378. The purpose of making this calculation is to come up with a number which will serve as a benchmark against which we can compare our WIM data. We ran this comparison against I-494 where the pavement is roughest and against TH 2 where the pavement is smooth. These are the results of that analysis:

Flexible ESAL Factor

| | Tandem | Heaviest Single | Tandem Factor / Heaviest Single Factor | # of Tandems |
|---|---|---|---|---|
| I-494 | | | | |
| Right Lane EB | .605 | .648 | .934 | 146 |
| Left Lane EB | .964 | .930 | 1.037 | 136 |
| TH 2 | | | | |
| Right Lane EB | 1.056 | .941 | 1.122 | 100 |
| Right Lane WB | .951 | .862 | 1.103 | 100 |
| Benchmark Value | .718 | .521 | 1.378 | 13 |

This shows that I-494, particularly the right lane, is worse than TH 2. The factor for the heaviest single axle is higher than the factor for the tandem. TH 2 is better but even it is well below the benchmark value. Extreme imbalances in weight data are generally caused by rough pavements and these rough pavements in turn cause more imbalances. This pounding likely hastens the deterioration of the pavements. The proper calculation of these ESAL's is something that should be considered by pavement researchers who study and develop these relationships.

### Overestimation of ESAL Factors

The accuracy of the data collected by a WIM system will vary from site to site depending on the smoothness of the approach and also on the type of WIM system being used. The accuracy of the data is important when the ESAL factors are calculated for each vehicle. There is a tendency for the ESAL's to be overestimated by WIM systems. This is not a fault of the WIM systems but it is due to the nature of the relationship of the factors as the weight changes. The data in Table 8 and Figure 7 shows what happens in the case of a 34,000 lb. tandem which is weighed with varying degrees of accuracy.

Table 8

Effect on ESAL factors as the Error in Measuring Weight Varies

Flexible ESAL factor for a 34,000 lb. tandem = 1.095

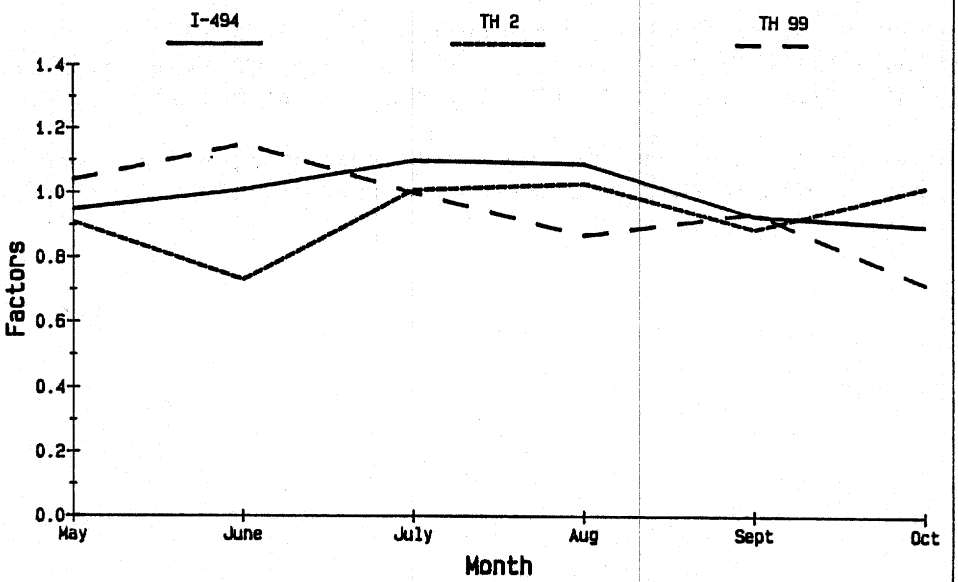
| Error | Weight on Tandem | Approximate ESAL Factors | Average Factor | % the factor isoverestimated |
|---|---|---|---|---|
| + 3% | 35,020 | 1.230 | | |
| - 3% | 32,980 | .971 | 1.101 | + 0.5% |
| + 6% | 36,040 | 1.380 | | |
| - 6% | 31,960 | .857 | 1.119 | + 2.2% |
| + 9% | 37,060 | 1.530 | | |
| - 9% | 30,940 | .753 | 1.142 | + 4.3% |
| + 12% | 38,080 | 1.700 | | |
| - 12% | 29,920 | .658 | 1.179 | + 7.7% |
| + 17% | 39,780 | 2.080 | | |
| - 17% | 28,220 | .495 | 1.288 | +17.6% |

In this example, if the system weighs a 34,000 lb. tandem 6% high one time and 6% low the next time so the average weight is 34,000 lbs., the ESAL factor is overestimated by 2.2%. One can see that the overestimation isn't too severe until the accuracy of the scales is perhaps plus or minus 12% or more. The problem really escalates for a system whose accuracy is plus or minus 17%. The same relationship exists for single axles and tridems as well as for varying weights of these axles or axle groups.

The problem is actually critical only if most of the weights are off by 17% for example. However, if the deviations are scattered uniformly between 0 and 17% (plus and minus), the overestimation will be a composite of all these individual values. This information should be kept in mind as it is a systematic bias.

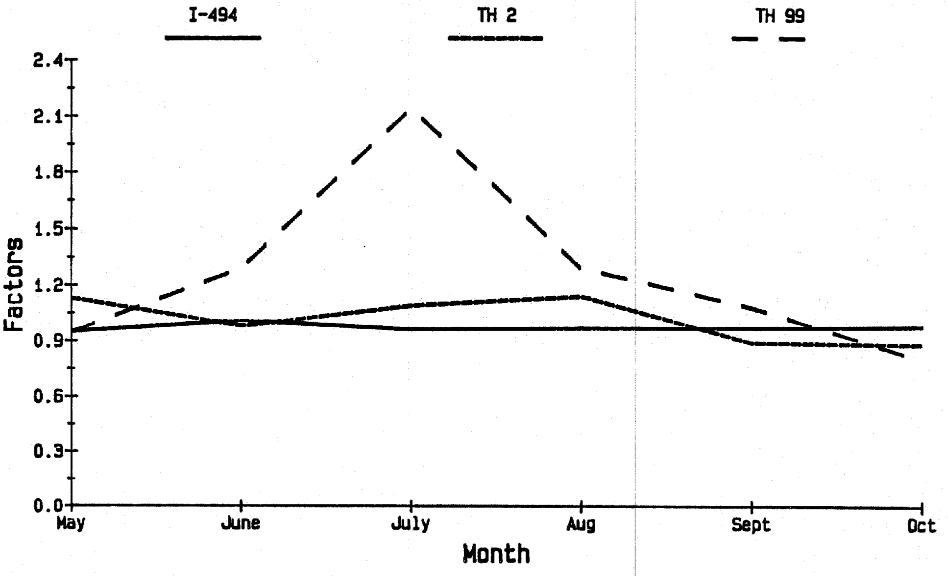
With more research, it may be possible to build correction factors. Regardless, it should be comforting to pavement design engineers to know that our estimates of ESAL's are conservative.

Figure 1
Factors to Adjust Average Weekday ESAL's
for 2 Axle 6 Tire Trucks to AADT



ESAL2ax

Figure 2
Factors to Adjust Average Weekday ESAL's
for 3 Axle Single Unit Trucks to AADT



ESAL3ax

Figure 3
Factors to Adjust Average Weekday ESAL's
for 5 Axle Semis to AADT

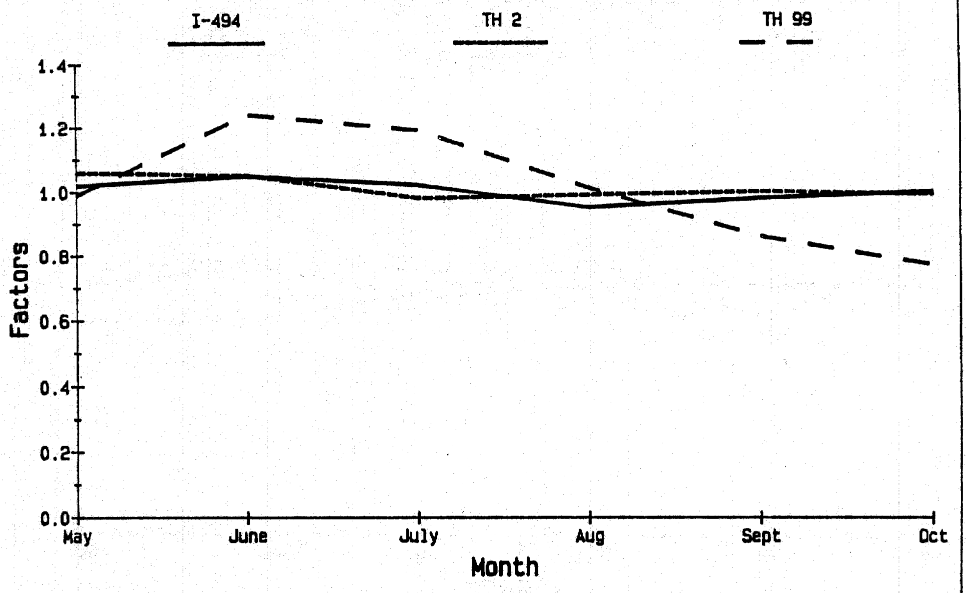


Figure 4
Factors to Adjust Average Weekday Volumes
for 2 Axle 6 Tire Trucks to AADT

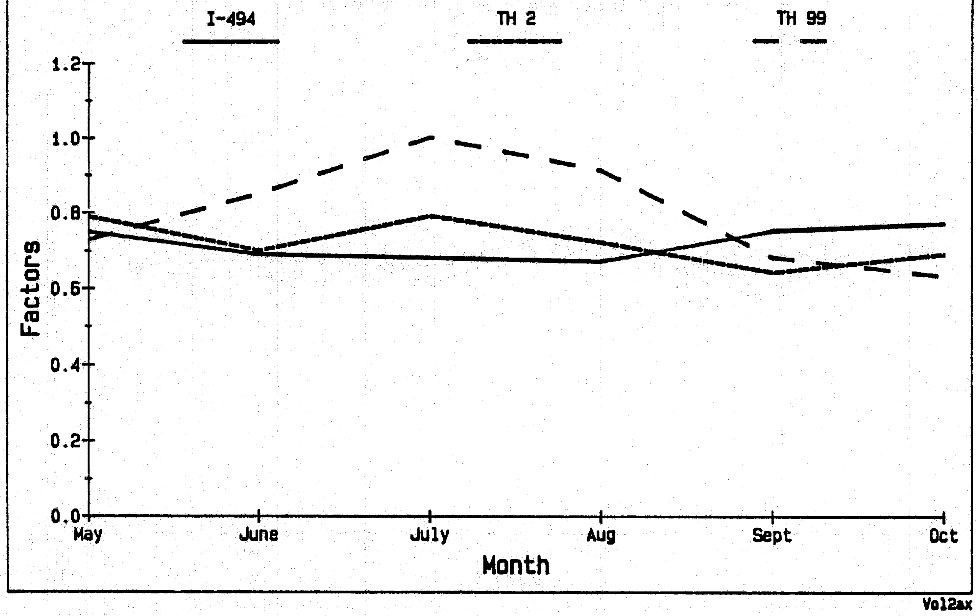
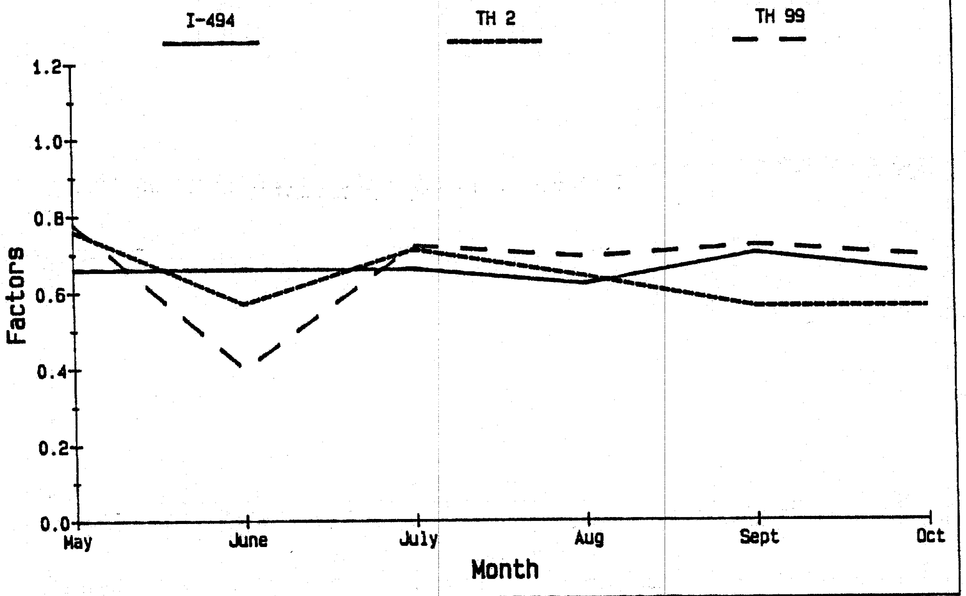
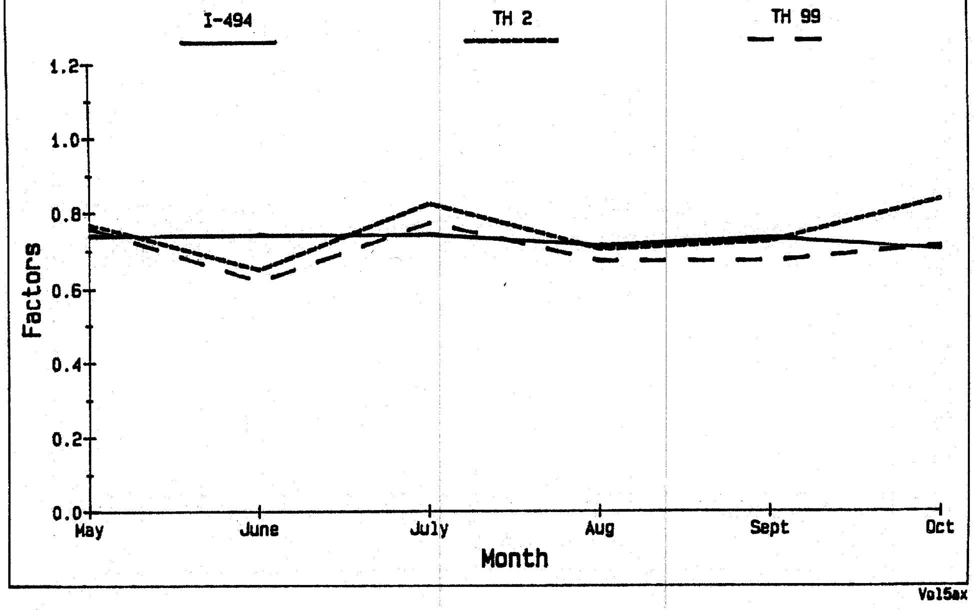


Figure 5
Factors to Adjust Average Weekday Volumes for 3 Axle Single Unit Trucks to AADT



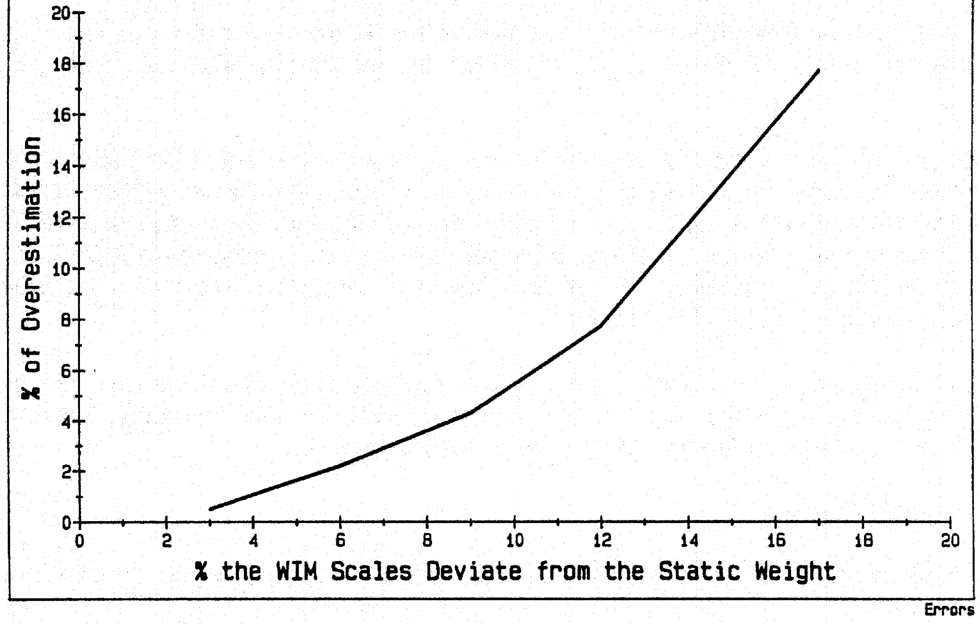
Vol3ax

Figure 6
Factors to Adjust Average Weekday Volumes for 5 Axle Semis to AADT



Vol5ax

Figure 7
Effect on Flexible ESAL Factors as the Error in Measuring the Weight Varies



## AN OVERVIEW OF ESAL ESTIMATION AND FORECASTING FOR PAVEMENT DESIGN

*Bruce Aunet, Wisconsin Department of Transportation*

### Introduction

This brief paper will attempt to provide an overview of some of the issues involved in equivalent single axle loading (ESAL) estimation and forecasting for pavement design. Many of the topics here, as well as additional related issues, are developed more fully elsewhere (1).

Numerous factors potentially affect the selection of the thickness of a pavement structure and the types of materials and pavement used. The primary factors are graphically portrayed in the flow chart in Exhibit 1.

Much is known about some of these factors, such as material limitations, for example, yet little is known about others, such as weather and climate related environmental stresses. And while the pavement damage caused by increasing truck tire pressures and particularly dynamic forces and uneven tandem axle load distributions may be substantial, the effects have generally not been added into ESAL Factors (which is why they dead end on the flow chart). Apparently only in Kentucky have they thus far adjusted their ESAL factors to take these variables into account.

While it is important to be aware of the larger picture, the focus here is on the issues involved in estimating and forecasting the number of trucks, the vehicle or truck mix, and the average ESAL factors per truck type that make up total cumulative ESALs (over the design life).

### The Cumulative ESAL Forecast

The cumulative ESAL forecast can be disaggregated by estimating base year values and forecasting design year values for:

1. total traffic (AADT);
2. vehicle mix (numbers of trucks by type); and
3. average ESAL factors (by truck type).

The cumulative ESAL forecast/calculation can be structured in a number of ways. Appendix D of the AASHTO Guide for Design of Pavement Structures provides one format. A Lotus "1-2-3" macro spreadsheet of Appendix D designed for FHWA is shown in Exhibit 2. A streamlined "1-2-3" spreadsheet was designed at WisDOT to: 1) use only those five truck types currently used by the department in pavement design, and 2) use explicitly forecasted design year truck type ESAL factors. An example is shown in Exhibit 3. Note that the increase in total ESALs between the exhibits is the result of the fore- casted design year ESAL factors.

Directional and lane distribution factors (DDF and LDF), though often neglected, are also important. They both refer to ESALs, not traffic, nor even just trucks. The DDF is usually assumed to be evenly split (50-50) in lieu of actual data, yet a 20 percent change in the DDF (from 0.5 to 0.6, for example) results in a corresponding 20 percent increase in the cumulative design ESAL forecast/calculation. Both the DDF and LDF are direct multiplicative factors. Thus to improve the cumulative design ESAL forecast/calculation, more information is needed on the direction and lane distribution of ESALs.

The state-of-the-art in ESAL forecasting is not very advanced. It has been a largely overlooked area up until very recently and data limitations also hinder current forecasting efforts. Because of limited sampling, equipment limitations, and the effects of dynamic forces, there is considerable uncertainty about the reliability and validity of current estimates, let alone forecasting from an uncertain base. Nonetheless, forecasts are required; for if they are not done explicitly, then the implicit assumption is that things will not change. And that doesn't seem very realistic over a 20 year design horizon.

## Data Requirements

The vehicle mix data base in Wisconsin is currently limited in both breadth and depth.

Spatial coverage is inadequate. The Traffic Monitoring Guide (TMG) recommends 300 sites over a 3 year cycle; WisDOT is currently collecting data at only 120 sites on a 3 year cycle.

Temporal coverage is also inadequate. Currently nighttime, weekend, and seasonal data are lacking. To what extent seasonality in truck traffic is an issue, if at all, cannot be determined from existing data.

Going to forty-eight hour machine automatic vehicle classification (AVC) counts will help. Much better data are expected from a number of automatic traffic recorders that are planned to be converted into continuous AVC stations. This will not only provide better data for forecasting, but will also serve as a good base from which to analyze seasonality and variance in truck traffic to further improve the vehicle classification data collection program.

The truck weight data base at Wisconsin suffers from essentially the same problems (with regard to lack of spatial and temporal depth). Only a few points are made here since the WisDOT's truck weight program is described in detail elsewhere (2).

Going from twenty-one sites on a two year cycle to sixty-nine sites over a three year cycle will improve the spatial coverage of the weight monitoring program. Seven different highway functional systems also will still be monitored.

Temporal coverage will be expanded to forty-eight continuous hours at all sites and seven continuous days on a bimonthly basis (May-October) at six "control" stations. Truly in depth temporal coverage - capturing hourly, daily, monthly, and annual variations over time - could be reached through the installation of some continuous automatic truck weight (ATW) stations. This will become increasingly feasible as technology and equipment improve and costs decline.

## Data Analysis and Summarization Requirements

The quantity of vehicle mix and particularly truck weight data has begun to increase markedly (through the use of WIM and AVC equipment). WisDOT, for example, is increasing the number of trucks weighed from 10,000 to roughly half-a-million per year. And even that is still low compared to some states. Going to continuous vehicle classification will also dramatically increase data collection.

As the quantity of the collected data greatly increases, it becomes increasingly important to stay current with the analysis and use of existing data. There is a real need to use the data already available to improve data collection programs, enforcement programs, and pavement designs.

Collected data need to be analyzed for validity and reliability. What exactly is being measured? (Weight? Dynamic forces?) Is the equipment performing up to standards over time? Judicious data edits need to be made as necessary to insure data quality. The importance of maintaining data integrity -so as to prevent credibility gaps which can cause users to reject the data - can not be overemphasized.

One way to check high speed WIM collected weight data is to compare it to enforcement scale collected weight data. Yes, some truckers avoid enforcement scales - about 15 percent in one case study done in Wisconsin (3); and thus total ESALs decrease (by about 15 percent). But average ESAL factors remained essentially unchanged, with or without enforcement presence. Trucks that did avoid the scale did so primarily because of registration or safety violations, not size or weight violations (4).

In addition to being checked for validity and reliability, data records need to be statistically summarized down to a meaningful and useful format. This means developing and annually updating current estimates for:

1) average numbers and percentages for truck types used in pavement designs;
2) average equivalency factors for each truck type used in pavement designs; and
3) each of the above data elements at each data collection location as well as at the highway functional classification system level.

If a 3-year data collection cycle is used then a 3-year moving average also should be used to smooth out sampling fluctuations.

Finally, some type of data management plan - specifying who needs what data in what format - is essential to organize and help insure expedient usage of the mountains of data that are being and or soon will be collected.

### Analyzing and Forecasting the Total ESAL Components

Assuming good, reliable data from which to derive current estimates and analyze historical patterns, attention can then be turned to forecasting out to the design year.

In terms of vehicle mix, a good place to start is by looking at trends. One obvious trend is toward larger trucks. Average daily single trailer 4-axle or less (ST4AX) trucks have declined, for example, while average daily single trailer 5-axle or more (ST5AXM) trucks are increasing in numbers. Examples of these trends on the rural interstate highway system in Wisconsin are shown in Exhibits 4 and 5. These plots are based on a 3-year moving average for the system. Plots for site specific locations are more erratic because they only show data points corresponding to the collection cycle, which in this case is three years.

Various simple data fitting, trend extrapolation techniques can be used to forecast. Such techniques include moving averages, exponential smoothing, linear regression, and curvilinear regression. It's important to forecast numbers of trucks here; not percentages.

Some combination of trend line and judgment is probably adequate for most project specific vehicle mix and ESAL factor forecasts.

Causal, econometric models, explicitly taking into account economic variables, are preferable from the standpoint of theory, and they are perhaps most useful on a general or statewide basis. But such models are difficult to define and use at a project level or even on a system wide basis. They are also dependent on independent economic forecasts (which are subject to their own set of problems). Finally, the level of effort generally required may not be justified for pavement design purposes.

Essentially the same process - trend analysis and extrapolation, tempered by judgment - can be used for forecasting average ESAL factors (by truck type). The FHWA W-Table microcomputer software, soon to be released, should enhance analysis and forecasting capabilities in this area. The important point here is to start forecasting design year average ESAL factors, since they are just as important, if not more so, than forecasts of numbers of trucks.

## Sensitivity of the Pavement Design Equations to ESALs

The old "rule of thumb" with regard to pavement thickness design and total ESALs is that adding one inch of pavement will accommodate a doubling in total ESAL carrying capacity. This is generally true, although it depends somewhat on other design variables and total ESAL magnitudes. The important point is that as total ESALs increase, required pavement thicknesses increase at a substantially decreasing rate.

Take, for example a continuous reinforced concrete (CRC) pavement designed to carry, say, 20 million ESALs over 20 years. This would typically require a 10 inch pavement thickness. If total ESALs were forecasted to be 40 million over the 20 years - a 100 percent increase - then an 11 inch pavement would be required (for a 10 percent increase in thickness, in this case). Assuming a direct relationship between cost and thickness, there also would be roughly a 10 percent increase in cost for the additional one inch of pavement required.

Design engineers at the WisDOT are completing a report that looks at this relationship between ESALs, pavement thickness, and cost in more depth (5).

So in terms of the consequences of forecasting error, it turns out that pavement thickness design is not highly sensitive to the total ESAL forecast. Other factors in the design equation also play a significant role. FHWA has graphically looked at the sensitivity of a number of these variables (such as the modulus of subgrade reaction, the modulus of rupture, the elastic modulus, the load transfer coefficient, and the drainage coefficient) and their Region 10 office has developed a Lotus "Symphony" program for pavement design (6).

WisDOT design engineers are also developing a menu driven Lotus "1-2-3" macro program for pavement design that explicitly takes into account forecasted ESALs (based on forecasts of total traffic, vehicle mix, and ESAL factors), pavement costs, and life-cycle costs (7).

The relative lack of sensitivity of forecasted ESALs in the pavement design process doesn't mean that efforts shouldn't still be made to provide better forecasts. On the contrary, decisions should be based on the most accurate information practicable. While the development of complex or sophisticated forecasting models may not be necessary, significant improvements can still be made. Efforts might also be fruitfully spent on developing more reliable current estimates, particularly with regard to ESAL factors.

## Summary and Conclusions

The state-of-the-art in ESAL forecasting is not very advanced and data limitations hinder current efforts. Yet just beginning the process of explicitly forecasting numbers of trucks and ESAL factors would be a step forward; and one that needs to be pursued.

Going to continuous data collection, for both vehicle classification and truck weighing, will help fill some key data gaps and form a solid basis for the establishment of trends. At the same time, computerizing data analysis and pavement design procedures will improve both the utilization of these data as well as productivity.

Much more will be able to be done in this area - of analyzing and forecasting the data - as the quantity, and hopefully quality, of collected data begins to greatly increase. This will allow assumptions to be verified or refuted. Some surprises should be expected along the way.

Finally, to be truly effective, greater intra-agency cooperation between planning, design, and enforcement personnel is also needed, including more inter-agency cooperation and information sharing as well.

## REFERENCES

1. B. Aunet. Forecasting Equivalent Single Axle Loadings For Pavement Design. Wisconsin Department of Transportation, Madison, Wisconsin, forthcoming.

2. P. Stein. Review and Revision of the WisDOT Statewide Truck Weight Study Program. Wisconsin Department of Transportation, Madison, Wisconsin, December 1987.

3. G. Grundmanis. Truck Avoidance of Enforcement Scales: Description and Results of a Field Study. Wisconsin Department of Transportation, Madison, Wisconsin, forthcoming.

4. Division of State Patrol. Do Truckers Avoid Enforcement Scales? A Report on Estimating Avoidance at One Wisconsin Interstate Scale and Testing Three Enforcement Strategies. Wisconsin Department of Transportation, Madison, Wisconsin, forthcoming.

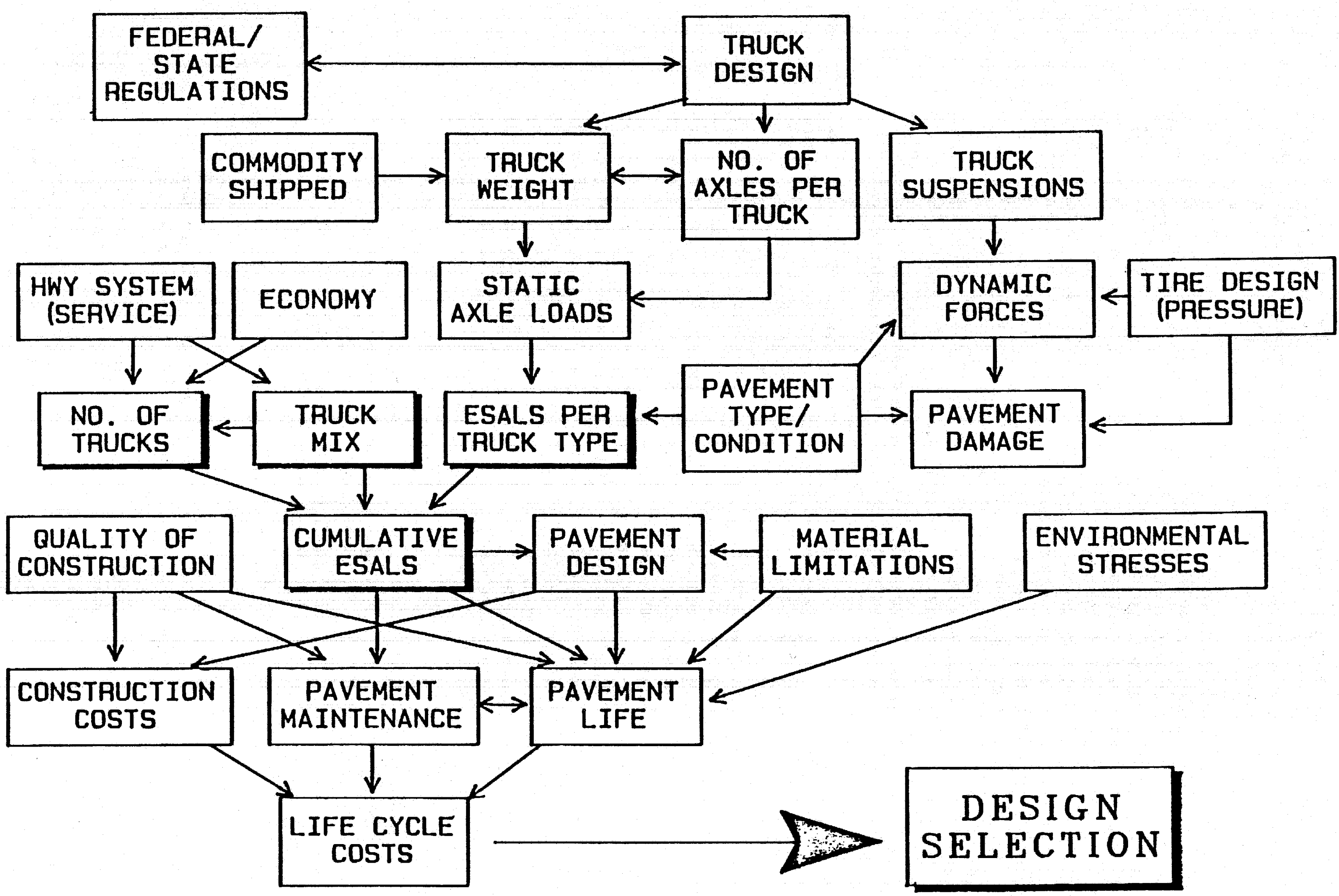
5. D. Friedrichs. The Effects of Truck Volume, Mix, and Weight Distribution Changes on Pavement Design. Wisconsin Department of Transportation, Madison, Wisconsin, forthcoming.

6. G. Owens and J. P. Hallin. Symphony 1.1 Worksheet Solutions for the 1985 AASHTO Pavement Design Equations. Federal Highway Administration, Region 10, Portland, Oregon, February 1986.

7. D. Friedrichs. WisDOT Pavement Design System. Wisconsin Department of Transportation, Madison, Wisconsin, forthcoming.

EXHIBIT 1

# FACTORS AFFECTING PAVEMENT DESIGN SELECTION



## EXHIBIT 2

```
                        HIGHWAY PAVEMENT CUMULATIVE ESALs  NCHRP 255
OFFICE OF PLANNING, FEDERAL HIGHWAY ADMINISTRATION
DESIGN PERIOD (1-40yrs)=   26         # OF LANES=    4
DIRECTIONAL DISTRIB. (0.50 TO 1.00) =        0.5  ** INPUTS **     ESAL
** VEHICLE TYPES **      BYr % BYr ADT   % GROWTH FYr % FYr ADT   FACTOR
PASSENGER CARS                                               0
BUSES                                                        0
PANEL/PICKUP TRUCKS                                          0
OTHR 2-AXLE/4 TIRE TRKS                                      0
2-AXLE/6-TIRE TRUCKS      2.2                      1.8     404      0.2
3 OR MORE AXLE TRUCKS     1.1                      0.8     180      0.8
3  AXLE TRACTOR SEMI                                         0
4  AXLE TRACTOR SEMI      1.4                      0.7     157      0.8
5+ AXLE TRACTOR SEMI     26.2                     41.0   9,205      1.6
5  AXLE DBL TRAILERS      1.0                      2.2     494      2.1
6+ AXLE DBL TRAILERS                                         0
3 AXLE TRUCK-TLRS                                            0
4 AXLE TRUCK-TLRS                                            0
5+  AXLE TRUCK-TLRS                                          0
** ALL VEHICLES **       31.9  14,770       - -   46.5  22,450

HIGHWAY PAVEMENT CUMULATIVE ESALs  NCHRP 255  11/6/85  MOD 4/16/86
Written by JHK & Assoc (K. Hooper) & COMSIS Corporation (M. Roskin)
                        *** RESULTS ***
                                        GROWTH   % OF         CUM
** VEHICLE TYPES **      BYr ADT  FYr ADT  RATE %   LOAD        ESALs
PASSENGER CARS                 0        0    0.0    0.0%            0
BUSES                          0        0    0.0    0.0%            0
PANEL/PICKUP TRUCKS            0        0    0.0    0.0%            0
OTHR 2-AXLE/4 TIRE TRKS        0        0    0.0    0.0%            0
2-AXLE/6-TIRE TRUCKS         325      404    0.9    0.7%      310,371
3 OR MORE AXLE TRUCKS        162      180    0.4    1.3%      584,255
3  AXLE TRACTOR SEMI           0        0    0.0    0.0%            0
4  AXLE TRACTOR SEMI         207      157   -1.1    1.3%      618,370
5+ AXLE TRACTOR SEMI       3,870    9,205    3.5   91.1%   42,200,010
5  AXLE DBL TRAILERS         148      494    4.9    5.6%    2,585,939
6+ AXLE DBL TRAILERS           0        0    0.0    0.0%            0
3 AXLE TRUCK-TLRS              0        0    0.0    0.0%            0
4 AXLE TRUCK-TLRS              0        0    0.0    0.0%            0
5+  AXLE TRUCK-TLRS            0        0    0.0    0.0%            0
** ALL VEHICLES **         4,712   10,439    - -     - -   46,298,945
```

## EXHIBIT 3

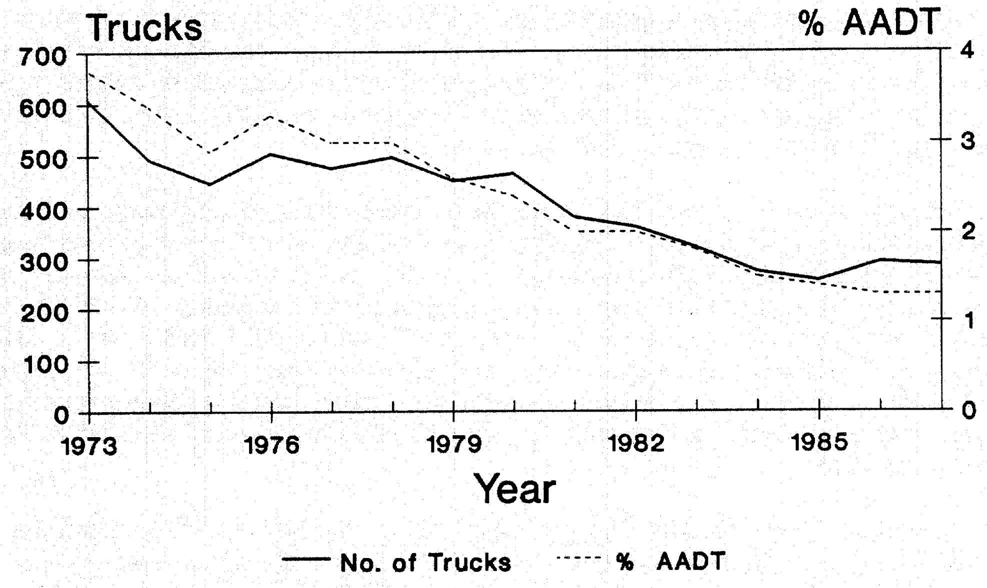
```
                        INPUTS
=============================================
Design Period   =    26   Lanes =        4
Base Year AADT  =  14770    DDF =      0.5
Design Year AADT=  22450    LDF =      0.9

                                                    RESULTS
                                                ====================
                                                % of
                      BY %    DY %   BY ESAL  DY ESAL  Total       Total
Vehicle Type          AADT    AADT   Factor   Factor   Load        ESALs
--------------------------------------------------------------------------
        SU2D          2.2%    1.8%    0.20     0.30    0.7%      397,894
        SU3AXM        1.1%    0.8%    0.80     1.00    1.1%      661,475
        ST4AXL        1.4%    0.7%    0.80     0.90    1.1%      655,669
        ST5AXM       26.2%   41.0%    1.60     2.10   91.7%   54,531,112
            MT        1.0%    2.2%    2.10     2.40    5.4%    3,195,518
--------------------------------------------------------------------------
Total Trucks        31.90%  46.50%                            59,441,669
```

EXHIBIT 4

## AVERAGE DAILY ST4AX TRUCKS

### On the Rural Interstate System

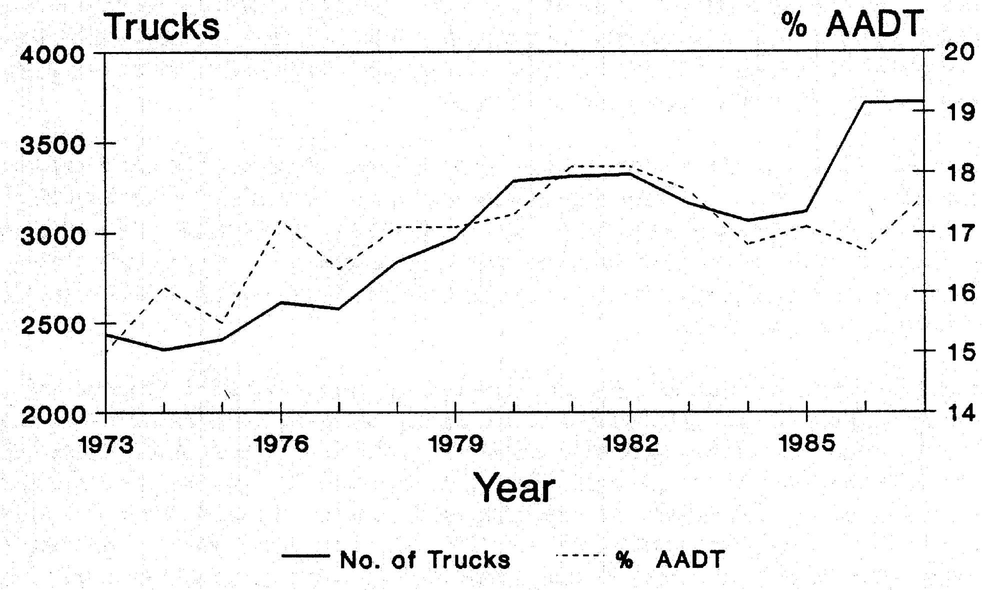


3 - Year Moving Average from 1977 On

EXHIBIT 5

## AVERAGE DAILY ST5AXM TRUCKS

### On the Rural Interstate System



3 - Year Moving Average from 1977 On

# SUMMARIZATION OF WORKSHOP ON WEIGHT ENFORCEMENT--PLANNING, OPERATIONS, AND WEIGH AND INSPECTION STATION DESIGN

*John F. Grimm, Federal Highway Administration, Washington, D.C.*

In our session, there were seven presentations covering WIM applications and truck weigh station design and operation. The WIM applications, covered in six presentations, included vehicle sorting and screening, WIM output as evidence of violations, and use of WIM equipment to monitor bypass routes. Truck weigh station design and operations, covered in five sessions, included ramp geometrics, truck flow and monitoring, mobile units, automation, and joint State use.

Captain Marsha Wiley of the Wisconsin State Patrol discussed a study of trucker avoidance of open, permanent scales. The study focused on the Rusk scale on I-94 and the methodology used to monitor the bypass routes with WIM equipment and patrol vehicles making visual observations. Not surprisingly, scale avoidance ranged from 35 percent to 67 percent of the eligible trucks. Surprisingly, WIM showed that only about 10 percent of these trucks were actually overweight. Further, special permit trucks and statutorily exempt (pulp and milk) haulers make a precise estimate impossible. The study concluded that there was a need for concurrent enforcement by both weight and Motor Carrier Safety Assistance Program personnel on bypass routes during permanent scale operations, and that these bypasses can be as far as 70 miles away from the permanent scales.

Chief John Bailey of the Arkansas Highway Police told us that because of the significant increase in heavy truck traffic on Arkansas highways and budgetary and staff limitations, which are no different in Arkansas than anywhere else, it is imperative that the use of WIM for issuing citations be tested in the courts of Arkansas and other States. He sees a parallel in the use of WIM data as evidence with the development of the use of "radar" data in the courts 20 years ago. He praised the use of WIM as both a screening device and a tool for planners. But he emphasized that using WIM as an enforcement tool is inevitable and hopefully it would occur soon.

Sergeant Calvin Karl of the Minnesota State Patrol discussed the development and operation of the St. Croix weigh station at Lakeland, Minnesota, which many of us visited and observed in operation this week. Specifically, he described the use of WIM as a sorter of truck traffic on the entrance ramp to the scales. The significant reduction in the number of trucks that actually have to be weighed on the static scales afforded by WIM enable the vast majority of trucks, including those weighed on the static scales, to pass through this state-of-the-art facility with little or no delay.

Captain Albert Corbin of the South Carolina Highway Patrol described the design of new weigh and inspection stations to be built in his State. He explained in detail the turning radii required, the necessary lengths of entrance and exit ramps and the use of WIM equipment, both as a screening tool for the identification of potentially overweight vehicles and as a means of collecting axle load and vehicle configuration data. Lighting, signing, pavement type and depth, building size and design, and personnel morale and efficiency were addressed.

Mr. Robert Ketner of the Virginia Department of Transportation discussed Virginia's statewide weight enforcement program that uses permanent and portable scales and WIM equipment. He described Virginia's self-contained, converted R.V. vehicle outfitted with WIM equipment to screen four lanes of traffic on some of the State's highest volume highways. This equipment identifies the vehicles that should be statically weighed. He emphasized the efficiency of this approach and how it has expanded the State's ability to screen truck traffic on heavily traveled highways such as U.S. 29, which previously had no permanent facilities nor appropriate geometrics for portable scales. Bob also answered a great many questions about the costs of the vehicle and its related equipment.

Mr. Jim Gunderson of the Utah Department of Transportation talked to us about a port-of-entry weigh and inspection station on I-15 that will be jointly operated by Utah and Arizona. The obvious economies of such joint operations were explained and the resulting greater coverage at lesser cost were described. Many legal questions were addressed including the need for intergovernmental agreements between the two States covering such aspects as issuing citations and special permits by officers of one State for the other. Despite having differing laws and regulations in such areas as trip permits, fuel taxes, registrations, operating authority, and the like, the joint operation by both States' officers has proven very successful. Utah, New Mexico, Arizona, and California plan to have several joint ports-of- entry in the near future.

Messrs. Milan Krukar and Ken Evert of the Oregon Department of Transportation described an experimental project in automation at their agency's Woodburn South Bound Port-of-Entry on I-5. This visionary project uses WIM, and automated vehicle identification (AVI) technology, as well conventional static scales and two major computer systems. These systems monitor and regulate trucks with respect to weight, size, safety, and weight-distance taxation.

Equipping high-usage trucks with transponders for fleet and vehicle specific identification allows these trucks to realize productivity gains by bypassing the permanent scales while passing through the port-of-entry, even hough virtually every aspect of the truck and carrier is checked and affirmed through the computers. Items checked include the currency of P.U.C. plates, safety records, and records of compliance with size and weight laws, and whether the operator/carrier is a "chronic offender." The productivity gains and monetary benefits of this automated system, including the collection of large amounts of unpaid taxes from carriers passing through the port-of-entry were described as well as improved data collection for planning and other purposes. This presentation was so interesting we could have easily spent twice the time available in discussing it.

I greatly appreciate each of the speakers for agreeing to participate in this session and taking the time to prepare their presentations. The presentations were excellent as well as informative.

# REMARKS ON WIM AS AN ENFORCEMENT TOOL

*John R. Bailey, Chief, Arkansas Highway Police*

Arkansas' state highway system, which is one the oldest interstate systems in the nation, consists of over 16,000 miles. With a price tag of approximately $6 billion, it is considered the largest single taxpayer investment in the State.

Close examination would credit the Arkansas Highway Police's comprehensive weight enforcement program. The preservation of the road surface has been the focal point to control of accelerated pavement wear caused by overweight vehicles. The Highway Police is comprised of 236 members assigned statewide in 17 port of entry weigh stations and 47 strategically located patrol units. Various studies have indicated that highways are constructed to last 10 years, if not for the diligent efforts of these officers, overweight vehicles could cause their failure as early as 4 years after construction.

Arkansas has always placed heavy emphasis on the enforcement of weight laws and the preservation of the highway surface, and as was displayed by being one of the last states to allow 80,000 pound maximum load limits. Today, however, we are challenged with a new problem.... the ever increasing volume of commercial vehicles using the State's highways in proportion to the number of trucks actually weighed for enforcement purposes. It is estimated that approximately 66,000 trucks travel Arkansas highways each day.

The Office of Highway Planning of the Federal Highway Administration revealed in a study from 1969 to 1979, the following information:

1) Truck volumes increased 25%

2) Total percent of trucks increased in vehicle population shifted to larger and heavier types.

   1969 - 8% of Interstate traffic are trucks

   1979 - 16% of Interstate traffic are trucks

   1983 - 17% of Interstate traffic are trucks

Therefore, law enforcement administrators are confronted with questions such as:

1) How to maximize manpower (our most important and expensive resource) to target potential violators... in lieu of Federal requirements that will not permit in excess of 171 hours worked in any 28 day work period? (Garcia vs. San Antonio)

2) How to apply technology to current portable wheel weighing concepts that will increase the number of overweight vehicles contacted in the most expeditious way?

3) How to address the 10-25% of trucks estimated to be overweight that are doing $1 billion damage to our nation's highways annually?

4) How to ensure the businessman in your community that unfair economic advantages are not being allowed by trucks operating overweight, thereby affecting the bid process?

5) How to address the safety factor that overweight trucks are more difficult to stop and impact damages in accidents are more severe?

6) How to address the static scale avoidance problem, whereas studies have revealed only 1% of trucks weighted at static scale locations are illegal, and as high as 30% are illegal when weighed at various portable scale locations?

Surely these are but only a few of the problems facing the weight enforcement community today. However, weigh-in-motion systems may be the answer to some of them.

Technological advances have not led us to a point where it can be said that weigh-in-motion is a sound approach exclusively for weight enforcement purposes. It is, however, capable of obtaining gross weights within ± 5% for 95% of the vehicles and tandem weights within ± 10% for 90% of the vehicles checked in surveys. With these figures as a basis, it is thought by some that the only obstacle to enforcement use is full acceptance by the judiciary.

For example, think back 20 years ago when "radar" was paramount for speed enforcement. The scientific principle behind the development of police Doppler radar was proven as far back as the mid 1800's. The principle has never changed, the applied technology has. Today, police academies, courts, manufacturers, as well as the National Bureau of Standards teach, recognize and will admit that police traffic radar devices and tuning forks are accurate to within ± 1 mile per hour. Example: If a traffic radar device indicates the speed of a vehicle traveling a true speed of 55 mph, the resulting radar display could indicate either 54, 55, or 56 mph. This is an acceptable deviation and is used successfully in the prosecution of traffic offenders. The courts require that the officers be sufficiently trained in the set up, verification of calibration, and use of the device. Landmark court decisions have ruled that the operator need not know the technical or scientific aspects associated with the Doppler radar theory.

If weigh-in-motion is not acceptable in a court of law for overweight violations, then we could possible explore a similar approach to that of radar. First, a nationally recognizable percentage of deviation should be established and efforts made to gain the confidence of the legal community nationwide as to WIM's accuracy. In so doing, the scientific principle and physical characteristics of WIM could be court tested. Until that occurs, WIM will continue to be limited in enforcement applications.

As a screening device, its applications are still exciting. The bridge weigh-in-motion system will allow hardware to fit easily in patrol units. The officer attaches a cable to a connection box and only upon detection of a potential violation by WIM does the officer weigh the vehicle through the use of static portable scales. Additionally, WIM is useful in estimating the scale avoidance or "by-pass" problem which enables planners to structure enforcement programs that maximize the "halo effect". This function is best suited for covert setups.

A new area of WIM application has also surfaced. It can be utilized in "alerting" enforcement planners of geographic locations where overweight vehicles are prevalent. For example: The Arkansas Highway Police obtains data from 90 locations (30 per year) on a 3 year rotation. Selective Enforcement Projects (SEP) are streamlined to improve efficiency in dealing with major overloading problems that vary with industrial and economic trends.

As I mentioned earlier, actual enforcement applications are currently limited, but WIM does increase the probability of being weighed. It assists in establishing the three primary criteria when considering voluntary compliance with size and weight laws and regulations. Those criteria are:

1) The probability of being detected

2) The probability of being weighed

3) The probability of paying a fine and/or off loading

Through technical studies and actual overweight violation statistics, it has been determined that trucks traveling through Arkansas have a 20% possibility of being weighed while on a 500 mile interstate trip. Weigh-in-motion could certainly increase this percentage. Coupled with the above criteria it creates, the positive results of WIM, currently and in the future, are obvious.

In conclusion, let me assure those of you who are advocates of weigh-in-motion systems, as we in Arkansas are, that as long as manufacturers keep manufacturing, trucks keep trucking, over loaders keep overloading, and the Federal Government maintains its generous funding, WIM's place in commercial vehicle enforcement will be secure.

# DESIGNING WEIGHT AND INSPECTION STATION

*Captain A. F. Corbin, South Carolina Highway Patrol*

South Carolina is embarking into a new era with commitment of new weight and inspection stations. Our commitment will include new WIM systems at our four new facilities. A very important must is in the selection of the right site to prevent by-passing. There is very little use for these weight and inspection stations to monitor just legal vehicles while the perpetual violator can easily by-pass these stations. This is very important to select a site that would be a natural barrier that would funnel all commercial vehicle traffic into these weight and inspection stations. You will never be able to prevent some by-passing your weight and inspection station, but in these situations portable WIM equipment, with cameras and alarm systems to be activated when a over-weight vehicle tries to slip around the check point, and the use of roving crews with portable wheel weighers will help to control this problem also. This is where the planning process pays off, with the help of consultants, your engineering staff, and enforcement personnel to resolve problems, to make these weight station workable and to eliminate the commercial vehicle over-loading problem.

In designing these facilities the projection for future expansion should be taken into consideration. The entrance and exit ramps should be lengthened to the maximum to accommodate traffic so there will not be any traffic backed up into traveled portion of highway. Also you must remember these entrance ramps should have the maximum length for WIM system, so as not to have the vehicles being checked, to have to stop and restart, as this will defeat your WIm system's screening tool for identification of potentially overweight vehicles. After the vehicles have been screened, a minimum of 800' should be maintained after the vehicle leaves the system to the gore. Exit ramps should be lengthen to the maximum for vehicles to accelerate back to highway speed to blend back into the highway smoothly. Another important factor is if WIM system is to be used, concrete ramp is a must to insure that the WIM system will give accurate readings. If asphalt is used for this application, it has a tendency to rut or roll up causing bumps. Wim system has been used for years for the collection of axle loads data and is a screening tool for the identification of potentially overweight vehicles. This technique (WIM) measures the mass of a vehicle, wheel, axle by detecting the change in dynamic force which is applied by the vehicle. The slightest bump or roll up will change the dynamic force causing a false reading from your WIM system, and your screening would not be accurate. This is where using concrete throughout the facility would be very beneficial as well as preventative maintenance as the vehicle leaking oil, gas, diesel fuel would penetrate asphalt causing deterioration of same.

Lighting is very important to these facilities. Your entrance and exit ramps as well as static scale area and parking or storing area should be well lighted. This makes for a better operation for your personnel as well as for the truckers, also they can be directed properly, without unduly delays.

The personnel to man the weight and inspection station should be kept in mind when planning the buildings, and their input should be sought. If they have a facility they are proud of, you can expect better performance, and good enforcement program will ensure. South Carolina is using the control tower format for our four new facilities. This gives the operators a better over all control and view of the weight station. They have eye contact of the over all physical plant, and can detect any problem that might occur.

We recommend that when selecting WIM system and static scale purchases, you select the same vendor for both projects. This is to ensure that both systems are compatible and the single vendor can render service along with warranty.

We have prepared some slides of our new weight and inspection station. They include the plans, drawing, of the building and pavement design.

We in South Carolina are proud of the new state commitment to move in the new era of technology of WIM system to better enforce all size and weight laws, and prevent overloading, and damage to our highway system (which is the 5th largest in the U.S.) and bridges, because we are all in this together. If we can prevent this damage, then we all could enjoy a lower tax bill in the future.

# NEW STRATEGIES FOR STATEWIDE PROGRAMS (VIRGINIA'S PERSPECTIVE)

*R. M. Ketner, III, Permits and Truck Weight Manager Virginia D.O.T.*

We all know the saying "If you don't know where you are going you are not likely to get there". This thought is applicable to all of us in accomplishing both personal and professional goals.

While we may say, "we know where we are going"; knowing how to get there requires study, money and action before we embark.

When I was asked to speak on the subject of "New Strategies for Statewide Programs" I expressed that I did not feel that I was in a position to tell you, "where you should be going and how to get there"!

Accordingly my comments are humbly offered for your information with the hope that by sharing Virginia's experience, more efficient truck weighing operations may evolve within your respective states.

Virginia's program consists of 14 permanent weigh stations strategically located throughout the state. To supplement these permanent facilities, the state has deployed 10 mobile units to provide for the enforcement of weigh laws in areas of the state where permanent scales are inappropriate and to monitor bypass violations, see Exhibit 1.

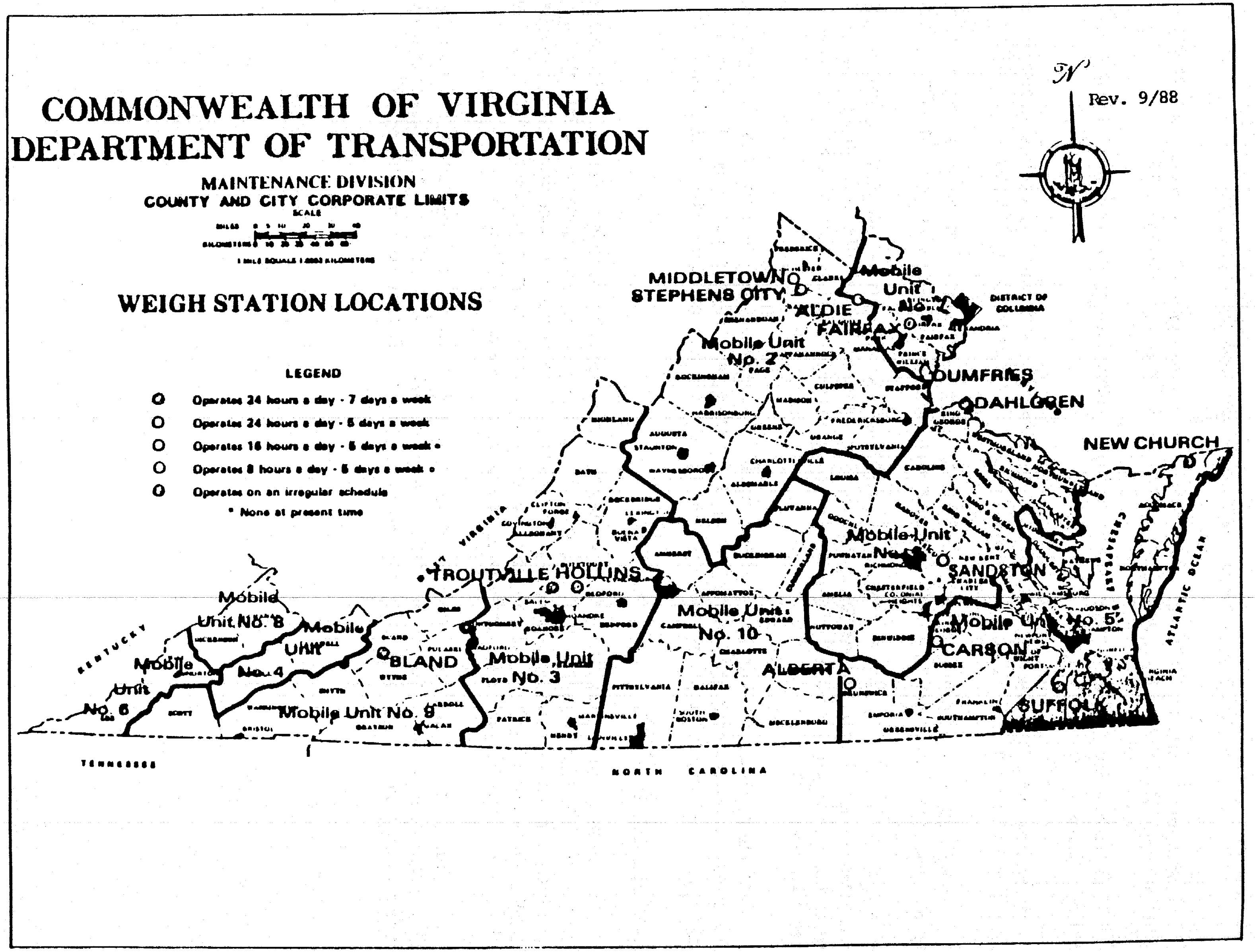
In addition, we have a fully self-contained mobile WIM vehicle that can screen four lanes of traffic and our highest volume permanent facility has been converted to a weigh-in-motion system which is being used to screen vehicles to determine which will be statically weighed and those which can continue on.

## PROGRAM RESOURCES

An effective program entails much more than the actual capability to weigh vehicles. In Virginia, the success of our efforts are primarily related to the personnel. A total of 138 employees are directly engaged in weighing activities on a full-time basis. In addition, there are 55 weight enforcement officers (Department of State Police) enforcing the weighing laws at the permanent facilities and a minimum of 10 State Police working with the mobile units. (A summary of personnel is provided in Exhibit 2).

In addition to the personnel assigned actual weighing duties and responsibilities, the state has a full-time staff of 7 Central Office administrative employees and 5 scale repair and maintenance employees responsible for maintaining the accuracy and reliability of both permanent and portable scales.

EXHIBIT 1



# COMMONWEALTH OF VIRGINIA DEPARTMENT OF TRANSPORTATION

## MAINTENANCE DIVISION

COUNTY AND CITY CORPORATE LIMITS

## WEIGH STATION LOCATIONS

Rev. 9/88

**LEGEND**

- Operates 24 hours a day - 7 days a week
- Operates 24 hours a day - 5 days a week
- Operates 16 hours a day - 5 days a week *
- Operates 8 hours a day - 5 days a week *
- Operates on an irregular schedule

* None at present time

EXHIBIT 1A

# VIRGINIA DEPARTMENT OF TRANSPORTATION

## PERMANENT WEIGH STATIONS

| STATION | ROUTE | TOWN | WEIGH PARTY CHIEF | PHONE | |
|---|---|---|---|---|---|
| ALBERTA | 85 | ALBERTA | J. W. BURTON | 804/949-7336 | 949-9340 |
| ALDIE | 50 | ALDIE | * | 703/327-6938 | |
| BLAND | 77 | BLAND | J. E. MILLS, JR. | 703/688-4721 | 688-9842 |
| CARSON | 95 | CARSON | N. R. SUITS | 804/861-6565 | 732-9578 |
| DAHLGREN | 301 | DAHLGREN | W. L. HENDERSON | 703/663-2295 | 663-9974 |
| DUMFRIES | 95 | TRIANGLE | W. S. CORNELL | 703/221-5344 | 221-9927 |
| FAIRFAX | 66 | FAIRFAX | C. M. STAKEM | 703/830-8662 | 830-8969 |
| HOLLINS | 11 | HOLLINS | * | 703/992-9486 | |
| MIDDLETOWN | 11 | MIDDLETOWN | | 703/869-9897 | |
| NEW CHURCH | 13 | TEMPERANCEVILLE | J. T. SHRIEVES | 804/824-4115 | 824-8940 |
| SANDSTON | 64 | SANDSTON | C. L. O'BRIEN | 804/737-1468 | 737-8979 |
| STEPHENS CITY | 81 | STEPHENS CITY | H. A. SHILEY | 703/869-2833 | 869-9861 |
| SUFFOLK | 58 | SUFFOLK | J. T. SOUTHERLAND, JR. | 804/539-0356 | 539-9782 |
| TROUTVILLE | 81 | TROUTVILLE | BILLY PIERCE | 703/992-4291 | 992-9401 |

*OPERATED PART TIME BY MOBILE WEIGHING UNITS

EXHIBIT 2

# VIRGINIA DEPARTMENT OF TRANSPORTATION

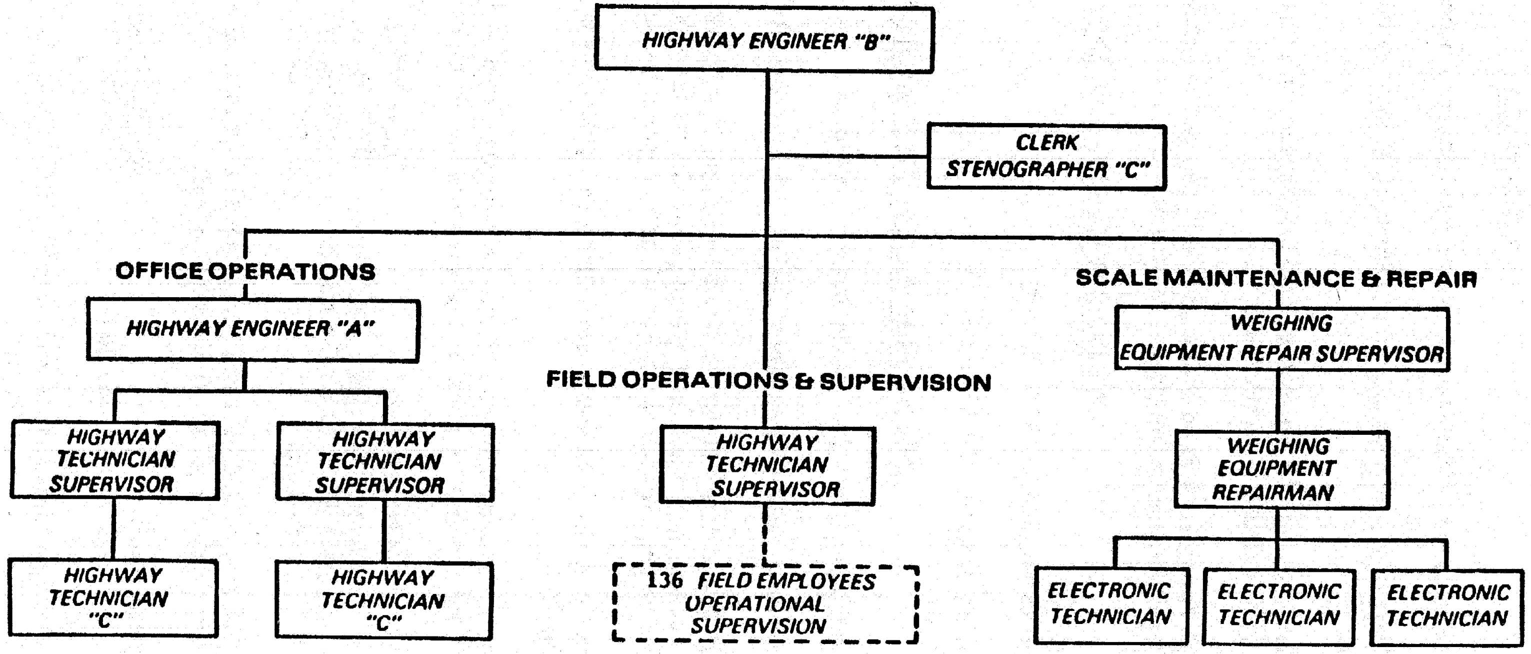
## MOBILE WEIGHING UNITS

| WEIGH PARTY CHIEF | CAR # | MOBILE UNIT | LOCATIONS |
|---|---|---|---|
| J. W. ALTHER | 406 | 2 | CULPEPER |
| J. D. BOWER | 407 | 3 | SALEM |
| F. W. BRANTLEY | 405 | 5 | SUFFOLK |
| T. W. BURKETT | 412 | 9 | WYTHEVILLE |
| J. W. DAVIS | 404 | 1 | RICHMOND |
| W. T. FRYE, JR. | 410 | 7 | LEESBURG |
| K. R. GRUBB | 411 | 8 | ABINGDON |
| M. C. HAND | 413 | 10 | LYNCHBURG |
| C. T. JONES | 408 | 4 | ABINGDON |
| H. L. KELLY | 409 | 6 | WISE |

EXHIBIT 3

# VIRGINIA DEPARTMENT OF TRANSPORTATION

## TRUCK WEIGH SECTION ORGANIZATION CHART



## SUMMARY OF PERSONNEL,

## VEHICLES WEIGHED AND MEASURED AND CITATIONS ISSUED

### PERSONNEL

| | |
|---|---|
| Number of Department of Transportation personnel engaged in portable scale weighing | 31 |
| Number of Department of Transportation personnel engaged in weighing at permanent weigh stations | 107 |
| Number of Department of State Police personnel engaged in actual measurement of sizes and in weighing at permanent weigh stations | 55 |
| Number of Department of State Police personnel engaged in actual measurement of sizes and in weighing other than at permanent weigh stations | 900 |

### VEHICLES WEIGHED AND MEASURED

| | |
|---|---|
| Number vehicles weighed 7-1-87 to 6-30-88 | 10,268,433 |
| Number vehicles measured 7-1-87 to 6-30-88 | 19,202 |

### CITATIONS FOR SIZE OR WEIGHT VIOLATIONS

| | |
|---|---|
| Number summonses issued for size violations 7-1-87 to 6-30-88 | 4,080 |
| Number summonses issued for weight violations 7-1-87 to 6-30-88 | 71,503 |

Central Office Personnel in the Truck Weighing Operations Sections are responsible for program scheduling, budgeting, planning and promulgating all matters related to policy and procedures. The organizational arrangement of the Truck Weighing Operations Section is shown in Exhibit 3.

Equipment is also a necessity and a summary of that which is assigned to the weighing operation is listed in Exhibit 4.

In order to achieve this level of success, Virginia directs a significant amount of resources to the truck weight enforcement program. A breakdown of agency expenditures for FY 1987-88 follows:

| | |
|---|---|
| Mobile Operations | $1,503,709.29 |
| Interstate Permanent Operations | 2,426,586.14 |
| Permanent Primary Operations | 886,933.40 |
| Subtotal | $4,817,228.83 |

In addition, it should be noted that financial requirements associated with weighing activities by the Department of State Police during FY 1987-88 were:

| | |
|---|---|
| State Police | $1,768,842.00 |
| Subtotal | 1,786,842.00 |

The total operational expenditure for FY 1987-88 was:

| | |
|---|---|
| Total | $6,586,070.83 |

## EXHIBIT 4
## EQUIPMENT ASSIGNED TO WEIGHING OPERATIONS

| Permanent Scales | Number | |
|---|---|---|
| Weigh-In- Motion - (Pat System) | | 2 |
| Electronic - Dial Type (3-scale platforms each side) | 3 | |
| Electronic - Digital Readout (3-scale platforms each side) | 69 | |
| Total | | 74 |

| Portable Scales | |
|---|---|
| Number | |
| Haenni 100 | 40 |
| Haenni WL 101 | 24 |
| General Electrodynamic MD500D & MD400 | 20 |
| General Electrodynamic MD500B | 92 |
| Total | 176 |

| Mobile Weigh-In-Motion Scales | |
|---|---|
| (Streeter AMET systems) | 2 |

| Motor Vehicles | | Number |
|---|---|---|
| Mobile Weigh-In-Motion Vehicle (35 foot Fleetwood Bounder) | | 1 |
| Vans assigned to mobile units | 11 | |
| Scale test truck | 1 | |

| Other Equipment | | Number |
|---|---|---|
| Air Jacks | 3 | |
| Air Compressors | | 3 |

Testing Equipment - Permanent Scales
19 - 1,000 Pound Weights
2 - 500 Pound Weights

Testing Equipment - Portable Scales
1 - 1,000 Pound Weight
1 - 4,000 Pound Weight
3 - 5,000 Pound Weights

## TIMES AND DAYS OF OPERATIONS

Virginia has 8 permanent weighing stations in operation on the state's Interstate facilities. Of these, 6 are operated on a continuous schedule for 24 hours a day, 7 days a week and 2 are operated 24 hours a day, 5 days a week.

In addition, there are 6 permanent weighing stations strategically located on the state's Primary System. Of these, 3 are operated on a continuous basis, 2 are operated 24 hours a day, 5 days a week, and 1 is operated on an irregular, periodic basis for a minimum of 8 hours.

The mobile units are assigned in a manner which covers the entire state according to State Police areas. The mobile units are required to conduct weighing operations for at least 40 hours each week. The crews usually work 8-hour shifts but the schedule is such that any 8-hour period of the day can be selected. This method allows for the conduct of weighing activities at those times which coincide with the needs of a particular area. For example, in Southwest Virginia a good deal of activity in the coal fields occurs during the early morning hours. Mobile crews, therefore, may conduct the weighing from midnight, 12:00 A.M. to 8:00 A.M., in the effort to monitor this area.

To avoid any detectable routines, daily and weekly schedules can change and the hours of operation may even be extended should the chief determine that vehicles are awaiting the end of the shift before resuming hauling activities.

## URBAN AREAS

It should be noted that the Weight Enforcement Program in Virginia is primarily designed to monitor state highway facilities. Unfortunately overweight vehicles are also encountered in urban areas, as well as on state facilities. Due to the autonomy of incorporated urban areas, this agency is limited in the manner in which commercial enforcement weighing can be provided to urban areas.

Since this is a recognized problem, this agency has made mobile units available to assist local governments in coordinating periodic weight enforcement programs. In addition, it has been determined through traffic analysis that many of the vehicles operating in violation of state law do not normally operate exclusively within the confines of the corporate limits. In order to facilitate travel time, these vehicles will utilize highways which are under Departmental jurisdiction and, therefore, can be routinely monitored by mobile units. It should be further noted that urban areas are prime pick-up/delivery areas which allow for monitoring activities on entry and exit traffic by both permanent facilities and mobile units.

Many jurisdictions conduct local weight enforcement programs which are, upon request, provided with training expertise and all scale certifications and testing by this agency. Virginia currently has 7 localities (Norfolk, Virginia Beach, Chesapeake, Hampton, Newport News, Fairfax County and Richmond) operating autonomous programs. In addition, employees of the Virginia Department of Transportation have assisted Alexandria, Blacksburg, Roanoke and Portsmouth in setting up weighing programs.

## BYPASSING PROBLEMS

The bypassing of permanent facilities has been recognized as a major problem since Virginia's initial attempts to monitor the weights of vehicles. To reduce the potential for bypassing, the Department of Transportation, State Police and local enforcement agencies have developed numerous strategies which have been quite effective.

Although these strategies are interrelated in that they focus on the same goal, each represents a unique mechanism for enforcement and should be identified as such. These primary strategies are as follows:

A. The location of permanent facilities is of critical importance in preventing or making it more difficult for truckers to bypass permanent facilities. Since our initial opening of weigh stations, a good deal of time and effort has been directed at site selection. Initially, locations are selected based on traffic volume and classification studies which assist engineers in identifying areas of need. From this data base, the site selection is further refined to insure that safety, accessibility and economic criteria are met. In line with these selection parameters, the bypass potential is assessed in an attempt to make it as unattractive as possible to circumvent the weigh station.

B. Virginia has attempted to cover the state as extensively as possible with permanent facilities as it is through this type of installation that high volume routes can be most effectively monitored. As new highways open to traffic and travel patterns shift, the Department has continued to maintain older weighing facilities in order to retain bypass monitoring capabilities. For example, when the Troutville Scales were opened on I-81 in Botetourt County, the older facility on Route 11 at Hollins was retained. The same situation occurred on I-81 at Stephens City with Middletown being retained. This combination of monitoring capabilities on parallel routes makes it much more difficult to effectively bypass the scales on the state's highest volume routes.

C. The Virginia Department of State Police and local enforcement agency personnel utilize the permanent weighing facilities to weigh vehicles presumed to be in excess of statutory weight limits. This is an extremely effective deterrent as potential bypass routes are identified and with the cooperation of enforcement personnel, vehicles are subject to being weighed as long as the weighing facility is within 10 road miles of the site. By utilizing local law enforcement personnel and State Police officers patrolling routes other than those monitored directly by the permanent facilities, the impact of weighing for a specific station actually covers a 10-road mile radius of the facility and encompasses the most potentially accessible bypass routes. When combined with mobile crews monitoring CB radio conversation of truckers and studies of commercial mix patterns in other areas, bypassing maneuvers are extremely difficult although they still occur. Since Virginia has recognized this problem from the inception of the program, a good deal of study and tests have been conducted and now, based on this experience, the methodology in use is felt to be the most effective possible within current manpower and resource constraints. It should be further noted that many of the State Police assigned an area of the state where scales are located also possess keys to the stations and can take a trucker suspected of being overweight to the scales and weigh the vehicle. This broadens the effectiveness of operations as even when scales are not scheduled for operation, weighing can still be conducted.

D. The most important strategy for monitoring bypass routes is the coordination of the permanent weigh stations and mobile operations. To deter vehicles from bypassing the permanent scales, the state has 10 mobile units comprised of 31 full time employees who are capable of setting up weighing operations at any site which is deemed safe and level. The crews perform weighing activities on roads not serviced by permanent facilities, as well as, monitor suspected or proven bypass routes. These activities are conducted on a rotating schedule as the crews, with State Police cooperation, move into an area, weigh until their actions are identified through the truckers' CB communication system, and then move on to another site. This flexibility allows for special weighing programs to be conducted throughout the year to determine the actual degree and impact of bypass movements. For example, one of the most prevalent bypass problems is occurring in Botetourt County. Truckers attempt to avoid the I-81 scales at Troutville by using Route 220A and/or Route 11 if the Hollins Scales are closed. To restrict this type of evasive action, this agency will bring in a sufficient number of mobile unit employees to operate the Hollins Scales and conduct weighing on Route 220A for 24 hours a day, 4 or 5 days at a time. To facilitate weighing on Route 220A, a graded turnout with a 24-foot concrete pad has been constructed which is lighted and provides a safe and efficient off-highway location for weighing. Additional strategies include utilizing the newer type wheel load weigher in the State Police cruiser with our mobile unit party chief riding with the trooper. The trooper then patrols the bypass routes, stops selected vehicles, calls the weigh crew to come in and weighs the vehicle. This strategy helps offset the CB system of communication that has become too pervasive.

E. The schedules for mobile operations are such that the crews work on a rotating shift basis. This work schedule can, and does, change from day-to-day and occasionally includes weekends. This strategy is to prevent potential overweights or truckers bypassing from anticipating a set operating schedule. Those permanent stations operating on a flexible time schedule are also an effective deterrent.

F. In recognition of the bypass potential, this agency in association with the Department of State Police has developed numerous additional strategies to identify bypass routes and effectively deter this type of action. The routes being used to circumvent our permanent scales are monitored by agency and enforcement personnel to help detect increased activity. Traffic volume counts and classification data are reviewed for bypass activities, with the time periods containing the heaviest movements referenced for future weighing activities. Special weight-in-motion studies are also utilized to determine the impact on commercial traffic mix when parallel permanent facilities are closed and the effects of bypass maneuvers on suspected routes (times, days, etc.). These strategies help to assure mobile operations work smarter instead of harder.

G. The entire truck weight enforcement program represents a continuing effort to counteract the ever changing actions by truckers to avoid the state's scales. Since the State of Virginia has a commitment to enforce vehicle weight limits, this agency is constantly assessing the locations of the mobile units, the number of mobile operations, the need for new permanent weighing facilities and other measures which allow our state to protect the sizeable investment in highways as effectively as possible.

H. 1988-1995 Virginia's Goals and Objectives:

(1) Establishment of two new mobile weigh station unit positions are planned in 1989.

(2) Advancement of plans to replace the I-81 Troutville, I-81 Stephen's City and I-66 Fairfax weight stations with a class A design model using Weight-In-Motion, a new control building, electronic overheight detectors, inspection pits and a controversial catch basin for leaking trucks.

(3) Systematically upgrade older weight stations to include Weight-In-Motion devices and associated buildings and facilities over the next six years based on the new class A design model.

(4) Build new and upgrade some existing mobile weighing turnout sites to facilitate expanded operation by Mobile WIM station vehicles.

(5) Push for increasing liquidated damage penalties to contemporary levels noting that the existing law is now 33 years old.

(6) Monitor data on overweight repeat offenders to determine if civil damages should be pursued by the Attorney General based on Texas's experience. Virginia, like all states, will never be in the financial position to operate programs of this nature at the ultimate level. Bypass routes could virtually be eliminated in Virginia if a sizeable increase in mobile crews was possible. However, this unlimited type of operation is not feasible from an administrative or economic standpoint; therefore, the Department will continue to strive for maximum utilization of existing facilities and manpower to minimize the number of overweight vehicles in the state. This comprehensive program is constantly assessed to insure the dollar expended returns the greatest possible benefit to the state in terms of safety and protection of the investment in our highway system.

Thank you for the opportunity to share Virginia's experience and strategy in conducting statewide Truck Weighing Operations.

# PLANNING FOR ENFORCEMENT OPERATIONS

*Captain Marsha Wiley, Wisconsin State Patrol*

In 1985, FHWA approached the Wisconsin Department of Transportation concerning a large scale truck scale avoidance study. The purpose was to use WIM collected truck data in planning pavement design and weight enforcement.

> "No data base had previously existed to estimate the scope and magnitude of the truck overweight problem or to quantify the amount of scale avoidance activity that occurs when enforcement and/or data collection weighing is in progress. Also while there is truck weight data from weight enforcement records and from our many years of loadometer studies, none of the data met the need for long-term pavement performance evaluation on a project specific basis.
>
> Given the short-term impracticality in collecting a nationwide sample of truck weight and avoidance data, an alternative approach to developing the required estimation was needed. That approach was to establish a statistically valid truck weight and diversion behavior data collection plan, to illustrate the use of WIM-collected truck weight data in pavement management in Wisconsin, and to disseminate the results nationwide through the Federal Highway Administration's (FHWA) demonstration project on Weigh-in-Motion."

In Wisconsin and across the nation, roads and bridges are designed to last for 20 and 50 years, respectively, and to withstand the effects of weather, traffic, age, and deferred maintenance.

Projected traffic, especially truck traffic, is critical to the design and pavement management of these roads and bridges.In the past, the estimation of the weights of trucks in the normal traffic stream has been extremely difficult to accomplish.

As a result of the Federal Highway Administration's (FHWA) strong encouragement of the development of weigh-in-motion (WIM)technology, many state DOTs have WIM systems. With these WIM systems states can begin to estimate the weights and frequency of trucks in the normal traffic stream. In addition some WIM systems can calculate the 18 kip equivalent single axle load(ESALs) for each truck.

The WisDOT purchased its Bridge WIM system in 1983 and has since gathered its annual Truck Weight Study (TWS) data under a statewide sampling plan using the Bridge WIM. As a result, it was the only state in the nation with three years of truck weight study data collected via WIM technology under a statewide sampling plan.

Both the Wisconsin DOT and the FHWA were interested in finding answers to three important questions regarding overweight trucks, scale avoidance, and pavement performance.

A. OVERWEIGHT TRUCKS
In Wisconsin it is known that State Patrol Inspectors annually cite approximately ten thousand overweight trucks, but the following question was unanswered:
What is the scope and magnitude of the overweight truck problem in Wisconsin?

B. SCALE AVOIDANCE
In Wisconsin it is known that enforcement weigh stations are easily by-passed by truck drivers, but the following question was unanswered:

What is the scope and magnitude of the avoidance of open enforcement scales by truck drivers in Wisconsin?

The third question relating to pavement performance will be addressed in other presentations.

Because of Wisconsin's leadership in the area of truck weight studies, the FHWA asked that WisDOT go a step further and attempt to analyze the three problem areas of overweight trucks, scale avoidance and pavement performance.

The intent of the FHWA was that WisDOT conduct a model study which may then be reviewed by other state DOTs. This study may well have been the "largest" study of overweight trucks and scale avoidance ever conducted in the United States.(The term largest here refers to data collection by WIM equipment, sampling plans, and statewide data collection.)

The State of Wisconsin had conducted truck weight(loadometer) studies from the mid 1930's to the early 1980's to document the characteristics of trucking operations and practices. Initially these studies were conducted at a variety of permanent and portable locations on the rural State Trunk Highway (STH) system throughout the state. By the latter1970's the program had switched to permanent enforcement sites on the rural Interstate and STH principal arterials in the southern one-third of the state.

A new program was developed that specified coverage of seven functionally classified highway systems, including urban as well as rural; statewide geographic random distribution of sites; temporal sampling of days and nights, weekdays and weekends across all seasons; and a minimum sample size by truck category to replace previous session criteria...all predicated on statistical rigor. A significant factor that allowed for the development of this improved program was FHWA's reduction of vehicle categories to a reasonable and workable set. The data now is unobtrusively collected utilizing a Bridge Weigh-in-Motion (WIM) system, predominately not in the proximity of permanent enforcement sites.

The new program was initiated in 1983 and continues today.It is intended to expand and establish a valid trucking characteristics data base for each of the seven functional highway systems.

Today the intensity of trucking data needs is shifting from system-wide to highway segments and even site specific in support of planning, cost allocation, pavement design, pavement management, research, enforcement and numerous other administrative or operational purposes. With an adequate system base the program emphasis can be shifted toward satisfaction of many of these program specific needs.

The highway configuration around the Rusk scale offers truck drivers one major by-pass road and three secondary by-pass roads.

The Division of State Patrol estimated that between 35%and 43% of the westbound trucks on I-94 avoid the Rusk scale.

The WisDOT has been collecting annual Truck Weight Study data at the I-94 Woodville site using the Bridge WIM equipment for two of the past three years.

The Woodville BWIM site is approximately 22 miles west of the Rusk scale location. Therefore, the past data collected at Woodville will be available for analysis and comparison to the data collected at and around the Rusk scale.

The Rusk scale facility is a brand new low speed weigh-in-motion (WIM) scale facility built in 1985 at a cost of over$600,000. The new facility was built at the same location as the old facility. It stands alongside the road and weighs westbound I-94 trucks only.

The following is a list of facts important to Rusk:

- It has been projected that Rusk will weigh over 200,000 trucks for the third highest total in the state. Only the Racine scale (290,000 trucks) and the Kenosha scale (260,000 trucks) located on the Chicago-Milwaukee I-94 corridor will weigh more trucks. The Racine and Kenosha scales are not weigh-in-motion facilities.
- Rusk weighs an average of 64 trucks per open scale hour.
- Approximately 1.6% of the weighed trucks receive citations (2,400 citations).
- Approximately 0.8% of the weighed trucks receive overload citations (1,20 citations).
- Approximately 50% of the citations are weight related.
- The average group axle overload is 1,800 pounds and the average license overload is 5,600 pounds.

The Rusk scale utilizes a Streeter Richardson low speed(5 mph) weigh-in-motion system. With the flip of a switch, the WIM platform becomes a static weigh scale. A computerized signal light directs possible overweight trucks to pull around and be static weighed.

The Rusk WIM presented two advantages to the scale avoidance project. First, the WIM system records the classification, the axle spacing and the axle weights of each truck weighed. It is also to calculate the ESALs for each axle,group axle combination. Therefore, when the scale was open in the research experiment, there will be a truck record for each truck across the scale. This data base can be analyzed as part of the experiment.

Secondly, because the WIM enables trucks to be weighed faster, the scale was then open to the entire experimental phase as called for. When the scale is open, truck drivers will not be able to drive past the scale.

In addition, the WIM scale also provides a benefit to the truck driver in that with a WIM scale the driver passes through the scale facility more quickly.

As part of the WisDOT Bridge WIM (Weigh-in-Motion) FHWA Rural Transportation Assistance Program (RTAP) demonstration project, the DB&B collected truck weight data at four sites to estimate the percentage of gross overloads.

At each site data was gathered for the Monday through Thursday period one shift per day. For Monday and Tuesday"normal" traffic data was gathered; i.e., there were no inspectors or enforcement presence.

The five axle combination truck with single trailer (5A-ST)was the most prevalent truck type on Wisconsin major highways.It accounts for 64% of all trucks weighed by WisDOT utilizing Bridge Weigh-in-Motion (BWIM) equipment between 1983 and 1985,(71% on the Rural Interstate) and produces greater than 80% of the attendant truck related Eighteen Kip Equivalent Single Axle Loads (ESALs). Based on these findings it was decided to limit the scope of this study to the 5A-ST. WisDOT collects data based on seven highway systems: Urban Interstate (UI); Rural Interstate (RI); Rural Interstate (RI); Urban State Trunk Principal Arterial (USTPA); Rural State Trunk Principal Arterial (RSTPA); Urban State Trunk Minor Arterial (USTMA);Rural State Trunk Minor Arterial (RSTMA); and County Trunk Highway Major Collector (CTHMC). For the study, data was collected on the Rural Interstate and Rural State Trunk Principal Arterials.

The original design of this study called for the analysis of regularly collected truck weight study data (basic data)followed by the data findings for repeatability at a new site.The test site chosen was located on the Rural Interstate on I-90/94 approximately two miles east of the USH 12 interchange at Wisconsin Dells. This site was chosen since trucks are directed by highway signs into the inside lanes of the four lane divided highway thus allowing the collection of data on the majority of trucks traveling in either direction through the use of one Pad Weigh-in-Motion (PWIM) system located in the median and connected to pads in the opposing inside lanes.

Although not part of this study's design, data were collected at six sites located on STH 29 and USH 45 on the RSTPA as part of a unrelated special study in 1987. All data collected in 1987 were collected for a minimum 48 hours.

Basic data, collected from 1983 through 1986, primarily consisted of data collected between the hours of 6:00 A.M. and6:00 P.M. on weekdays during the months of May through October.At one control station on each of seven highway systems data were also collected between 6:00 P.M. and 1:00 A.M. once per collection cycle (every other year) and one weekend day per collection cycle. Up to three additional weekday day sessions per cycle were conducted at these stations to create a base for seasonal comparisons.

The major by-pass route (H29W) was monitored by portable high speed WIM (PWIM) equipment. Secondary by-pass routes were monitored by counter/classifiers since additional WIM equipment was not available. High speed PWIM equipment was also situated on the mainline (I-94) one mile east of the Rusk scale and it recorded all traffic and weights from both westbound lanes. Additionally, high speed bridge WIM (BWIM)equipment was located 27.5 west of the scale on the mainline near Woodville. The experiment was designed so that the BWIM site would capture the volume and weight of some of the trucks returning to the mainline after diverting around the scale.Low speed permanent WIM equipment weighed trucks at the Rusk scale so that three different types of WIM equipment were used and results cross-compared.

Foster, Grandma's, and I-94 Rest were rest stops monitored by personnel in automobiles (cruisers or runners) who tabulated the number and type of trucks on a regular schedule. The aim here was to quantify time avoidance, i.e., the number and percentage of trucks waiting it out for the scale to close.So, both geographical based and time based avoidance were quantified.

This study may well be the largest study of overweight trucks and scale avoidance ever conducted in the U.S. Nearly60,000 trucks were monitored over 248 study hours during October 1986. October was selected because 1985 westbound vehicle count data on I-94 at Hersey, Wisconsin (located between Rusk scale and Woodville (BWIM) showed May, April,December, and October, in that order, to be the months most representative of annual average monthly traffic (ratios were1.04, .94, .93, and 1.08 to annual average monthly traffic,respectively). December and April were eliminated because portable WIM equipment is not operable in snow and cold and logistics and timing requirements precluded May. Weekly traffic variations during four weeks of October 1985 at Hersey showed ratios to annual average weekly traffic of 1.02, 1.00, .97, and.94 for both westbound and eastbound data (separate westbound data is not available).

Beginning October 7, 1986, the same time frame was monitored for three consecutive weeks: from Tuesday at 9:00A.M. through Friday at 9:00 A.M. or 72 continuous hours.During the fourth week, 32 consecutive hours were monitored from 9:00 A.M. Tuesday, October 28, 1986, through 5:00 P.M.,Wednesday, October 29, 1986. Less monitoring was done during the fourth week since this was a highly labor intensive,maximum, allowable effort. From statewide truck volume patters(all road types combined), Tuesday - Thursday were most average in terms of traffic with the high truck traffic on Fridays and the low on weekends.

Experienced state police officers who are responsible for statewide truck size and weight enforcement programs know that heavy truck drivers by-pass open enforcement scales.

The State of Wisconsin owns 21 permanent enforcement scale facilities located on interstate, U.S., and state highways. Each scale can be, and easily is, avoided by heavy trucks.

The Division of State Patrol, within the Wisconsin Department of Transportation is responsible for motor carrier enforcement (MCE) and Patrol officers conduct approximately 98%of all the MCE in the state.

The major heavy truck traffic corridors in Wisconsin are three interstate highways: I-90, I-94, and I-43. There are ten secondary truck corridors: the east-west corridors are US-2, US-8, US-10, and US-14; and the north-south corridors are: US-41, US-141, US-51, US-151, US-53, and US-63.

Traffic volume varied by time of day, day of week, and month of year.

Truck Traffic by Time of Day

One peak traffic period is 8:00 A.M. - 5:00 P.M. and contains approximately 53% of the total daily truck traffic.

Another peak traffic period is 6:00 A.M. - 6:00 P.M. and contains approximately 68% of the total daily truck traffic.

Another peak traffic period is 5:00 A.M. - 11:00 P.M. and contains approximately 88% of the total daily truck traffic.

Truck Traffic by Day of Week

The Monday through Friday period contains approximately 85% of the total weekly truck traffic flow.

The peak days are Wednesday (28%) and Monday (18%) which, when combined, comprise 46% of the total weekly truck traffic.

Truck Traffic by Month of Year

May through September (five months) is the peak truck traffic period.

The experiment was set up in four phases whereby each consecutive week different and increased enforcement scenarios were tested for impacts on truck volume, overweight trucks, and ESALs as follows:

Phase 1: Scale closed. Base case. Normal traffic monitored at all locations and number of trucks at rest stops monitored without any enforcement presence for 72 continuous hours.

Phase 2: Scale open for 48 continuous hours. Except for the extended hours, this was a normal enforcement activity within the realm of current enforcement capability. Traffic at locations other than Rusk was monitored for the same 48 hours plus an additional 24 hours to determine patterns of traffic normalization after scale closure. Number of trucks at rest stops was monitored for 72 hours to quantify time avoidance.

Hypothesis: 30% or more of truck drivers will avoid the scale. Most of the avoidance will be geographical based avoidance on the major by-pass with some avoidance on the secondary by-passes. The rest of the avoidance will be time based.

Phase 3: Scale Open with wing. Enforcement and measurement as in Phase 2 with additional patrol of the major by-pass route (H29W). Again, except for the extended time period, this was a normal enforcement activity within the realm of current enforcement capability.

Hypothesis: 30% or more of truck drivers will avoid the scale. Truck traffic will decrease on the major by-pass and appear on the secondary by-passes. Time based avoidance will increase.

Phase 4: Scale open with wing emphasis. Scale open for eight hours with a large number of inspectors patrolling the major and secondary by-passes. An exception here was that the secondary by-pass I-90 was not patrolled. Reason: It was expected this would create diversion beyond the study area and therefore beyond measurement. Moreover, personnel and equipment requirements beyond capabilities and safety considerations for such a high volume enforcement activity precluded an I-90 effort. Phase 4 was a one-time, all-out enforcement effort at the scale and at by-pass routes designed to test the upper limits of enforcement. It is far beyond the present Wisconsin enforcement capabilities for staffing, resources, and funding. Data was collected at all points other than the Rusk scale for an additional 24 hours to test traffic normalization time frames and patterns.

Hypothesis: 30% or more of the truck drivers will avoid the scale. Truck traffic on the major and secondary by-passes will decrease and time-based avoidance will be very high.

Wisconsin has two permanent scales equipped with WIM. The Rusk scale located on I-94 near Menomonee and the Coloma scale located on Highway 51, south of Stevens Point. The Coloma scale is a median one. In addition, Wisconsin has purchased 72 portable wheel weighers. These have been distributed throughout the state.

Wisconsin also has two Lodec scales. The Lodec operation indicates that 9% or more of the loaded trucks are overloaded but the permanent scales do not record this high an overload level. The highways Lodec operations cover are no different than permanent scale highways. Therefore, the overloaded trucks must be avoiding the permanent scale on a regular basis.

In fact the first hour or so a Lodec scale is open, the Patrol's professional estimate is that approximately 20% of the loaded trucks crossing the scale are overloaded. Note: This is an opinion.

An experienced Lodec crew may get four or five hours of Lodec weighing out of an eight hour shift. The truck traffic is heavy for the first hour or so of the weighing and then declines throughout the remaining three or four hours.

The overloads are very frequent the first hour or so and then drop to almost none.

The conclusion, of course, is that the first hour or so of Lodec operation is probably more representative of the size of the overloaded truck problem in the traffic stream than any other statistic. In addition, truckers who are listening to their CB radios will be able to by-pass the Lodec as soon as it is open.

The Division of State Patrol's position is that yes, heavy truck drivers by-pass open enforcement scales. Within a few minutes of the opening of an enforcement scale, truckers relay to other truckers via CB radios that the scale is open. The same relay takes place when the scale closes.

In many instances, the truck drivers avoid the scales by taking by-pass routes. In other instances, the drivers avoid the scales by waiting at truck stops or rest areas until the scales close.

The study indicated that on the rural interstate, 69% of the violators were the "box" type semi-tractor and trailers while on the rural state trunk principal arterials, those box type units were 36% of the violators, on the rural state trunk principal arterials.

## CONCLUSION:

Because permanent scale operations only find 1% of the loaded trucks overloaded and Lodec operations find 10% over-loaded (an estimated 20% overloaded during the first hour or so) it is apparent that substantial overloaded truck traffic avoids permanent scale facilities.

At the four experimental Bridge WIM sites 14% to 55% of the loaded semi trucks in the "normal" truck traffic stream were potential gross overloads; i.e., statistically the trucks may weigh over 80,000 pounds.

At the Portage site as soon as inspectors began to conduct weight enforcement, the percent of loaded semis that were potential gross overloads dropped from 19% to 5% to 0% within hours. The extremely heavy trucks avoided the area as soon as enforcement began.

In absolute terms. of the 15% avoiding truckers off the I-94 mainline, 5.2% geographically avoided on the by-pass routes monitored (2.5% on the major by-pass route), 3.4% time avoided,1% showed up at BWIM around the scale via by-pass routes or routes unknown, and 5.6% were unaccounted for, i.e., they avoided on unmonitored routes or waited it out at unmonitored points.

During 48 continuous hours of scale operation and weight enforcement in Phase 2, truck volume declined 15% on the I-94mainline from Phase 1 when there was no enforcement presence;3S-2 volume declined even more: 18%.

While mainline truck traffic was declining, traffic on the major by-pass route (H29W) was up 32% for all trucks and up 82%for 3S-2s. This is one measure of scale diversion, although reasons for avoidance (i.e., weight, safety, etc.) are unknown.

Diversion was greatest at the by-pass routes closest to the scale. Besides the 82% 3S-2 diversion on the major escape route (3 miles from the scale), H10W (approx. 20 miles away)incurred a 68% increase in 3S-2 volume, H64W (30 miles away) a58% increase, whereas I-90 (80 miles distant) showed only a 3%increase.

There were 18% more trucks at the 3 rest stops (RESTOPS)monitored indicating the extent of time avoidance or truckers waiting for the scale to close.

Diversion was generally more pronounced for 3S-2s and occurred most frequently during evenings (5 PM - 12:59 AM) on the by-pass routes and at the rest stops.

Adding a wing patrol to the major by-pass route caused overweight trucks to leave mainline I-94 in droves. In reality, however, since it was the third consecutive week of the truck weighing experiment and truckers, especially regular travelers may have therefore been more apt to be legal.

Regardless, overweight truckers likely left the mainline to a larger extent than Phase 2. Significant diversion occurred to the most distant I-90 secondary by-pass route.Most overweight truckers opted against mainline I-94 during evening hours.

Overweight 3S-2s reappeared around the scale at BWIM.Most diverted during daytime hours and other figures show they diverted quickly, during the first eight hours. They may have passed the word back to I-94 where overweight trucks didn't fall off until evening. In other words, there occurred a diversion lag time. Subsequent diverters apparently didn't get to BWIM to the same extent as those in the first eight hours.

The State of Wisconsin has created statutes which allow timber, refuse, and milk haulers to carry more per axle weight on highways other than the interstate. As a result, the weights and excess ESALS could be higher on those highways, but the transportation of those commodities in excess of "legal limits"is accepted under current law.

The instigation of the Motor Carrier Safety Assistance Program (MCSAP) and the presence of MCSAP inspectors at the interstate scale have created another reason for trucks to by-pass the scale. While some of these may be overweight, the majority have equipment or logbook violations which they do not want detected.

Initial findings of the Scale Avoidance Study showed there were more violations on the by-pass routes than at the interstate scales. Yet, there were still violations occurring at the open scales. Mainly overweight. This would indicate the apparent need for coordinated enforcement efforts at both the scale and on the by-pass routes.

Scale avoidance was found to range 15%-18% by truck volume,6%-34% by overweight trucks, and 14%-26% by ESAL's (the engineering standard unit for pavement wear) depending on the enforcement configuration in place.

Of the 15%-18% avoidance by truck volume, 5%-11% was geographical, 3%-5% was time based (i.e., waiting at rest stops for the scale to close) and 4%-6% was unknown, (i.e., it could have been geographical or time based at points beyond our monitoring stations).

On eight-hour instead of 48, all enforcement effort at the scale and at every by-pass route (except I-90) designed to test the upper limits of enforcement created trucker confusion and unusual truck volume patterns.

Volume on the major by-pass route was half of base case for all trucks and signifying that a heavy patrol presence diverted truckers to by-pass routes they thought less known to the patrol.

It appears that truckers took to the more distant by-pass routes to hopefully avoid the wing emphasis as traffic volume ratios were highest for I-90, H10W, and H64W for all trucks.It is felt that some truckers used unpatrolled by-pass routes,even beyond the catch-all BWIM site beyond the scale where volume was 9% lower.

The wing emphasis caused little time avoidance at rest stops. Perhaps with all the inspectors around, truckers felt rest areas would be checked too.

Such a continued effort would require the use of certified portable wheel weighers. The Lodec and the permanent scale.The Division of State Patrol could use printouts from the BWIM studies showing location, time of day, and day of week data.That would enable the State Patrol to more effectively schedule its personnel. It would also give a statewide as well as a local picture of the problem.

Additionally, a future modification of the State Patrol's weight enforcement program would be to use groups of size and weight inspectors as well as troopers in order to have the manpower necessary to adequately staff the scales and by-pass routes. A statewide coordinated effort during a given period of time is another consideration. For example, having a detail in the Eau Claire area could coincide with a detail in the Tomah - La Crosse area to cut off the use of I-90 as a by-pass when the Rusk scale is open.

When such weight enforcement efforts are considered, one needs to look at the overweight trucks on highways other than the interstate. As stated previously, much of the overweight may be legal due to state statutes. If that is the case, even though there is damage to the pavement, enforcement efforts would not be the answer. Enforcement can ensure that those haulers given special exemptions remain legal within their allowances. Since the data for this study were collected during summer months, the study does not address seasonal weight limitation laws (i.e., spring thaw) which may or may not impact local enforcement efforts.

It appears as if the State Patrol may need to prioritize the areas/types of highways where enforcement efforts are needed based on WIM data. Requirements of the federal government would put the interstate system first followed by U.S.numbered highways, then state trunk highways, followed by county trunk and town roads.

In final conclusions it is of vital interest not only where the worst violations occur, but also which type of highway is most adversely affected.

# WEIGH AND INSPECTION STATION DESIGN ST. CROIX WEIGH SCALE LAKELAND, MN

Calvin D. Karl, Sergent, Minnesota State Patrol

## PROXIMITY OF SCALE

The St. Croix weigh scale is situated on a main access artery to the twin city metropolitan area. This artery carries the highest truck traffic count in the state of minnesota. The entrance to the scale is adjacent to a state highway entrance to the freeway. These two factors necessitated designing a weigh system capable of handling the truck count in a normal scale operation as well as assuring that scale traffic would not back up onto the freeway.

## PURPOSE OF WIM

A WIM was incorporated into the scale design to serve as a sorter scale and to provide preliminary data to the scale operator. Coupled with axle sensors, off scale detectors, over height detectors, and loops, the wim becomes the focal point governing the system's operation.

## HOW THE WIM WORKS

As a truck passes over the wim, the following characteristics of the truck are determined:

1. Speed
2. Axle spacing
3. Axle weights
4. Gross weight
5. Vehicle classification
6. Bridge formula violations

also determined at this time are violations due to tailgating, missed scale, over height, and off scale.

Data collected is then fed into a computer and, based on that data, the computer directs the truck through the weigh scale by means of traffic signals. If a truck does not meet established criteria, it is directed to the by-pass lane and back out onto the freeway. If the information gathered by the wim meets certain criteria, the truck is sent to one of the two static scale lanes for observation at the scale house.

When the truck arrives on the static scale at the scale house, the information previously gathered on the truck is presented on a video screen in front of the scale console operator. This screen display tells the operator:

1. Date and time
2. Report flags
3. Speed
4. Gross weight
5. Total length (first to last axle)
6. Number of axles
7. Classification of vehicle
8. Axle weights
9. Three heaviest axles or groups of axles (legal or o.W.)
10. Tandem or tridem weights
11. Axle spacings

this preview of the truck assists the operator in obtaining an overall picture of the size-weight-load aspects of the truck thereby decreasing the needed observation time.

An error in crossing the wim such as too slow, excessive speed change, off scale, or following too close will cause the truck to be routed to the static scales. The information fed to the operator will include these errors in the form of report flags.

The sorting of trucks is based on thresholds fed into the computer by the operator. The weight threshold is set to the desired percentage of maximum legal weight for the truck configurations. The safety threshold is set to the percentage of trucks desired to be brought to the static lanes for observation of possible safety and/or driver violations. The computer randomly selects this percentage from those that would normally be directed to the by-pass lane and redirects them to the static lanes.

The computer tracks all trucks as they progress through the facility by means of loops in the various lanes. By the same means, the computer also knows when the scale lanes are full and redirects all traffic to the by-pass lane eliminating a back-up onto the freeway.

## ACCURACY OF THE WIM

Historically, wim weights have been subject to a percentage of error. The wim used in this configuration produces extremely close weights consistently because the wim and static scales are cross checked. If the wim is off at all, the computer parameters are adjusted to compensate for the error. Similarly, axle spacings are likewise checked and may be adjusted. These two factors are important for both the day-to-day operation and the integrity of cumulative data.

## ADVANTAGES OF WIM

The existence of a wim in the scale operation gives a definite advantage to data gathering. In this case, a simple truck count can be broken down into number per hour, number per hour by vehicle classification, speed, length, suspected over weights, suspected over heights, etc... Most of this information is retained in the computer for at least one year.

There are other facets that reduce the truckers time spent going through the weigh scale but no other single component allows a "look" at every truck that comes in, whether it is physically observed or not. The highly automated system at the st. Croix scale is designed to handle 5000 plus trucks per day and should easily meet that criteria.

# THE METAMORPHOSIS OF WEIGHT ENFORCEMENT STRATEGIES IN OREGON

*Milan Krukar*[1] *and Ken Evert*[2]

## I. INTRODUCTION

Like anything else, people and conditions change. This is the natural order of life. Weight enforcement is no exception, and in Oregon weight enforcement strategies have evolved over the years to reflect the changing economy, highway infrastructure, personnel, and technology. An efficient and effective weight enforcement program requires that it meets current conditions and is structured to meet future needs.

## II. PURPOSE OF PAPER

The purpose of this paper is to examine Oregon's weight enforcement strategies in the light of past and current requirements, and to describe strategies to meet future needs and technology.

## III. HISTORY OF WEIGHMASTERS

The motto of the Weighmasters Unit is "Weigh the load and save the road". This philosophy governs the tasks, responsibilities, and actions of the unit and is their raison d'etre. Additional duties such as truck safety inspection have also been given to the weighmasters.

Early in Oregon's highway program, it was recognized that roads needed protection from excessively loaded truck axles and gross weight. In 1921, a weighmasters unit was formed within the Highway Department to enforce truck weights. This continued until 1931 when the weight responsibilities were transferred to the Oregon State Police. The reasons for this change-over are rather obscure but, because of the depression, a perceived need to consolidate enforcement duties may have been the rationale.

In 1941, the weight enforcement responsibility was returned to the Highway Department, as it was generally perceived that the State Police had other, more pressing, responsibilities. This reasoning was valid, since the Oregon State Police had been given full police powers to enforce all laws of the state, and it was becoming apparent that a highly specialized group was needed to administer weight enforcement laws.

To this end, the State Highway Engineer, in 1941, hired a Chief Weighmaster and 20 Weighmasters. The Weighmasters were sent to various parts of the state for temporary tours of duty. They were paid $135.00 a month and there was no expense allowance for travel.

Facilities consisted of 34 stationary scales located throughout the state and ten sets of vintage Black and Decker portable scales transferred from the State Police. During the first half of the 1940's, only log trucks were weighed and no citations were issued.

After World War II, the number of Weighmasters was increased to 40. Data collection became a part of their duties. Punch cards were coded for each truck weighed. In 1947, enforcement was extended to trucks having commodities other than logs.

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The decade of the '50's was the greatest time of employment growth. The number of field Weighmasters rose to 81 in 1957 after a truck combination stuck in the pavement in eastern Oregon catching the attention of a Legislative Committee. Also, during this period, the Weighmasters were given the authority to issue a Uniform Traffic Citation and to make arrests for violations of size and weight laws.

From the 20 weighmasters hired in 1941, the number has grown to 124 people today, of which 116 are field personnel, and the remainder support staff. The annual budget has risen from less than $100,000 in 1941 to approximately $4 million a year. Weighmasters now operate four ports-of-entry (a fifth is under construction and one more is planned). There are 62 permanent weigh stations. Seventy portable scales are used along with five semi-portable type scales used in pits.

Since 1941, the Highway Department had weight enforcement responsibilities through their Weighmaster Unit under the Maintenance Section. In 1986, the Weighmasters Unit was consolidated into the new Permits and Weighmasters Section, under the Operations Branch of the Highway Division. Funding of the Weighmasters Unit comes from highway user revenues.

## IV. WEIGHT ENFORCEMENT STRATEGIES

### A. Past Strategies: 1921-1975

#### 1. 1921-1945

Past weight enforcement strategies were related to Oregon's economy. The economy before the second world war was principally rural, highly dependent upon timber and agriculture. Enforcement strategy was to protect the roads from log trucks.

Portable scales were used to weigh the log trucks. The truck axles were jacked and then lowered on the scales, a slow and dangerous procedure. The enforcement strategy was to be flexible to meet the changing seasonal nature of the timber industry. During this period, only log trucks were weighed and no citations were issued, nor was any data collected.

#### 2. 1945-1960

Weight enforcement strategies continued to be based on Oregon's rural economy, timber and agriculture. During this period, the majority of the permanent weigh stations were installed (Figure 1). Their locations were based on timber haulage to the local mills, and most were located between the timber supply and the mill, outside town boundaries. As the towns grew, they encompassed the weigh stations. Complaints about trucks being weighed in town became common.

Portable hydraulic cam scales were employed until the '50's when Black and Decker loadometer scales were introduced. During the '50's, the use of portable scales in conjunction with the fixed scales became commonplace.

#### 3. 1960-1975

The diversification of Oregon's economy, along with the construction of freeways, broadened weight enforcement duties and responsibilities. Although weighing of log trucks and agricultural produce trucks continued, weighings of other commercial trucks increased.

Protection of the interstate system became increasingly important as those routes became the main throughways. The collection and audit of weight-distance taxes became increasingly important as the number of trucks grew rapidly. By the mid-'60's, data collection became part of the weighmaster responsibilities. Truck weight data collection for PUC tax audits were now routine. Prior to this, the only statistics collected were on citations.

The equipment for weight enforcement and data collection remained unchanged from the '50's: Black and Decker portable scales and fixed platform scales at weigh stations.

## B. Present Strategies: 1975-1990

Oregon's economy continued to boom until the beginning of the '80's when the timber industry was hit hard by the recession. Recovery was slow. The decline in the trucking industry and heavy vehicle miles of travel reflected the ups and downs of Oregon's economy.

Technology was the prime mover in changing weight enforcement strategies during this period. Development of the electronic scale, semiportable scales, low-profile wheel weighers, ports-of-entry (POE), enforcement with data collection duties, the introduction of weigh-in- motion (WIM) equipment such as the medium-speed WIM sorter, high-speed data collection WIM, and bridge WIM system, automatic vehicle identification (AVI) and the automation of POE's are all a part of the technological revolution. In addition, a new attitude of cooperation and mutual respect was encouraged and promoted by the weighmasters and trucking industry representatives. This may have influenced the 1980 Oregon State Legislature to give the weighmasters the duty of enforcing truck safety.

### 1. Development of Electronic Scale

The development of a reliable load cell and digital readouts allowed the weighmasters to convert their fixed platform scales to the more reliable and rapid weight readings made possible by the new equipment. This increased the productivity of personnel.

### 2. Semi-Portable Scales

In 1983 the Weighmasters obtained five semi-portable scales to supplement the permanent weigh stations. These scales are easy to place, able to weigh trucks more quickly and accurately than conventional portable scales. They are ideal for monitoring truck traffic in special situations where the equipment can be used flush with the road surface.

### 3. Low-Profile Wheel Weighers

In 1983, the weighmasters obtained General Electrodynamics Corporation MD 500 portable scales to replace the Black and Decker loadometers. These are light weight, and lower profile, thus safer. Unfortunately, these scales are not as durable as the Black and Decker portables.

### 4. Ports-of-Entry Concept

Beginning in 1975, ports-of-entry were developed. They are jointly operated by weighmasters and PUC. A port-of-entry provides a single location where all services relating to motor carriers entering the state are provided. This broad coverage increases the probability that most truckers are in compliance with all the size/weight and safety laws of the state. The first POE was built at Ashland on I-5 northbound in 1975. Farewell Bend on I-84 westbound was added in 1977, Klamath Falls on U.S. 97 in 1979, and Woodburn I-5 southbound was opened in 1986. Other POE's are scheduled to be built in Cascade Locks on I-84 eastbound and at Umatilla on I-82 southbound in the near future.

POE's are operated 24 hours a day, 363 days a year. The new POE's will be automated similar to Woodburn Southbound POE, and each will have an all weather inspection building. All existing POE's will eventually be retrofitted with WIM sorters, AVI systems, and supervising system computers.

5. Enforcement and Data Collection

With the advent of POE's, data collection became an increasingly important function of the weighmasters. Data collection is now viewed as an integral part of weight enforcement. Data is collected for highway planning, design, and tax auditing purposes. Weight records are now kept on each individual vehicle. These records are available for use by the various highway sections and by PUC.

6. Introduction of New Technology

In 1984, electronic technology ushered in the new era in Oregon's weighing program. During this year, a high speed WIM data collection system, a WIM sorter system, a portable WIM system, and AVI systems were installed at test sites on Oregon highways.

i. High-Speed Data Collection WIM Systems

Two CMI-Dynamics high-speed WIM scales were installed in both lanes on I-5 northbound, milepost 245.5 in February 1984. This system is still in operation with minimal downtime and has weighed over 27 million vehicles. The data has been used by weighmasters for scheduling purposes for some of the weigh stations, and to check overloads and peak traffic. The data is also used for planning and design purposes.

ii. Medium Speed WIM Sorter

The first medium-speed WIM sorter was installed at the Woodburn weigh station on I-5 northbound, milepost 273.8 in March 1984. This is also a CMI-Dynamics WIM. In January 1987, another CMI-Dynamics WIM was installed at the new Woodburn southbound port-of-entry on I-5 at milepost 274.5. These systems allow legal weight trucks to bypass the static platform scales. This reduces the number of vehicles weighed and improves safety by reducing the back-up of vehicles waiting to get to the scales.

iii. Portable WIM System

In January 1984, OSHD bought a Bridge Weighing Systems WIM (BWIM) system. This is a portable WIM which uses a bridge span as a large scale. Strains are measured by strain gauges attached to the bottom of bridge girders. Thirty bridges, mostly in northwest Oregon, have been instrumented and calibrated. The BWIM has been used for scheduling, overload violations check, and data collection for planning and design purposes. The system has enabled the weighmasters to measure the extent of violations in certain areas. The BWIM system has been refitted with a new, more powerful computer and software.

iv. Automatic Vehicle Identification

In July 1984, General Railway Signal (GRS) AVI systems were installed at four locations on I-5 northbound. Two AVI systems were integrated with the existing WIM systems at

Jefferson and Woodburn, allowing the identification of the vehicle while its weight was being recorded. Another GRS AVI system was installed and integrated with the WIM at Woodburn southbound POE in July 1987. Two were stand-alone units, one located at the Ashland POE sixteen miles north of the California border and the other at the Ridgefield, Washington POE, about 16 miles north of the Oregon border. The GRS system uses passive transponders with roadside reader-activators. Transponders were originally installed on 200 trucks. Presently 350 trucks have transponders.

The AVI system allows the weighmasters to identify the vehicle immediately. Integrating the AVI with WIM allows potential for automatic weighing-identification, and for computer checking of safety inspections, registration, or permits issued.

## 7. Woodburn Southbound Port-of-Entry Automation Experimental Project

The development of new integrated microchips has led to the development of small powerful minicomputers with large data storage capacity. New software and computer language developments have also brought on rapid changes. AVI and WIM systems were integrated with the two static scales at Woodburn and with the PUC database, using a powerful minicomputer as the supervising system computer (SSC).

The purpose of this integration was to allow trucks with transponders, meeting legal weight as shown by the WIM, and PUC criteria from the PUC vehicle database, to bypass the static scales. Data on these trucks is stored by the SSC. Trucks, without transponders, meeting the legal weight as shown by WIM, are directed to the static scales (where their PUC identification number is keyed into the computer). The SSC brings the PUC information onto the screen. If the trucks meet the PUC criteria with respect to taxes and safety, only its weight from the static scales is recorded. It then is allowed to pass through. Those trucks that do not meet weight or PUC criteria are stopped and issued citations and/or go to the PUC location to obtain permits.

The data is downloaded to the mainframe and changes in the PUC database are uploaded on a regular basis. Daily statistical records and tables are produced by the SSC.

The system hardware and custom software, supplied by Motorola Computer Systems, has been operating since December 1987. It has functioned very well with very few glitches. The weighmasters have enthusiastically embraced the system. Time is saved by both the weighmasters and truckers. The automation system has allowed the weighmasters to weigh vehicles more quickly, reducing congestion. The system has also revealed outstanding weight-distance tax payments owed by some firms. A chronic offender list is being developed through the use of the SSC. Such offenders typically are found to have a history of overweight or permit violations.

If all trucks had transponders, the automated system would dramatically reduce the number of vehicles weighed at Woodburn (perhaps by 50 percent), thus greatly reducing the weighmaster workload. This would allow for rescheduling personnel to other weigh stations, improving overall weight enforcement. All ports-of-entry, new and old, will be similarly automated in the next three years.

## 8. Truck Safety Enforcement

In 1980, the Oregon State Legislature directed the OSHD to conduct safety inspections. Since then, the number of weighmasters assigned to safety inspections has increased to 14 full time equivalents, and all weighmasters take truck safety inspection training. The work load has increased while the number of weighmasters has remained static.

9. We/They Attitude

Early in the '80's, the longstanding adversary relationship between truckers and weighmasters began changing to one of cooperation. Before that time, all the weigh stations were protected with steel shutters and locks. Vandalism by unfriendly truckers was common.

Weighmaster and Highway administrators visited various trucking organizations and firms to explain the need for weight enforcement to prevent the small minority of illegal operators from damaging the roads. They pointed out that illegal operators were gaining unfair competitive advantage by having more per load, but not paying their share of road use taxes. Legally operating truckers appreciated that illegal truckers were unfair competition, and an attitude of mutual help and respect slowly developed. Weigh stations scale readouts were made available so that the truckers could weigh themselves. Vandalism has been reduced as the truckers have a friendlier attitude towards the need for truck weight enforcement.

In addition, the WIM sorters have been enthusiastically endorsed by truckers. The automation of Woodburn POE has stirred the interest and support of the trucking industry. The use of AVI on a volunteer basis has received the support of many trucking firms. All this has served to reduce the traditional conflict, but to be realistic, there will always be differences between the two groups - the regulator and the regulated.

## C. Future Strategies: Beyond 1990

In the future, the weighmasters will probably be given additional responsibilities and be required "to do more with less", with staff size kept at its present level. They will have to be given the tools to accomplish their expanding tasks; this means more technology. Future enforcement strategies will incorporate these new technologies and will change enforcement methods and practices.

1. Automated Unmanned Weighing Facilities

The OSHD has one such site in place on I-5 NB at Jefferson on a demonstration basis. Here, AVI and WIM are married. Trucks are weighed and identified. This demonstration has shown that the system is feasible, but to make it work as a full scale operation, all trucks must have transponders. The Crescent Project, or Heavy-Vehicle Electronic License Plate (HELP) program, will enable us to see how feasible this on a large multistate scale.

Unfortunately, WIM data cannot presently be used for enforcement purposes because of the accuracy, i.e., WIM weights versus static scale weights. The NCHRP project on WIM calibration standards may provide a methodology for calibration and error correction. WIM/AVI data can, however, be used for enforcement personnel scheduling, and to identify potential violations.

A recent WIM site location study done for OSHD by Portland State University indicated that 12 WIM sites are needed on the Interstate and over 30 on the primary state highways. This cannot be done at once, but it is a long-term goal.

2. New WIM/AVI Technology

The use of piezo-electric cables for WIM show considerable promise. This system has accuracy limitations which may, however, be offset by its potential low-cost. If all the problems are solved, the use of WIM would become more universal. OSHD has just started an experimental study using different piezo cable configurations for accuracy at three Interstate sites to determine whether accuracy may be improved by changing configuration.

If the costs of these WIM systems can be held under $10,000, including installation, then many WIM sites will be feasible. This will revolutionize data collection and enforcement strategies.

In addition, the low-cost bridge WIM system, developed under a NCHRP research project, will be field tested soon. Oregon is one of the states where this system will be field tested.

New AVI equipment, as part of the Crescent Project, will be tested this fall and installed next year. This will change our present AVI system since the reader-activators will be in the pavement rather than the side of the road.

3. Automated Ports-of-Entry

The success of the automation project at the Woodburn southbound POE will lead to the automation of both new and old POE's. This will free manpower for enforcement elsewhere. Weigh stations near the ports will be manned more frequently. Enforcement will be more widespread.

4. Local Area Enforcement Network

The weighmasters are considering developing a local area enforcement network (LAEN) using ports-of-entry as centers for data collection. Nearby weigh stations would be tied to the central location via telemetry or portable computers. All the data collected at a weigh station would be stored in an on-site computer and transferred at the end of the shift to the central area, either by telemetry or by disk. The computer would be connected to the static scales and the weights would be automatically recorded. Only the PUC identification number would have to be entered by the weighmaster. This would free the weighmasters, and eliminate the need for PUC to enter the weight data for PUC audits. The data from each weigh station would be stored at this central station and periodically loaded to the ODOT mainframe.

To make this concept functional, personal computers will be required at each weigh station. The static scale readouts at the weigh station will have to be hardwired to connect with the personal computer. This type of operation should enhance equipment efficiency and improve the productivity of personnel.

5. High-Speed Sorting

The OSHD is seriously considering using a high-speed WIM as sorter in the highways. Vehicles would be sorted before they enter the POE. The installation would be installed on I-82 southbound on the Washington side of the Columbia River. AVI would be used to identify the vehicle and the SSC would be used to check PUC files on that vehicle for taxes, inspections, safety violations, and other information. If it meets legal weight and PUC requirements, the vehicle would be allowed to go through without taking the exit ramp to the Umatilla POE. The data collected from WIM/AVI would be stored for enforcement and tax audit purposes.

There are challenges that need to be addressed before such a concept becomes reality. Signing is of paramount importance. Directing the trucks to the proper lanes is a challenge, as are trucks trying to by-pass the system. OSHD is working on this. If this system works, then we have a truly automated system where only overweight, illegal and non-PUC registered vehicles would be directed into the POE. The savings in manpower would be tremendous.

6. Automated Vehicle Measuring Systems

One area that has been overlooked is the measuring of a vehicle's overall length, and the width and length of individual trailers in a combination. OSHD will be working with manufacturers in the future to develop such a system. Initial research indicates there may be several potential technologies to this end.

7. Shipper Responsibility Enforcement

This concept is to have enforcement at point of origin. Two scenarios are possible here. One would be for the weighmasters using portable or semi-portable scales to weigh the trucks at the shipper's yards. The other is to have a certified scale at the point of origin and have the shipper certify that shipment met all legal weight requirements. If found in violation, a bail system would assess large fees based on the overload. This latter concept shifts the responsibility onto the shipper rather than the truck driver. The truck driver would no longer be coerced into carrying over legal weight.

8. User Fee Enforcement

The OSHD is investigating the possibility of making the fine structure based on potential damage to the roads. The fine structure would be based on the AASHTO road test and the damage factor developed from these tests. Fines would be proportional to the ESAL factor which increases to the power of four. This would be a huge deterrent to offenders and would reduce the number of overloads.

9. Chronic Offender Profiles

The Woodburn automation system has the ability to develop a chronic offender list and profile. Already, several companies have been identified as repeat offenders of weight laws. The plan is to develop similar chronic offender profiles for each port and area. These offenders would be warned to clean up their act. If they continue, penalties would be levied, and if there is no response, their operating authority could be suspended. This would help remove the bad actors from Oregon's highways and would be another enforcement tool for the weighmasters.

## V. IMPACT OF MODERN TECHNOLOGY ON PRESENT WEIGHMASTER ACTIVITIES

What has been the impact of modern technology on weighmaster activities in Oregon? The answer will predict future activities.

## A. Staffing Levels

Table 1 and Figure 2 show the staffing levels for the years 1957 to 1987. There is one obvious trend; the staffing levels have remained constant during the past three years. This trend will continue for at least the next five years or longer.

One aspect not shown is that, since 1980, the weighmaster responsibilities have expanded to include truck safety inspection. Of the 116 field people, 14 F.T.E. are working on truck safety inspections. Only 102 weighmasters are weighing trucks.

## B. Weighmaster Activities

### 1. Truck Weighings

Table 2 and Figure 3 show the number of truck weighings. The figure shows that number of truck weighings have dramatically increased. It should be noted that, since 1981, empty trucks have not been weighed. Oregon is weighing more trucks with fewer field people. This is due to the introduction of ports-of-entry, and new technology concepts such as weigh-in-motion. As more WIM sorters and other technology is introduced, productivity should continue to increase.

### 2. Citation Issuance

Table 3 and Figure 4 show the citation issuance. The number of issued citations was fairly constant from 1957 to 1971, increasing from 1972 to 1975. After 1975, there was a huge increase, but the number of citations dropped in 1982 and is now slowly increasing. The reason for the huge drop since 1981 is that the weighmasters stopped issuing $2 tickets for minor overloads. It was costing more to process them than it was worth. Slow growth in citations can be correlated with the increase in truck traffic. The citations rate has been around two percent of weighings. Based on WIM data on I-5, the violation rate may be 6 to 8 percent while the violation rate off the Interstate system, based on bridge WIM data, may be as high as 20 percent on some local roads. Only a small number is being caught. New technologies will give us a better understanding of the overload problem.

### 3. Vehicle Safety Inspections

Table 4 and Figure 5 show the number of vehicle safety inspections. As can be seen, safety inspections had a fairly constant growth from 1980 to 1984, a slight decline in 1985 and 1986, and an increase in 1987. The reason for this increase was the new safety inspection station at the Woodburn port-of-entry. As new bays are built, the number of inspections should increase.

### 4. Vehicle Legalizations

Table 4 and Figure 6 show the number of vehicle legalizations. Each year since 1983 has seen an increase in legalizations as parking space for this function is being built into the new ports-of-entry and some of the weigh stations. As more space is provided, and more trucks weighed, legalizations should increase.

## VI. SUMMARY

Over the years, enforcement strategies in Oregon have evolved to meet economic changes, regulations, and accommodate new technology. The Oregon weighmasters have gone with the tide and have based their enforcement strategies on new technology. The result is that they are doing more with less human capital. New technologies and plans will help them continue this trend. The only problem is financing some of this new technology, and also its acceptance.

The new technologies on the horizon with Oregon's plans for the future should make the next ten years ones of excitement and challenge in weight enforcement.

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## TABLE 1: FIELD PERSONNEL STAFFING LEVELS: 1957-1987

| Year | Field Personnel |
|---|---|
| 57 | 81 |
| 58 | 84 |
| 59 | 84 |
| 60 | 85 |
| 61 | 86 |
| 62 | 87 |
| 63 | 68 |
| 64 | 67 |
| 65 | 66 |
| 66 | 66 |
| 67 | 68 |
| 68 | 66 |
| 60 | 67 |
| 70 | 59 |
| 71 | 71 |
| 72 | 71 |
| 73 | 70 |
| 74 | 70 |
| 75 | 79 |
| 76 | 79 |
| 77 | 87 |
| 78 | 87 |
| 79 | 93 |
| 80 | 93 |
| 81 | 93 |
| 82 | 91 |
| 83 | 91 |
| 84 | 109 |
| 85 | 116 |
| 86 | 116 |
| 87 | 116 |

## TABLE 2: TRUCK WEIGHINGS: 1957-1987

| Year | Weighings |
|---|---|
| 57 | 552,163 |
| 58 | 623,993 |
| 59 | 695,506 |
| 60 | 664,558 |
| 61 | 645,152 |
| 62 | 707,192 |
| 63 | 528,905 |
| 64 | 538,660 |
| 65 | 585,476 |
| 66 | 601,926 |
| 67 | 598,625 |
| 68 | 676,342 |
| 69 | 526,327 |
| 70 | 646,182 |
| 71 | 760,672 |
| 72 | 732,127 |
| 73 | 827,980 |
| 74 | 842,927 |
| 75 | 921,232 |
| 76 | 1,014,997 |
| 77 | 1,051,277 |
| 78 | 1,194,552 |
| 79 | 1,327,269 |
| 80 | 1,472,561 |
| 81 | 1,744,313 |
| 82 | 1,400,978 |
| 83 | 1,333,492 |
| 84 | 1,538,071 |
| 85 | 1,819,393 |
| 86 | 1,918,029 |
| 87 | 2,530,979 |

## TABLE 3: NUMBER OF CITATIONS ISSUED: 1957-1987

| Year | Citations |
|---|---|
| 57 | 6,621 |
| 58 | 7,137 |
| 59 | 7,062 |
| 60 | 7,032 |
| 61 | 6,767 |
| 62 | 8,471 |
| 63 | 6,313 |
| 64 | 6,265 |
| 65 | 7,197 |
| 66 | 8,027 |
| 67 | 8,086 |
| 68 | 9,916 |
| 69 | 9,179 |
| 70 | 8,420 |
| 71 | 12,277 |
| 72 | 12,955 |
| 73 | 17,049 |
| 74 | 15,180 |
| 75 | 12,244 |
| 76 | 31,455 |
| 77 | 43,170 |
| 78 | 54,303 |
| 79 | 54,468 |
| 80 | 59,019 |
| 81 | 53,162 |
| 82 | 33,507 |
| 83 | 25,063 |
| 84 | 29,889 |
| 85 | 30,786 |
| 86 | 29,685 |
| 87 | 31,659 |

## TABLE 4: NUMBER OF TRUCK SAFETY INSPECTIONS AND LEGALIZATIONS

| Year | Safety Inspections | Year | Legalizations |
|---|---|---|---|
| 80 | 2,597 | | |
| 81 | 4,409 | 81 | 1,932 |
| 82 | 8,040 | 82 | 1,881 |
| 83 | 9,222 | 83 | 2,219 |
| 84 | 11,828 | 84 | 2,861 |
| 85 | 10,500 | 85 | 3,304 |
| 86 | 10,329 | 86 | 4,241 |
| 87 | 13,814 | 87 | 5,256 |

FIGURE 1: Location of Scales

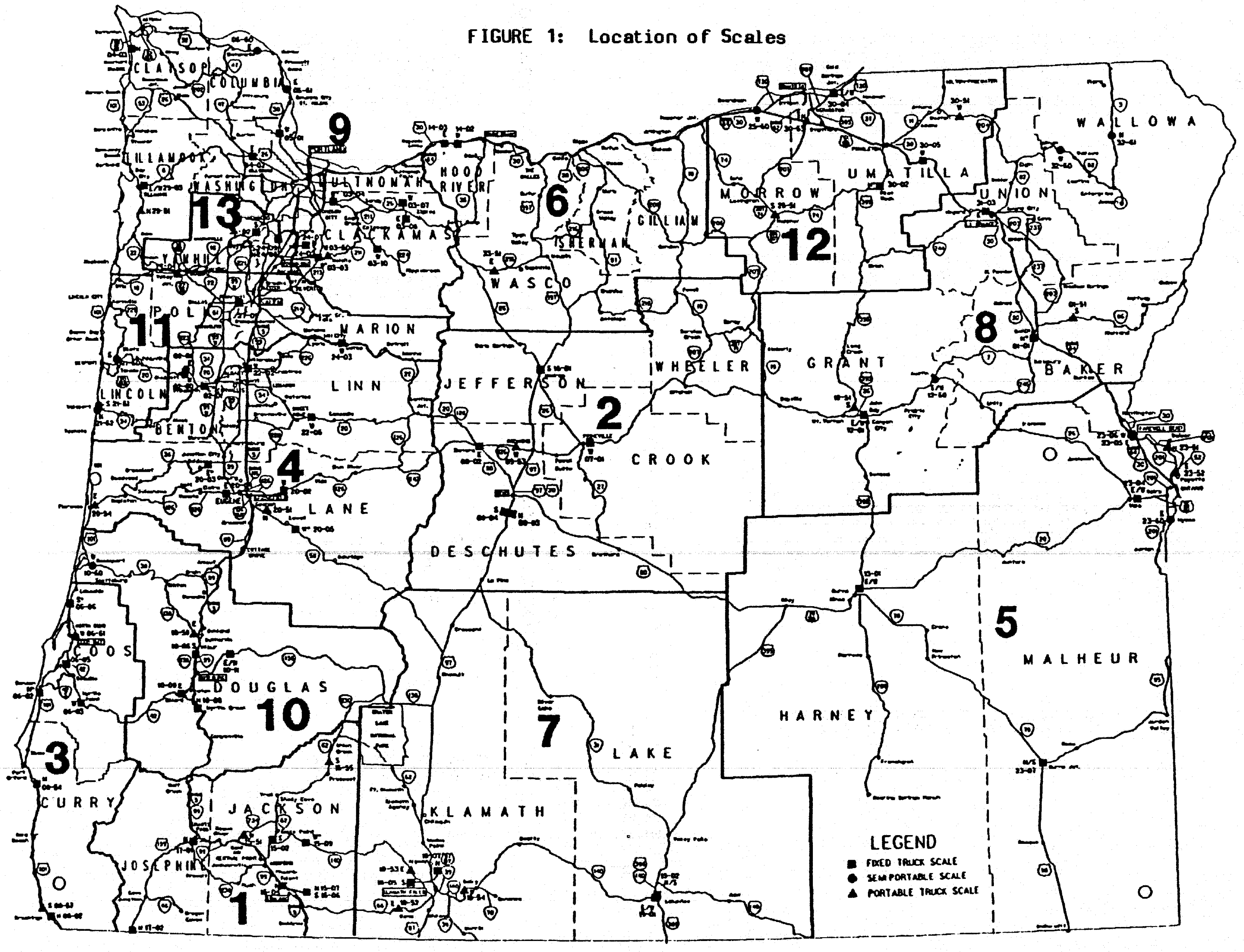


FIGURE 2: Weighmaster Staffing

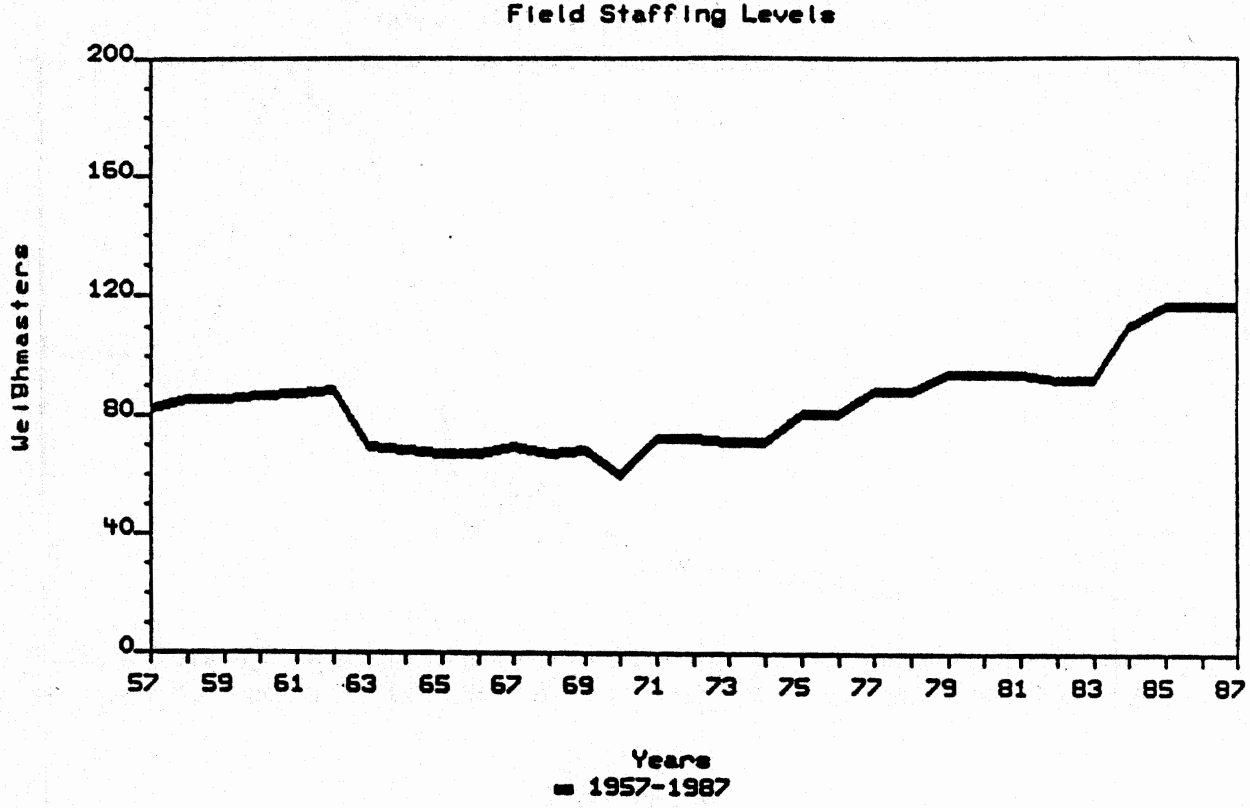


FIGURE 3: Weighmaster Activities

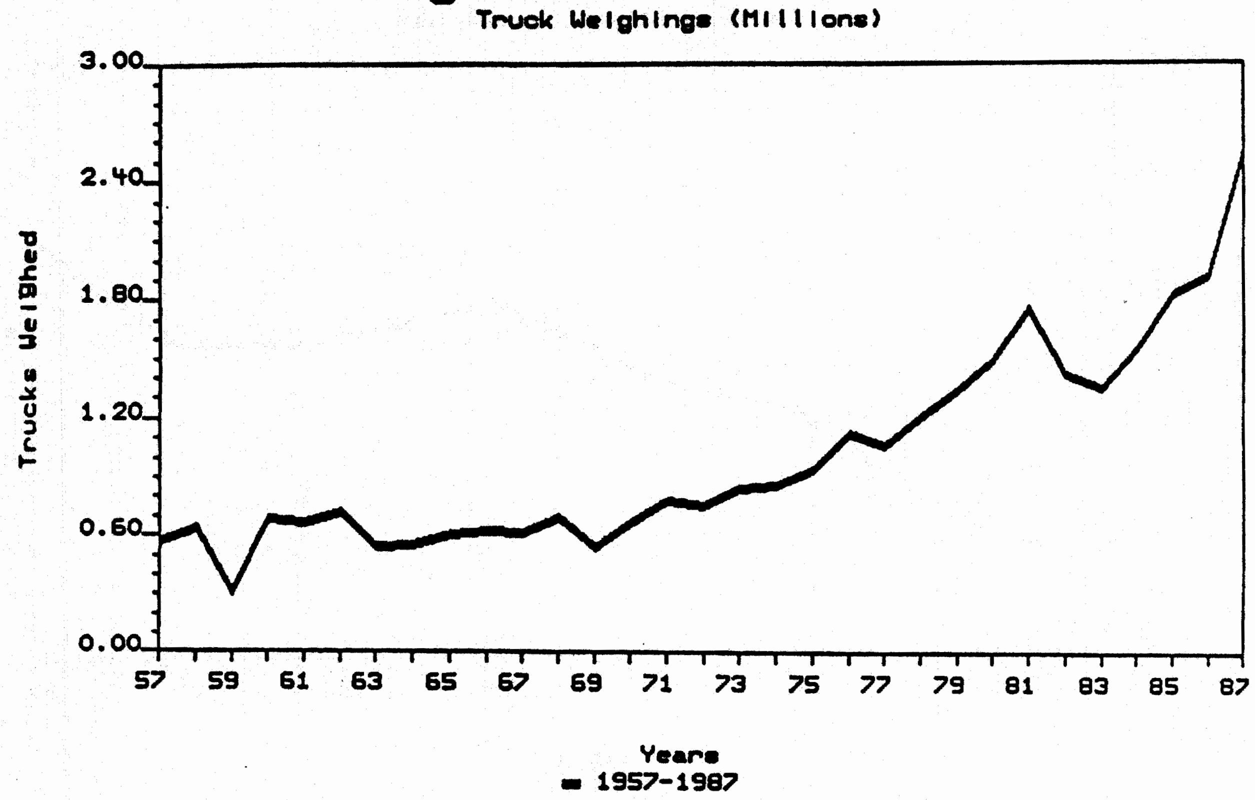


FIGURE 4: Weighmaster Activities

Citation Issuance (Thousands)

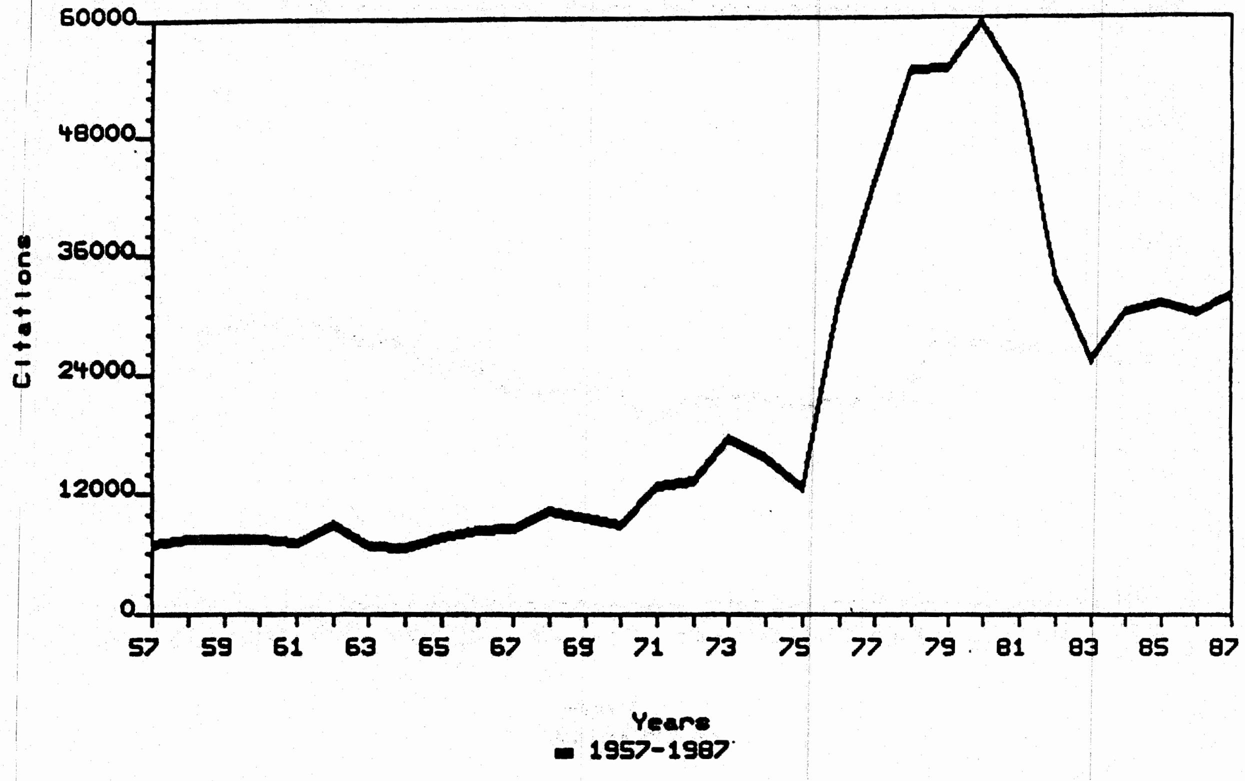


FIGURE 5: Weighmaster Activities

Vehicle Safety Inspections

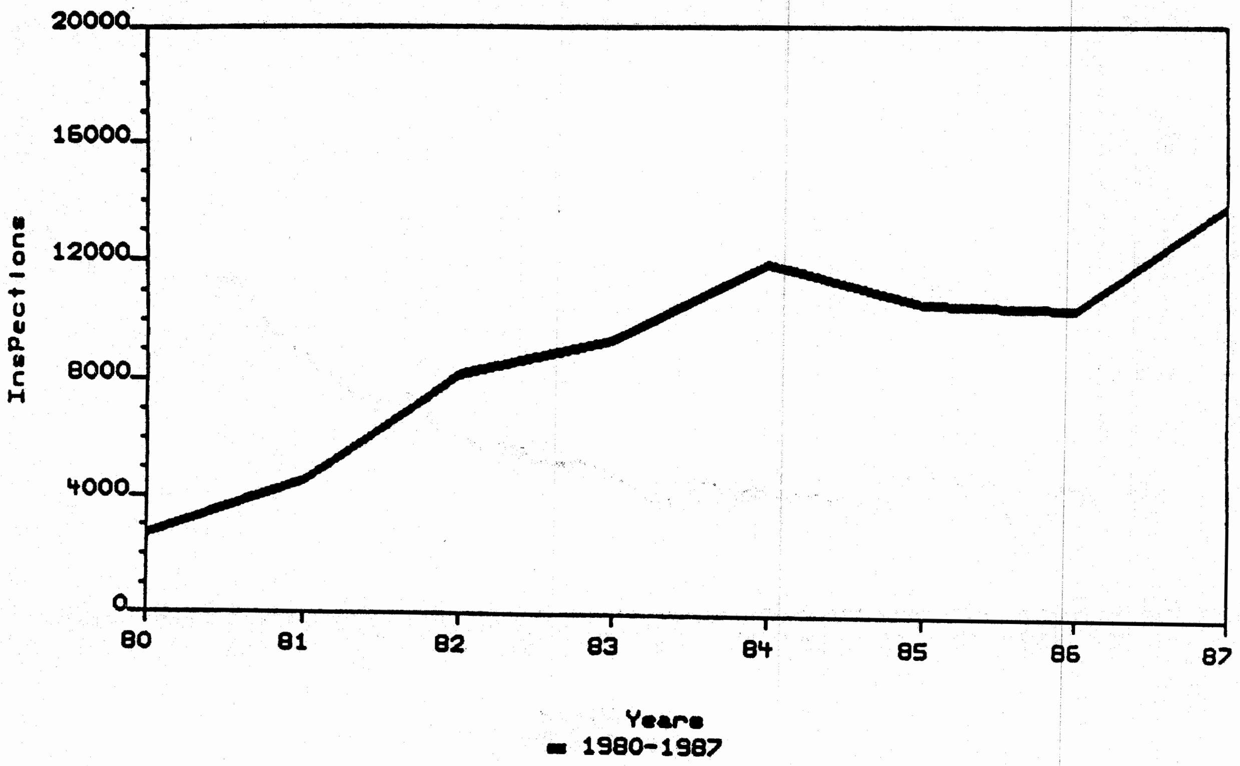
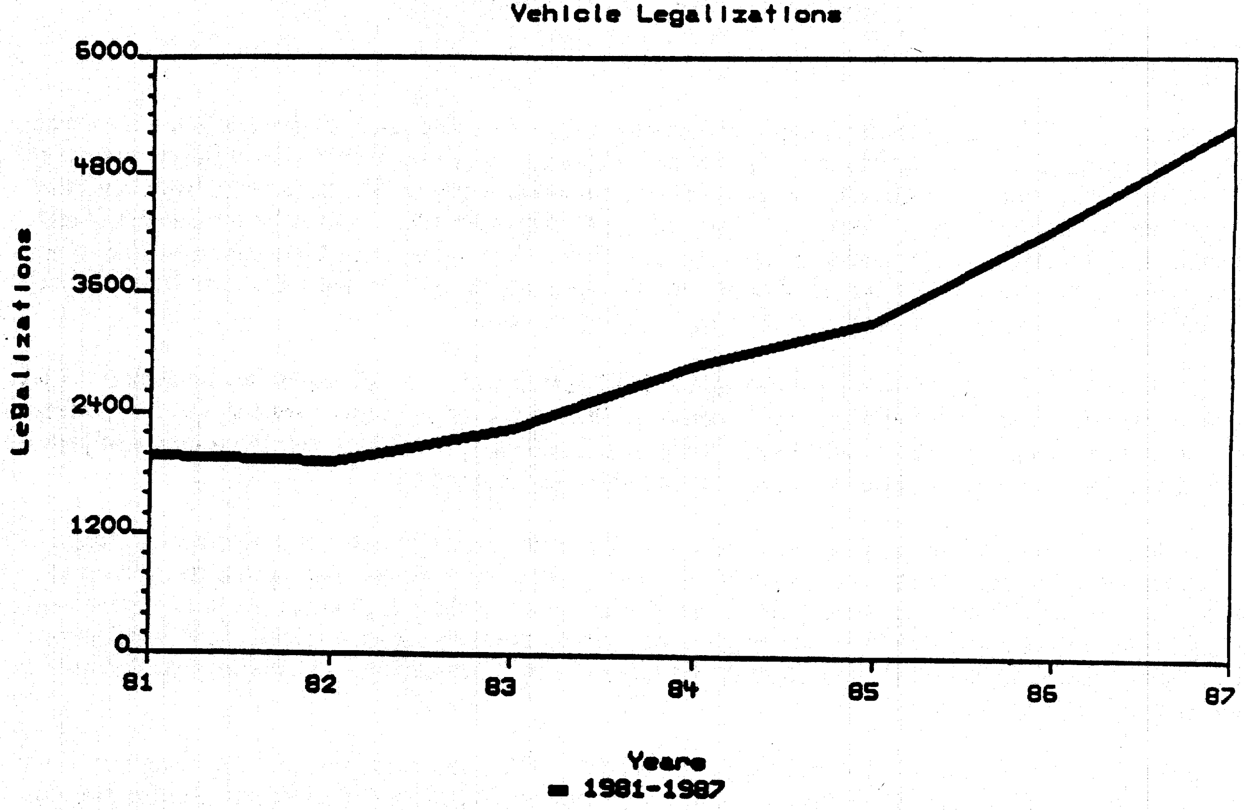


FIGURE 6: Weighmaster Activities



# THE AUTOMATION OF THE WOODBURN SOUTHBOUND PORT-OF-ENTRY ON INTERSTATE 5

*Milan Krukar*[1] *and Ken Evert*[2], *Oregon DOT*

## 1.0 Introduction

Interstate 5 (I-5), which starts at the California-Mexico border and ends at the Washington-Canada border, is the main north-south highway in the Pacific Northwest. It also serves as Oregon's principal heavy vehicle commercial route. Yet, for many years, there was no port-of-entry on I-5 southbound, when entering Oregon from Washington State. There is a Public Utility Commission (PUC) office by the Jantzen Beach Interchange in Portland, where trucks entering Oregon from Washington can obtain permits. The weigh station located on I-5 southbound at Woodburn, 35 miles south of Portland, did not handle PUC transactions and was open only on a part time basis to weigh trucks.

In the early 1980's, both the weighmasters and PUC realized that this situation was inadequate. The station at Woodburn had the following shortcomings: 1) access and egress lanes were too short for safety; 2) not enough parking capacity for vehicles; 3) inadequate facilities for weighing present volumes of heavy vehicles; and 4) inadequate facilities for the "one-stop shopping" concept.

Present day heavy vehicle enforcement has evolved from monitoring heavy vehicles carrying Oregon's basic commodities, such as timber and agricultural products, to one of service to help the truckers to stay within Oregon's laws. This service concept has evolved into "one-stop shopping" where the facilities are built to weigh heavy vehicles, provide PUC services, and conduct truck safety inspections. PUC and weighmaster personnel are now located in the same building and there is a truck inspection facility with bays. Delays are minimized as much as possible.

Before the Woodburn Southbound Port-of-Entry (SB POE) was built, the three existing ports did not entirely meet the "one-stop shopping" concept. The weighmasters and PUC decided to entertain the idea of combining weight and size enforcement, PUC permits, and truck safety inspection at one location. In late 1983, the Oregon State Highway Division started a weigh-in-motion (WIM) and automatic vehicle identification (AVI) demonstration project, testing a medium speed WIM sorter with AVI systems at Woodburn NB weigh station and a high-speed WIM data collection system with AVI on I-5 NB at Jefferson. The results have been reported by Krukar(1).

In late 1984, based on the initial success of the WIM/AVI Demonstration Project, the idea of interfacing WIM/AVI with the static scale, and installing a supervisory computer with appropriate software to monitor, store, modify, hold the PUC database, and transfer weight data was discussed. This concept developed into the Woodburn SB POE Automation Demonstration Project and has been described by Krukar (2).

## 2.0 Woodburn Southbound Port-of-Entry

The Woodburn Port-of-Entry (POE) is located on Interstate Highway I-5 Southbound at approximately mile post 274.40. The Woodburn POE has one weigh-in-motion sorter system and two electronic static scales. The latter are located by the Weighmaster and PUC offices. A truck inspection building is also on the premises off to the west side. Figure 1 shows an aerial view of the POE.

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The Woodburn POE is the busiest POE in the state. All ports-of-entry are operated around the clock, 7 days a week. A minimum of 2000 trucks pass through the facility during a 24-hour period. During peak periods, over 3,300 trucks per day pass through the POE. One hundred fifty to 200 trucks may pass during a peak hour.

When this POE was designed, it was estimated that the port would handle an average of 1700 vehicles per day with peak days of 2200-2300. Table 1 shows the weekly weighings by the WIM system. These estimates have been rapidly exceeded and there was a need to lessen this workload increase on the weighmasters. The automation of the port was an answer to this need.

The plan was to automate this POE to minimize the Weighmaster and PUC tasks; improve weight, size, and safety enforcement; provide more data for planning and design purposes; save and manpower and time for the State and the trucking industry. The WIM, AVI, and static scales, along with the PUC Motor Carrier database would be tied into a supervisory system computer which would control truck traffic and data.

## 3.0 Purpose of Paper

The purpose of this paper is to describe the automation of the Woodburn POE. This paper describes the hardware and software, system operation, data obtained, benefits, limitations, and future goals.

## 4.0 Automation of POE

### 4.1 The Need for Automation

Present technology offers the opportunity to improve efficiency at our POE's. POE's are presently labor intensive for the weighmasters. Automating the system provides long-term increases in productivity resulting in reduced manpower requirements, better data collection, more efficient truck weight, size and safety enforcement, improved weight-mile tax collection and audits, and time savings to POE users.

### 4.2 Components

The automation of the Woodburn SB POE consists of six elements: (1) the Weigh-in-Motion (WIM) Sorter; (2) the Automatic Vehicle Identification System (AVI); (3) the electronic static scales; (4) the supervisory computer (SC); (5) the various software interfaces; and (6) Motor Carrier Data Base. Table 2 shows the components used for this project.

## 5.0 What the System Will Do

### 5.1 Existing POE Functions

The purpose of a POE is to monitor and regulate trucks using state highways with respect to weight, size, safety, and weight-distance taxation. These various functions are divided or shared between the weighmasters and the Public Utility Commission.

The purpose of the weighmasters is to protect the Oregon highways from overloaded and oversized trucks, and monitor truck safety and the transport of hazardous materials. Their functions are tied to their purpose. Weighmasters' functions are to weigh trucks to ensure that they are legal with respect to gross, axle and tandem weights, height, width, and length and comply with bridge formula. Weighmasters have statutory authority to control weight, size and safety and cite violations. They, along with PUC, monitor trucks for safety and the transport of hazardous materials. The weight information is used by PUC for weight-distance tax audits.

PUC has both regulatory and tax collection functions. The Motor Carrier Division's functions at POE's are to collect weight-distance taxes from those vehicles who are not already registered, authority compliance, enforce truck equipment safety standards, and monitor the transport of hazardous materials. The latter two functions are shared with weighmasters although PUC has statutory responsibility and control.

At present, it takes a Weighmaster 20 to 40 seconds to weigh a truck at a static scale, depending upon the truck type. More time is needed if the truck is found to be in violation. The Weighmaster manually records the truck identification, commodity, number of axles, gross weight, and axle weights. Thirteen manual tasks are required to complete the above procedure. This information is sent to the Public Utility Commission Motor Carrier Division, where it is manually entered into the Oregon Department of Transportation (ODOT) mainframe computer. This information is used for tax audit purposes.

About 85 percent of the trucks passing through the POE have appropriate PUC papers and are within legal weight. The remaining 15 percent are either cited for some kind of weight violation, need an extended weight permit, or a PUC permit for weight registration, or both. These trucks will have to go to the legalizing loop and park. The truck driver will have to make a stop which may vary from 5 to 25 minutes, longer if his load is weight illegal and has to be adjusted or removed. Extra time is needed by the Weighmaster to write citations.

## 5.2 Automated POE Functions

The automatic system at the Woodburn POE allows trucks with transponders to bypass the static scales and the PUC office. Eighty-five percent of the transponder equipped trucks will be able to take advantage of this, minimizing their productivity losses. A truck with a transponder has its identification number read by the AVI reader and is also weighed by the WIM. This data is transmitted to the supervising computer (SC) where it is stored for future transfer to the ODOT mainframe computer. The SC had data on 250,000 vehicles which includes information as to whether any given PUC plate is suspended, or for some other reason invalid. This allows the weighmaster to take immediate action in cases of suspended plates. In the past this information was not readily available to provide timely action at the POE. The SC also has name and address files on 40,000 carriers. If the truck meets both the weight limits and registration requirements, then it is automatically permitted to bypass the static scales and the PUC office, minimizing time loss.

The "chronic offender" list is a list of truckers and trucking firms that continually violate weight, size and safety laws. The information on repeated weight, size and safety offenders will be supplied by the weighmasters. The PUC safety division will provide additional information associated with safety violations. At this time, the weighmasters do not have an official "chronic offender" list, but individual weighmaster districts keep informal tabs on "chronic offenders" in their area. This list is now being developed for eventual statewide use. The weighmasters use this list to try to get additional sanctions on the individual truckers and trucking firms. Trucking firms that are in continual violation will be visited by weighmasters and warned about their performance. PUC also provides information about "chronic offenders" of safety laws and rules. This list will enable the weighmasters and PUC to identify violators immediately. The use of this list enhances weight, size and safety enforcement.

If the WIM shows that the truck does not meet gross or axle weight limits and/or bridge formula, or oversize criteria, and the SC shows that it meets PUC requirements, and/or safety inspection validation, and is not on the "chronic offender" list, then the truck has to go only to the static scales to be weighed. If in violation, it is ticketed. If the WIM shows that the weights are legal, but SC shows that PUC registration requirements are not met, then the truck can bypass the static scales but still has to go to the PUC office to obtain the necessary papers. If the truck violates both the legal weight limits and/or size limits, and PUC requirements, then the truck goes to both the static scales and the PUC office. This automated system reduces the number of vehicles going to the static scales by 30 percent. All WIM data is stored and telemetered daily. The WIM data on trucks that are allowed to bypass the static scales is transferred and stored on the SC computer.

The linking of the Weightronix static scales to the SC allows the automatic recording and storing of the static weights. The Weighmaster directly feeds the truck identification (PUC number) with the commodity data number into the SC. This automated system improves Weighmaster productivity by reducing the present 13 manual tasks to four. PUC saves on keypunch operator's time and key-punching errors.

Safety inspection information is also in the SC files. Weighmasters can tell when a truck was inspected. If it has not been recently inspected, they send the truck to the safety inspection bay.

This static weight information, along with the WIM information on trucks bypassing the static scales, is stored and transferred to the ODOT mainframe computer. The SC provides the Weighmaster a daily summary on the number and types of vehicles weighed at the static scales and number of violations by type. PUC is able to update the vehicle files to the SC on a hourly basis.

The combination of AVI, SC and WIM permits trucks to bypass the static scales and the PUC office provided they meet both PUC and weight limit requirements and regulations. A POE with a WIM sorter scale, but without AVI and SC, will not permit trucks to bypass the PUC station, only the static scale. Therefore, an AVI and SC system are needed to make the POE automation demonstration work properly.

It should be noted that only 350 trucks are presently equipped with transponders. About 75 to 100 trucks with transponders pass through the Woodburn POE daily. This limited system does demonstrate the feasibility of the fully automated POE. This small sample does not affect the linkage of the Weightronix static scales with SC, and demonstrates even more forcefully the improved productivity of the weighmasters.

The Heavy-Vehicle Electronic License Plate (HELP), the Crescent Study, demonstration project currently underway will provide information on which AVI technology is superior. These tests will take about two years. By 1989, there will be enough information for the State to decide which AVI system it will adopt and what kind of transponders will be issued to all trucks. (It is possible that the present AVI system and transponders may not be the system of the future.) The goal is to have all trucks in Oregon carrying transponders by the end of the century. This will make the port-of-entry truly automated.

## 6.0 Potential Benefits from Automation

The State and the trucking industry both benefit from such a system. These benefits will occur when the system is fully automated and all vehicles carry transponders. Both the weighmasters and PUC will benefit from improved productivity. The State will benefit from improved weight and safety enforcement.

Various Highway Division functions will benefit from improved data collection. The trucking industry will benefit from time savings from minimizing productivity losses at the POE. The assumption is that all trucks will have transponders by 1999.

## 6.1 Weighmaster Benefits

### A. Monetary Benefits

This POE will be the busiest in the state, handling 2,000 or more trucks per day with a peak of 150-200 trucks per hour. With a fully automated system, this number will be reduced by 85 percent to 300 trucks daily. This will reduce Weighmaster POE manpower requirements by about 30 percent. The POE is manned 24-hours a day, requiring 2 persons per shift. During the weekend, only one person is required per shift. The number of people may potentially be reduced from 13 to 9, thus freeing 4 weighmasters for other assignments which will allow for enhancement of weight control. Estimated benefits annually are $82,200.

### B. Productivity Gains

The reduction of 13 manual tasks to 4 will increase the Weighmaster productivity by reducing fatigue. The SC will allow the Weighmaster to spot potential violators immediately. All this should improve weight enforcement.

In addition, the files in the SC will let the Weighmaster know if the truck was recently inspected for safety. If not, the truck can be sent for inspection at the bay. This should result in improved safety inspection, and benefit the public by providing safer highways.

The Weighmaster will also benefit from having summary tables automatically prepared by the computer rather than manually. This should free some of POE supervisor's time for other duties. These tables will allow for more effective scheduling of the available personnel.

## 6.2 PUC Benefits

### A. Monetary Benefits

#### 1. Manpower Benefits

The truck data will be automatically stored in SC from the WIM and static scales. It will be transferred to ODOT mainframe on a daily basis. In the past, the manually written information from the Weighmaster had to be keypunched into the mainframe by an operator. This will eliminate this step and save personnel for other uses, such as safety inspection or increased weight enforcement on the other highways. Estimated monetary savings per year is $10,000.

#### 2. Additional Truck Weight-Mile Taxes

The automated system at this POE should increase the collection of truck weight-mile taxes through improved truck weight information. PUC estimates this at $11,500 annually.

### B. Productivity Gains

Productivity gains will come from more efficient truck weight information resulting in improved tax audits. Automation should eliminate the keypunch errors made by PUC operators.

The data should be more reliable, thus helping with tax audits. PUC will have the ability to update their vehicle and "chronic offender" files on a daily basis thus keeping information current. All this should result in more efficient truck weight-mile tax collection.

## 6.3 OSHD Data Collection

Various Highway functions will benefit from improved truck weight data. Data from the WIM and the static scales will be available for planning purposes, pavement design, research, traffic, and cost responsibility. In past, this data was available but had to be processed manually. Now it will be available immediately on a daily and weekly basis.

## 6.4 Improved Weight/Tax Enforcement

The WIM information will help the weighmasters with bridge formula violations. The "chronic offender" list should allow the Weighmaster to spot repeat offenders. The vehicle file allows the Weighmaster to see if the vehicle has all the necessary registration and permits. The result will be a more efficient weight enforcement.

The freeing of weighmasters at the port-of-entry will allow for scheduling manpower for additional weigh station operations on other highways. This will increase the number of weighings on these routes, thus enhancing weight and size enforcement.

In the past, truck traffic at peak volumes frequently backed-up at weigh stations, causing bottlenecks and safety hazards. The only solution was to let trucks bypass the scales until the truck volumes were reduced. This meant that the trucks bypassing the static scales were not weighed. Now, with WIM, all trucks can be weighed safely during peak traffic volumes. Even if they are allowed to bypass the static scales, a record of their weight is available, thus enhancing weight enforcement.

Trucking firms, behind in their tax payments, will be identified at the POE. Although tax audits would have caught them eventually, since they are supposed to be done every two years. The automation system will allow this to happen a lot sooner. One large trucking firm was recently caught owing $41,000. They paid up and PUC was ahead, not losing interest.

## 6.5 Improved Safety Enforcement

The vehicle safety files will contain information on truck safety inspection. This will enable the Weighmaster to know if the truck's safety inspection is current and whether the carrier has a high or low safety profile. Thus this system can improve and increase truck vehicle safety inspections.

## 6.6 Truck Productivity

The automated POE will allow 85 percent of the trucks to bypass the static scales and PUC office. This will minimize time losses. Time savings will be on the order of 60 seconds per vehicle. This will result in savings in operating costs amounting to $370,200 annually.

The improved enforcement of weight limits and safety will help the legitimate trucking firms and improve their competitive situation by reducing illegal or unethical operations.

## 6.7 Pay-Back Period

Total annual monetary benefits to the State are $103,700. The costs of WIM/AVI/Automation is $404,000[3]. The pay-back period, excluding interest, is 3.9 years.

## 7.0 How the System will Operate

### 7.1 Operation of System

Figure 2 shows the overall layout of equipment in the POE. This system is designed for measuring weights at truck speeds of 20-40 MPH. The system can be manually overridden by the weighmasters at any time.

The following points describe the events as a vehicle equipped with a transponder passes through the system:

1. The vehicle trips loop 1 (located several feet upstream from the WIM scale). This causes the WIM to begin accepting data from the AVI Reader.

2. The vehicle's axles pass over the WIM platform, the axle sensor, and the overheight detector.

3. The AVI Reader activates the vehicle's transponder (assuming GRS system) and transmits the vehicle ID to the WIM.

4. The vehicle leaves loop 2 (located several feet downstream from the WIM scale).

5. The WIM calculates the axle spacings, single axle, tandem axle, and gross weights, bridge formula compliance, height, and determines (using the "standard" sorting algorithm) whether the vehicle should be directed to the "Report" or "Bypass" lanes.

6. The WIM transmits a "vehicle packet" to the SC computer. Among other things, this packet contains the axle weights and spacings, the vehicle ID, and the current sorting threshold.

7. The SC computer looks up the vehicle ID (2) and determines the direction the vehicle should take based on permits for extended weight.

8. The SC computer sends back an "override packet" to the WIM. This packet contains the information the vehicle should take and the size of the worst three axle group overloads if such overloads exist.

9. The vehicle trips loop 3 (located 140 feet and 110 feet downstream from loop 2 and the directional signal lights, respectively), and the WIM activates the appropriate signal in S1 (signal lights for the "report" and "by pass" lanes).

10. Operation continues for another vehicle.

    (a) If the vehicle obtains the "bypass" lane signal, it will continue on lane 1 until it triggers loop 4 (located approximately 175 feet downstream from the directional signal lights). This activates a signal at the Weighmaster station, telling him whether this vehicle is legal. Weight

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[3] This assumes a fully automated system and does not include the costs of the necessary transponders. The latter can be issued as electronic license plates bought by the trucking firms for each truck. This may occur by 1990. The costs to automate other ports-of-entry, including WIM/AVI, will be about $330,000. Most of the custom software can be used at the other ports-of-entry.

and ID information from the WIM are automatically transferred and stored in the SC. If the vehicle is in the wrong lane, an alarm alerts the Weighmaster to change the variable message sign to notify the truck driver to return to get weighed.

(b) If the vehicle obtains the "report" signal (3), it will continue in either lane 2 or 3, triggering loop 5 or 6, respectively. (These loops are located 300 ft. downstream from the directional signal lights and 300 feet upstream from the static scales). These loops determine which CRT screens are to be activated by that vehicle.

11. (a) As the vehicle approaches the Weightronix static scales in lane 2 or 3, the Weighmaster will enter the PUC plate number into the SC. The SC will flash on the CRT screen whether or not this vehicle is on the "chronic offender" list, and if it meets both PUC and Weighmaster regulations and permits.

    (b) The Weighmaster will also automatically have WIM information on the vehicle from the WIM computer as it enters either lane 2 or 3. The Weighmaster can have 4 screen options on the CRT from the WIM. These are:

    Option A: Vehicles and weights in lanes 2 and 3.

    Option B: Vehicles in the bypass lane (1).

    Option C: Vehicles in option A or B showing weight by wheel loads and balance of load for each wheel.

    Option D: Data Collection Tables:

    (1) Cumulative Vehicle tables - 7 days information (2) Number of vehicles by speed, axles, vehicle lengths and vehicle classification.

12. As the vehicle is weighed on the static scale, the axle weights and bridge formula are recorded and the gross weight automatically calculated when "total" button is pressed. These are shown on the CRT screen and are entered via the "enter" button to the SC and stored for later transmission to the mainframe.

13. (a) If the vehicle is weight and size legal and has met all the PUC and Weighmaster requirements, the Weighmaster will manually activate the variable message sign for the vehicle to go back to the freeway.

    (b) If the vehicle is weight and/or size illegal, and/or does not meet PUC or Weighmaster regulations, then the Weighmaster will manually activate the variable message sign for the vehicle to go to the parking lot, and the driver to see the Weighmaster and/or the PUC personnel.

14. As the vehicle passes through the Weightronix static scales, it will trigger either loop 7 or 8 (located approximately 28 feet downstream from the static scales) in lanes 2 and 3, respectively. These loops will automatically clear the vehicle from the CRT screen.

15. Operation continues for another vehicle.

16. Hourly, the accumulated data on vehicles with transponders weighed by the WIM, and vehicles weighed on the static scales in the SC will be transmitted to the ODOT mainframe

via the appropriate file transfer software and SNA/SDLC communications. Updated vehicle data from PUC will be downloaded to the SC.

17. The SC will also give the weighmasters a daily summary list on:
    - i. Number of vehicles weighed by class type, commodity, and weights obtained from the static scales during the 24-hour period.
    - ii. Number of violations by axle, tandem, group of axles, combination or vehicles, oversize, and non-weight related.
    - iii. Number of vehicles weighed by the hour during a 24-hour period.
    - iv. Violation percentage by each category, and total violations.
    - v. Historical statistics - by month, quarter, and year.
    - vi. Number of vehicles weighed by the WIM scales during the 24-hour period by hour.

## 7.2 Important Aspects

Some of the important aspects of this system are outlined below:

1. The WIM works independently of the SC. If the supervisory computer is out of service, all sorting is based on the "standard" sorting algorithm.

2. The vehicle reader's antenna must be positioned so that the reader-activator does not send anything to the WIM until the vehicle trips loop 1 and has sent the complete vehicle ID by the time the vehicle leaves loop 2. The minimum time is 1/5th of a second between loops at 45 MPH.

3. The override packet must be received by the WIM before the vehicle trips loop 3, otherwise the WIM will sort on the "standard" algorithm. This places quite a tight time constraint on the SC computer. For example:

   - Assume 120 feet between the trailing edge of loop 2 and the leading edge of loop 3.

   - Example vehicle has 7 axles, is 80 feet long and is travelling at 40 miles per hour. This results in about 680 milliseconds between the rear of the vehicle leaving loop 2 and the front of the vehicle entering loop 3.

   - The vehicle packet from the WIM would be about 78 bytes which would take 150 milliseconds to transmit to the supervisory computer (assuming a 4800 baud link between the machines).

   - The override packet from the supervisory computer would be about 18 bytes which would take about 4 milliseconds to transmit to the WIM.

   - The supervisory computer thus has about half a second to look up the vehicle's identification and to determine whether the vehicle should be directed to the static scale. The present system accomplishes this in approximately 140 milliseconds.

## 8.0 Supervisory System Applications Overview

The applications of the functions have been developed by Rytter (3) in Motorola's Functional Specifications.

### 8.1 Weigh Station Parameters Application

This application sets up weigh station application program parameters of:

Inspection Date Threshold - The Weighmasters are able to instruct the Supervisory System to signal any vehicle which has not had a safety inspection within 'x' days to report to the static scale.

Updated Program Interval - The Weighmasters are able to set the frequency of execution, in minutes, of the unattended program which processes database updates from the host, and schedules PUC Weight Reports and citation images for transmission to the host.

Statistics Collection Time - The Weighmasters are able to set the time of day that the unattended time-triggered monthly statistics collection program will wake-up and execute. This program is executed once daily to extract data from previous days statistics for monthly report statistics.

### 8.2 Weighmaster Applications

WIM Interface - This application executes as an unattended program providing the interface between the Motorola equipment and the CMI-Dearborn WIM/AVI equipment for the real time sorting of vehicles.

Static Scale Weigh - This application executes the main application used by the Weighmaster. The application accepts information from the Weighmaster, look up and display PUC and other data from the database, and reads weight data from the Weightronix static scale.

Citation Writing - This application is used to input violation information and print a citation on preprinted forms. An image of the citation is also prepared for transmission to the host.

PUC Plate Number Assignment - This application is used to update the temporary vehicle identification number, assigned by the Weighmaster and saved in the Supervisory System vehicle statistics when an unregistered vehicle reports for a static weigh, with a plate number assigned by the local PUC representative.

Chronic Offender Review - This application is used to confirm the assignment of Chronic Offender status to a carrier.

Citation Modification - The prime function of this application is the notation on previously written citations of load legalizations through off loading or load shifting. This application is used to modify and reprint citations, to modify only the database copy of the citation, or to delete citations from the database. An audit trail of citations which have been changed is maintained for management report purposes. An image of the modified citation, or a record identifying the deleted citation, is prepared for transmission to the host.

Vehicle Statistics Modification - This application is used to modify or delete vehicle statistics which would be reported in the PUC Daily Weight Report. An audit trail identifying weigh statistics records which have been changed or deleted is maintained for management report purposes.

## 8.3 Report Generation

PUC Daily Weight Report - This application is used to produce a printed copy, and/or file for transmission to the host, of the PUC Daily Weight Report. The Weighmasters are able to specify the starting and ending periods for which the report is to be produced.

Daily Summary Reports - This application is used to produce a printed copy of the:

Daily Operation Summary
Average Gross Weight by Hour Summary
Vehicle Class by Hour Summary
Commodity by Hour Summary
Citations by Hour Summary

Monthly/Quarterly Triples Activity Report - This application is used to produce a month-to-date or quarter-to-date report identifying the triples which have passed through the weigh station.

Monthly/Quarterly Operation Summary Report - This application is used to produce a month-to-date or quarter-to-date Weigh Station Operation Summary Report.

Monthly/Quarterly Statistics Modification Report - This application is used to create a month-to-date or quarter-to-date report identifying vehicle weigh statistics which were modified or deleted from the database.

Monthly/Quarterly Citation Modification Report - This application is used to produce a month-to-date or quarter-to-date report identifying citations which had been written and then modified or deleted from the database.

Monthly/Quarterly Productivity Progress Summary - This application is used to produce a month-to-date or quarter-to-date summary by employee number identifying weigh station production during the hours that the employee worked.

Monthly/Quarterly Chronic Offender Report - This application is used to create a month-to-date or quarter-to-date report identifying carriers which have been assigned Chronic Offender status during the selected period. Optionally, a report identifying all carriers noted as Chronic Offenders can be created.

## 8.4 Application Program Selection

The application system is developed as a set of hierarchial menus which guide the Weighmaster to the entry point of the application to be executed. The menu tree is shown in Table 3.

## 8.5 Host Communications

File Transfers - File transfer capability, uses 3770 emulation, for updating the PUC NAME and PLATE records in the Supervisory System database and for transferring the PUC Daily Weight Report and citation images to the host will be provided.

Host Inquiry - This application allows 3270 terminal emulation for host inquiry operations.

## 8.6 System Maintenance

Record Maintenance Application - This application is used to delete from the database those records maintained by the Supervisory System as the source for weight reports, daily, monthly, and quarterly summaries, when they are considered to be of no further historical value.

Database Backup and Restore - Utility programs for tape backup and restore of the database is provided through UNIX-executable scripts.

System Files Restore - When the system was installed, a complete copy of system-level software was provided for purposes of restoring a "crashed" system. This function is executed only by Motorola support personnel.

Initial Database Record Load - A UNIX-executable script has been provided for executing the utility program to load the initial PUC NAME and PLATE record database from tape.

## 9.0 In Retrospect

Hindsight is always 20/20 and this project is no exception. When the project specifications were was first developed, nobody on the Technical Advisory Committee or on the Steering Committee knew what kind of problems would occur, nor what would be truly needed. After nine months of operation, a better understanding of the limitations has been developed.

### 9.1 Communications

The communications between the PUC mainframe and the SC should have been studied and further developed. An error tracking system in the data system between the two systems has been developed as a result.

### 9.2 Fine Tuning of Some Functions

A. Hazardous wastes identification codes needed to be put into the existing programs.

B. Simplification of some of the output and tables should be done. This would make some of the output easier to read for the weighmasters.

C. Development of an automatic calibration system for the WIM sorter needs to be done. The weights from the static scales would be used to calibrate the WIM whenever the statistics program shows certain levels of deviation.

D. Estimated costs of these changes would be around $30,000, and would update the system and smooth operations.

### 9.3 Limits of Automation

The system is incapable of measuring truck width or overall vehicle length. At present, no equipment is available which will measure these two parameters, which is a serious limitation of the automated system. Weighmasters need the ability to enforce these two important parameters. There is a need to get manufacturers interested in developing such equipment.

The complete success of the automation system at Woodburn southbound port-of-entry will depend upon all trucks carrying some kind of identification which can be automatically read. The limited number of transponders in the demonstration has shown that this system can work successfully.

## 10.0 Future Plans

All the ports-of-entry will be automated as a result of the success of the Woodburn system. Automation of the POE at Ashland has begun, soon to be followed by automating the other two existing POE's. The two new ports-of-entry will also be automated.

## 11.0 References

1. Krukar, Milan, "The Oregon Weigh-in-Motion/Automatic Vehicle Identification Demonstration Project", Final Report, Highway Division, Oregon Department of Transportation, Salem, Oregon, September 1986.

2. Krukar, Milan, "Woodburn Southbound Port-of-Entry Automation Experimental Project", White Paper, Planning Section, Highway Division, Oregon Department of Transportation, Salem, Oregon, March, 1986.

3. Rytter, D.A., Functional Specifications for Woodburn Port-of-Entry Project, Motorola Computer Systems, Inc., April, 1987.

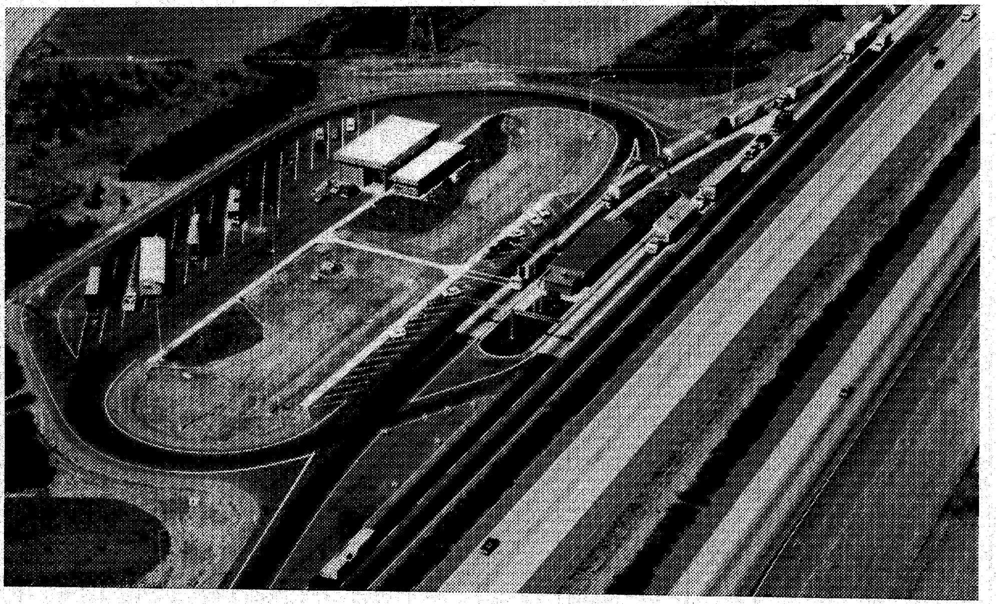
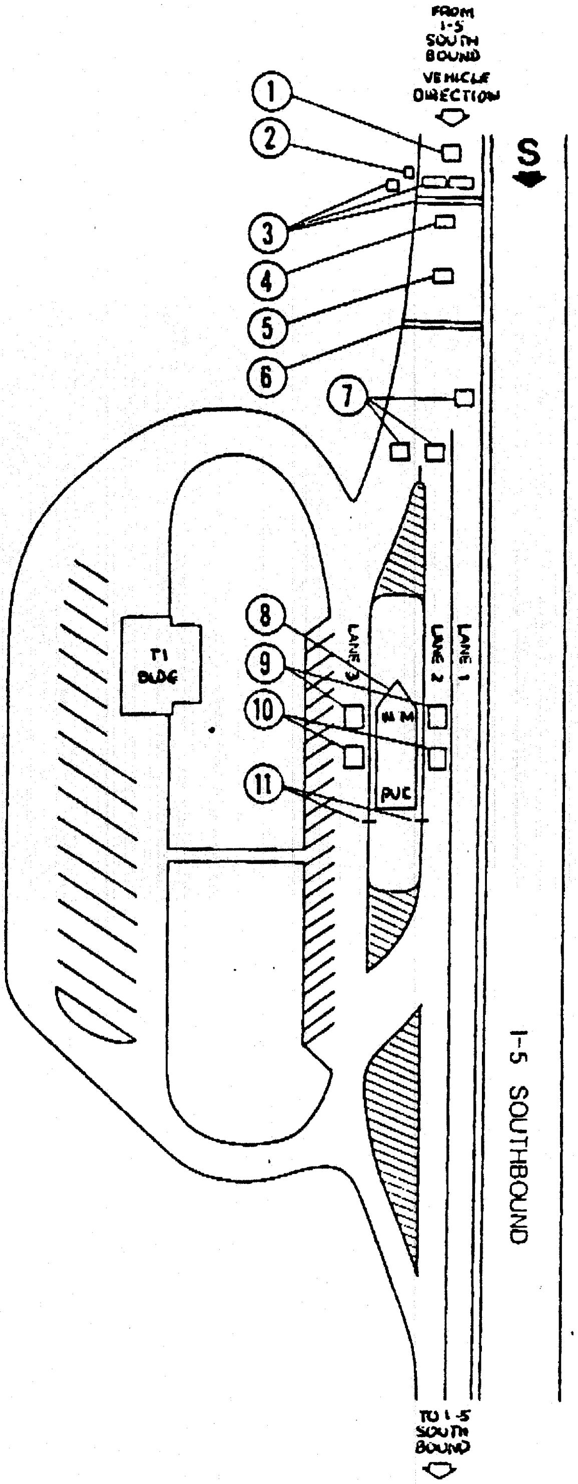


FIGURE 2

## WOODBURN SOUTHBOUND PORT-OF-ENTRY



1 DETECTOR LOOP
2 AUTOMATIC VEHICLE IDENTIFIER
3 WEIGH-IN-MOTION SCALE CABINET, AXLE BAR
4 DETECTOR LOOP
5 DETECTOR LOOP
6 DIRECTIONAL MESSAGE SIGN
7 DETECTOR LOOPS
8 WEIGHSTATION SCALE HOUSE
9 STATIC SCALES (2)
10 DETECTOR LOOPS
11 VARIABLE MESSAGE SIGNS (2)

NOTE: NOT DRAWN TO SCALE

## TABLE 1
## Number of Vehicles by Type and Day of Week
## Woodburn Southbound Port-of-Entry, 09/26 to 10/03/88

| Type | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| 1 | 100 | 86 | 84 | 106 | 103 | 45 | 29 |
| 2 | 9 | 3 | 5 | 4 | 10 | 1 | 2 |
| 3 | 285 | 310 | 310 | 311 | 299 | 90 | 55 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 97 | 85 | 98 | 88 | 94 | 33 | 21 |
| 6 | 72 | 74 | 73 | 77 | 80 | 14 | 9 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 72 | 72 | 56 | 74 | 71 | 29 | 27 |
| 9 | 12 | 22 | 20 | 22 | 25 | 6 | 4 |
| 10 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 11* | 1660 | 1636 | 1578 | 1421 | 1316 | 674 | 583 |
| 12 | 154 | 159 | 189 | 186 | 192 | 110 | 91 |
| 13 | 305 | 280 | 290 | 291 | 268 | 109 | 55 |
| 14 | 148 | 124 | 124 | 145 | 115 | 85 | 64 |
| 15 | 84 | 88 | 73 | 74 | 85 | 42 | 19 |
| 16 | 45 | 86 | 95 | 93 | 69 | 66 | 19 |
| 17 | 151 | 139 | 161 | 169 | 169 | 51 | 55 |
| 18 | 102 | 100 | 111 | 99 | 106 | 32 | 23 |
| 19 | 17 | 17 | 16 | 10 | 23 | 7 | 7 |
| **Total Trucks Weighed** | 3204 | 3192 | 3194 | 3061 | 2912 | 1348 | 1032 |
| **Total Vehicles Weighed** | 3313 | 3281 | 3283 | 3171 | 3025 | 1394 | 1063 |

*Five-axle semis

## TABLE 2
## Equipment & Software Used in Port-of-Entry Automation

| Type | Manufacturer | Model | Amount |
|---|---|---|---|
| WIM Sorter | CMI-Dynamics | SS 200-IDC (R) | 1 |
| AVI Transponders | General Railway Signal | 01320-30 | 350 |
| Reader-Activator | General Railway Signal | 41795 | 1 |
| Antennas | General Railway Signal | 59656-12/13 | 1 |
| **Static Scales** | | | |
| Readout | Weightronix | | 2 |
| Load Cells | Matrix | | 2 |
| Deck | Contractor | | 2 |
| **Supervisory Computer** | | | |
| Computer | Motorola | 8400 E, 161 MB Hard Disk | 1 |
| Processor | Motorola | 68020 | 1 |
| Streaming Tape | Motorola | 60 MB | 1 |
| D.R.A.M. | Motorola | 8 MB | 1 |
| CRTs | Motorola | TM 228 | 3 |
| Printers | IBM | 4224 | 2 |
| **Software** | | | |
| Relational Database Software | Motorola | Informix | |
| Mainframe Communications | Motorola | | |
| Relational Database | | 4th Generation Language for Customware Programming | |

## TABLE 3
## Hierarchial Menus Used in Application System

### MAIN MENU

Weighmaster Applications Menu
Report Generation Applications Menu
Record Maintenance Application
Weigh Station Parameters Application

### WEIGHMASTER APPLICATIONS MENU

Static Scale Weigh
Citation Writing
PUC Plate Number Assignment
Chronic Offender Review
Citation Modification
Vehicle Statistics Modification

### REPORT GENERATION APPLICATIONS MENU

PUC Daily Weight Report
Daily Summary Reports
Monthly/Quarterly Triples Activity Report
Monthly/Quarterly Operation Summary
Monthly/Quarterly Statistics Modification Report
Monthly/Quarterly Citation Modification Report
Monthly/Quarterly Productivity Progress Summary
Monthly/Quarterly Chronic Offender Report

Record Maintenance Application
Weigh Station Parameters Application

# REMARKS ON THE FEASIBILITY OF A NATIONAL HEAVY VEHICLE MONITORING SYSTEM

*Joseph R. Stowers*

For details on this presentation see:

Lance R. Grenzeback, Joseph R. Stowers, Ashok B. Boghani; *Feasibility of a National Heavy Vehicle Monitoring System*. NCHRP Report Series, Forthcoming, Jan. or Feb. 1989.

# TRAFFIC IMPACTS OF ESTABLISHING PERMANENT WEIGH STATIONS

*Curtis Dahlin, Program Management Division, Minnesota D. O. T.*

The effect of a permanent enforcement weigh station on truck traffic has long been a subject for speculation. It has generally been felt that the volume of trucks would decrease to some extent, but the actual impact has not been quantified. There are a variety of reasons for truckers to avoid weigh stations. Perhaps some of the more prominent ones are overweight vehicles, safety violations on the truck, and driver violations such as logbook, permits, etc.

We have had the opportunity to study this issue by looking at continuously collected data before and after the opening of a weigh station. Data collection scales on I-94 east of St. Paul became operational in December 1986. These scales monitor both eastbound and westbound traffic on the 6-lane facility. The scales are located in the right and center lanes. Manual vehicle classification counts indicate that about 4 % of the truck traffic is in the left lanes. The St. Croix Weigh Station which monitors westbound I-94 traffic opened for business on June 28, 1987. The Minnesota State Patrol began operating it 24 hours a day, 7 days a week in July. It is located 1 mile west of the Minnesota-Wisconsin border with the data collection scales being 3 miles west of the weigh station. There are no major interchanges between the enforcement site and the data collection scales.

Information from the data collection station for the 7 months prior to the opening of the weigh station and the 12 months after it opened were analyzed. The numbers of trucks and their weights in terms of flexible ESAL factors for 5 axle semi and all other trucks were analyzed. Even though the weigh station monitors only westbound traffic, our analysis used data collected in both directions. The eastbound traffic was used as the benchmark for making comparisons with the westbound traffic.

Figures 1 and 2 show changes to the numbers of 5 axle semi and all other trucks over this 19 month period. The eastbound traffic base line is held constant at 100%. Figure 1 shows that the number of 5 axle semi heading westbound remained relatively steady through April 1987. In May and June the volume was down about 10% and the weigh station was not even yet open. It had visibly been under construction for several months. It appears that just the presence of construction activity coupled with the uncertainty (from the truckers viewpoint) as to when it would open was enough to persuade some truckers to seek an alternate route.

From July to November the numbers hovered at 20 to 25% below the level of eastbound traffic. That amounted to about 300 5 axle semi per day which were avoiding the weigh station. In the last part of the period, traffic recovered to some degree. It was down about 15 %. There are some aberrations in the pattern such as in December 1987. When we look at December 1986 and 1987, we see that they are similar in that they are both higher than the norm. Perhaps the westbound traffic in December is usually 6-7% higher than the eastbound traffic. The volume of 5 axle semi in the past year did not recover to the pre-weigh station levels.

The data contained in Figure 2 for all other trucks also showed a drop in volumes but not as sharp as for 5 axle semi. Figure 2 is similar to Figure 1 in that prior to the opening of the weigh station the volumes were on a par with the eastbound volumes. After the opening of the station, the volumes dropped 10 to 15% instead of the 20 to 25% we saw with the 5 axle semi. This amounted to about 100 trucks per day which were avoiding the weigh station. Figure 2 is also similar to Figure 1 in that there was a recovery in the last phase of this time period. In fact May and June brought us above the levels we were seeing prior to the opening of the station. It is interesting to note that December 1986 and 1987 once again seem to have a unique pattern but it is just the opposite of what we saw in Figure 1. The westbound volumes are lower than the eastbound.

The weights of the trucks before and after the opening of the weigh station were analyzed next. Figures 3 and 4 show a comparison of ESAL's for 5 axle semi and all other trucks respectively. Only part of the same basic pattern appears here that appeared with volumes. It is different in that there is not one steady level prior to the opening of the weigh station. In Figure 3 we start out well below the baseline and then climb quite sharply before the station opened. Figure 4 shows an erratic pattern with trucks other than 5 axle semi. After the opening there is a more steady pattern. The after opening factors are about 25% lower than the pre-opening factors. Figure 4 also shows that the westbound data is all above the eastbound data baseline. This simply means that the westbound weights for this group of trucks are heavier than for those eastbound. It is the relative changes in the westbound line that are important.

This question of what happened to truck weights is not answered quite as conclusively as the question of what happened to truck volumes. It appears that there has been some drop in the weights because of the weigh station, however, we will need a longer series of data to determine if these results are due to seasonal variation or changes market forces and not weight enforcement.

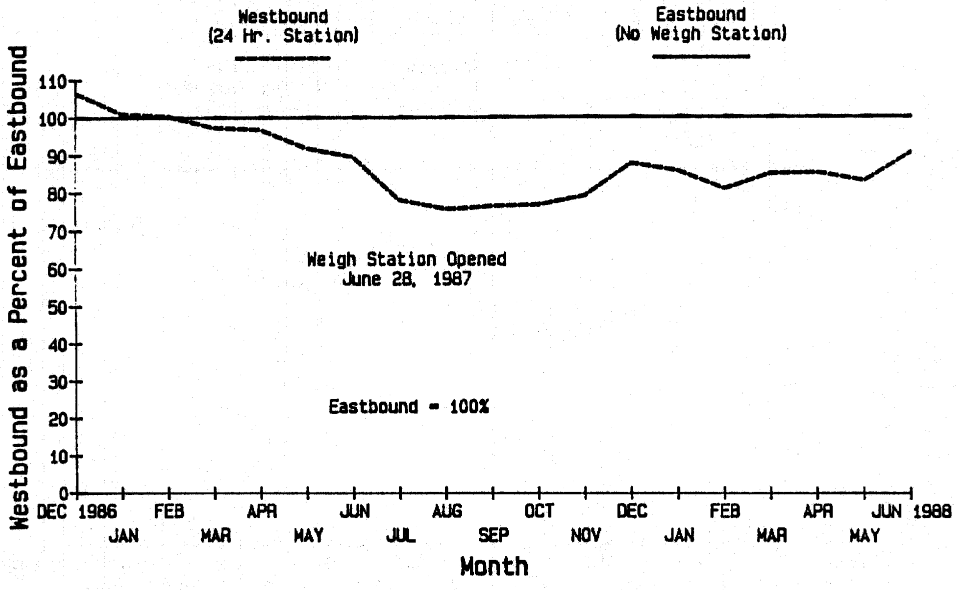
The weigh station is inconvenient for truckers to bypass. The St. Croix River serves as a natural barrier which funnels trucks to the bridge crossings. The Twin Cities of Minneapolis/St. Paul are located 20 miles away. The Twin Cities are very likely either the final destination or a stopping-off point for most of these trucks, especially the 5 axle semi. I-94 is the principal route to reach the Twin Cities from the east.

If truckers approaching Minnesota from the east on I-94 desire to avoid the weigh station, they can go about 15 miles out of their way to the north to Stillwater or 30 miles south to Red Wing. There is a bridge at Prescott 15 miles to the south but it is restricted to 30,000 lbs. gross weight. These alternates are all 2-lane facilities. If the trucks are coming from Milwaukee, Chicago or points east, they may take I-94 to the west junction with I-90 in Wisconsin. They could then take I-90 to TH 52 at Rochester and follow that into the Twin Cities. This would give them 4-lane facilities for the entire trip. The I-90/TH 52 routes would only add about 8 miles to their trip so that is a good alternative if their origins and destinations are convenient to this route. It appears that mainly 5 axle semi are in a position to take this I-90/TH 52 alternate. The single unit trucks generally do not regularly travel such great distances. Perhaps some single unit trucks are using the two lane alternate routes more in the vicinity of the weigh station.

The normal inconveniences caused by delays in weighing trucks can't be attributed to this weigh station. It has a WIM system which screens the vehicles and then directs them: 1) to bypass the weigh station, 2) to proceed to one of the two platform scales, or 3) to proceed to an inspection station. There is little delay in the pre-screening weighing process. This means that they have another reason for avoiding the station, as was alluded to earlier. It is the impression of some members of the State Patrol that it is generally trucks with safety violations on the equipment which are avoiding the scales. They do not feel that it is an overweight issue.

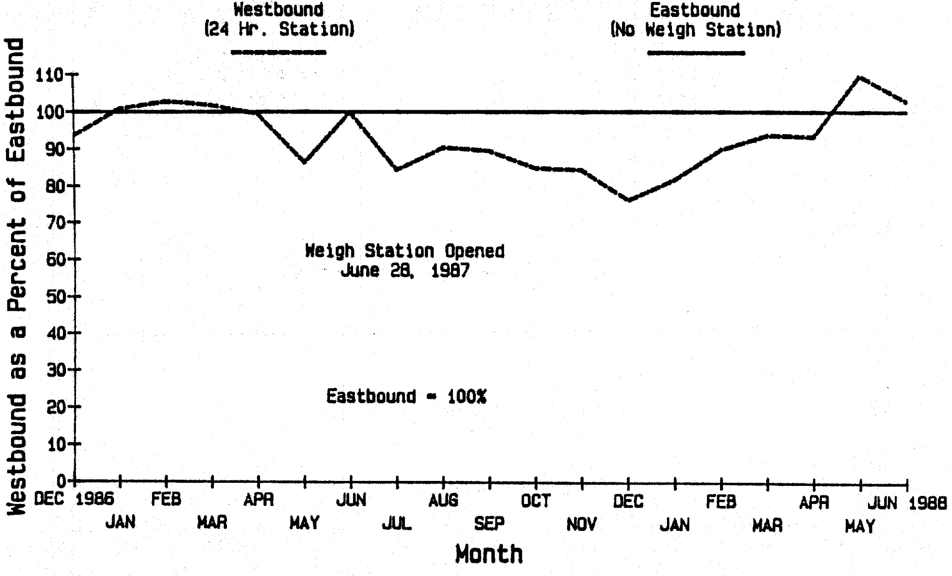
The conclusions we have arrived at here do not necessarily apply in the same manner to all weigh station locations. The specific location of a given weigh station obviously plays an important role in determining the impact on traffic. However, we have demonstrated in this study that the impact on traffic is significant, especially as it relates to 5 axle semi. Much attention should be given to avoidance of the scales and enforcement strategies for alternate routes.

## Figure 1
## Impact of the St. Croix Weigh Station on 5 Axle Semi Volumes on I-94



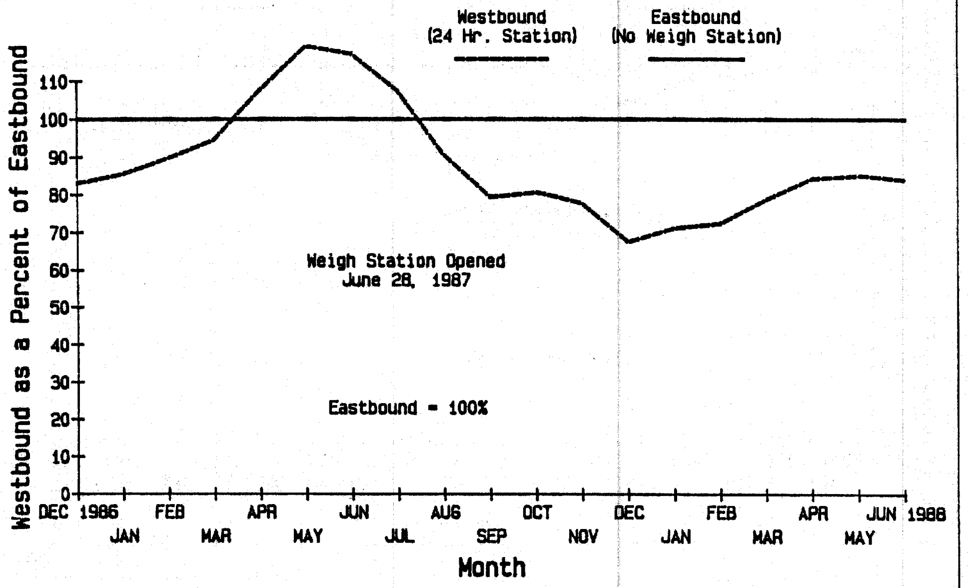
st5axvol

## Figure 2
## Impact of the St. Croix Weigh Station on Volumes of All Trucks But 5 Axle Semis on I-94



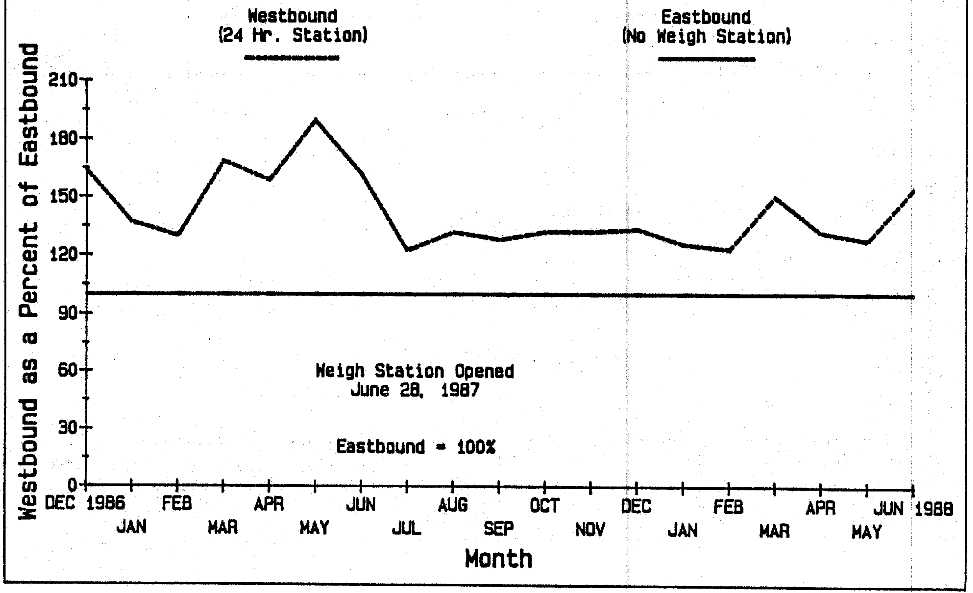
stothvol

Figure 3
Impact of the St. Croix Weigh Station
on 5 Axle Semi ESAL's on I-94



st5axesal

Figure 4
Impact of the St. Croix Weigh Station
on ESAL's of All Trucks but 5 Axle Semis on I-94



stallesal

# BRIDGE WEIGH-IN-MOTION SYSTEM AS AN ENFORCEMENT TOOL

*David A. Bochenek, Bureau of Highway Statistics*
*Maryland State Highway Administration*

This paper is a summary of Maryland's use of the Bridge Weigh-in-Motion (WIM) system as a screening device for enforcement.

The Maryland State Highway Administration's (SHA) Bureau of Highway Statistics (BHS) took possession of the WIM in late 1984. By mid 1985 the Bureau was ready to conduct tests using this system as a screening device to select vehicles that may be in violation of Maryland weight laws. With the cooperation of the Maryland State Police (MSP) Truck Enforcement Division, five screening efforts were conducted between 1985 and 1986. (See Appendix I).

A typical screening effort requires a two man WIM crew, enforcement officer, cadet and communication person. The communication person can be a member of the WIM crew or cadet. When possible, the WIM vehicle is located under the bridge. One member of the WIM crew is stationed in the right-of-way adjacent to the roadway. This crew member is classifying truck body types and has radio contact with the WIM vehicle.

The other WIM member is in the vehicle observing the data screen (CRT) looking for violations. When a violation is observed he contacts the observer and the observer describes the vehicle to the communication person who simultaneously gives the information to the enforcement officer. The truck is then pursued and captured. The vehicle is pulled off the travel-way for static weighing. This is usually done on a nearby road or the shoulder of the roadway being screened.

Since the system does have limitations, i.e., ±5% on gross weight and ±10% on axle weight, predetermined parameters were set. Only trucks exceeding 88 kips (88,000 lbs.) or having tandem weights exceeding 40 kips (40,000 lbs.) were selected for enforcement weighing.

The first site to be selected was I-95 northbound over Campbell Road. It was calibrated using a 3S-2 weighing 74,000 lbs. This site is located three miles northeast of the Baltimore Beltway. It is a six lane divided highway with 20% trucks and an ADT of 78,250. Trucks must stay in the two right lanes. Only the right lane adjacent to the shoulder was monitored. Trucks selected for static weighing were taken to a nearby route MD 43.

The screening test began on the I-95 site on June 11, 1985 at 11:45 a.m. and ended at 4:15 p.m. the same day. During this time, an officer and a cadet of the MSP Truck Enforcement Division used portable scales to weigh the potential violators. Five vehicles were selected, of which four were overweight. The fifth had a permit for 110,000 lbs. Fines for the vehicles totaled $3,000.00.

The MSP returned the next day at 5:30 a.m. and enforcement operations were resumed. Again, four vehicles were selected for overweight violations with the result that three vehicles were ticketed for a total of $1,673.00 in fines. At 8:35 a.m. it began to rain so the test was stopped.

During the I-95 screening test conducted on June 11, 1985, 21 other vehicles that were potential violators passed the WIM site. These were not stopped because the police were busy weighing a flagged vehicle. Each portable weighing takes approximately 20 to 40 minutes.

A comparison of the WIM weights to the MSP police weights on the selected vehicles for this site can be found in Appendix II.

Since our success rate for screening vehicles was 100% at our first site a second test was conducted on US 50 westbound over Cox's Creek in Queen Anne's County. This site is located about 30 miles southeast of Baltimore and was calibrated using a 3 axle dump weighing 50,000 lbs. Vehicles must pass by this site in order to obtain access to the Bay Bridge. At this site, US 50 is a four lane divided highway with 12% trucks and an ADT of 21,500. For this test both lanes were monitored using the same parameters established at the I-95 site. The weighing of selected vehicles was conducted on the shoulder of US 50 two miles west of the WIM site. The MSP Truck Enforcement officers arrived at 7:00 a.m. and stayed until 1:30 p.m. During this time seven vehicles were flagged as potential overweights. Three vehicles received citations with fines totaling $490.00. Our success rate for screening at this site dropped to 42%.

In 1986, to further evaluate the use of WIM as an effective enforcement tool, three additional sites were monitored in a coordinated effort with the MSP Truck Enforcement Division.

The three sites monitored were suggested by the MSP as likely locations for overweight truck traffic:

1. I-81 at MD 68 and MD 63 in Washington County,
   ADT - 22,000 24% trucks

2. MD 26 at MD 97 in Carroll County,
   ADT - 6,400 6% trucks

3. I-270 at Old Baltimore Road in Montgomery County,
   ADT - 46,400 15% trucks

On August 13, 1986, screening operations were conducted at the I-81 site. The calibration factor used at this site was from our June data collection effort. A three axle dump weighing 50,000 lbs. was used to determine the factor. This site was anticipated to be an ideal location for enforcement activities because of the high truck volumes, previous data collected and the geometrics of the location. Enforcement weighing was conducted on the outside shoulder of I-81. Immediately upon the arrival of the MSP, the C.B. channel was alive with warnings of some type of enforcement activity in the area. After five hours of screening, approximately 600 trucks had passed over the span. Of these, 13 were observed as possibly being in violation; however, the MSP were only able to stop and weigh six of those identified by the WIM crew. Data from this survey can be found in Appendix II. None of the trucks weighed by the MSP on portable scales were found to be in violation. These trucks were either exempt by Maryland law or legal. At this site we experienced problems with communication or the officers were involved with weighing a vehicle when another candidate was sighted. Our rate of success was zero at this site. A comparison of WIM weights to enforcement weights for this site can be found in Appendix II.

The second screening study was conducted at MD 26 on September 4, 1986. This site was suggested by the MSP as an alternative route used by truck drivers to bypass the new I-70 permanent weigh stations. Our preliminary observation supported the MSP suspicions. A classification count revealed a high number of loaded dump trucks on this route. MD 26 is a two lane roadway, both lanes were monitored. The calibration factor for this site was determined by weighing vehicles using the roadway. Enforcement weighing was conducted on the shoulders of MD 26 near the WIM site.

Once again, shortly after the MSP presence was noticed, the C.B. radio was broadcasting the message that "portable chicken coops" were on MD 26 at MD 97. At this site approximately 300 trucks were sampled over a five hour period. Seven trucks were identified by the WIM system as being possibly overweight. Two of those identified by the WIM system were issued citations amounting to a total of $420.00. Our rate of success for this location was 28%. A comparison of WIM weights to enforcement weights can be found in Appendix II.

The noticeable decrease in loaded dump trucks on this particular day was assumed to be due to the broadcasting of enforcement activities on the C.B. radio.

To fortify this assumption, this particular site was revisited on October 2, 1986 and more data collected without enforcement activity. This survey was conducted on a Thursday, which was the same day of the week that the September 4, 1986 enforcement study had been done. Discretion was a very important aspect of this survey, since the Bureau of Highway Statistics (BHS) did not want to draw attention to its weighing operations. All sensors were put in place the day before.

After comparing the data from both studies, the following conclusions were made:

- The total number of 3 axle single unit vehicles over 50,000 lbs. went from 28 with enforcement to 35 without enforcement.

- The size of the truck sample with and without enforcement was comparable, 294/303.

- Without enforcement 20 - 3 axle single unit vehicles were over 65,000 lbs. as compared to three of this type with enforcement. (See Appendix III).

This data indicates that the vehicles did not try to bypass our location but rather adjusted their loads so that they would be legal.

On September 9, 1986, a WIM enforcement operation, coordinated with the MSP, was conducted on I-270 at Old Baltimore Road in Montgomery County. This site was calibrated using a three axle dump truck weighing 50,000 lbs. As soon as the tape switches were installed and the lane opened to traffic, C.B. communications became very active. Truck drivers' interest ranged from curiosity to stating that tire pressure could be obtained from their vehicles by the sensors. This was the first time any area took notice of the tape switches. It wasn't long before a dump truck operator broke into the communications and stated that he knew what the sensors were used for and would tell them when they were further down the road. The WIM crew recognized that he was one of the drivers who used his dump as a calibration vehicle in Western Maryland, so we had no doubt that the truckers would know what was going on at this site.

The site was monitored from approximately 10:00 a.m. to 7:00 p.m., and a total of 739 trucks were screened in this time. From this sample, 14 potential overweight vehicles were stopped and weighed by the MSP of which six were in violation. Our rate of success for this location was 43%. The total amount of fines levied was $705.00. During the operation, 10 possible violators were missed because police weigh crews were busy weighing other trucks. While the MSP and part of the WIM crew were at lunch (12:15 p.m. - 1:15 p.m.), 33 possible overweights were monitored. During this period the C.B. was broadcasting that the police had stopped weighing.

Also during our enforcement evaluation we conducted WIM surveys at I-70 over the Transcontinental Pipeline. This site is located four miles east of the West Friendship scale-house. Data was collected in both lanes before and after the scale-house was open. A graph was constructed from both sets of data comparing the ESAL values. There was a definite decrease in ESAL values once the scale-house opened. (See Appendix V).

The following conclusions are drawn from these studies:

1. It does not take long for the truckers to identify and start avoiding a weighing operation.

2. The data associated with enforcement activities is very similar to a typical loadometer study. (See Appendix IV).

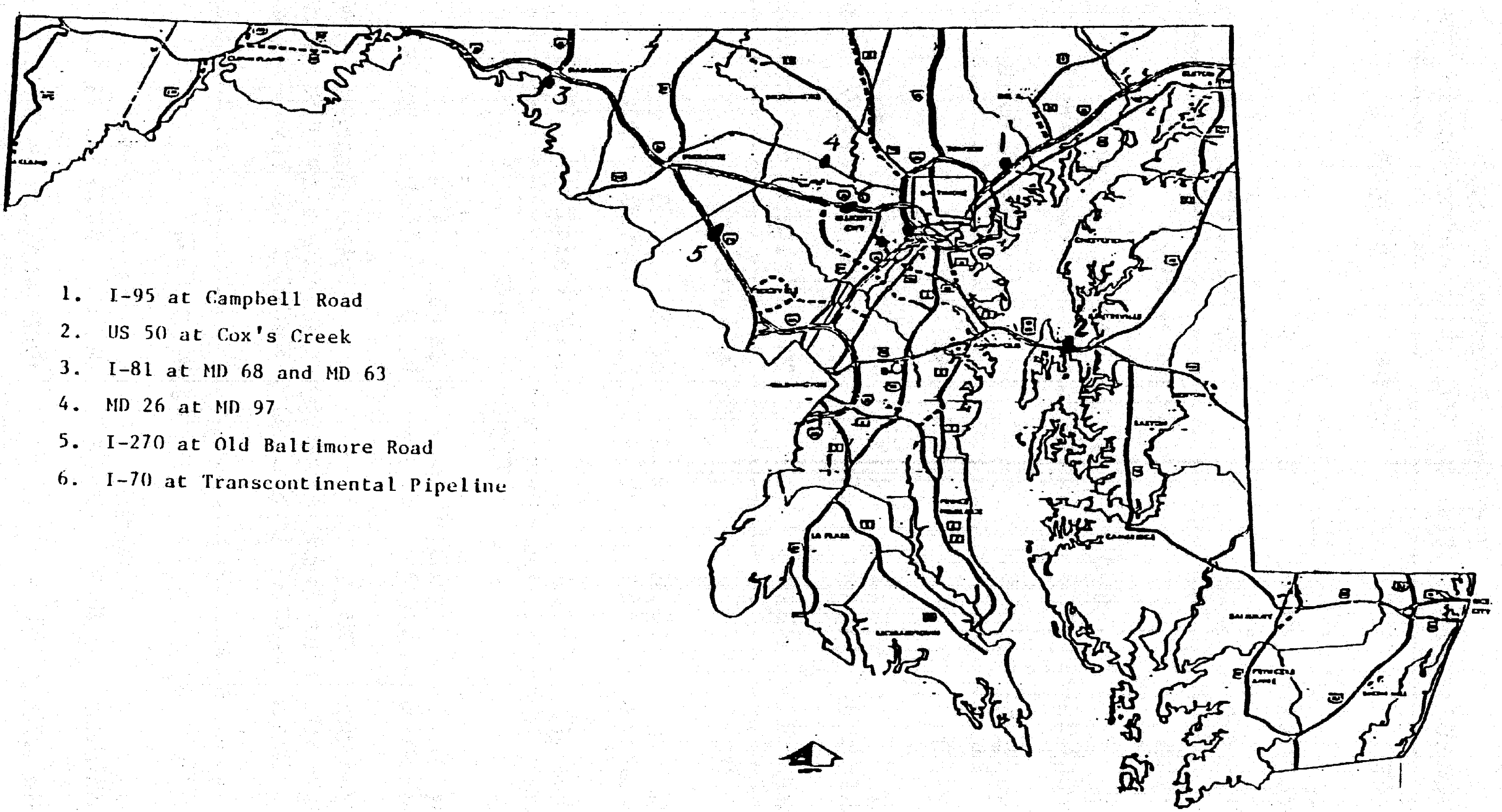
3. It is virtually impossible for one system and definitely cost prohibitive for the system to be used at different locations during the course of a day.

4. WIM enforcement screening is more effective on high volume roads. The higher number of trucks increases the possibilities of capturing at least a few violators before the operation is identified. However, the cost of this type of operation, which includes maintenance of traffic, WIM equipment, WIM personnel, and one to two police crews plus a communications officer and vehicle exceeds the probable return from the fines levied. It seems that a more portable or (low cost) system would be more appropriate for use by the MSP.

5. Overall success rate was 40%.

# APPENDIX I

## LOCATIONS OF ENFORCEMENT SCREENING SITES



1. I-95 at Campbell Road
2. US 50 at Cox's Creek
3. I-81 at MD 68 and MD 63
4. MD 26 at MD 97
5. I-270 at Old Baltimore Road
6. I-70 at Transcontinental Pipeline

## APPENDIX II

## FIELD DATA OF VEHICLES SCREENED FOR ENFORCEMENT

### I-95 at Campbell Road

Vehicles selected by WIM for Enforcement Weighing

Truck ID 297 Type - 3 Single

Spacing 13.4 4.6
Axle Weights 19.4 27.7 27.7

Total Weight 74.8 MSP Weight 71.6

Truck ID 133 Type - 3S-3

Spacing 15.0 4.1 21.4 4.94.0
Axle Weights 11.3 15.0 15.0 14.4 14.4 14.4

Total Weight 84.6 MSP Weight 86.4

Truck ID 120 Type: 3S-4

Spacing 10.2 4.1 33.3 4.5 4.5 4.5
Axle Weights 10.9 16.3 16.3 4.3 14.7 14.7 14.7

Total Weight 92.0 MSP Weight - Permit to 110

Truck ID 138 Type - 3S-2

Spacing 10.6 4.3 28.5 4.0
Axle Weights 10.3 12.9 12.9 20.9 20.9

Total Weight 77.9 MSP Weight 79.2

Truck ID 1 Type - 3S-2

Spacing 12.5 4.4 18.2 4.2
Axle Weights 10.4 13.7 13.7 20.8 20.8

Total Weight 79.1 MSP Weight - 91.2

Another 3S2 was just leaving the span as the above vehicle arrived. This caused the gross weight of the above vehicle to be light.

Truck ID 239 Type - 3S2

Spacing 9.6 4.4 34.6 4.1
Axle Weights 6.9 18.8 18.8 13.7 13.7

Total Weight 71.7 MSP Weight - 75.2
Drive Tandem 37.6

## I-95 at Campbell Road - Continued

Truck ID 65 Type - 3S-2

Spacing 11.9 4.2 26.7 4.2
Axle Weights 11.0 19.7 19.7 22.7 22.7

Total Weight 95.9 MSP Weight - 95.9

Truck ID 158 Type - 3 Single

Spacing 13.5 4.3
Axle Weights 17.3 24.1 24.1

Total Weight 65.6 MSP Weight - 66.0

Truck ID 234 Type - 3S-2

Spacing 9.9 4.2 30.2 4.1
Axle Weights 10.3 16.5 16.5 17.1 17.1

Total Weight 77.5 MSP Weight - 75.9
Rear Tandem - 35.8

## I-81 at MD 68 and MD 63

Vehicles Selected by WIM for Enforcement Weighing

Truck ID 13 Type - 3S-2

Spacing 10.2 4.4 32.7 4.0
Axle Weights 8.4 19.1 19.1 17.8 17.8

Total Weight 82.2 MSP Weight - 75.5
Drive Tandem - 32.3
Rear Tandem - 33.0

Truck ID 27 Type - 3S-2

Spacing 11.5 4.3 35.0 4.1
Axle Weights 12.2 18.2 18.2 17.6 17.6

Total Weight 83.9 MSP Weight - 77.4
Drive Tandem - 32.3
Rear Tandem - 34.4

## I-81 at MD 68 and MD 63 - Continued

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Truck ID 37 Type - 3S-2

| | | | | | |
|---|---|---|---|---|---|
| Spacing | 13.0 | 4.4 | 30.1 | 4.1 | |
| Axle Weights | 9.6 | 22.0 | 22.0 | 13.8 | 13.8 |

Total Weight 81.3
MSP Weight - 78.2
Drive Tandem - 33.2
Rear Tandem - 31.6

---

Truck ID 260 Type - 3S-2

| | | | | | |
|---|---|---|---|---|---|
| Spacing | 12.5 | 4.4 | 27.4 | 4.2 | |
| Axle Weights | 9.0 | 18.3 | 18.3 | 16.9 | 16.9 |

Total Weight 79.2
MSP Weight - 74.5
Drive Tandem - 31.5
Rear Tandem - 32.9

---

Truck ID 261 Type - 3S-2

| | | | | | |
|---|---|---|---|---|---|
| Spacing | 12.5 | 4.4 | 27.4 | 4.2 | |
| Axle Weights | 10.6 | 17.9 | 17.9 | 16.7 | 16.7 |

Total Weight 79.9
MSP Weight - 73.7
Drive Tandem - 30.9
Rear Tandem - 32.4

---

Truck ID 445 Type - 3S-2

| | | | | | |
|---|---|---|---|---|---|
| Spacing | 18.7 | 4.4 | 31.6 | 4.1 | |
| Axle Weights | 11.1 | 17.9 | 17.9 | 17.4 | 17.4 |

Total Weight 81.7
MSP Weight - 79.9
Drive Tandem - 34.0
Rear Tandem - 33.9

---

## MD 26 at MD 97
Vehicles Selected by WIM for Enforcement Weighing

---

Truck ID 99 Type - 2 Single

| | | |
|---|---|---|
| Spacing | 11.4 | |
| Axle Weights | 10.2 | 28.2 |

Total Weight 38.5
MSP Weight - 39.1
Rear Axle - 28.0

---

**MD 26 at MD 97 - Continued**

```
----------------------------------------------------------------
Truck ID 112                  Type - 3 Single

  Spacing           13.3    4.5
  Axle Weights        15.2    24.3     24.7

  Total Weight     69.2       MSP Weight - 64.4
----------------------------------------------------------------
Truck ID 142                 Type - 3 Single

  Spacing            13.3    4.5
  Axle Weights       14.9    26.0     26.0

  Total Weight     67.5       MSP Weight - 65.7
----------------------------------------------------------------
Truck ID 307                 Type - 3 Single

  Spacing           15.6     4.2
  Axle Weights       18.0    25.3     25.3

  Total Weight     68.7       MSP Weight - 65.5
----------------------------------------------------------------
Truck ID 32               Type - 3S-2

  Spacing         10.1    4.2    27.8   4.0
  Axle Weights   10.3    14.0   14.0   17.6     17.6

  Total Weight   73.2            MSP Weight - 74.8
                             Drive Tandem - 32.8
                             Rear Tandem  - 31.7
----------------------------------------------------------------
Truck ID 56               Type - 2A

  Spacing         23.1
  Axle Weights   12.9  25.6

  Total Weight   37.7            MSP Weight - 37.9
                             Real Axle - 24.5
----------------------------------------------------------------
Truck ID 97               Type - 3S-2

  Spacing        13.6     4.2     20.1     4.1
  Axle Weights    9.3   12.2   12.2   18.7   18.7

  Total Weight   71.2            MSP Weight - 75.2
                             Drive Tandem - 30.5
                               Rear Tandem  - 35.8
      Truck was cited for inner bridge violation
----------------------------------------------------------------
```

## I-270 at Old Baltimore Road

### Vehicles selected by WIM for Enforcement Weighing

```
----------------------------------------------------------------
Truck ID 10                Type - 3 Single

  Spacing          14.0    4.6
  Axle Weights    18.2    25.7   25.7

  Total Weight    69.5            MSP Weight - 66.0
----------------------------------------------------------------
Truck ID 14                Type - 3S-2

  Spacing         12.4     4.4    19.2   4.1
  Axle Weights    10.3   12.3   12.3   21.1   21.1

  Total Weight    77.1               MSP Weight - 75.6
                             Drive Tandem -  29.3
                             Rear Tandem  -  37.5
----------------------------------------------------------------
Truck ID 86                Type - 3S-2

  Spacing         14.4     4.2   29.5     5.2
  Axle Weights    10.1   19.6   19.6   16.4   16.4

  Total Weight    82.0            MSP Weight - 73.1
                             Drive Tandem - 35.6
                             Rear Tandem  - 28.0
----------------------------------------------------------------
Truck ID 88                Type - 3S-2

  Spacing         13.7     4.4    29.0   4.1
  Axle Weights    10.2   19.7   19.7   18.5   18.5

  Total Weight    86.1            MSP Weight - 80.0
                             Drive Tandem - 37.1
                             Rear Tandem  - 32.7
----------------------------------------------------------------
Truck ID 131                  Type - 3S-2

  Spacing            12.2     4.3   28.3   4.3
  Axle Weights    8.4    19.1   19.1   19.0   19.0

  Total Weight    84.5            MSP Weight - 77.2
                             Drive Tandem - 34.1
                             Rear Tandem  - 33.3
----------------------------------------------------------------
```

## I-270 at Old Baltimore Road - Continued

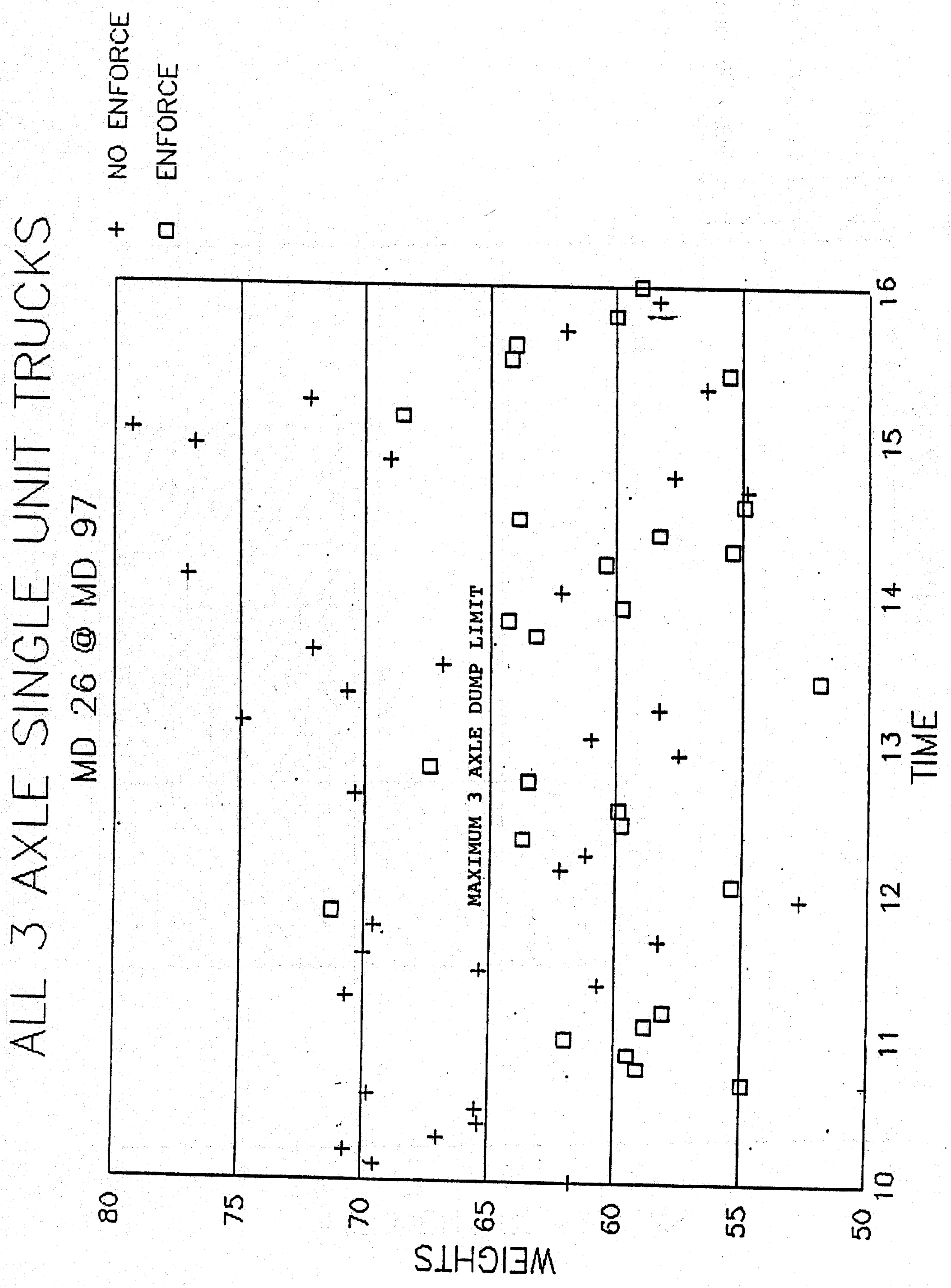
```
-----------------------------------------------------------------
Truck ID 164                    Type - 3S-2

  Spacing          18.2      4.4   29.1    4.1
  Axle Weights    10.0    19.1    19.1    16.9    16.9

  Total Weight    82.1              MSP Weight - 78.6
                               Drive Tandem - 35.7
                               Rear Tandem  - 33.2
-----------------------------------------------------------------
Truck ID 188                    Type - 3 Single

  Spacing              14.4     4.5
  Axle Weights    19.9     28.6    28.6

  Total Weight    77.1              MSP Weight - 64.7

-----------------------------------------------------------------
Truck ID 222                    Type - 3 Single

  Spacing              13.6      4.6
  Axle Weights    19.1     27.2     27.2

  Total Weight    73.5                 MSP Weight - 65.0
-----------------------------------------------------------------
Truck ID 384                    Type - 3S-2 SPL

  Spacing             16.3      4.3     24.2    9.3
  Axle Weights    10.0     19.2    19.2    14.0    24.8

  Total Weight    87.2              MSP Weight - 80.9
                               Drive Tandem - 36.0
                               Axle Four    - 16.2
                               Axle Five    - 18.7
-----------------------------------------------------------------
Truck ID 465                    Type - 3 Single

  Spacing           13.4     4.2
  Axle Weights    19.0      27.1     27.1

  Total Weight    73.2              MSP Weight - 63.7
-----------------------------------------------------------------
Truck ID 485                    Type - 3S-2

  Spacing             12.2     4.3   23.2    4.1
  Axle Weights    8.2     13.7    13.7    24.0    24.0

  Total Weight     83.6             MSP Weight - 77.4
                               Drive Tandem - 31.7
                               Rear Tandem  - 36.8
        Truck was cited for inner bridge violation.
```

**I-270 at Old Baltimore Road - Continued**

```
----------------------------------------------------------------
Truck ID 496                 Type - 3S-2

  Spacing           13.1     4.4  29.8    4.2
  Axle Weights   9.5    22.1   22.1   18.0   18.0

  Total Weight   89.6          MSP Weight - 79.7
                           Drive Tandem - 38.0
                           Rear Tandem  - 31.5
----------------------------------------------------------------
Truck ID 601                 Type - 3S-2 SPL

  Spacing          15.0  4.4    25.4  9.2
  Axle Weights   8.5   18.8   18.8   17.2   22.9
  Total Weight   86.3          MSP Weight - 79.0
                             Drive Tandem - 34.4
                           Axle Four    - 18.6
                           Axle Five    - 17.8
----------------------------------------------------------------
Truck ID 675                 Type - 3S-2

  Spacing          13.9   4.3    27.3     4.0
  Axle Weights   8.5    16.8   16.8   19.4   19.4

  Total Weight   80.8          MSP Weight - 73.6
                           Drive Tandem - 32.3
                           Rear Tandem  - 31.8
----------------------------------------------------------------
```

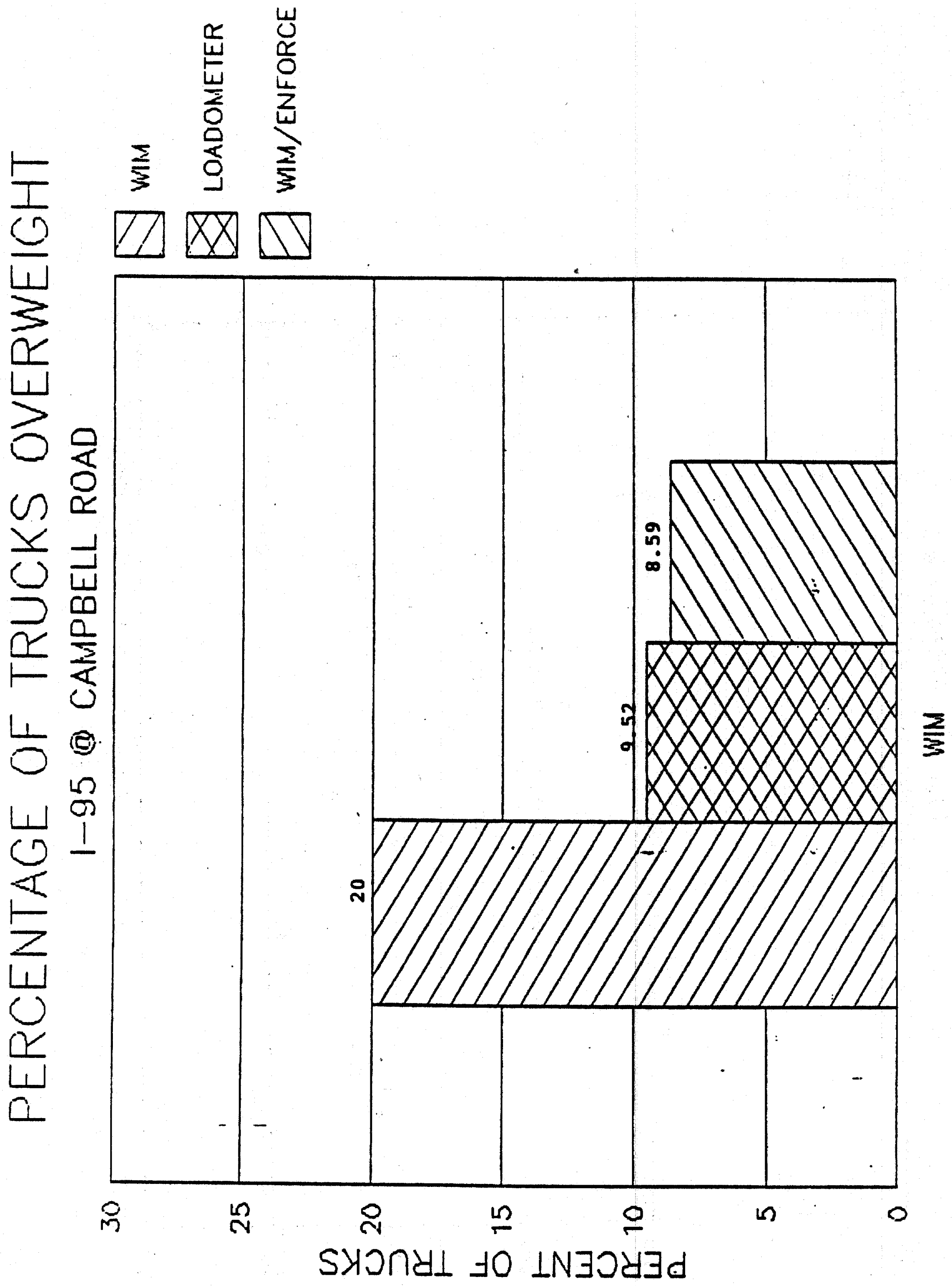
## APPENDIX III

## COMPARISON OF 3 AXLE DUMP WITH AND WITHOUT ENFORCEMENT



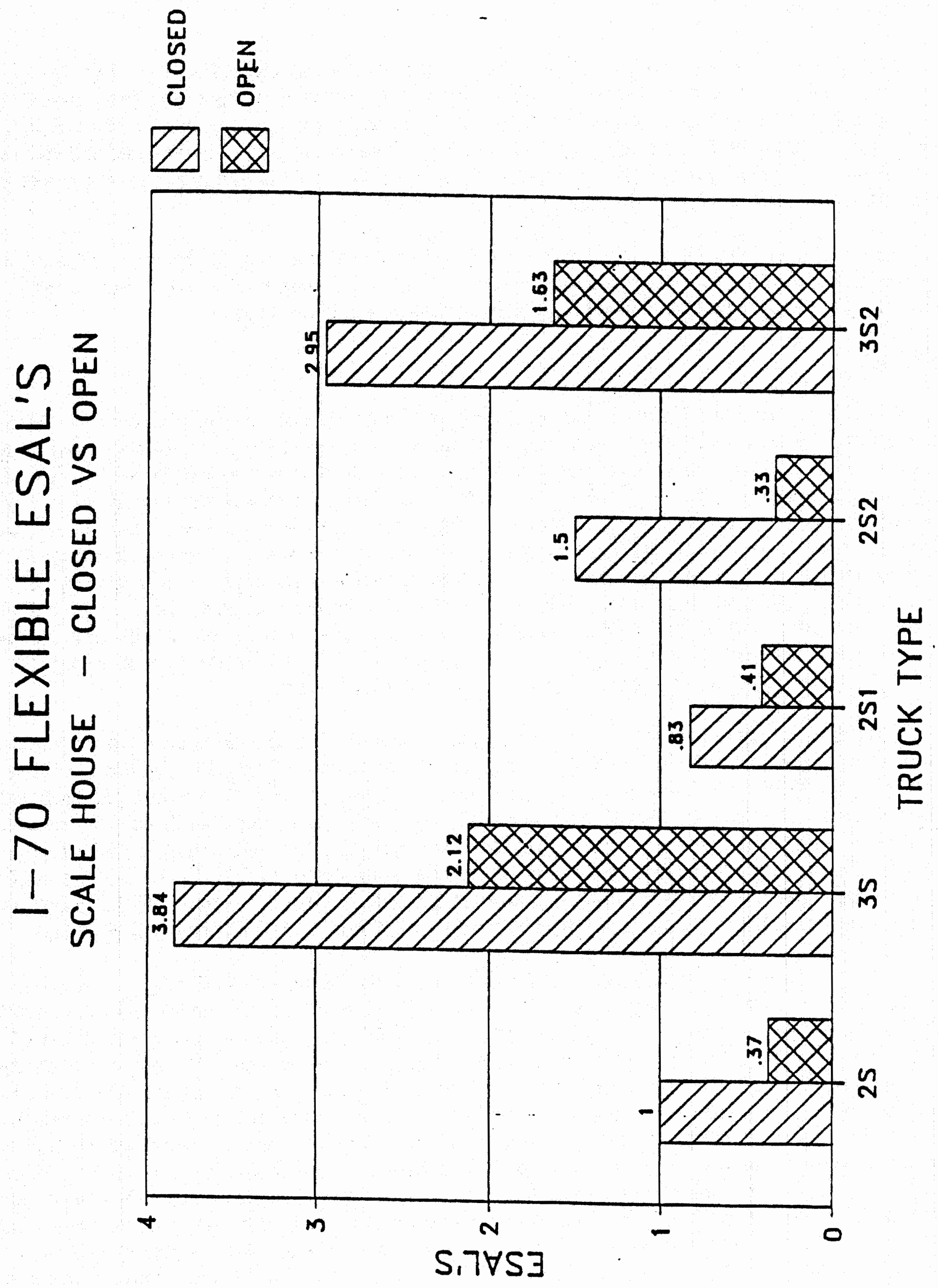
# APPENDIX IV

## I-95 PERCENT OF TRUCKS OVERWEIGHT WITH AND WITHOUT ENFORCEMENT



## APPENDIX V

### I-70 FLEXIBLE ESAL'S, SCALE HOUSE - CLOSED VS. OPEN



# MINNESOTA'S RELEVANT EVIDENCE LAW

*Peter J. Gibson*

## INTRODUCTION

Minnesota's Relevant Evidence Law requires by statute that businesses who weigh goods before or after unloading or a person who loads or unloads goods on the basis of liquid volume measure, shall keep a written record of the origin, weight and composition of each shipment, the date of the loading, the name and address of the shipper, the total number of axles on the vehicle or combination, and the registration of the power unit. This record shall be retained for 30 days and shall be open to inspection and copying by a state law enforcement officer upon demand.

The Relevant Evidence Law enables State Troopers to initiate overweight cases without detecting or witnessing a violation. Investigators bring cases after record searches of grain elevators, gravel pits, oil refineries, etc. reveal that a overweight shipment has been made or received.

## HISTORY

Minnesota's Relevant Evidence Law (Civil Weight Enforcement) was passed during the 1980 legislative session as a result of concerns by law enforcement, industry, and lawmakers that many overweight loads were going undetected. There were indications that many loads of more than 100,000 lbs. were being hauled over Minnesota highways. In the beginning, only a few State Patrol Troopers were assigned as Civil Weight Investigators. Over a period of time, additional investigators were added to make a total of 10 investigators and a full-time coordinator. Originally the County Attorneys were responsible for the handlinh of the cases. This system did not work out for various reasons. The County Attorneys placed low priority on these cases for manpower, political and other reasons. In 1981 the legislature gave the Attorney General the responsibility of handling Civil Weight violations. The Attorney General has a full-time attorney and a legal assistant assigned to the Civil Weight program. In 1982, the State Patrol began to set up a computerized record system to monitor progress on civil weight cases.

As a result of some firms accumulating heavy civil penalties for hauling overweight loads, the Attorney General, in the summer of 1982, declared a moratorium on large civil penalties. A few potential penalties totaling $100,000 or more became a political issue. As a result of the moratorium, demand letters were discontinued for four months. These large penalties were settled at reduced levels and the moratorium was lifted. Ignorance is no longer an excuse and therefore, the fines for civil weight violations are no longer discounted. Since the centralized recordkeeping system was instituted in 1982, more than one million dollars has been collected through civil penalties. More importantly, the Civil Enforcement Program has fostered a better understanding of the weight laws and better compliance with the highway weight laws.

Relevant Evidence - Minnesota Statutes, Section 169.851; 169.871; 169.872. A law passed in 1980 provided that bills of lading, weight tickets, volume documents and other records that reveal (directly or indirectly) a vehicle's weight can be used as evidence in establishing that a weight violation has taken place. 169.851 Subd. 4 states, "A document evidencing the receipts of goods issued by the person consigning the goods for shipment of a person engaged in the business of transporting or forwarding goods, which states a gross weight of the vehicle and load or the weight of the load when combined with the empty weight of the vehicle that is in excess of the prescribed maximum weight limitation permitted by this chapter is relevant evidence that the weight of the vehicle and load is unlawful." A violation is established in this matter in a civil action. In a civil action, the driver, the shipper, the owner and the lessee can each be assessed all or part of the fine depending on the involvement of each in causing the overweight movement. Contrary to criminal truck overweight enforcement, this form of enforcement recognizes that there are times when the driver is not responsible for the truck being overweight. For example, there are cases where the driver or carrier have been told that he must transport an overweight load. In the civil action, the party who required the truck to be overweight is prnalized

If there is a preponderance of evidence (more evidence supporting than refuting a claim) demonstrating that an overweight vehicle movement did occur, then the violation is proven. A bill of lading showing an overweight load is sufficient evidence to establish the violation and must be disproved by the defense. Under civil procedure, the courts attention is directed toward whether there was an overweight vehicle movement rather than whether a criminal act had occurred. Therefore, there is a lesser burden of proof under the civil procedure since there is no criminal prosecution.

Apprehension of the vehicle on the road is not necessary under the civil procedures. The civil weight law augments Minnesota's traditional method of weight enforcement. Law enforcement officers now have the legal right to review weight tickets at elevators, grain exchanges, warehouses. If bills of lading or other documents indicating overweight trucks are found, an investigation report is prepared and a letter of demand is sent by the Department of Public Safety outlining the violation to the owner, lessee, and/or shipper.

## PROCEDURES

I. Investigators initiate cases from four types of records.

  A. Cases discovered by the investigator through record searches.

  B. Cases from criminal weight records in the patrol district where the investigator works.

  C. An overload referred from an outside agency such as a police department or a sheriff's department.

  D. A case referred from another civil investigator.

I-A. Cases discovered by an investigator through record searches.

  1. To be able to initiate a case from a records search, the investigator must contact the person who is the custodian of records. The initial contact with the custodian of the records is necessary to establish a time and place convenient to the custodian for a preliminary record examination by the investigator.

  2. The investigator should try to establish a good rapport with the record holder. The investigator should make every effort to cooperate with the record holder.

  3. The investigator should check to see that the records conform with the statute with the following.:

    a. written record

    b. weight or volume of the load

    c. date of loading or receipt

    d. origin of the load

    e. composition of the load

    f. name and address of the shipper

g. total axles on the vehicle or combination

h. some means to identify the power unit (license etc...)

i. records are being maintained for at least 30 days (not necessarily at the scale site, but at some Minnesota location)

4. After the initial examination and an agreement between the record holder and the investigator as to how the records are to be kept, an inspection date 30 days hence should be established.

5. The investigator should establish if a copy machine is available.

6. The investigator enters the name, address, and phone number of the record custodian on an alphabetized card file with all other pertinent information. Each time an investigator makes a record check he/she notes in there card file, the number of records checked, number of overweights, and number referred to another district.

7. The investigator makes copies of the records of any overweights, he/she initials the record.

8. The civil investigator will take action on any load of 3001 pounds or more overweight discovered by a record search.

I-B Cases from criminal weight records in the patrol district where the investigator works.

1. The civil investigator will be responsible for maintaining a criminal weight file in the district where he/she works.

2. Copies of all weight report forms from mobile and platform scales will be sent to the civil investigator.

3. The civil investigator keeps a file of all report forms.

4. The civil investigator will take action on any load of 8001 pounds or more overweight.

5. The civil investigator will take action on any permit violation, however, action will only be taken for the amount over the permit weight.

I-C An overload referred from an outside agency.

1. These type cases will be handled the same as cases initiated by the State Patrol.

2. One exception are the cases referred to us by the Hennepin County Deputies, from their weighing operations.

a. Three-eighths of the penalty we receive will be paid back to Hennepin County.

II. Case preparation

1. Once the investigator determines that he/she will be investigating the case:

   a. A notice of investigation of overweight (PS01839) must be sent immediately and in no case more than 30 days of discovering the overweight.

   b. The truck owner or lessee and/or the shipper's name and address must be determined, by bill of lading, registration, etc...

2. An ICR number will be obtained from the District radio.

3. The investigator must determine who is responsible for the overweight, the shipper, the trucker, or in fact there was a civil violation.

4. The investigator can interview the following people, (by phone or in person).

   a. Examples of questions asked of the truck driver and/or owner.

      1) Where was the truck loaded?

      2) On a scale?

      3) Did the driver know how much he was hauling or did he know he was overweight?

      4) The empty weight of the vehicle.

      5) What are the axle spacings?

      7) Date of loading?

      8) Who is responsible for the truck, owner, lessee, or driver?

      9) If the truck belongs to a corporation, what is the correct address and who is the responsible person for the company or corporation?

      10) Advise the owner about the civil program and tell him/her what the penalty for this load is.

      11) Check with the owner to see if he is responsible for the driver's actions.

      12) It may be necessary to get permission from the owner to measure the truck and weigh it empty.

      13) If the truck is leased, contact the lessor and get a copy of the lease agreement to tie the lessee to the truck and load.

   b. Questions of the shipper.

      1) Was the load loaded on a scale or was the driver aware of the correct weight at the time of loading?

      2) Is the shipper a company or corporation? Obtain the address of the responsible person.

c. Questions of the load recipient

1) Does he recall the load?

2) Any other circumstances relevent to the case.

3) Any comments made by the trucker.

5. At this time the investigator should be able to determine if he has a sueable case. It is the investigators responsibility to determine who is liable for an overload.

6. Exceptions.

a. "First Haul" means the first, continous transportation from the place of production or on farm storage sites to any other location within 50 (road) miles of the place of production or on farm storage sites.

b. The provisions of this law does not apply to the first haul of raw farm products and the transportation of raw unfinished forest products.

c. "Shippers good faith exception", stipulates that when a shipper loads a vehicle to a weight level which does not exceed the legal maximum weight allowed on a road leading from the place where the vehicle was loaded, this shipper is not liable for a penalty resulting from a subsequent violation on a road where the designated maximum legal weight limit is exceeded by the vehicle. In other words, a shipper cannot be expected to know the routes the operator will use during the course of the commodity movement and therefore, this shipper will not be required to pay any part of a penalty for a violation that the shipper could not have anticipated.

III. The Demand Letter

A. The demand letter is sent by the Civil Weight Coordinator in accordance with the following penalty schedule:

| | |
|---|---|
| 1,000 lbs. or less | 1 cent per lb. in excess of legal limit |
| 1,000 lbs. to 3,000 lbs. | $10.00 plus 5 cents per lb in excess of 1,000 lbs. |
| 3,000 lbs. to 5,000 lbs. | $110.00 plus 10 cents per lb. in excess of 3,000 lbs. |
| 5,000 lbs. to 7,000 lbs. | $310.00 plus 15 cents per lb. in excess of 5,000 lbs. |
| 7,000 lbs. or more | $610.00 plus 20 cents per lb. in excess of 7,000 lbs. |

In addition, the minimum penalty for overweight violations of weight limits established by special permits is $100.00 or 5 cents for each pound over the weight allowed by the permit, whichever is greater.

A civil penalty and criminal fine are not pursued for the same illegal movement, however, a violation of the registration, equipment, or other laws may be pursued criminally as well as a civil penalty for the overweight movement.

B. The demand letter tells the violator that we will accept 80 percent of the total penalty if we receive it within 30 days. We demand 90 percent once the case is sent to the Attorney General and 100 percent if the case goes to court.

IV. Court

A. If the defendant fails to respond to the demand letter, the case will be referred to the Attorney General's Office.

1. Cases that qualify for conciliation court, ($2000 or less) will be filed by the Attorney General in the county of the residence of the violator.

a. Cases in conciliation court will be handled by investigators. Attorneys are not allowed in conciliation court matters.

b. The Attorney General will represent the state in cases of more than $2000.00 that go to District court.

## ADVANTAGES OF THE RELEVANT EVIDENCE PROGRAM

I. Before the use of Relevant Evidence, weight enforcement had two limiting factors.

A. The process of physically checking a truck for weight violations is time consuming and labor intensive. With the Civil Weight Program, a large number of truck movements can be checked with little effort.

1. In 1987, Minnesota platforms and portable scale operations weighed approximately 1,117,000 loads.

a. 11 portable crews, 31 people

b. 56 people employed at platform scale sites.

2. In 1987, Minnesota State Patrol Civil Weight Investigators checked approximately 610,000 bills.

a. 10 Civil Weight Investigators.

B. The practice of avoiding scale locations with the use of CB radios has become common. With the use of the Relevant Evidence Law, we no longer have to weigh every load to obtain a violation.

## DISADVANTAGES

I. When Investigators check bills of lading and other documents, only gross weight is recorded. Only gross weight is dealt with in the record search method of Civil Weight Enforcement.

II. Other traffic regulations are not dealt with, such as overlength, overwidth and safety regulations because trucks are not physically inspected.

## CONCLUSIONS

I. Compliance to Minnesota's weight laws has increased noticeably since the imposition of the Relevant Evidence Law.

II. With the Relevant Evidence Law, patrol officers check nearly double the loads as were previously checked.

III. The money collected from the civil penalties goes into the Highway Users Fund.

IV. The data available supports the contention that the Revelant Evidence Law is an effective addition to Minnesota's weight enforcement program.

## COMPLIANCE

I. Since the computerized record-keeping began in 1983, the following statistics have been recorded:

A.

| Year | No. Viol. | O/W Loads | Amt. Rec'd |
|---|---|---|---|
| 1983 | 2402 | 1779 | 448,738.46 |
| 1984 | 1012 | 852 | 333,748.87 |
| 1985 | 684 | 556 | 181,973.27 |
| 1986 | 2240 | 2118 | 251,819.19 |
| 1987 | 821 | 665 | 239,308.19 |

# TRICKS OF THE TRADE

*George J. Novenski, P.E., Wisconsin Department of Transportation*

You've attended conferences with both broad and in-depth agendas, but there have been times when you left the presentations feeling just a little disappointed. That one topic of particular interest to you was omitted, or perhaps was not covered to the extent you had desired. Or, you've had an experience, good or bad, within the theme of the conference that you wanted to share with other participants, but the opportunity to do so was not available.

That was the purpose of the "Tricks of the Trade" session: to allow any participant to suggest subjects to be presented and discussed. These could include topics to make the entire conference coverage more complete or the reporting of an activity that was tried, but its results not widely publicized. More specifically, its intent was the informal exchange of information and, most importantly, knowledge among professionals with a common interest and responsibility in the further development of the field of highway transportation. Further, it allowed for any or all conference attendees to actively participate by volunteering to join-in the discussion of a selected subject.

Prior to the actual two hour session a few preparations were necessary. It was anticipated that four to eight subjects would be discussed ranging from fifteen to thirty minutes each. However, each would need to be introduced for the discussion to proceed, so twenty registrants were contacted as potential candidates for introducers. The twelve individuals that agreed to twelve different subjects was considered adequate, even though it was unknown what topics would be proposed.

Sign-up sheets were posted in hallways and near break-areas, where people informally congregated prior to and during the session. Appended to this report are the lead sketches for several of the posters.

The actual session consisted of a short formal presentation and seven discussion items. The formal presentation explained a unique method using a falling weight deflectometer (FWD) for initial and confirmation calibration of a weigh pad (that was physically demonstrated at the Rusk, Wisconsin site during a field trip).

The seven discussion items covered a variety of subjects and experiences. Each was commented on by one to a half dozen speakers with several having to be terminated due to time limitations.

The formal conference evaluations completed by attendees confirmed the acceptance and success of this type of free information exchange. It is recommended a "Tricks of the Trade" style session be included in future WIM conferences.

To improve on this initial effort it is suggested that the purpose and concept be explained in more detail during housekeeping announcements and well in advance of the actual session for improved understanding, willingness to offer topics, and ease of subsequent presentation. The moderator should have more flexibility to roam around for a group as large as three hundred people. This means there is a need for more roving mikes. Consideration also should be given to using co-monitors in the same room or a separation into two groups.

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## Sign Up Posters

**TRICKS OF THE TRADE**

**SESSION**

**1:30 PM - 3:30 PM**

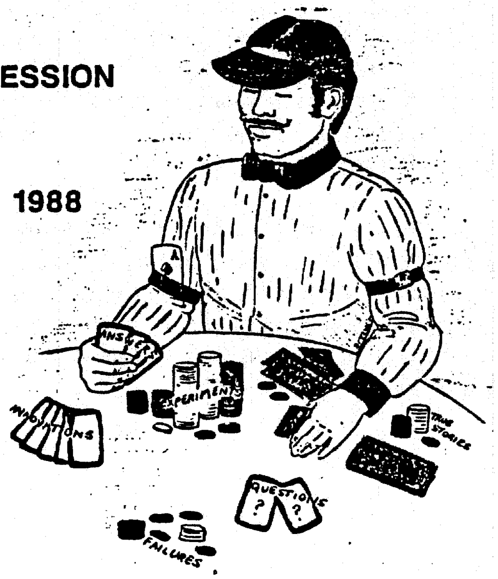
**THURSDAY, OCTOBER 20, 1988**

### SHARE THE WEALTH

**TRICKS OF THE TRADE SESSION**

**THURSDAY, OCTOBER 20, 1988**

**1:30 PM - 3:30 PM**



# SITE SPECIFIC LOAD MODELS FOR BRIDGE RATING

W. David Liu*, C. Allin Cornell**, Roy A. Imbsen*

To be presented at the
Third National Conference on Weigh-In-Motion Applications and Future Directions
St. Paul, Minnesota, Oct. 17-21, 1988

## INTRODUCTION

The goal of structural design and strength evaluation (load capacity rating) is to ensure an adequate safety margin and reflect the actual strength and load environments. Lack of precise knowledge about load and strength, and confidence in load effect calculations, has unavoidably resulted in simplified assumptions which are in general biased toward the conservative side. These conservative simplifications in various aspects of the design process may have contributed to much of the inherent structural safety in past practice.

Recently, strength evaluation of existing bridges has received considerable attention. This is because of the large number of "structurally deficient" bridges in the nation's aging bridge inventory. It is expected that the number of deficient bridges will remain at the same level or more likely grow in the future. This poses a severe financial burden to the government and the public.

To justify the continued use of a "deficient" bridge and to prioritize the limited maintenance/rehabilitation/replacement expenditure more effectively, a comprehensive bridge management system is required. The design, construction process and in-service management of bridge structures are schematically illustrated in Figure 1. The essential components of in-service bridge management are:

- Actual truck load survey;
- Actual structural behavior monitoring; and
- A consistent and flexible evaluation criteria.

With the development of in-motion weighing technology, large-scale unbiased truck loads can now be collected. Recently, truck weighing activities in the United States have been increased signifi-

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** C. Allin Cornell, Inc., Portola Valley, California

cantly both in the amount of data collected and in the broader geographical coverage. However, most of these studies are not intended for bridge structural applications.

In developing a load model applicable nationwide, all possible situations must be considered. For example, it is generally assumed in design code that the variability of loads is reasonably uniform across the country. To account for the most severe load environment and the potential for future load growth, the code is therefore unavoidably conservative.

In evaluating existing bridges, the situation is quite different. It is a well known fact that current truck loads are frequently much heavier than the standard design loads established some 40 years ago. Since existing bridges may have routinely carried such overloads, they may be considered to a certain degree as *service-proven* structures with a satisfactory past performance record. To take advantage of this existing information, two issues must be addressed:

1. The evaluation code must be flexible enough, i.e. *"information-sensitive"*, to allow for the incorporation of site-specific data in the evaluation process.

2. Routine data collection and processing effort should be extended such that relevant data for bridge loading applications can be readily made available to bridge departments.

The first issues has been and is currently being studied (Imbsen et. al., 1987; Moses and Verma, 1987). The second issue has, however, so far been ignored. It will take a coordinated effort among bridge engineers, data collection agencies, and other interested data users to make the most use of the hard data. Perhaps, with this effort, we may establish a better classification for deficient bridges and reduce the number of bridges currently being classified as "structurally deficient" to a manageable level.

This paper will describe briefly the modern reliability-based LRFD (Load and Resistance Factor Design) methodology to account for the uncertainties in load and strength variables. Specifically for site-specific load models, we want to identify the sources of the total uncertainty in extreme load effects and data needs to reduce them. A large database of truck loads has been assembled from FHWA, Wisconsin, Florida and Illinois WIM studies including over 220,000 trucks. Results of statistical analysis of these load data and the implication to load model development will be discussed. Several different ways to increase the information of local, site-specific loading are suggested.

We are hoping that through these discussions with other data users and data collection agencies, unbiased WIM truck load data can be directed toward bridge loading applications.

## Reliability-Based Load Capacity Evaluation of Existing Bridges

The objective of any bridge evaluation procedure is to maintain a satisfactory safety level. This is ensured by requiring that the characteristic strength (a conservative low estimate) be greater than the maximum load effect (a high estimate). This is shown schematically in Figure 2. In the Load and Resistance Factor Design (LRFD) format, the required conservatism, as specified by the target safety index (or probability of failure), is distributed among resistance and various load effect variables in accordance with the associated variabilities and uncertainties. The checking equation may be written as:

$$\phi R \geq \gamma_D D + \gamma_L L \qquad (1)$$

where

R = nominal resistance
D = nominal dead load effect
L = nominal live load effect
$\phi$ = resistance factor (< 1)
$\gamma_D, \gamma_L$ = dead and live load factors, respectively (> 1).

Partial safety factors, $\phi$, $\gamma_D$, and $\gamma_L$,, are selected to reflect the associated uncertainties and to achieve the specified target safety index, $\beta$, (typically in the range of 2.5-3 for existing bridges). Variabilities are represented by the coefficient of variation (COV). In its simplest form, the live load factor may be defined as:

$$\gamma_L = \delta_L \exp(\alpha \beta V_L) \qquad (2)$$

where $\delta_L$ is the mean-to-nominal ratio; $\alpha$ is a constant (ranging from 0.6 to 0.8) depending on the dead-to-live load ratio; and $V_L$ is the total variability in the live load effect. It is clear that the greater the total variability in loads the greater the live load factor, and consequently the greater the structural strength is required.

## Uncertainty Analysis

It is generally recognized that among these variables involved in bridge rating, the uncertainty associated with the live load is the greatest and deserves closer scrutiny. For site-specific applications, it is crucial that we distinguish two types of variability in loads:

1. Randomness, $V_{LR}$ - An inherent property of the load.

2. Uncertainty, $V_{LU}$ - This is due to our currently incomplete knowledge about the load.

The two variabilities may be conveniently represented by their COVs, $V_{LR}$ and $V_{LU}$, respectively. The total variability, $V_L$, may be written as:

$$V_L = \sqrt{V_{LR}^2 + V_{LU}^2} \tag{3}$$

For example, the maximum truck weight at a specific site is *random*; whereas the mean weight or the 95th percentile value of the weight distribution is *uncertain*. Furthermore, at the specific site, the mean weight can be determined with certainty if an infinite amount of data at the site is available; however, we still cannot determine the mean weight at any other site or statewide with certainty. Therefore, the uncertainty variability may be further decomposed into two components:

1. Site-to-Site Variability; and
2. Statistical Uncertainty--depending on the sample size.

The inherent randomness is irreducible. However, the site-to-site/statistical uncertainties may be reduced based on a better understanding of the local load environment. By focusing on a specific site or a specific class of sites of similar characteritics, the site-to-site variability may be minimized. By collecting a sufficient sample size of data the statistical uncertainty may be reduced or, for all practical purpose, eliminated.

With the WIM technology, unbiased truck load data collected in recent years has been increased significantly. In addition, with the recent embarment of SHRP program, it can be anticipated that truck load data collection nationwide will grow at an even faster pace in the near future. We are certainly in a position to make the most use of the data for broader applications at a minimum cost.

For bridge rating applications, these large-scale data collection efforts may help to reduce the site-to-site and statistical uncertainties, and therefore the total variability in bridge loading as indicated by Eq. (3). As suggested by Eq. (2), this reduction in $V_L$ may reduce the unnecessary conservatism in the form of a smaller load factor value, $\gamma_L$. As a result of this effort and the effort in developing a more flexible rating criteria, some of the "deficient" bridges may perhaps be reclassified as adequate.

## Modeling Bridge Live Load Effects and Data Needs

To establish a load model for design or rating, the probability distribution of extreme load effect over a specified period of time is required (say, two to five years for bridge rating). From this distribution, the characteristic load value and uncertainty may be extracted to establish the design loading and the corresponding load factor. The following variables need to be considered to calculate the distribution of maximum live load effect:

1. Vehicle-dependent variables such as gross vehicle weight (GVW), axle weight distribution, axle spacings, and dynamic characteristics.

2. Traffic-dependent variables such as traffic mixture (percentage of various vehicle types), truck traffic volume, truck traffic pattern (free-flowing, congested), and truck headway.

3. Effectiveness of weight enforcement and permit truck weight level.

4. Bridge-dependent variables including bridge type, span length, continuity, and shape of influence surface (longitudinal and transverse).

Most of these variables must be treated as random variables. By carefully examining the random traffic stream, one can identify all significant *loading events* possible for a bridge and assess their contributions to the probability distribution of extreme load effect. The bridge load effect calculation is shown schematically in Figure 3. Figure 4 shows several multiple truck loading events and the associated probability distribution of maximum load effect. The probability distribution of extreme load effect may be calculated by the modern First Order Reliability Method (FORM).

The relative frequency of truck loading events involving different number of trucks on the bridge depends on:

- bridge span length,
- truck traffic volume and composition of different truck types,
- headway distance between consecutive trucks in the same lane or in adjacent lanes.

For short span bridges with one or two trucks on the bridge, the extra heavy trucks in the upper tail of the GVW histogram are extremely important.

For multiple lane bridges under multiple truck loading, the distribution (histogram) of the headway distance is crucial to establish the multiple truck presence effect and the multiple lane reduction factor. This piece of loading information is very rarely collected. Ideally, we would like to have the joint probability distribution of GVW, lane position, and headway distance. Currently, there are only five Ohio sites where high-precision, *short* headway data has been collected. More data in this aspect can be very helpful in establishing the design or rating load model.

Frequently, truck weight data are reported in the form of GVW histogram. A typical bimodal GVW histogram is shown in Figure 5 with two modes centered on 30 and 70 kips, respectively. The corresponding cumulative probability distribution is shown in Figure 6 on a lognormal probability paper. For ultimate strength considerations, the most important portion in the weight distribution is the upper tail (say, the upper 5%) because it contributes most to the risk of extreme load effects. It is, therefore, crucial that this upper portion be represented well. An "Upper-Tail Equivalent" (UTE) distribution may be constructed by simply fitting the upper tail to a prescribed type of distribution, e.g. a log-normal distribution. This UTE distribution is also shown in Figures 5 and 6.

The UTE distribution may be characterized by a characteristic weight level and the coefficient of variation. For practical reasons, we use two fractile weights $W_{95}$ and $W_{99}$, i.e. 95% and 99% level, to establish the UTE coefficient of variation $V_W$ which gives the local "slope" at the upper tail, i.e., an indicator of extreme tail values such as $W_{99.9}$. $W_{95}$ has been used by Moses and Ghosn (1985) for characterizing truck weight at different sites. However, it is clearly the tail above the 95% level that governs the 50-year maximum load effect.

To allow for more pragmatic treatment of partial information available, a simple random-variable-based live load model has been proposed by Moses and Ghosn (1985). The multiple presence random variable, H, is defined as:

$$H = \frac{\text{Median of the Extreme Load Effect over T years}}{aW_{95}} \qquad (4)$$

where a is a deterministic constant converting load to load effect, and ($aW_{95}$) is the load effect of a standard truck with weight $W_{95}$. For application to different situations, H needs to be calculated as a function of weight distribution shape, headway distributions, traffic volumes, etc. The load model may be written as:

$$L = a\ m\ W_{95}\ H\ g\ (1+I) \qquad (5)$$

where m is a random variable reflecting the uncertainty in axle configuration, g and I are (random) girder distribution and (random) impact effect, respectively.

Based on the uncertainty analysis discussed earlier, we want to introduce an explicit *"information-sensitive"* form of this same load model by recognizing the two distinct kinds of variability, i.e., randomness ($V_R$) and uncertainty ($V_U$). By identifying the source of variability, two coefficients of variation are assigned to each of the random variables appeared in the load model, Eq. (5). With new (relevant) site-specific information available, the corresponding COV may be updated. At the same time when COV is updated, the new information may also bring about changes in estimates of the site-specific parameter value (such as $W_{95}$) away from the national or statewide population average.

Based on the FHWA truck weight survey (Snyder et al, 1985) and simulation studies (Moses and Ghosn, 1985), the total COV in each of these random variables are obtained as shown in Table 1. Based on our interpretation, these COVs are further identified as *randomness* COV and *uncertainty* COV.

The advantage of this load model and the *information-sensitive* format becomes apparent in that we can update the load model with partial information that is available. For example, truck weight surveys routinely carried out by federal and state agencies can be very useful in quantifying the level of $W_{95}$ and associated uncertainty. State agencies may compile the statewide data and update a state-specific loading code. In the next section, data collected from several sources will be discussed.

## Analysis of Bridge Live Loads

A large database of truck loads is assembled (IAI, 1987) including over 220,000 trucks from the following sources:

1. FHWA - 33 sites over 7 states with a total of 26,613 trucks weighed.
2. Wisconsin - 23 sites with a total of 72,848 trucks weighed.
3. Florida - 18 sites with a total of 71,010 trucks weighed.
4. Illinois - a four-lane site with a total of 49,969 trucks weighed.

All trucks were weighed by Weigh-in-Motion techniques. For tractor-trailer trucks, the site-to-site averages and COVs of $W_{95}$ in each state are shown in Table 2. While a site-to-site COV of 10% is adequate for most states, it is apparently too low for Wisconsin which has a $V_{W95}$ of 24%. Tables 3 and 4 shows the statistics of GVW upper tails by highway systems in Florida and Wisconsin, respectively. By this simple-binning and excluding several abnormal sites, the site-to-site $V_{W95}$ may be reduced to below 10%.

Past surveys indicated that typically the GVW has a bimodal distribution; one mode corresponds to unloaded trucks and the other corresponds to fully loaded trucks. The GVW distributions at six Florida Interstate sites (two urban and four rural sites) are shown in Figure 7 on the log-normal probability paper. At these sites, GVW is well behaved at upper tail. In Wisconsin, the GVW distributions are quite different: a large number of overloads (permit or illegal) are mixed with regular heavy trucks. Two types of abnormal GVW distribution may be identified (Liu et al, 1988):

1. Extra-Heavy sites - The GVW distribution is basically bimodal; however, there are 10% to 40% of trucks weighed exceeding 100 kips (Figure 8).
2. Third-Mode sites - The GVW distribution has an apparent third (overload) mode. These overload trucks, centered around 120 to 150 kips, constitute about 0.5% to 2% of the truck traffic at the site (Figure 9).

This irregularity in GVW upper tails adds an extra dimension to the data application in that it provides an opportunity to study the impact of these overloads on the rating load model. As indicated by the five sites shown in Figure 9, the averge $W_{95}$ is only 81.4 kips; however, this fractile weight gives no indication whatsoever about the extreme truck loads. The average $W_{99}$ and $W_{99.9}$ of these five sites are 102.7 and 156.2 kips, respectively. It is worth mentioning that Wisconsin truck weighing sites were selected based on statistical considerations to ensure sufficient coverage in highway types and variations of weight (Wisconsin DOT, 1982).

## Levels of Site-Specific Bridge Load Information

With the information-sensitive load model and code format in place, we want to suggest several different ways that one might increase the information about a specific site and the implied reduction in uncertainty, $V_U$. For clarity, we shall focus on the GVW parameter (e.g., $W_{95}$ or $W_{99}$) and the associated uncertainty, $V_W$.

### *Information Level A: No Local Information*

This is the starting point. All we know about the loading is based on the load database which has been used in establishing the initial (or *a priori*) code. Therefore, any bridge site can only be considered to be one selected "at random" from that load database. For this database, the upper tail weight level is represented by the population average $\overline{W}_{95}$ and the site-to-site COV, $V_{W_{95}}$.

The FHWA study (Table 2) which covers 36 sites over 7 states may be considered as the initial database. However, after examining the Wisconsin and Florida WIM data and particularly the large site-to-site variability in the Wisconsin data, one might prefer to establish at least state-specific and maybe even within-state, highway-system-specific load values as the starting point.

*Information Level B: Site Descriptors Information*

It is relatively inexpensive to obtain limited, but readily available information about a specific site that may have some "explanatory" power in estimating the site parameter value, e.g., here $W_{95}$. This information may include characteristics of the highway system (e.g., county secondary), the location (e.g., rural), the number of lanes (e.g., two opposite directions), the average daily truck traffic (e.g., ADTT = 500), etc. Let us denote these "variables," $X_1, X_2, \ldots X_n$, where $X_i$ might be a continuous variable such as ADTT, surrounding population density, distance to nearest town, etc., or a discrete variable such as number of lanes ($X_i = 1,2,\ldots$) or system type ($X_i = 1$, if the system is county secondary, 0, if it is not).

The objective here is to construct an empirical descriptive model that is effective in reducing the uncertainty in $W_{95}$ (from the Level A or population level of uncertainty). For convenience we will typically build a *linear* model in Y (or $W_{95}$) as a function of the $X_i$:

$$Y = \sum_{i=1}^{n} a_i X_i + \varepsilon$$

in which the $a_i$ are empirical coefficients to be estimated and $\varepsilon$ is a site-to-site "random" variable with zero mean whose "residual variance," $\sigma_\varepsilon^2$, describes the remaining uncertainty in $W_{95}$ after the effects of these site descriptors have been accounted for. The coefficients of the model are estimated by "regression analysis," that is by using a set of representative sites where the values of the descriptors, $X_i$, and the dependent variables, Y, are known, and conducting a common least-square fitting procedure to estimate the values of the coefficients, $a_i$, and the residual variance, $\sigma_\varepsilon^2$. (The latter is usually assumed to be a constant, independent of the values of $X_i$ or Y.)

Note that $\sigma_\varepsilon$ will be used to obtain a new estimate of $V_{W_{95}}$, which will be less than (or at worst equal to) the original (Level A) value. The reduction is usually measured by the so-called "multiple correlation coefficient," r:

$$\sigma_\varepsilon^2 = (1 - r^2)\,\sigma_{W_{95}}^2 \; ; \; |r| \leq 1$$

Clearly if r = 1, the uncertainty will have been reduced to zero, whereas an r of 0.5 will imply a 75% reduction in the variance and a

13% reduction in the uncertainty in W95. While one should not be overly optimistic about the likelihood that such models can show large r values and hence major reductions in $V_{W95}$, it must be remembered that this information can be obtained at negligible cost. The models may prove to be good for preliminary screening, especially to identify those situations (e.g., county secondary roads) in which the predicted W95 is less than the population average.

For this regression model to be effective, we would like to have data sets (i.e., sets of sites) where large samples of WIM data are available, where many different, possibly informative site descriptors are available, and where representative sampling across these descriptors within the state had been completed (e.g. at least 5 to 10 sites with each "level" of a given descriptor; say 10 interstate sites, 10 primary sites, 10 secondary rural sites, etc.). The data we have assembled is less than perfect in this respect. Perhaps the model and applications that we are proposing will encourage and guide more such thought about site selection and descriptor collection in the future.

### *Information Level C: Truck Type Frequency Information*

In this scheme, we adopted a dissegregated approach to estimate site-specific truck weight parameters (e.g. W95) by truck-type frequency. The assumption is that the observed site-to-site variability of upper tail truck weight is contributed by the relative frequencies of various truck types. These truck types may be represented by the axle configurations, hauling types, body types, etc.

Based on WIM data collected at many sites, the truck weight distribution by truck type may be established, e.g. the population average of the exceedance probability of truck type q is $\bar{G}_q(\omega) = \text{Pr.}\,[W \geq \omega]_q$. Then, for a specific site where no weight data is collected but with truck-type frequencies, $\hat{f}_q$, available, the site-specific weight distribution $\hat{G}_W(\omega)$ may be estimated as:

$$\hat{G}_W(\omega) = \sum_q \hat{f}_q \; \bar{G}_q(\omega)$$

in which the hats, "^", indicate site-specific estimates. From this, the site-specific weight level (e.g. W95) may be estimated as $\hat{W}_{95} = \hat{G}_W^{-1}(1\text{-}0.95) = \hat{G}_W^{-1}(0.05)$.

Similarly, by assuming a distribution tail form, we can also estimate the site-specific COV, i.e. $V_{W_{95}}$.

We experimented this scheme using Florida and Wisconsin data sets. The benefits gained are not great. This is because the only reliable truck type classification available is by the axle configuration. In almost all cases, the weight distribution is dominated by the 3S-2 truck types. Even in those Wisconsin sites where extra-heavy upper tails are observed, they are mostly of the usual 3S-2 configuration. The results suggest that we should focus directly on weight rather than frequencies, i.e. on Information Level B or D.

It might work better if we can identify the truck type as the body type or hauling type which may reflect the weight level. However, such information is either unavailable or unreliable in the database.

*Information Level D: Direct Site-Specific Truck Weight Measurement*

In this case, we assume that a sample of truck weight data is collected at the site. We may then carry out a formal Bayesian updating process (Benjamin and Cornell, 1970, Chapter 6) utilizing the statewide population average as *a prior*, using the sample information to construct a likelihood function, and obtaining a *posterior* distribution on the upper tail weight (e.g. $W_{95}$). If the at-site sample size is sufficiently large, the prior information may be ignored. This is the case where site-to-site variability is completely eliminated and we need to focus on the statistical uncertainty associated with the limited sample size. The statistical uncertainty, based on Bernoulli trial assumption, is proportional to $\frac{1}{\sqrt{n\,p}}$, where n is the sample size and p is the exceedance probability of the weight level (e.g. for $W_{95}$, $p = .05$).

This is clearly the most direct way to establish site-specific loads but at a much higher cost than Information Levels B and C.

## Conclusions and Recommendations

Various aspects of the existing bridge rating have been briefly described. In particular, the "information-sensitive" format of the rating code allows the pragmatic treatment of available data as they become available. Large-scale unbiased truck loads have been collected and more data collection are being planned under various SHRP programs. These data, though not specifically intended for bridges, can be used to establish more realistic site loading and, therefore, more effective bridge management decisions.

Figure 10 shows the flowchart of bridge rating procedure and how site-specific data may be incorporated into the overall rating process. In view of the load data collected from Wisconsin, regional highway agencies may now want to assess the adequacy of specification loads. By coordinating efforts of traffic, planning divisions and bridge raters, the effectiveness of weight enforcement and the impact of overload permit policy on bridge rating may be assessed. If necessary, *state-specific* loading criteria may be established to reflect the industrial/economical activites and overload permit policy in the state. This is at policy level (step 2a, Figure 10). Also at this level, some regression model (Information Level B) may be conducted to identify those site characteristics that will help reduce the load variability. For specific bridges with low load capacity, local load data may be collected (Information Level D) to quantify the site-specific load level and the associated uncertainty (step 2B, Figure 10) and thereby establish the necessity and priority for retrofit.

Currently, unbiased truck loads are routinely collected on a large scale. This is due to the advancements in various Weigh-in-Motion technologies. For extreme loading events involving multiple trucks on multiple lanes, we need more precise descriptions of the interarrival time (or headway) and the lane occupancy. This information has not been collected. What we need is the necessary data to establish the *joint distribution of headway (longitudinal), transverse lane position, and GVW*. This would allow an analysis of the dependence of load and lane position, and may lead to a more rigorous definition of the "lane reduction factor" for multi-lane bridges.

## Acknowledgement

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## TABLE 1: Randomness/Uncertainty Variabililties of Load Model Variables

| | $W_{95}$ | H | m | g | i=1+I | Product |
|---|---|---|---|---|---|---|
| Randomness COV | 2% | | 7% | 8% | 8% | 14% |
| Uncertainty COV | 10% | 7% | -- | -- | -- | 12% |
| Total COV | 12% | | 7% | 8% | 8% | 18% |

## TABLE 2: Site-to-Site Average and COV of $W_{95}$

| | # of Sites | $W_{95}$ (kips) | $V_{W_{95}}$ (%) |
|---|---|---|---|
| Arkansas | 6 | 71.90 | 3.1 |
| California | 7 | 78.23 | 7.8 |
| Georgia | 3 | 69.24 | 9.8 |
| Illinois | 5 | 79.88 | 13.3 |
| New York | 5 | 78.08 | 8.6 |
| Ohio | 2 | 82.60 | 6.8 |
| Texas | 9 | 84.86 | 7.2 |
| Total | 36 | 78.49 | 9.9 |
| Florida | 16 | 82.68 | 8.3 |
| Wisconsin | 45 | 86.25 | 24.35 |

# TABLE 3: Site-to-Site Average and Variability of GVW Upper Tails-Florida

| | | | UTE Parameters† | | Characteristic GVW | | |
|---|---|---|---|---|---|---|---|
| Highway System | | n†† | $W_m$ | $V_w$ | $W_{95}$ | $W_{99}$ | $W_{99.9}$ |
| Urban & Rural Interstate | (1) | 6 | 70.86 (3.8%)* | 0.102 (11.6%) | 83.94 (4.3%) | 89.81 (4.3%) | 97.71 (5.8%) |
| Urban Principal Arterial | (2) | 4 | 57.42 (26.0%) | 0.190 (61.2%) | 75.40 (11.1%) | 85.14 (4.3%) | 97.14 (5.0%) |
| | (3) | 3 | 65.40 (10.0%) | 0.126 (31.4%) | 80.02 (3.6%) | 87.11 (1.6%) | 96.19 (5.5%) |
| Rural Principal Arterial | (4) | 6 | 70.33 (7.2%) | 0.126 (24.9%) | 86.27 (4.5%) | 93.96 (4.9%) | 105.01 (3.6%) |

† Parameters of the "Upper Tail Equivalent" log-normal distribution (based on $W_{95}$ and $W_{99}$)

†† n is the number of site included.

* Number in ( ) indicates the site-to-site variability (COV) of W or $V_W$.

NOTE: In Row (3), Site 012 is excluded.

## TABLE 4: Site-to-Site Average and Variability of GVW Upper Tails-Wisconsin

| | | | UTE Parameters† | | Characteristic GVW | | |
|---|---|---|---|---|---|---|---|
| Highway System | | n†† | $W_m$ | $V_W$ | $W_{95}$ | $W_{99}$ | $W_{99.9}$** |
| Urban Interstate | (1) | 6 | 69.48 (12.8%)* | 0.220 (30.9%) | 99.77 (16.2%) | 116.33 (19.6%) | 148.21 (20.4%) |
| | (2) | 4 | 65.30 (4.6%) | 0.189 (14.8%) | 88.99 (7.4%) | 101.23 (8.9%) | 137.00 (22.8%) |
| Rural Interstate | (3) | 11 | 59.90 (26.2%) | 0.216 (95.0%) | 80.29 (6.3%) | 92.84 (12.6%) | 123.38 (24.0%) |
| | (4) | 8 | 68.51 (7.2%) | 0.104 (26.5%) | 81.18 (6.4%) | 87.15 (6.9%) | 109.63 (20.5%) |
| Urban State Trunk Principal Arterial | (5) | 7 | 58.90 (10.1%) | 0.147 (31.7%) | 74.74 (6.3%) | 82.52 (6.7%) | 113.42 (27.8%) |
| Rural State Trunk Principal Arterial | (6) | 11 | 71.28 (21.6%) | 0.114 (30.5%) | 85.54 (18.4%) | 92.34 (17.5%) | 116.16 (22.1%) |
| | (7) | 9 | 64.29 (7.1%) | 0.122 (27.6%) | 78.40 (5.7%) | 85.19 (6.6%) | 109.70 (21.8%) |

† Parameters of the "Upper Tail Equivalent" log-normal distribution (based on $W_{95}$ and $W_{99}$)

†† n is the number of site included.

** $W_{99.9}$ estimated based on interpolation or extrapolation of probability plots.

* Number in ( ) indicates the site-to-site variability (COV) of W or $V_W$.

NOTE: In Row (2), Sites 002-01-01 and 002-02-02 are excluded.
In Row (4), Sites 672-01-01, 672-02-02 and 559-02-01 are excluded.
In Row (7), Sites 254-01-01 and 254-02-01 are excluded.

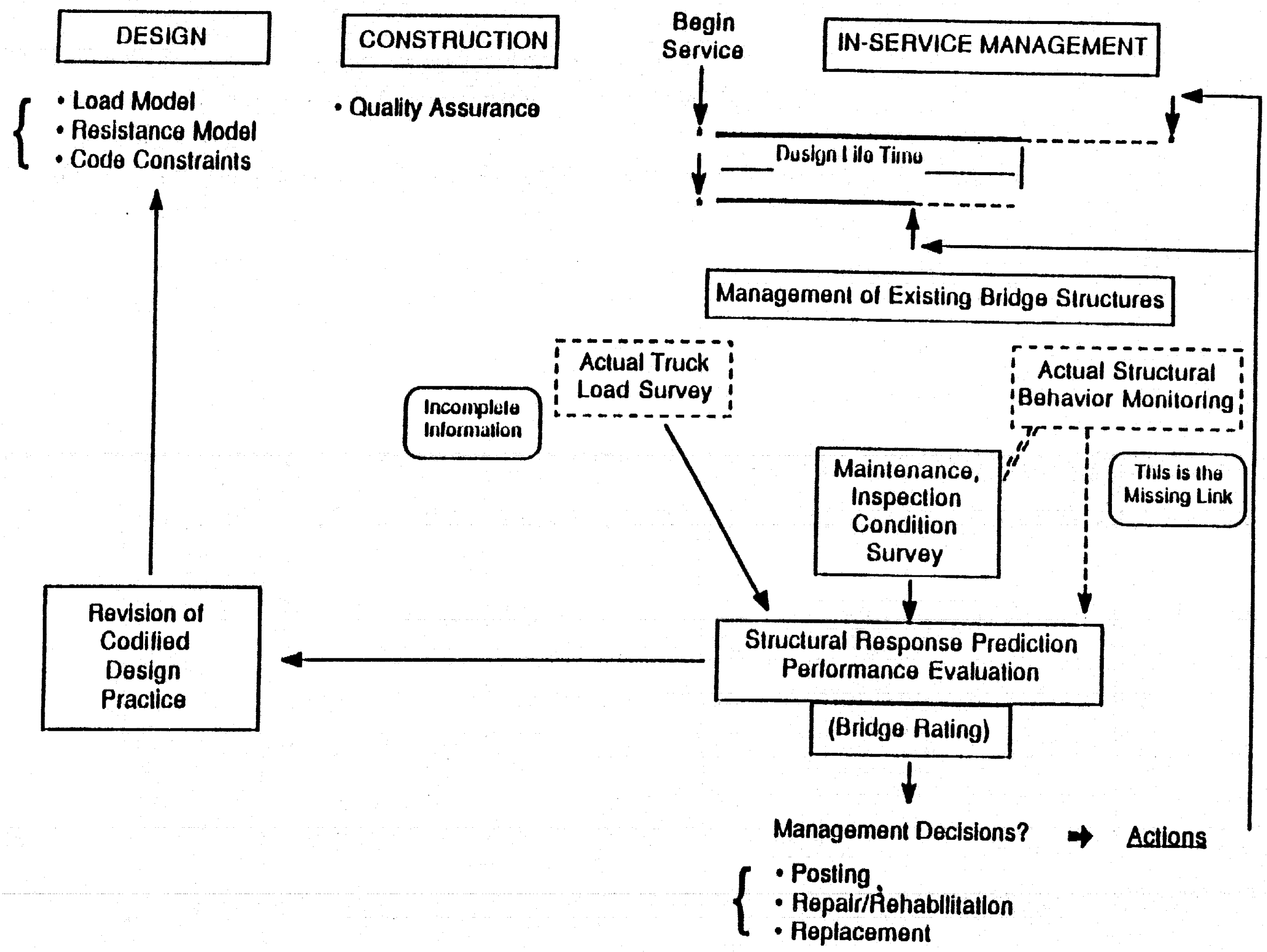


FIGURE 1: OVERALL BRIDGE MANAGEMENT SYSTEM

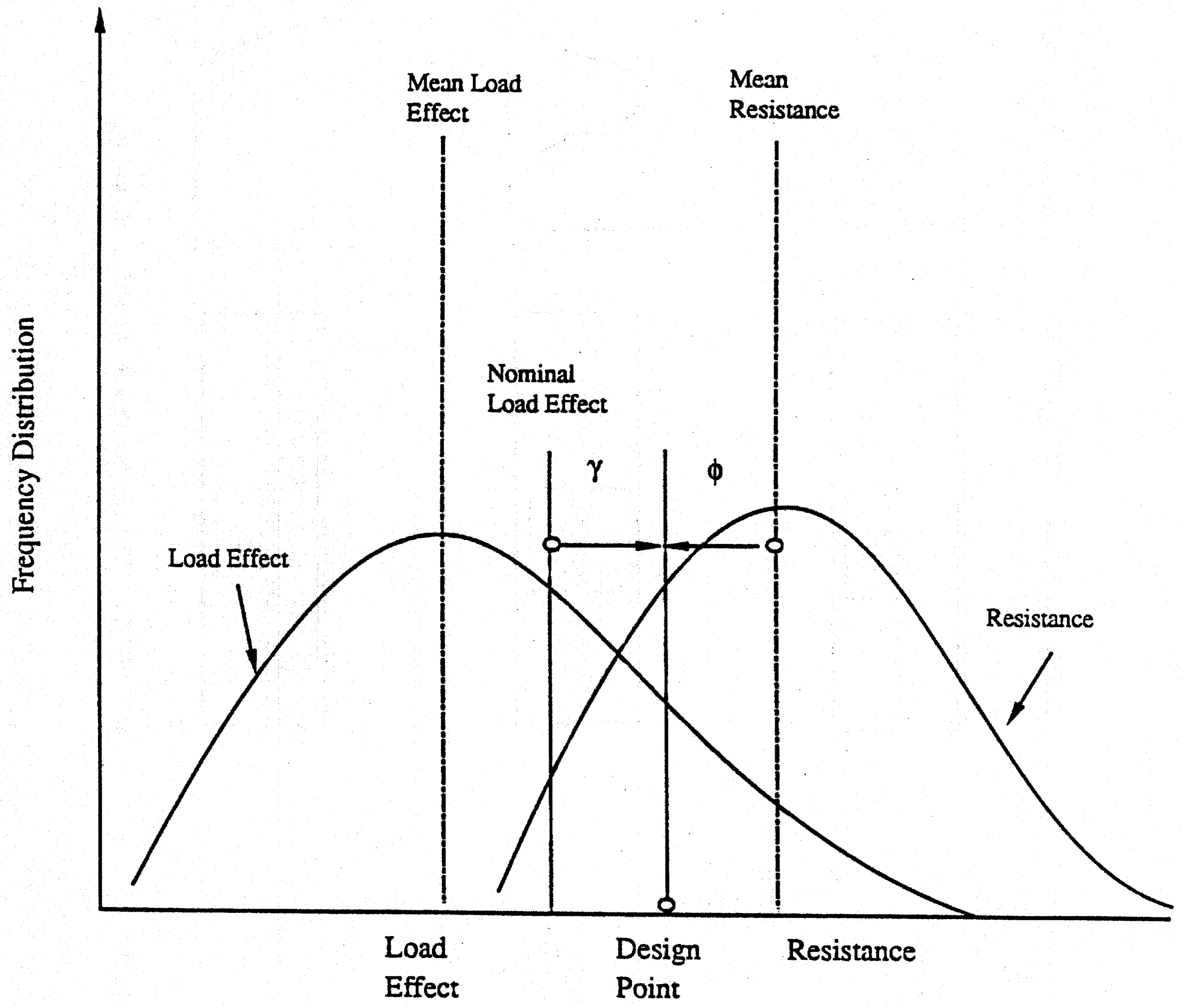
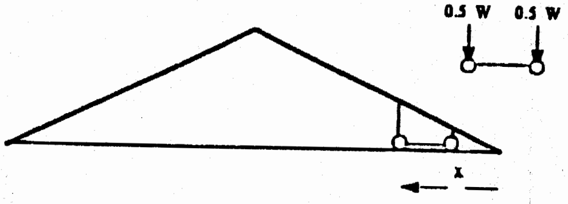
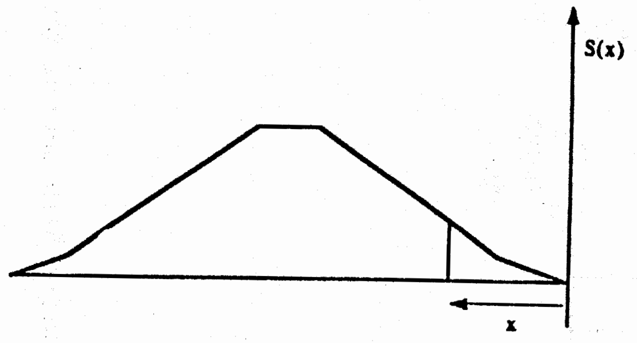


FIGURE 2 : Load and Resistance Factor Design



(a) Bridge Influence Line



(b) Load Effect Pulse

FIGURE 3: Individual Truck Crossing the Bridge

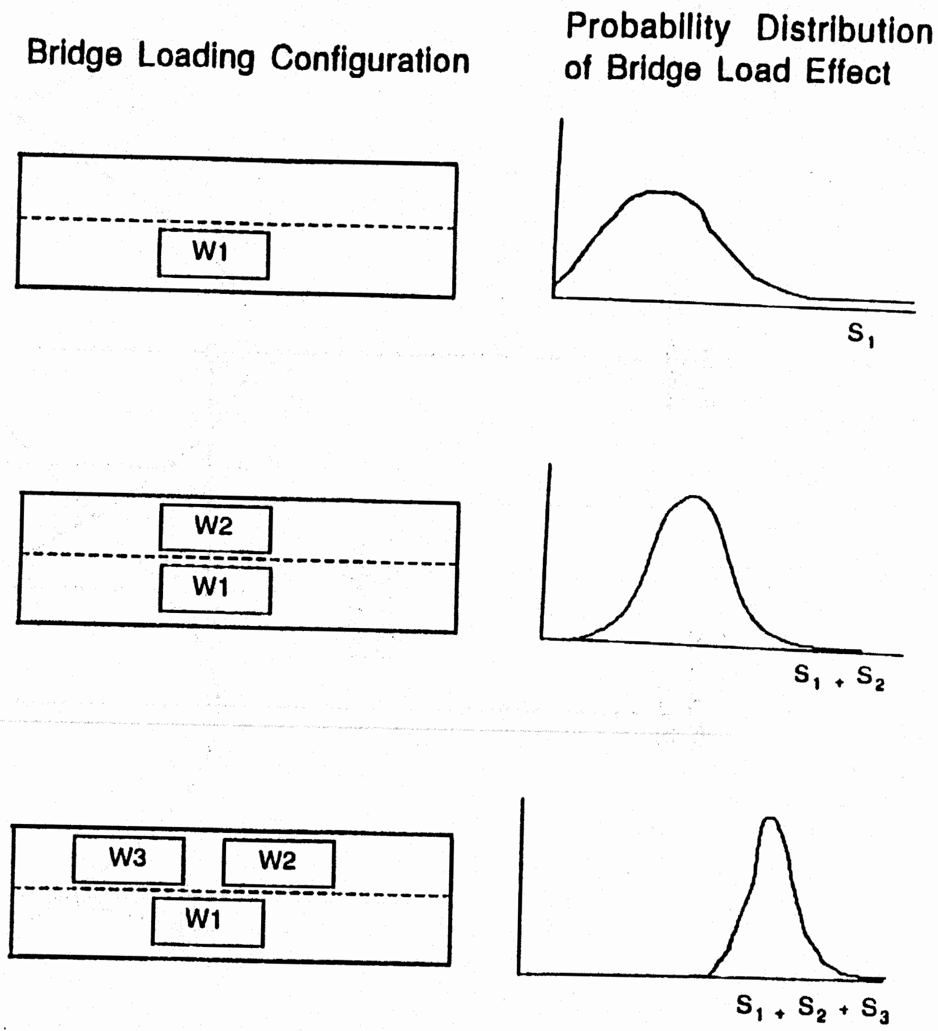


FIGURE 4: Multiple Truck Loading Events

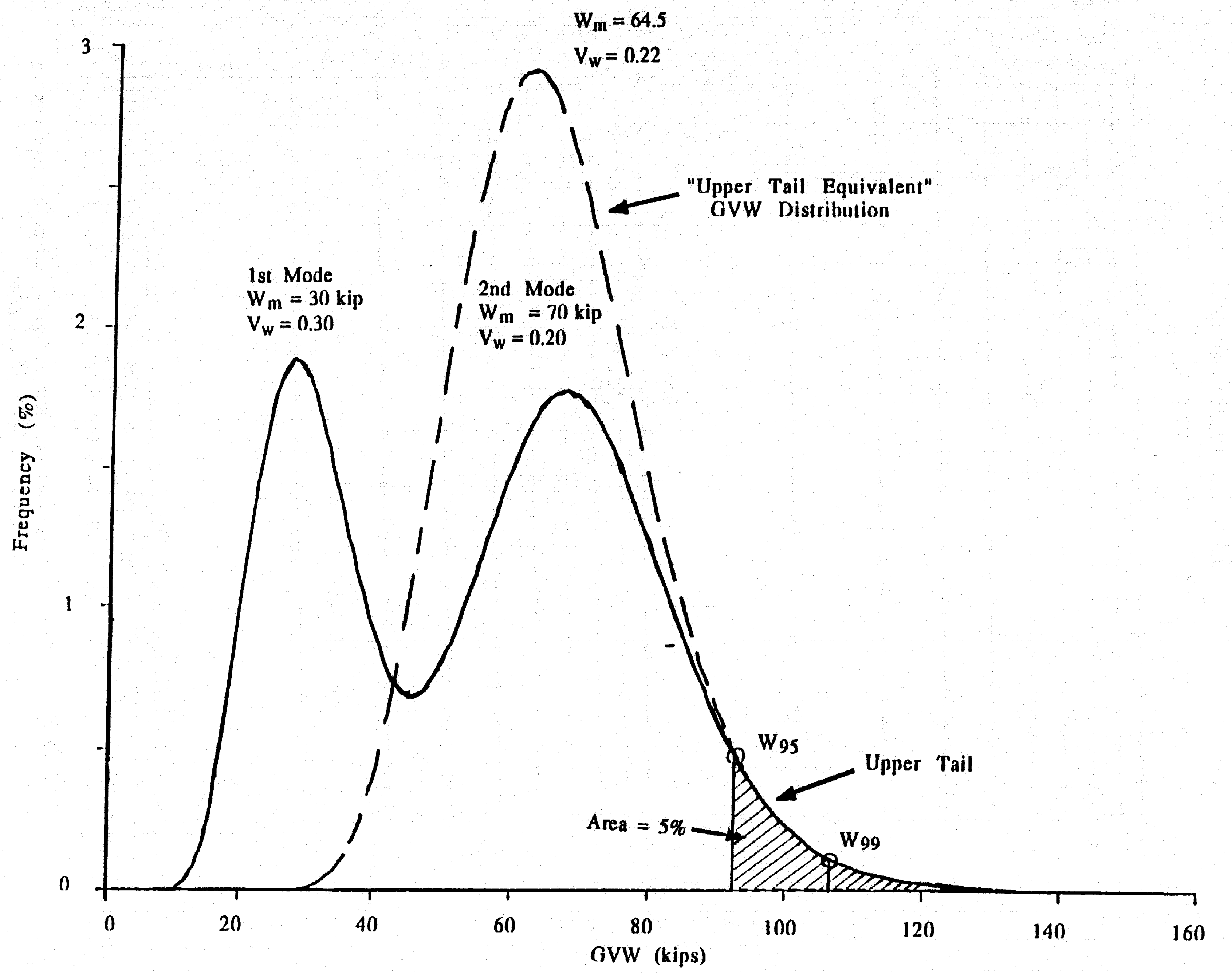


FIGURE 5: Typical Bimodal GVW Distribution and "Upper Tail Equivalent" Log-Normal Distribution

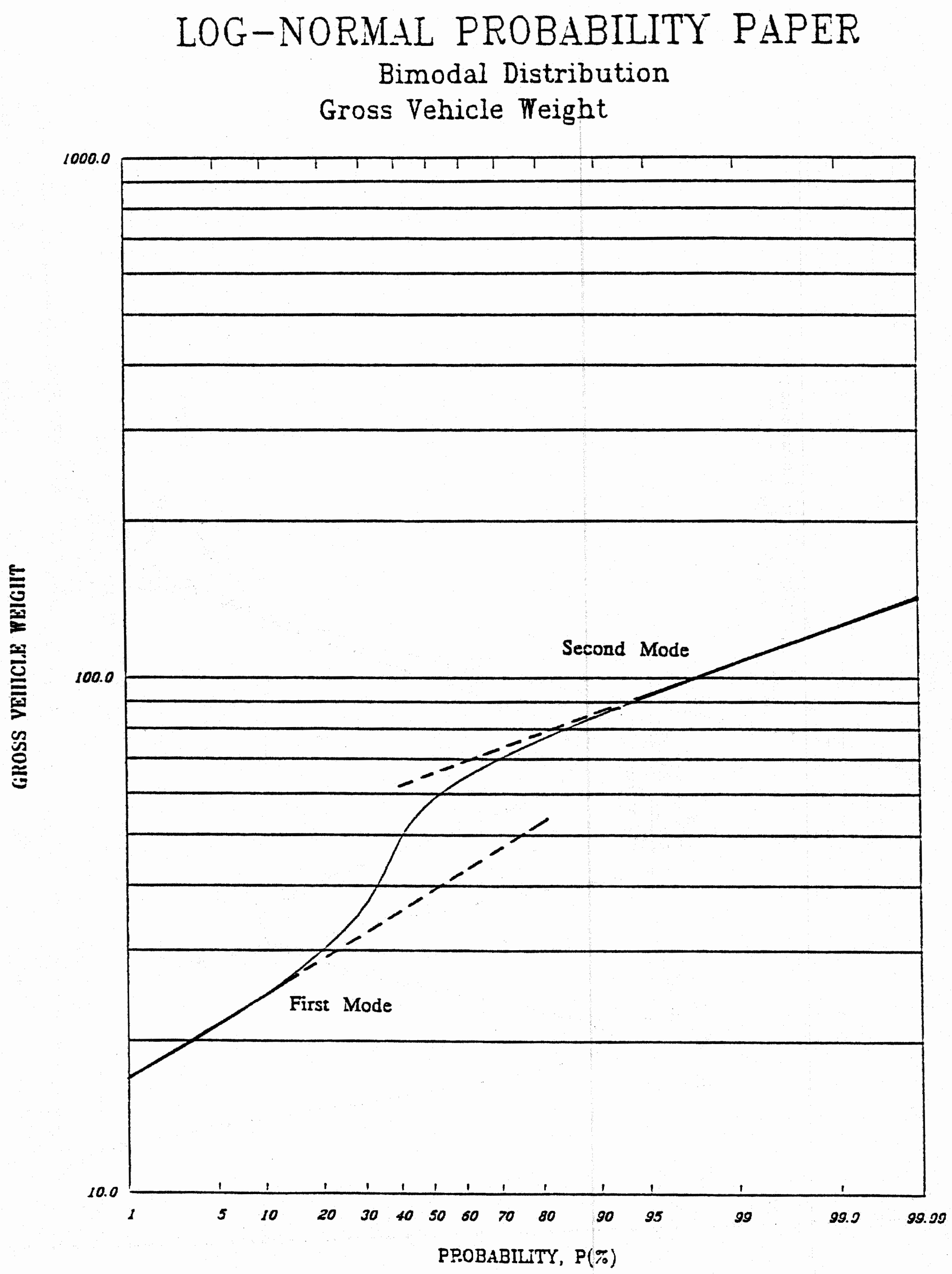


FIGURE 6: Cumulative Probability Distribution of a Bimodal GVW Histogram

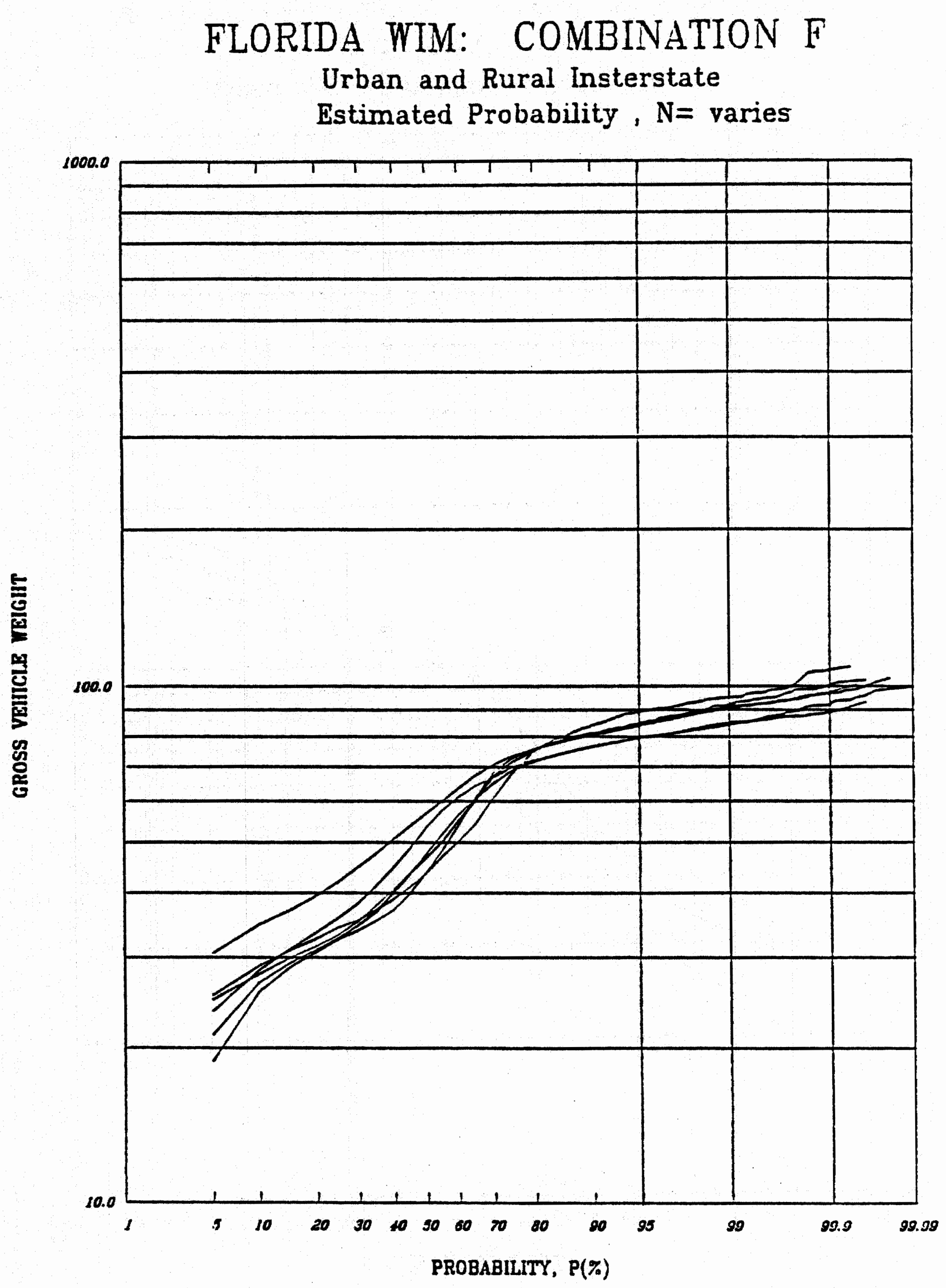


FIGURE 7: GVW Probability Distribution - Florida, (Urban and Rural) Interstate Sites

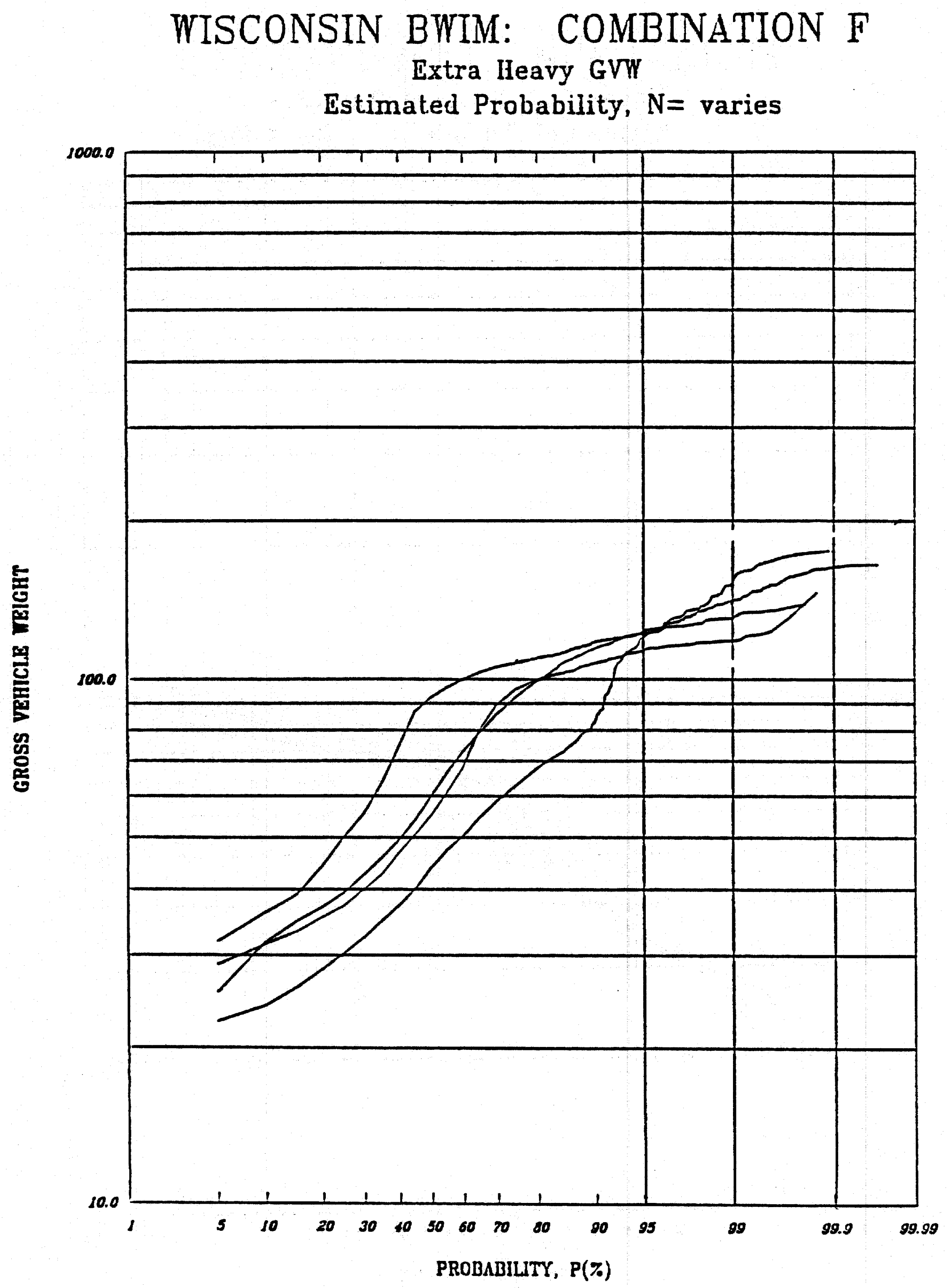


FIGURE 8: Extra-Heavy GVW Probability Distributions

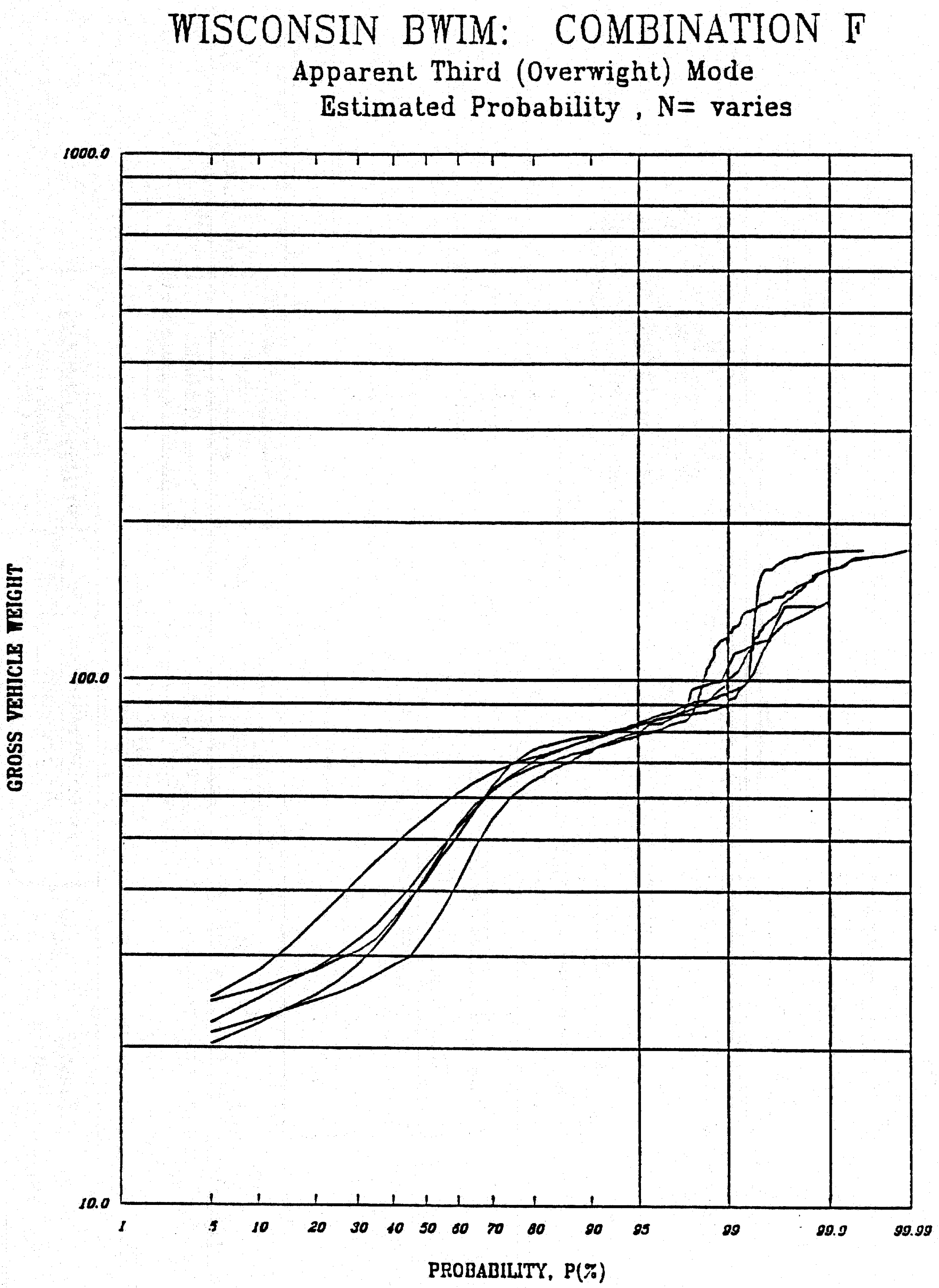


FIGURE 9: GVW Probability Distribution with Apparent Third (Overweight) Mode

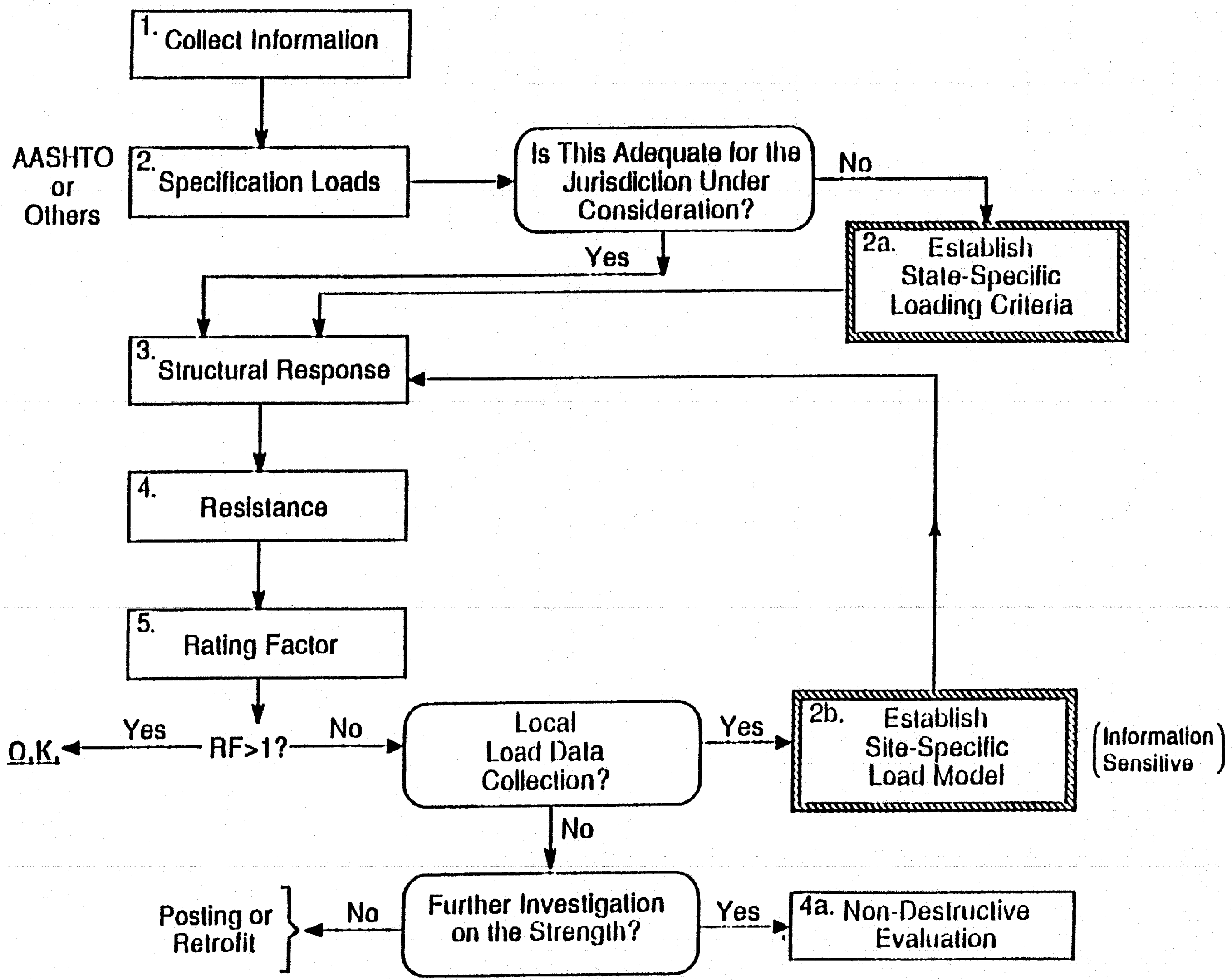


FIGURE 10: Bridge Rating Flowchart

# CALIBRATION OF WEIGH-IN-MOTION SYSTEMS

*J.M. Zuieback, J.D. Bailey, G.D. Wonacott*

## FOREWARD

This work was performed by SPARTA, INC., Engineering Technology Group and was supported by the Office of Research, Federal Highway Administration under Contract DTFH61-85-C-00080. The Nevada Department of Transportation (NDOT) were subcontractors to SPARTA on the effort. NDOT provided invaluable assistance in the conduct of the field test program which was conducted at in-service WIM sites in the state of Nevada.

## CHAPTER 1 INTRODUCTION

Truck weight data have been obtained for many years for a wide variety of reasons. These data have been obtained by making static weight measurements using single draft or individual wheel scales. However, development of weigh-in-motion (WIM) technology has produced equipment which is effective in measuring the total wheel loads (dynamic plus static load) of vehicles in motion at highway speeds.

The need to effectively monitor and control truck weights is well established. The most recent FHWA Truck Characteristic Report indicates that not only are truck volumes increasing, but there is a shift toward heavier ve-hicles.(1) Skinner gives some insight into the estimated pavement damage which occurs as a result of the heavier vehicles:(2)

- One 5-axle truck loaded to 80,000 lbs does equivalent damage to the pavement as 9,600 two-thousand lb cars.
- One 20,000 lb axle does equivalent damage as 4,000 cars, but one 26,000 lb axle does equivalent damage as 12,000 cars.

The above data highlight two important facts. First, heavy trucks cause significantly greater pavement damage than cars. Second, incremental increases in single axle loads cause amplified pavement damage. It is clear that there is a need not only to monitor truck weights, but to enforce truck weight laws to the maximum extent.

Truck weight data provide input to the following activities: pavement design, monitoring, and research; bridge design, monitoring, and research; size and weight enforcement; legislation and regulation; and administration and planning. Pavement design and planning require weight data to provide current estimates and trends of the characteristics of axle loads which must be accommodated by pavements. These data are statistically based and are often organized by weight classes, truck configuration and type.

The use of these data require that large quantities of truck weight data be collected in an efficient and safe manner. The statistical nature of the data preclude concern about the weight of specific individual vehicles; however, the distribution must be established within specified accuracy and confidence levels. In general, these accuracy levels are ±10 percent for individual axles, and ±5 percent for gross weight.

Size and weight enforcement requires truck weight data to support several levels of activity; assessment of the magnitude of the overweight vehicle problem; weighing of individual trucks to determine compliance; and monitoring the traffic stream to determine whether enforcement efforts are effective.

The use of these data require accurate weighing of individual vehicles in a safe and efficient manner. Enforcement weighing requires more stringent accuracy requirements. According to the National Bureau of Standards, individual wheel load weighers must be certified at 1 percent and maintained at ± 2 percent.(3)

WIM technology has been applied to both the gathering of design/planning data and to size and weight enforcement. The advantages of WIM technology include: high vehicle processing rate; improved safety to both trucks and the driving public; increasing coverage; minimized scale avoidance; reduced unit cost for trucks weighed; and availability of dynamic loading information. The major disadvantage of WIM systems is the uncertainty of using WIM output to compute single axle and gross vehicle weights.

In-motion-weighing of a highway vehicle approximates the weight of a vehicle, a wheel, an axle, or a group of axles, by measuring the vertical component of the total force applied to the pavement surface by successive tires. The total force is, in general, different from the static weight due to the vertical motion of the vehicle system. This vertical motion generates a dynamic force component which is dictated by the amplitude and frequency spectrum of the pavement surface. Therefore, the accuracy of a WIM system is dependent upon the dynamic coupling of the roadway and the vehicle.

In response to these issues, the FHWA sponsored the research program described in this paper the details of which may be found in Reference 4 and 5. The objectives of this program were:

(1) Determine the accuracy of an in-service WIM system when installed on pavements of various roughness including both older as well as newly resurfaced pavements. The accuracy goals for the system were:

a. ±10 percent on axle weights.

b. ±5 percent on gross weight.

c. ±6 in on the determination of axle spacing and total wheel base length.

(2) Determine the length and smoothness of an approach section of pavement which is required for the WIM system to meet the accuracy goal in those locations with pavement roughness which would otherwise result in accuracies poorer than the goal.

This paper summarizes the results of a FHWA sponsored combination analytical and experimental project designed to meet the objectives listed above. The project consisted of two sets of field studies to collect the data to meet the objectives: (1) statistical comparisons of WIM and static axle weights, and (2) tire-pavement force measurement experiments using specially instrumented vehicles. A dynamic simulation model was developed and utilized to identify the key influential vehicle, roadway, and operational parameters to guide the experimental design. Chapter 2 summarizes the results of dynamic simulation analysis and Chapter 3 describes the two field study programs performed. Recommendations are contained in Chapter 4.

## CHAPTER 2 DYNAMIC PAVEMENT LOADING

### Overview

A literature survey was performed to provide insight into the important vehicle parameters which affect the magnitude of dynamic wheel load. Due to the limited amount of relevant literature a dynamic simulation model was developed and used to perform parametric sensitivity analyses to identify the vehicle and operational factors which contribute to dynamic loading. The following paragraphs briefly summarize the most important factors which affect pavement dynamic loading.

Pavement factors

Probably the single most important factor influencing wheel dynamic loading is tuning of the road roughness with vehicle dynamic characteristics. The frequency of significant road roughness can range from less than 1.5 Hz to greater than 20 Hz depending on vehicle speed. There are numerous tractor/trailer rigid body, structural and axle natural frequencies also in this frequency range shown in Table 1.(6)*

Road roughness is often described as a combination of random ampli-tudes having a Gaussian distribution which can be statistically represented by a power spectral density (PSD). Random road roughness is distinguished from discrete pavement damage such as patches, rutting, cracking, spalling and raveling or damage to the pavement substructure such as subsurface shifting and road-bed deterioration. The power spectral density (PSD) quantifies the intensity of road profile amplitudes as a function of spatial or temporal frequency through the velocity. The PSD of a typical pavement is given in Figure 1. Three conclusions can be drawn from this PSD.

- There is significant energy up to about 20 Hz.
- There is significantly greater energy at the lower frequencies (i.e., 1.5-4 Hz) than at the higher frequencies (i.e., 10-20 Hz).
- A greater intensity derives from a higher vehicle velocity for the same frequency.

The implication of the first point is that sufficient energy is available to excite truck rigid body, structural and axle modes (i.e., frequencies ranging from 1.5 to 20 Hz). The second point suggests that the principal source of dynamic response should derive from the vehicle rigid body modes, assuming the same amount of modal damping is available for rigid body, structural and axle modes. This assumption is dependent on vehicle configuration. Lastly, it can be inferred from the third point that greater vehicle dynamic response is expected at higher vehicle velocities and that unsprung mass modes will become more important for higher vehicle velocities(7).

The presence of the weigh-in-motion scales in the pavement can also induce dynamic wheel loads, thus increasing the possibility of WIM errors. The geometry of the scales (i.e., whether flush with the pavement) is the predominant effect; however, compliance of the scales in the vertical direction can effectively induce a bump.(8) For example, a single 1/4 inch step discontinuity can induce significant dynamic wheel loads as shown in Figure 2. Some finite time and distance, dependent on the vehicle characeristics, is required for these dynamic loads to decay. The dynamic response data in Figure 2 indicates that 0.5 - 1.0 seconds of damping time is required for the 1/4 in step excitation to decay to a few percent of the peak dynamic wheel load.

Vehicle factors

The dynamic simulation analysis results identified suspension system factors, tire pressure, coupling between units, axle type, vehicle configuration, tire and wheel unbalance and runout, frame bending, and speed as key vehicle factors which influence dynamic load. These factors are discussed below.

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* All figures and tables are contained at the end of the text

### Suspension system

Several important classes of truck suspensions were identified including; four leaf spring, walking beam, torsion spring, air, and rubber-block. The largest suspension system class in the national fleet is the four leaf spring type which approaches 80 percent. Other data indicate that the four leaf spring suspension is responsible for some of the largest dynamic wheel loads only surpassed by the walking beam.(9,10) The torsion and air suspensions represent the smallest percentage of the population and result in relatively smaller dynamic wheel loads. The affect of suspension system type was evaluated parametrically by varying suspension system unsprung mass, damping, and stiffness.

Analysis results indicate that unsprung mass is a first order effect. Three values of unsprung mass ranging from 0.67 to 1.5 of nominal were analyzed in the simulation model as shown in Figure 3. For example, increasing the unsprung mass by a factor of 2.25 from 0.67 to 1.5 of nominal, increases the pavement dynamic wheel loads by 2.50. It could be inferred that larger gross axle load requirements, which usually mean larger axle designs, will result in larger dynamic wheel loads.

The analysis results suggest that the peak dynamic loads derive primarily from excitation of the highly damped axle modes which decay very rapidly compared to the tractor/trailer bounce and pitch modes. The analyses further revealed that variations in the suspension damping coefficients by a factor of ± 50 percent did not significantly affect the magnitude of the peak dynamic loads, or the time for these loads to diminish to insignificant levels. In contrast, the rate at which the bounce and pitch rigid body modes decay is directly dependent on the magnitude of suspension damping which is considered a first order effect on the damping distance. Figure 4 shows the results for the pseudo-random time history for a 3S-2 driver tandem axle. The results indicate that the damping distance can vary by 40 to 50 feet for 50 percent variations in the suspension damping.

### Tire Pressure

Tire pressure was found from the analyses to be a very important parameter potentially affecting WIM accuracy for two reasons. First, the peak pavement loads were found to be directly proportional to the tire pressure, and second, fairly large variations in tire pressure are anticipated in the field. A recent survey in Texas revealed average pressures of 95 psi with extremes in excess of 135 psi reference.(11) The 95 psi average is significantly higher than the 70-75 psi assumed by most researchers. These findings were confirmed by data collected as part of the field test program where average "hot" tire pressures exceeded 95 psi with the range 90 to 100 psi. The relationship between tire pressure and dynamic loading is shown in Figure 5.

### Coupling

The force coupling between axles in the same tandem group and the coupling between the drive and trailer tandem were examined using a 3/8 inch bump excitation in the simulation model. The degree of coupling between axles in the same tandem and between the drive and trailer tandems, in the context of dynamic wheel load, is dependent upon the vehicle speed, vehicle suspension geometry, and inertia properties. The small mass of the tractor relative to the loaded trailer (i.e., ratio of four to five) results in little transfer of energy from the tractor to the trailer. In contrast, the trailer response does tend to drive the dynamic wheel loads in the steering axle. The analysis results shown in Figure 6 show that the trailer mass can excite the tractor steering axle wheel loads to levels of about 25 percent of the trailer levels, thus effectively increasing the damping distance.

A second coupling analysis was performed to examine axles in the same tandem. The results indicate that coupling between axles in the same tandem does not affect the damping distance, that the peak of the dynamic wheel load is not increased.

### Single Versus Tandem Axle

The objective of these analyses was to determine if the ratio of dynamic wheel load to static wheel load is larger for a single or tandem suspension. The baseline static tandem axle load is 17 kips (34 kips per tandem) for the trailer suspension. The static axle load for the single axle system analyzed is 20 kips. All other elements of the system (e.g., percent of critical damping and suspension stiffness) were equal for the two configurations. The magnitude of the peak loads was found to be about the same for both suspensions, but the smaller static axle load on the tandem axle results in the ratio of dynamic to static axle load a few percent higher for the tandem system.

### COE Versus Conventional Cab

The first order effect of tractor inertia on dynamic wheel load was examined using the simulation model by varying the pitch inertia of the tractor by factors of 5 and 10 while keeping all other mass, stiffness, damping, and geometric properties constant. The results indicate that conventional tractors have lower dynamic wheel loads on the steering axle and higher dynamic wheel loads on the driver axles than COE configurations.

### Tire and Wheel Unbalance and Runout

This factor may set a lower limit on accuracy which can be achieved by the WIM scales. While this effect is often masked or lost in the noise level on rough roads, it can be a predominant source of wheel dynamic loads on a smooth surface.(7) This is particularly true if the wheel unbalance or runout frequency coincides with a rigid body or axle dynamic mode. The interference diagram presented in Figure 7 shows the potential speed ranges where the wheel unbalance could excite the rigid body and axle frequencies. Assuming a three (3) foot wheel diameter and a potential range of speeds from 35 to 65 mph, the following observations have been made:

- The first excitation order (i.e., one per tire revolution excitation) can potentially excite the rigid body pitch mode up to about 40 mph. There is also potential for exciting axle modes which are less than 10 Hz at vehicle speeds ranging from 55 to 65 mph.

- The second excitation order could potentially excite axle modes. The third and higher excitation orders probably are not a factor for speeds greater than 35 mph.

More information is required regarding the types, frequency and magnitudes of wheel unbalances and runout which can occur. From the observations above, it appears that significant resonance from wheel unbalance or runout, in the 35 to 65 mph range, has a relatively low probability of occurrence. However, if it does occur, it could likely be the most important excitation for smooth road conditions for some vehicle configurations.

### Frame Bending

The structural dynamic characteristics for some trailer types have structural modes which are at a relatively low frequency. The data presented in Table 2 is for a flat bed trailer. The vertical bending modes at 1.5 to 2.0 Hz for a loaded trailer and 8.5 Hz for the unloaded trailer are in the frequency range of interest. It is anticipated that sufficient road excitation will pass through the suspension to excite the structural modes. In addition, data from the 1975-1979 National Truck Characteristic Report indicate that 20-25 percent of the truck population are flat bed trailers.(1)

### Speed

An increase in vehicle speed results in an increase in the frequency of road roughness with respect to the vehicle and therefore, the intensity of the input to the vehicle suspension system (see Figure 1). For example, tuning of the vehicle dynamics with the road roughness or wheel unbalance may result in high dynamic wheel loads at a lower velocity.

## CHAPTER 3 WIM DATA COLLECTION PROGRAM

A two part program of field experiments was conducted to collect data which could be used to relate WIM error to pavement roughness attributes. The first part of the program utilized in-service WIM sites in Nevada to gain an understanding of how WIM weighing and spacing error is related to vehicle parameters. This program was accomplished by comparing WIM generated weight and spacing data with static data for a sample of in-service vehicles. The second part of the program utilized several instrumented vehicles to develop specific data to relate pavement roughness attributes to measured dynamic wheel force.

### Wim field tests

The objective of these field tests was to characterize WIM error by making direct comparisons of WIM generated axle and gross weight, and axle spacing with static measurements made on the same vehicle. A series of such surveys were conducted at three in-service WIM sites in the State of Nevada.

Although some data were collected for other than 3S-2 configurations, the study focussed on this configuration due to its relative numbers in the population. Table 3 shows the actual number of vehicles for which usable WIM static data were collected for various configurations at each test site. In this table COE refers to CAB-over-engine; CON refers to conventional CAB; and the other designations follow established usage.

### Test Methodology

The selected measures for determining the accuracy of WIM systems is the calculation of gross weight, single and tandem axle weighing errors, and the spacing errors. Radian WIM scales were used to measure the axle and gross weights, axle spacing, and speeds for randomly selected trucks travelling along the highway. These scales were deployed, calibrated, and operated by NDOT personnel. A short distance down the highway, the same vehicles were flagged down by NDOT and weighed on static scales at in-service static weigh sites. Documentation for each test vehicle included such information as tractor and trailer type, type of commodity, number of axles, type of suspensions, wheel-base, tire pressures, etc. The WIM and static weight data were then analyzed to determine the WIM error which derives primarily from dynamic wheel load.

Prior to the collection of weight data, pavement profile height was measured in each wheel track using Pentax model GT-4B surveying equipment. Measurements were taken every 6 inches for 200 feet upstream of the WIM scales and 80 feet downstream of the WIM scales. These profile height data were then analyzed to produce continuous pavement profiles for each wheel track.

### Test Results

A total of 657 vehicles were sampled at three test sites in southern Nevada from which 415 usable data records were obtained. Analyses were conducted to determine the distribution of weighing error and spacing error stratified to the lowest level where statistically reliable results could be obtained. In each case WIM measured data were compared with static data. Errors are defined as follows:

$$\text{Weighing errors} = \frac{\text{Static weight - WIM weight}}{\text{Static weight}} \times 100 \text{ (percent)}$$

$$\text{Spacing error} = \text{Static spacing - WIM spacing (in)}$$

Table 4 summarizes these results for 3S-2 axle weights and gives the percentage of vehicles falling within ± 10 percent of the static weight. Note should be made that it was not possible to measure individual axle weights in a tandem or tridem combination due to limitations of the static scales, therefore, the driver axle and trailer axle errors are tandem axle weighing errors. Table 5 lists the mean error and standard deviation for the 3S-2 sample for all sites combined stratified by configuration and suspension type.

Several observations can be made based upon the results given in Table 5: (1) the steering axle error is highest when a leaf spring driver axle is used (the most prevalent in the sample); (2) the standard deviation is approximately the same for the steering axle and the driver but, 20 percent higher for the trailer tandem axle; (3) leaf spring suspensions produce higher errors than air ride suspensions as expected; and (4) COE configurations have generally higher errors than conventional configurations as a result of the lower pitching moment of the inertia of the COE.

Table 6 summarizes the gross weight error results for all 3S-2 vehicles. This table gives the percentage of vehicles falling within the ±5 percent error criterion. Several observations can be made: (1) generally fewer vehicles fall within the gross weight criterion than the single axle criterion; and (2) the conventional configuration has less error than the COE configuration, consistent with the single axle data.

Table 7 summarizes the axle spacing error results for 3S-2 vehicles. This table gives the percentage of vehicles which fall within ±6 inches of the static spacing. It can be noted from the table that, apparently, a small percentage of vehicles meet the spacing error criterion. However, a review of the procedures for measuring the static spacing indicate a high degree of measurement error for the longer span measurements. This is confirmed by noting the high percentage of agreement for the tandem axles. Therefore, only the tandem axle error results should be used.

In addition to these results, the data for all sites combined were utilized to draw general conclusions regarding the effect of vehicle configuration and type and suspension system type. The conventional configuration falls within the ±10 percent criterion more often than the COE (91.5 percent vs. 83.8 percent), however there are no statistically significant differences between the mean and standard deviations of the distributions. Similar results were obtained for the steering axle however the mean error for the COE case is significantly higher than for the conventional configuration. This confirms the results of the dynamic simulation analyses.

Additional data showed that the air ride performs significantly better than the leaf spring suspension. These results are confirmed by driver interviews conducted during the field data collection activity wherein the drivers reported significantly better riding comfort with air ride compared with leaf springs.

The results of the dynamic simulation analysis raised questions regarding the degree of dynamic coupling between adjacent trailers in a double or triple combination. Although the experimental sample was small the means and standard deviation for the data were calculated with the result that no significant differences were found. Therefore, it appears based upon these limited data that any vertical force coupling between adjacent trailers is likely to be insignificant.

Although sufficient data was not obtained at each site to evaluate the performance of the 2SD configuration, the data were combined for all sites and indicate considerably poorer performance of the driver axle in meeting the error criterion than the steering axle. Although this result is contrary to the result for the tractor trailers, it is consistent with the expected performance of a nonarticulated single unit vehicle. In addition, comparisons of the steering axle weighing error performance with the 3S-2 results indicate consistent agreement where a high percentage of vehicles fall within the error criterion.

A comparison between vehicle weighing error and pavement roughness was made. Figure 8 shows a plot of the percentage of vehicles meeting the weighing error criterion (either tandem axle or gross weight) versus the RMS profile height. The RMS profile height is the average RMS profile height obtained from the right and left wheel tracks. This figure shows the effect of the pavement in statistical weighing accuracy. Similarly, Figure 9 shows the same weighing error data plotted against Quarter Car Index which was obtained directly from the pavement profile by averaging the values from the right and left wheel tracks. A similar trend is evident as would be expected.

### Dynamic loading tests

The objective of these tests is to generate a data base of dynamic wheel load and damping distance data for a range of pavement roughness. The test series was conducted using two vehicle configurations, a 3S-2 COE and a 2SD vehicle. Three flexible and one rigid pavement section, described in Table 8, were selected to provide a range of roughness from smooth to levels which would result in anticipated dynamic wheel loads in excess of 20 percent of the static wheel loads.

The objective of the tests was to develop a data base of dynamic wheel load and road roughness, where the road roughness, as an independent variable, was stratified into the four levels mentioned. The road profile data was reduced and analyzed using power spectral analysis as discussed in the previous section so that simple criteria could be formulated from the dynamic wheel load and road profile relationships.

### Test Methodology

The dynamic loading tests consist of a series of controlled tests wherein the tire-pavement force time history is measured for specific vehicles operating over test sections whose wheel track profiles have been measured using rod and level techniques. Tire-pavement force history is measured using a wheel hub force transducer/accelerometer system designed for this purpose.

### Pavement Measurements

Both wheel track pavement profile for each pavement section was measured using a rod and level technique at 6 inch intervals. Figure 10 is the PSD representation for the pavement profiles. As discussed earlier, a speed of 60 mph was chosen to convert the profiles from a spatial representation to a frequency representation. This value was chosen to represent the typical operational speeds observed for in-traffic WIM weighing during the field test activity.

### Test Results

A total of 93 dynamic pavement loading tests were performed. As previously discussed, these tests were limited to two vehicle configurations tested at three speeds on four pavement sections selected to represent a significant range in dynamic response.

Although it would be useful to attempt to investigate relationships between the spectral content of the pavement profile and that of the response, it was determined that such relationships would not provide implementable guidelines for users who would not be able to characterize such spectral properties. Therefore, as with the statistical data, a relationship between macroscopic measurable pavement properties and weighing error was developed.

Figures 11 and 12 summarize the results by comparing the Weighing Index with the Quarter Car Index (QCI) and the RMS profile height computed from the RMS average of the actual profile. The QCI and RMS profile height are averages of the left and right wheel tracks at each test site. The Weighing Index is defined as the probability that the dynamic force is within ± 10 percent of the static force. Therefore, a larger value of Weighing Index indicates less dynamic effect.

In addition to determining the influence of pavement roughness on dynamic loads, several tests were performed to determine the distance required to damp the dynamic force response to levels which would meet the ± 10 percent criterion. These tests were conducted at 60 mph at Site A where approximately 0.21 inch pavement discontinuity exists. Figure 13 is the calculated dynamic force response. This figure, which gives dynamic force as a percentage of static force, shows that approximately 0.9 second (80 feet) is required for sufficient damping. This result is considered a worst case since no WIM site would be selected with such a large visible pavement discontinuity. Therefore, it appears that a minimum distance in excess of 80 feet will provide a sufficiently smooth WIM approach to meet the error criterion.

## CHAPTER 4 RECOMMENDATIONS

Recommendations as to the level of pavement roughness and length of approach section to achieve specific levels of WIM measurement accuracy have been developed from the results of the two field study programs described in Chapter 3. The recommendations are based, in part, upon statistical data and therefore represent the results which might derive from an "average vehicle." Since the largest proportion of the vehicle fleet consists of the 3S-2 configuration and the testing focussed on this configuration, the recommendations are based primarily on this vehicle configuration.

Figure 14 shows the weighing error as a function of pavement roughness (in/mile) for the driver tandem, trailer axle, and the vehicle gross weight. This figure was developed with the assumption that the pavement roughness upstream of the WIM scale would be homogenous and have the roughness value indicated. The figure does not account for specially prepared smooth pavement sections upstream of the WIM scale.

Figure 15 gives adjustment factors to account for provision of smooth pavement upstream of the WIM scale. The adjustment factor computed is multiplied by the roughness level to yield an adjusted roughness for application to Figure 14. The damping time is the length of smooth pavement associated with the vehicle speed and is interpreted as the damping time required to achieve a level of smoothness desired.

Application to a particular site is accomplished as follows:

1. Measure the pavement roughness of the site (in/mile) over a section of at least 100 feet upstream of the potential location.

2. Check the anticipated weighing error on Figure 14. If the error is unacceptable, then surface preparation is required.
3. Determine the level of acceptable error and use Figure 14 to determine the associated roughness value.

4. Calculate the necessary adjustment factor (AF) as follows:

$$AF = \frac{\text{desired roughness}}{\text{actual roughness}}$$

5. Utilize Figure 15 to associate the necessary AF with a damping time, t.

6. Using the table in Figure 15, calculate the total damping time $t_T$ as follows:

$$t_T = t + t^*$$

7. Based upon the design/operating speeds expected at the site, calculate a minimum smooth pavement length, L(min) as follows:

$$L(min) = speed \times t_T$$

8. Calculate the smooth pavement length required by including the vehicle factor, VF, which accounts for the range of vehicle suspension system response properties:

$$L = L(min) \times VF$$

Based upon the results of literature reviews and dynamic simulation analyses, a value of VF = 2.5 has been used.

## Example

If 5 percent is the maximum acceptable error for gross weight, Fig- ure 14 indicates a maximum roughness of approximately 130 in/mi as shown. This value has associated with it approximately 6 percent and 9 percent error for the tandem driver axle and tandem trailer axle respectively.

However if the roughness at the site is 300 in/mi, for example, then the errors appear to be unacceptable and a section of smooth approach pavement is required. In order to determine the length of smooth
pavement required, the adjustment factor, AF, is calculated from Step 4 above AF = 130/300 = 0.43 which from Figure 15 yields an approximate value of t = 0.43. The total damping time, $t_T$, is calculted from Step 6. Then the minimum pavement length required for specific speeds is calculated using Step 7. Step 8 is used to adjust the minimum requirements to account for vehicle variations. Sample calculations for this example are given in the table below for VF = 2.5.

Smooth Pavement Length, ft

| Speed (mph) | L(min) | L(min)xVF |
|---|---|---|
| 40 | 44 | 110 |
| 50 | 51 | 130 |
| 60 | 59 | 150 |
| 70 | 65 | 165 |

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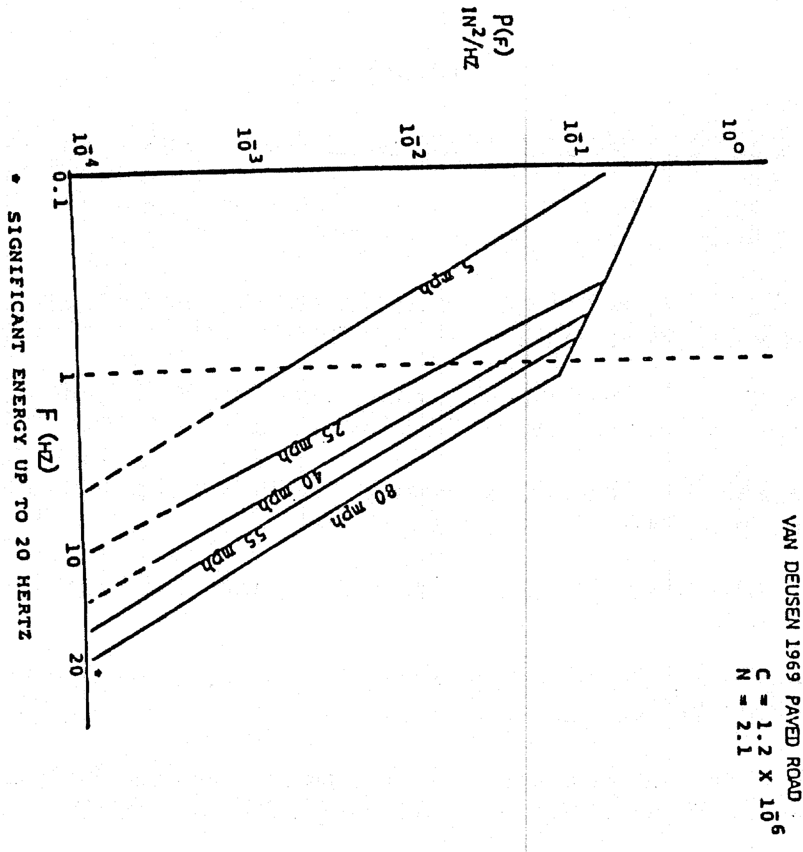


Figure 1. PSD Representation of Typical Terrain.

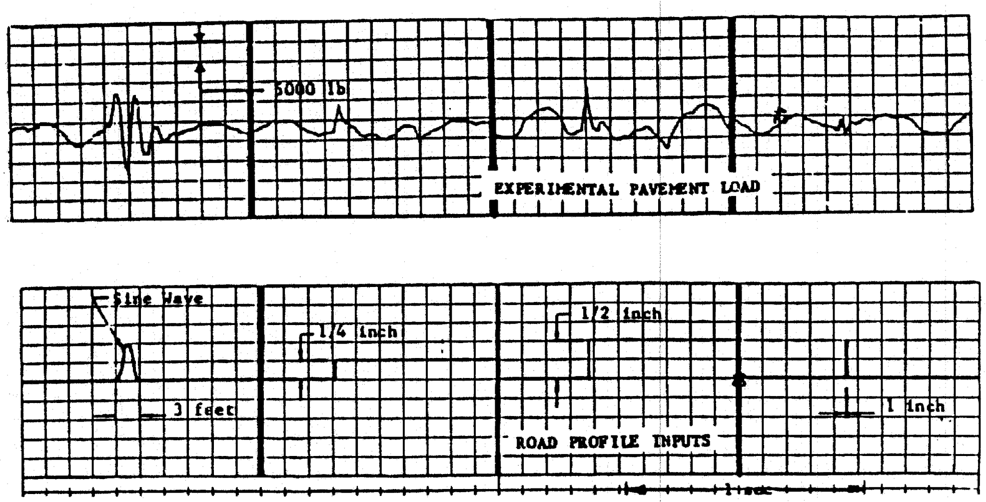


Figure 2. Computed and Experimental Load For Deterministic Inputs. Vehicle Speed = 34 MPH, Static Load = 9,400 Lbs. (Ref. 7)

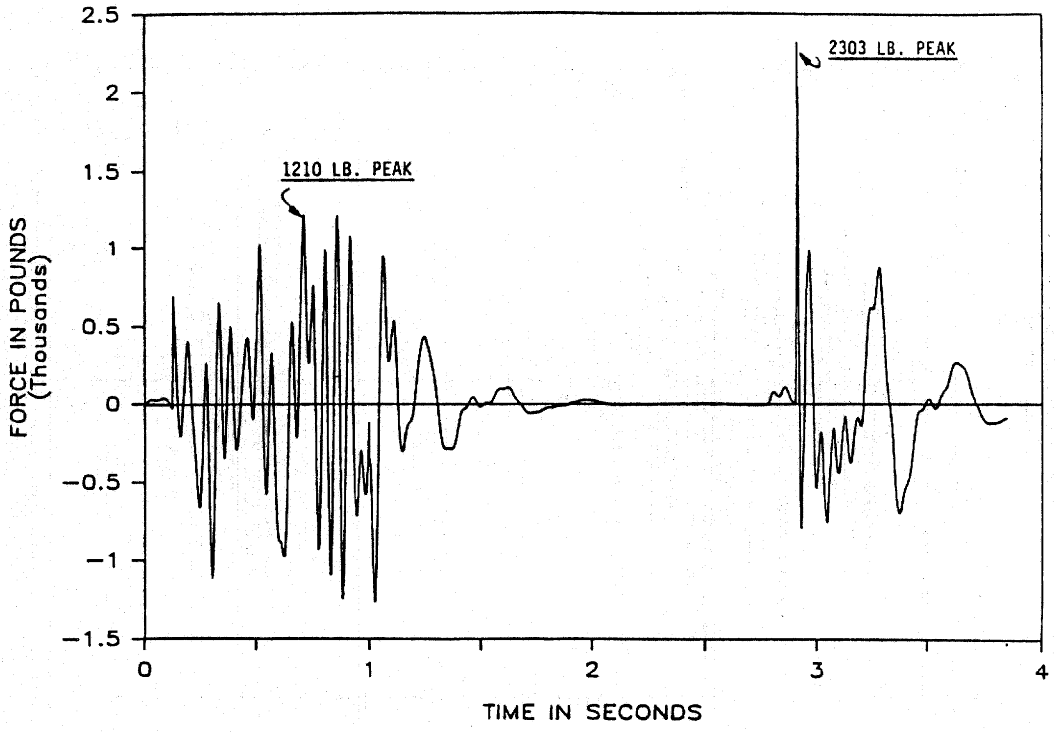


Figure 3a. Time History Response to Rough Road Input Axle Unsprung Mass x .67 - Axle 2.

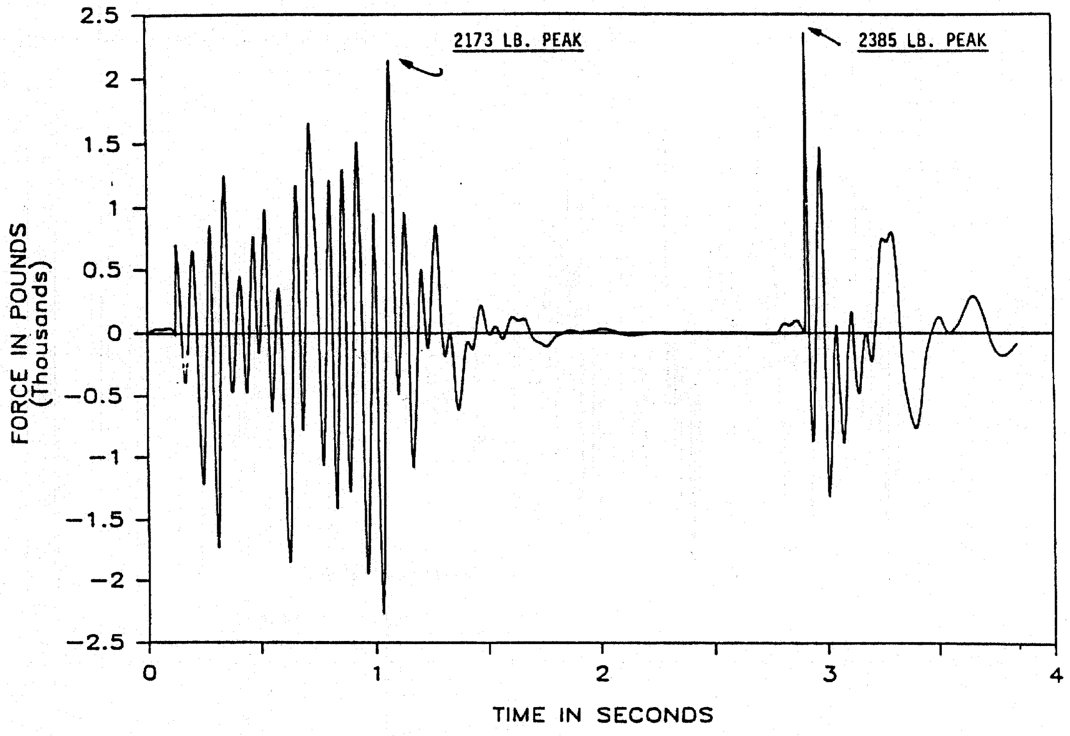


Figure 3b. Time History Response to Rough Road Input Baseline - Axle 2.

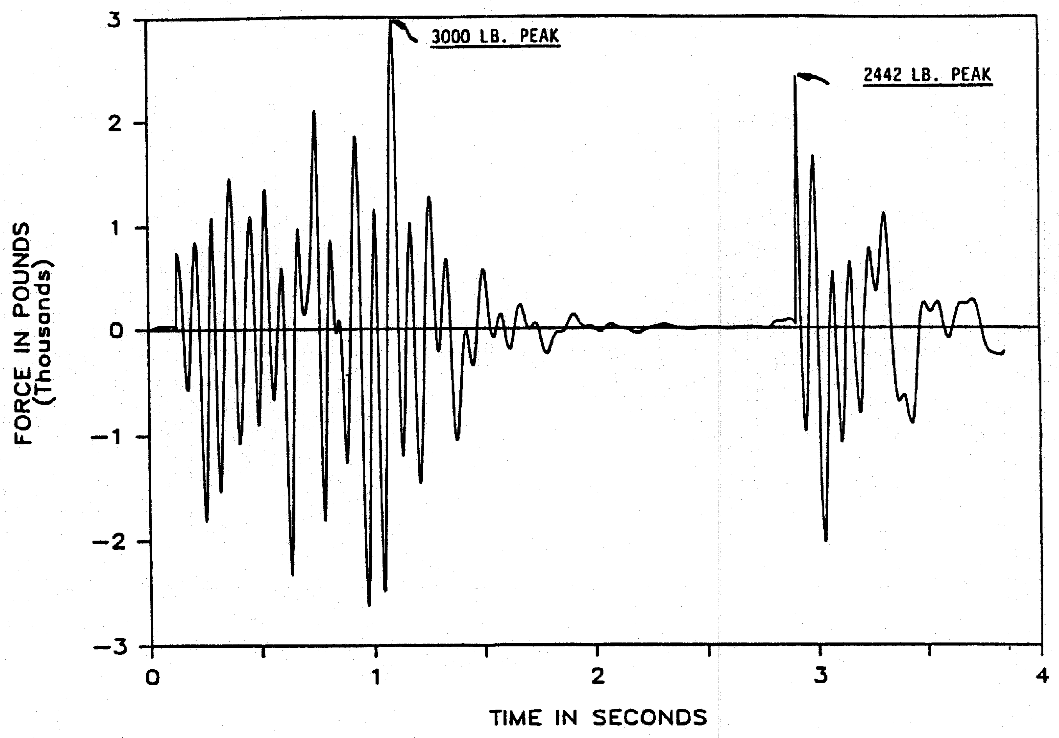


Figure 3c. Time History Response to Rough Road Input Axle Unsprung Mass x 1.5 - Axle 2.

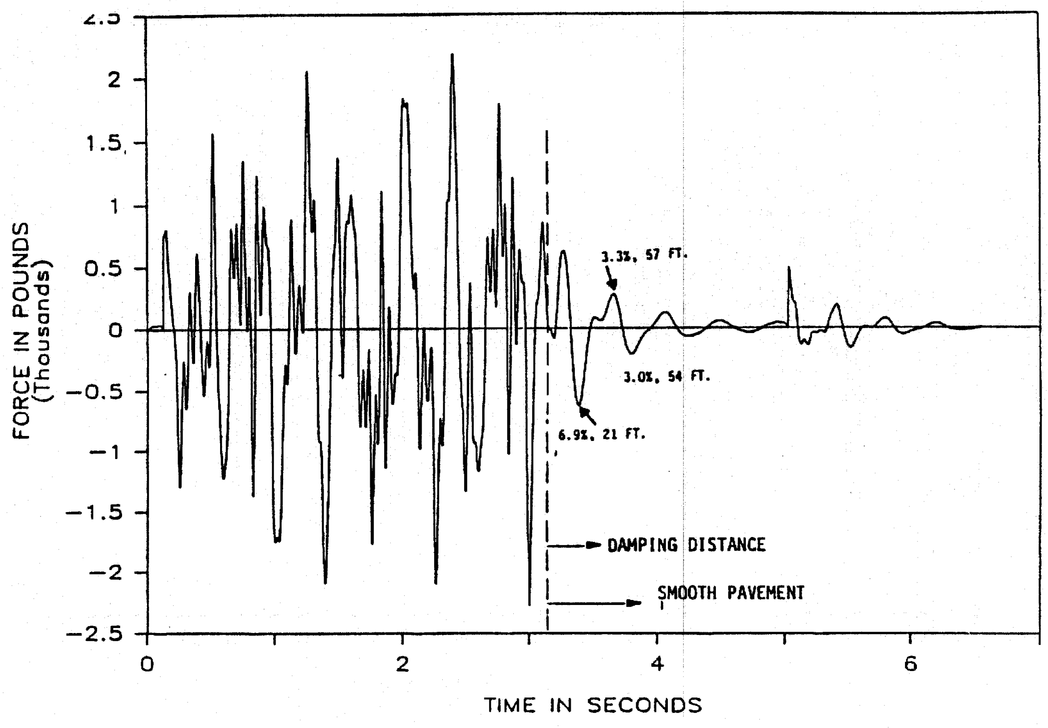


Figure 4a. Time History Response to Rough Road Suspension Damping x .67 - Axle 2.

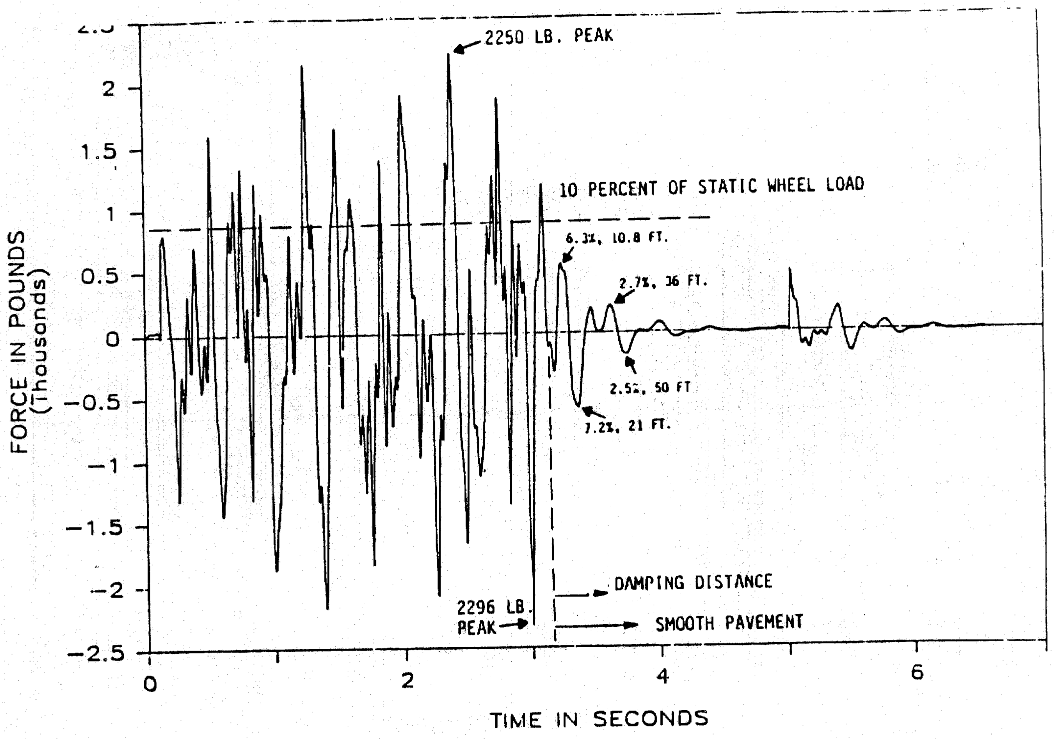


Figure 4b. Time History Response to Rough Road Baseline Configuration - Axle 2.

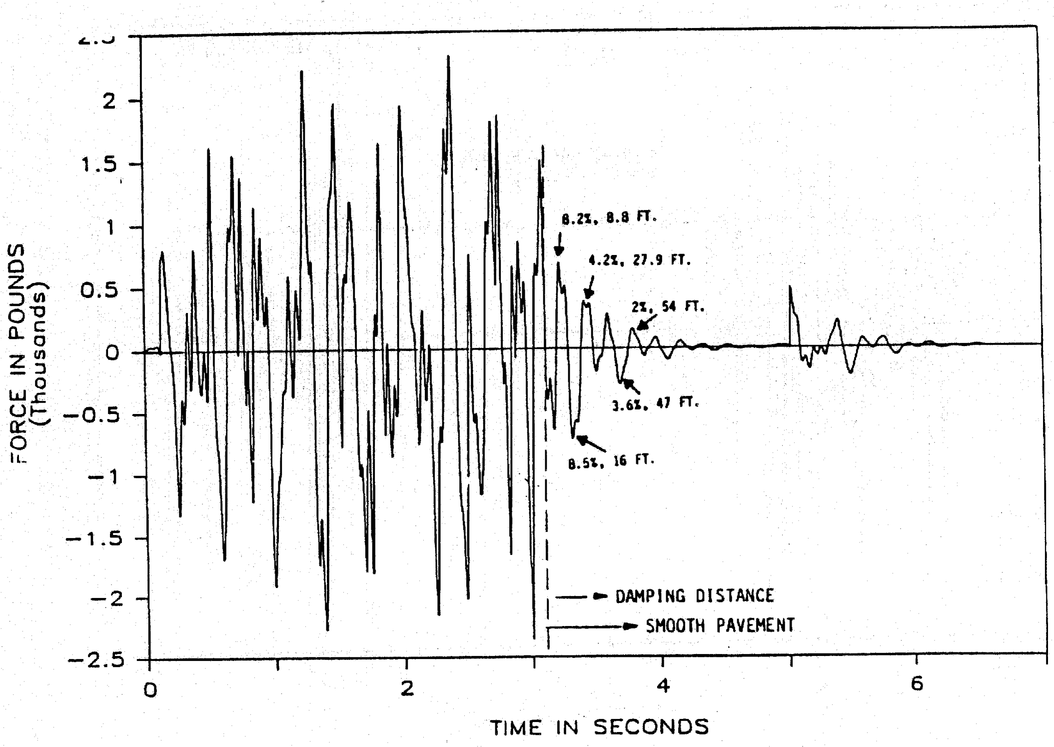


Figure 4c. Time History Response to Rough Road Suspension Damping x 1.5 - Axle 2.

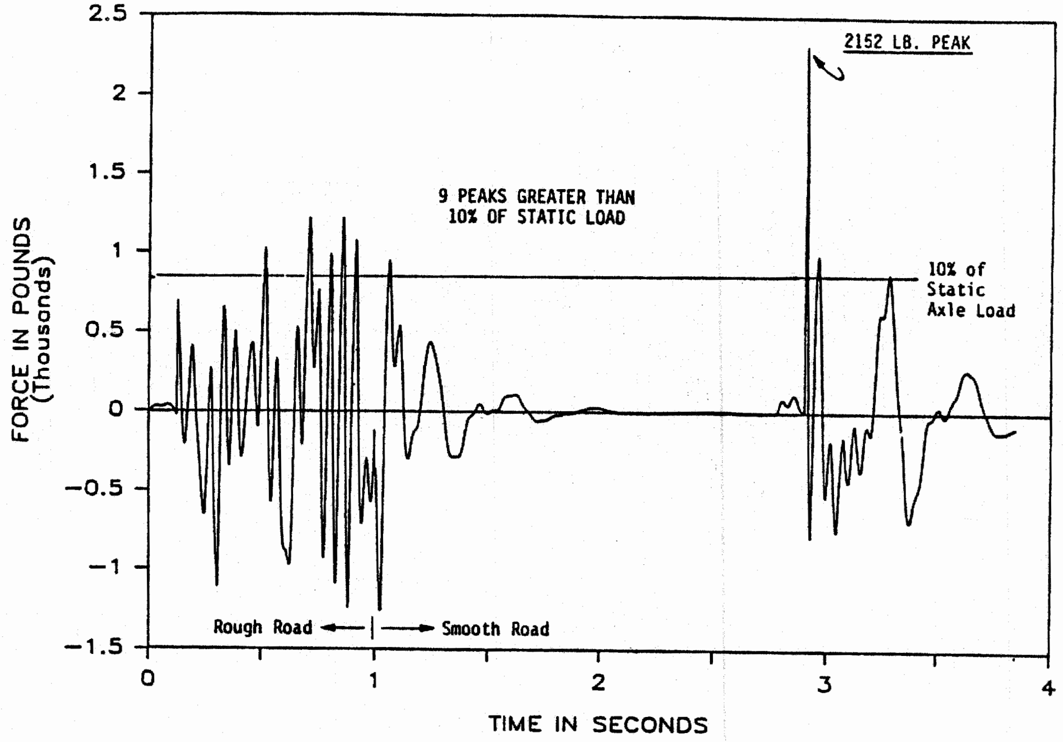


Figure 5a. Time History Response to Rough Road Input Tire Pressure - 50 psi - Axle 2.

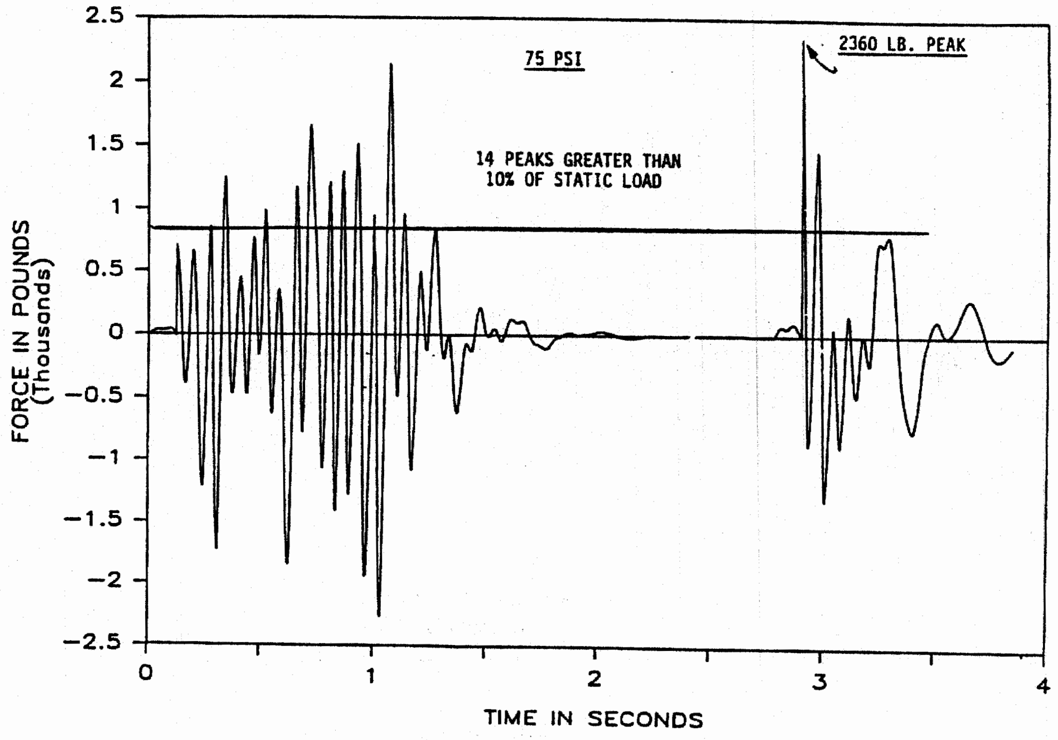


Figure 5b. Time History Response to Rough Road Input Baseline - Axle 2.

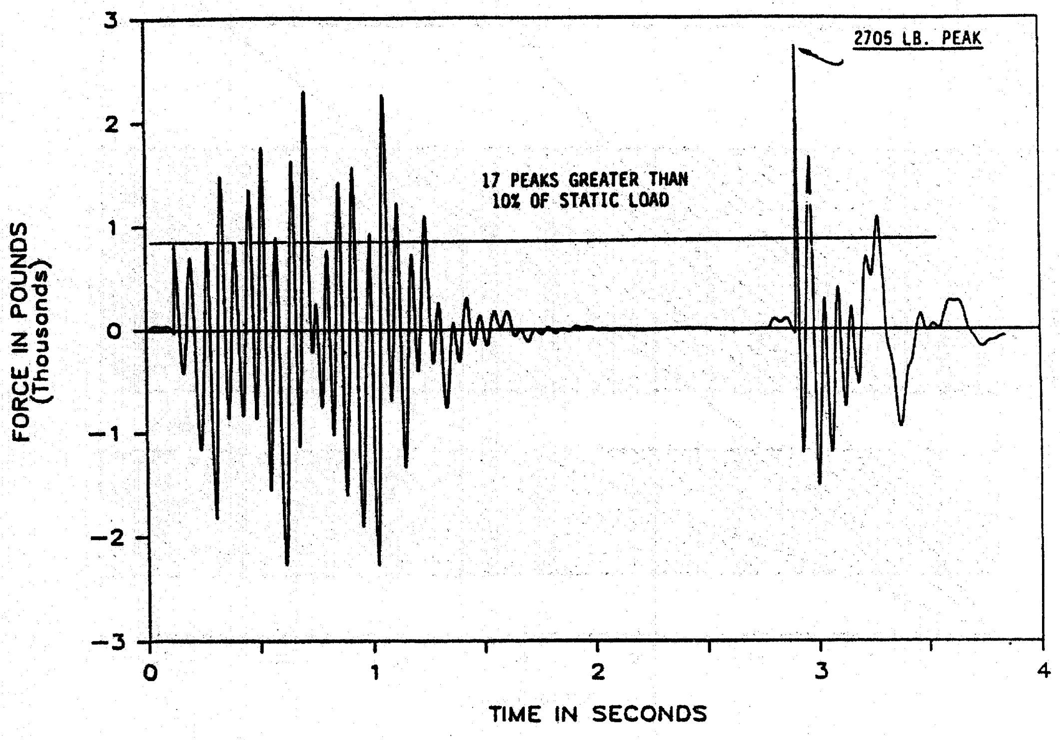


Figure 5c. Time History Response to Rough Road Input Tire Pressure 90 psi - Axle 2.

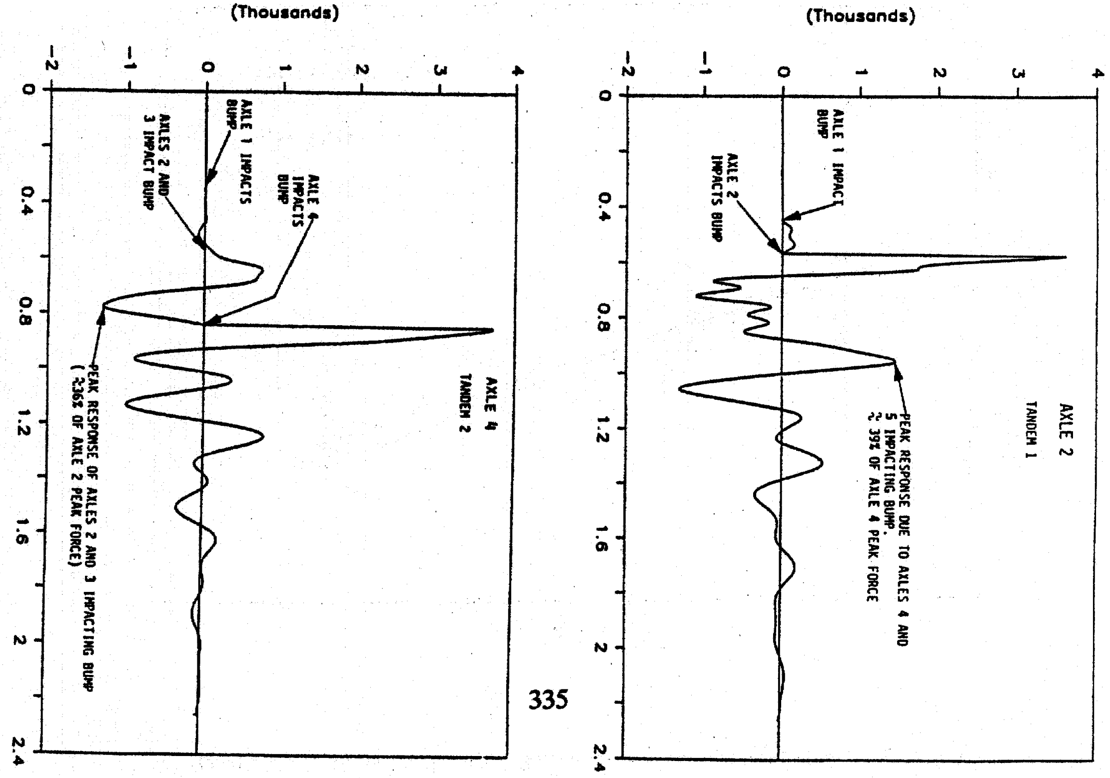


Figure 6. Coupling Between Axles - Response to 3/8 Inch Bump.

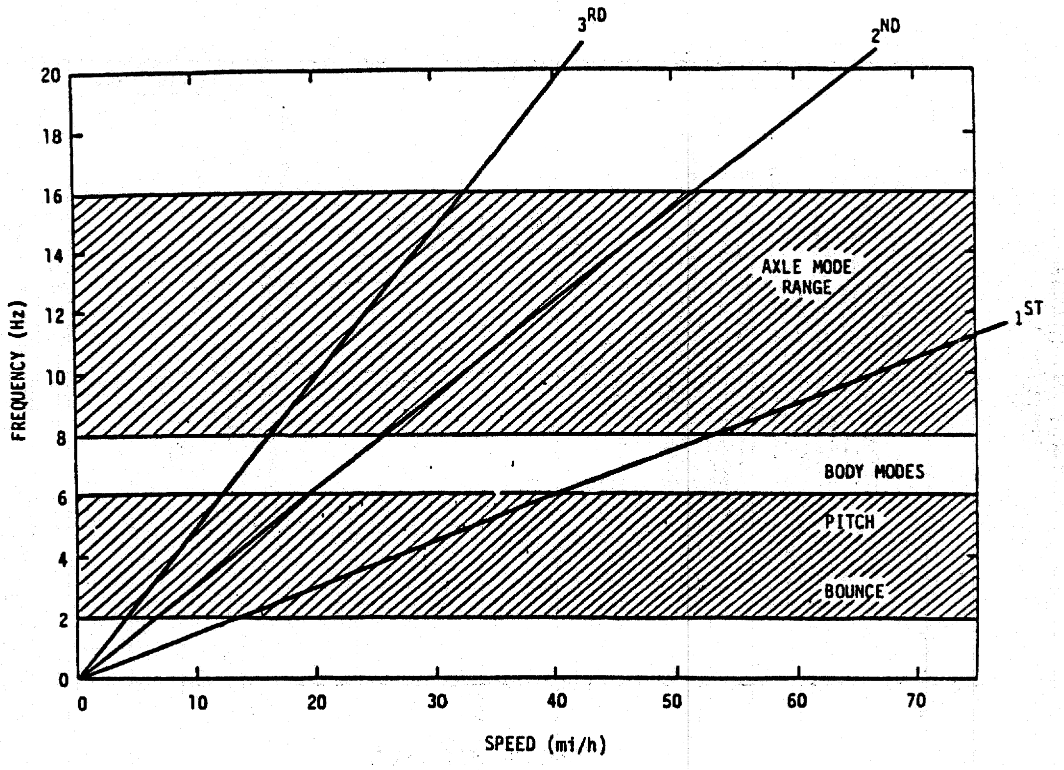


Figure 7. Truck Wheel Rotation Interference Diagram.

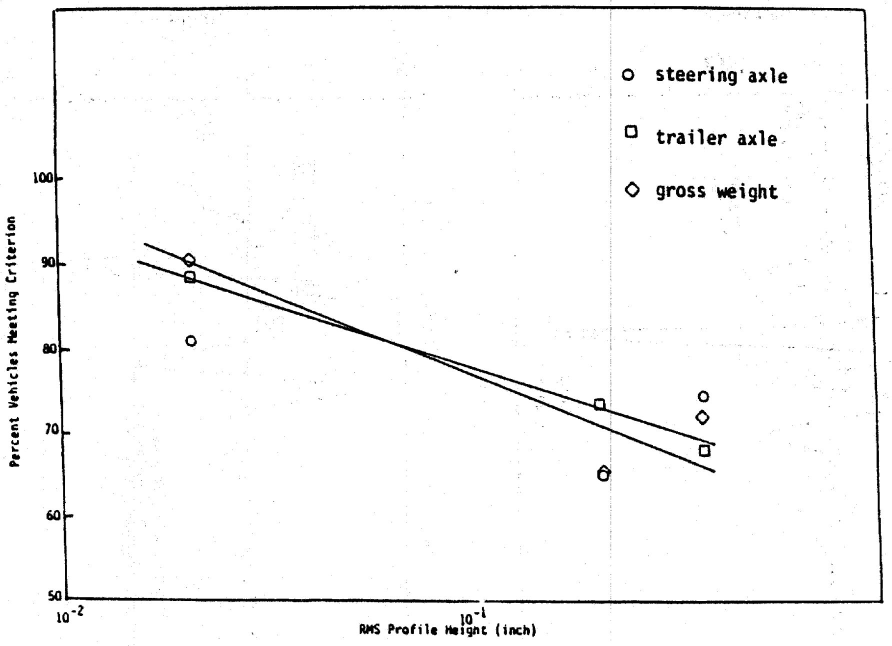


Figure 8. Percentage of Vehicles Which Meet Weighing Error Criteria (3S-2).

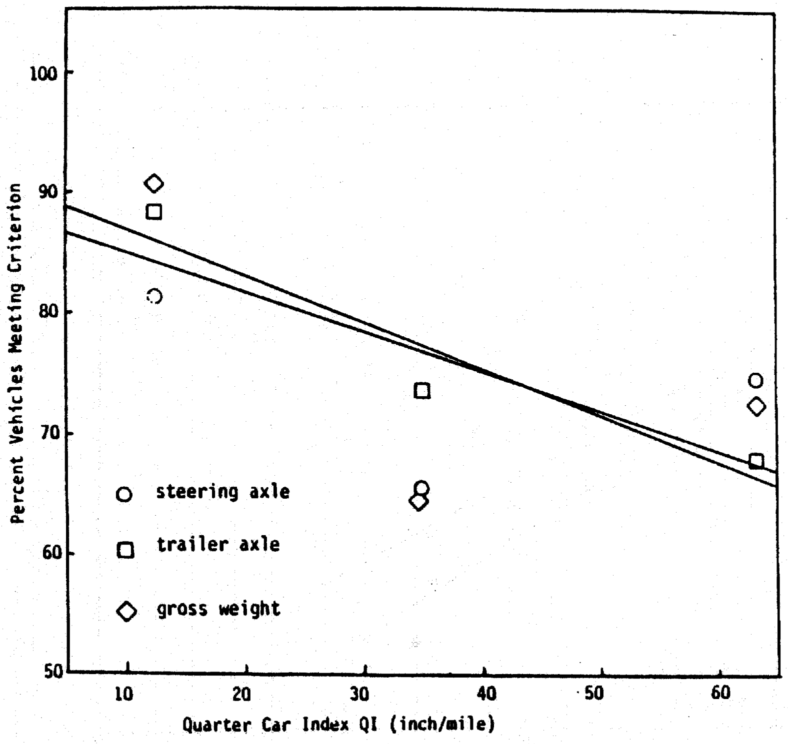


Figure 9. Percentage of Vehicles Which Meet Weighing Error Criteria (3S-2).

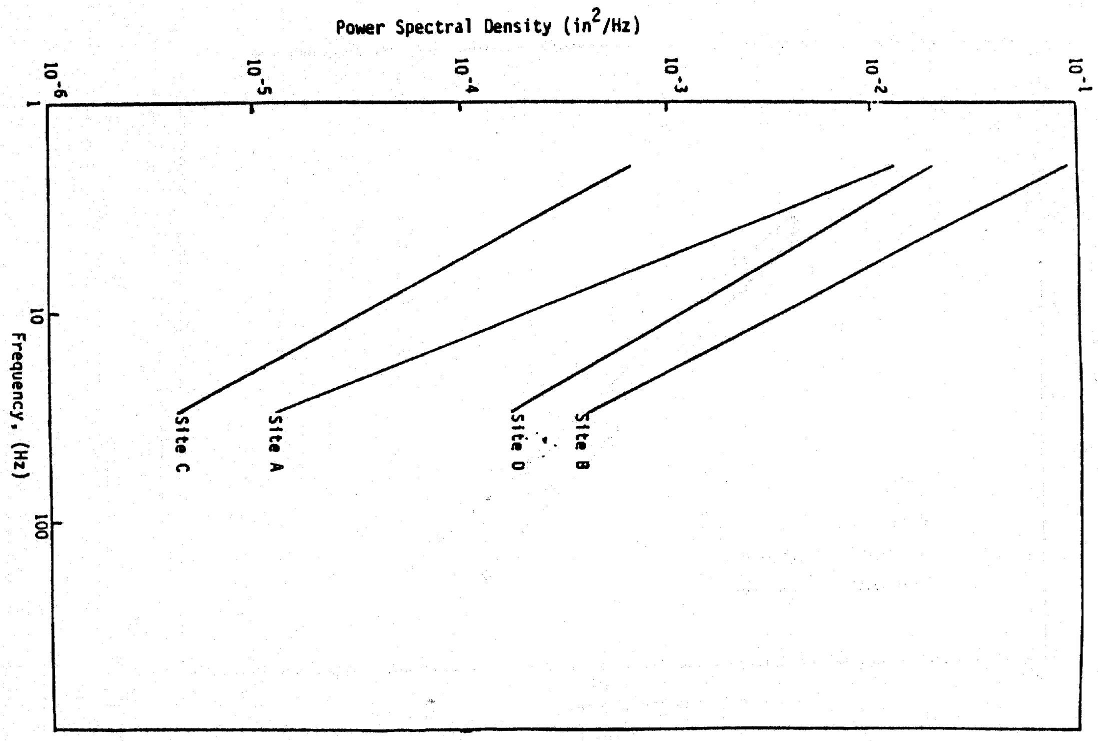


Figure 10. PSD of Pavement Profiles.

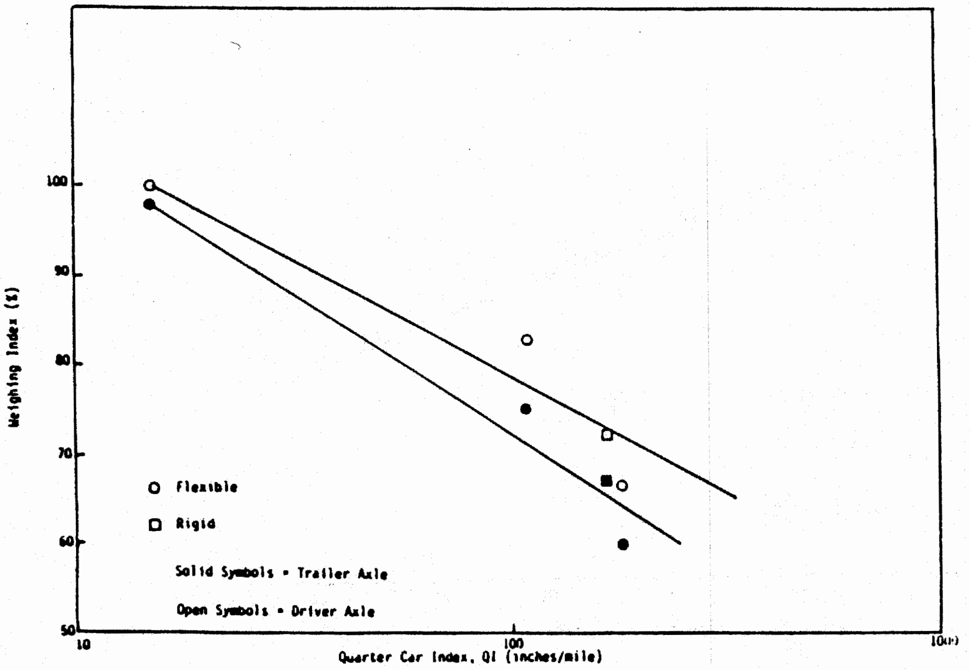


Figure 11. Relationship Between Weighing Index and QCI.

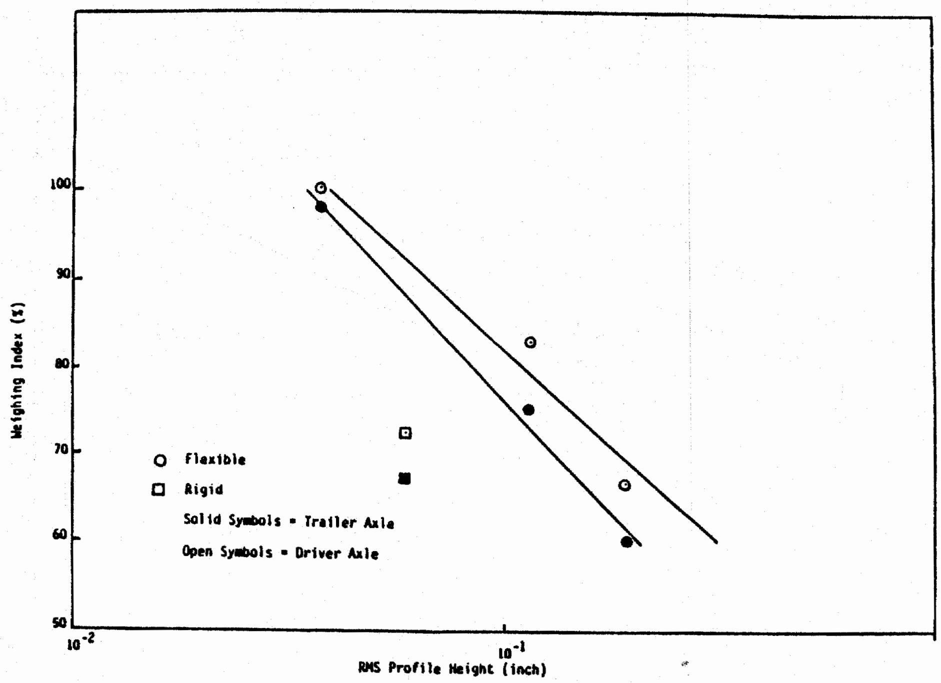


Figure 12. Relationship Between Weighing Index and RMS Profile Height.

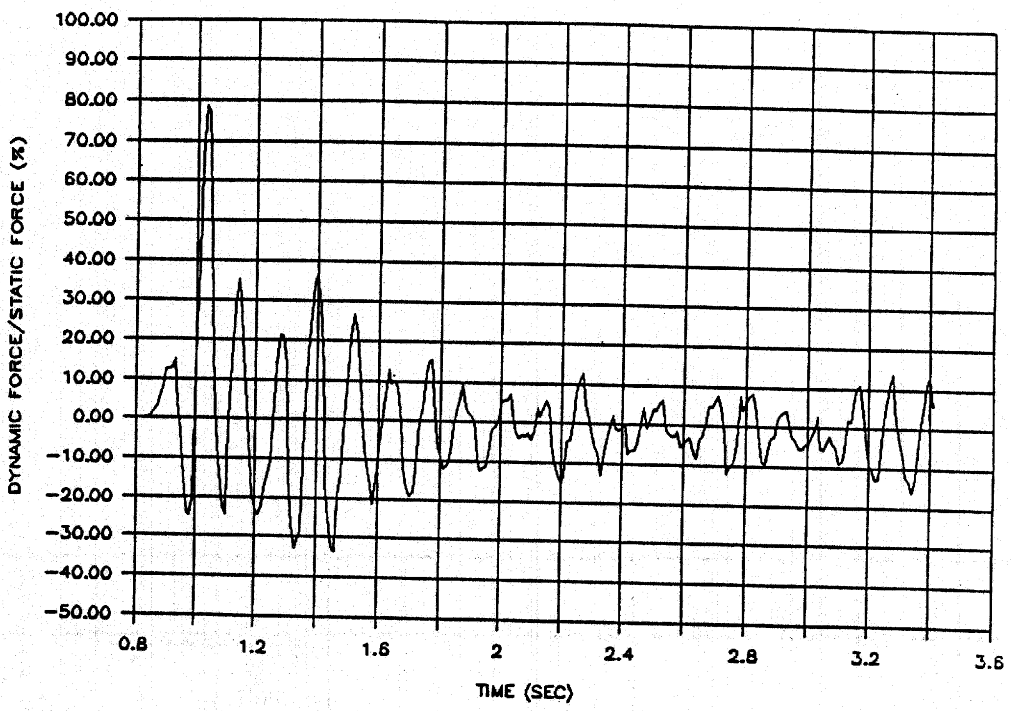


Figure 13. Force Time History 3S-2 Driver Axle.
Site A - 60 MPH.

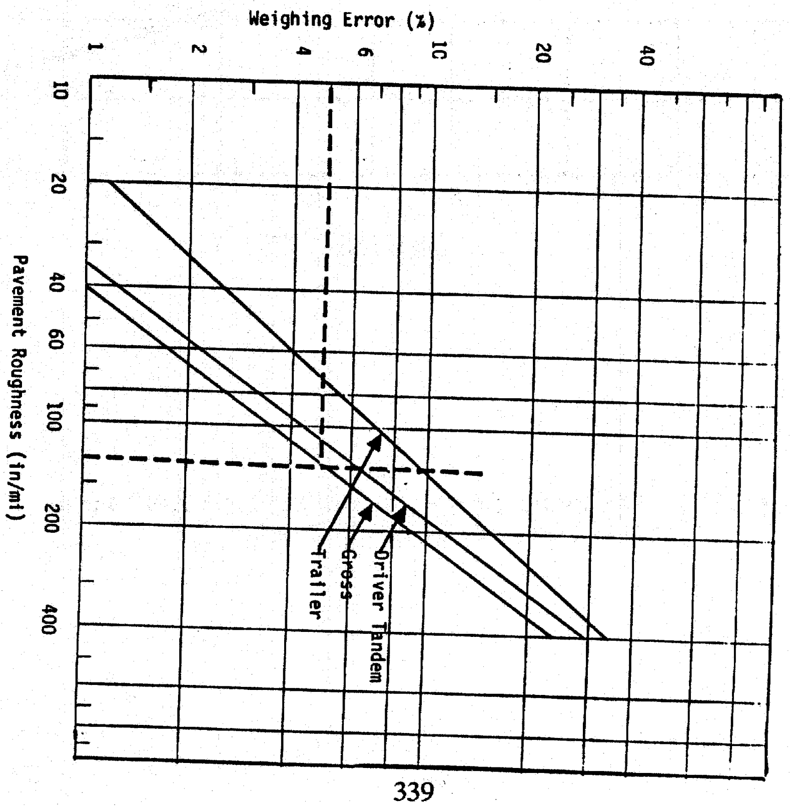
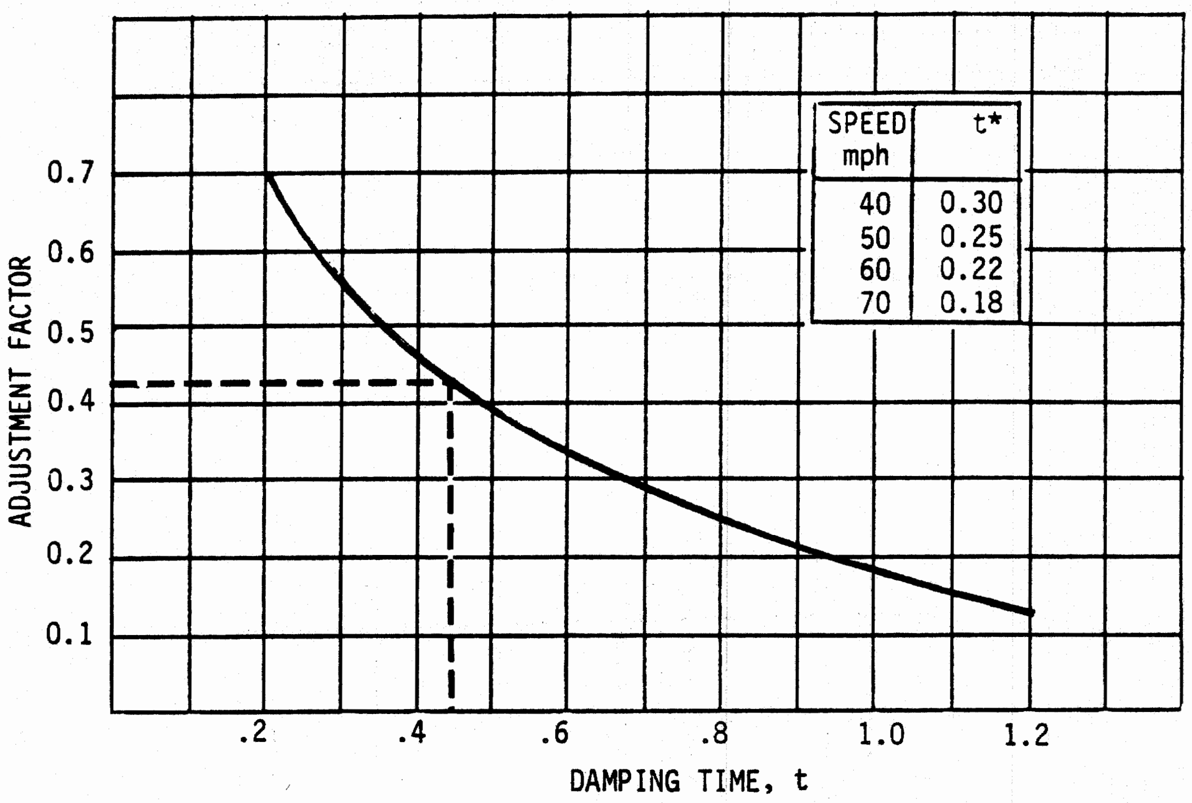


Figure 14. The Effects of Pavement Roughness on Weighing Error.



| SPEED mph | t* |
|---|---|
| 40 | 0.30 |
| 50 | 0.25 |
| 60 | 0.22 |
| 70 | 0.18 |

Figure 15. Weighing Error Adjustment Factor as a Function of Damping Time.

Table 1. Vibration Modes of a Tractor Van-Trailer Combination.

| Mode Description | Frequency (Hz) |
|---|---|
| Rigid body lateral translation | 1.45 |
| Rigid body fore/aft translation | 1.4-1.5 |
| Vehicle yaw | 2.1-2.3 |
| Front end lateral/trailer yaw* | 2.7-3.0 |
| Vehicle vertical translation | 3.2-3.6 |
| Front end torsion | 3.8-4.1 |
| Tractor pitch/trailer bounce | 4.0-4.3 |
| Tractor pitch/trailer pitch | 4.4-4.9 |
| Complex mode* | 4.9-5.2 |
| Tractor roll/cab motion at mounts* | 6.1-6.2 |
| Exhaust stack fore/aft | 6.9 |
| Tractor vertical bending | 6.5-7.0 |
| Battery box and fuel tank lateral* | 7.3** |
| Complex fuel tank mode* | 7.6** |
| Lateral bending of tractor | 7.9 |
| Tractor tandem yaw mode | 8.9 |
| Tractor torsional mode* | 9.7** |
| Exhaust stack fore/aft | 9.9-10.0 |
| Tractor tandem lateral/exhaust active | 9.8-10.3 |
| Radiator pitch | 10.1 |
| Tractor second torsional mode | 11.6-13.1 |
| Tandem bounce (axles out-of-phase) | 11.7-12.7 |
| Battery box/fuel tanks/exhaust stack* | 12.6 |
| Battery box/fuel tanks mode* | 12.6-12.8 |
| Engine/transmission bounce at rear | 14.7 |
| Shift tower/battery box | 14.9 |
| Cab bounce at rear/fuel tank vertical | 15.2 |
| Front axle roll mode | 15.3 |
| Tandem roll (axles out-of-phase) | 15.8-17.0 |
| Complex mode* | 16.0** |
| Tandem bounce (axles in-phase) | 16.5-17.1 |
| Radiator lateral mode | 17.3 |
| Cab and engine/transmission pitch | 18.4** |
| Trailer tandem bounce (out-of-phase) | 18.6 |
| Tractor tandem roll (axles in-phase) | 18.7 |
| Front axle bounce | 20.4 |

*Complex modes not readily recognizable as a basic mode

**Not observed experimentally on-the-road

Table 2. Modal Survey Results For Unladen Trailer.

| MODE NO. | FREQUENCY (HZ) | MODAL DAMPING (percent OF CRITICAL) | MODE SHAPE | DUE TO TEST SETUP |
|---|---|---|---|---|
| 1* | 8.5 | 2.9 | 1ST VERTICAL | |
| 2 | 9.9 | 4.7 | YAW | SUSPENSION MODE |
| 3 | 10.1 | 2.4 | 1ST TORSIONAL | |
| 4 | 12.1 | 2.1 | 1ST TORSIONAL | SUSPENSION MODE |
| 5 | 15.3 | 3.8 | BOGIE BOUNCE | SUSPENSION MODE |
| 6 | 16.3 | 2.2 | 1ST LATERAL | |
| 7 | 16.7 | 1.8 | 2ND TORSIONAL | |
| 8 | 25.8 | 1.9 | 3RD TORSIONAL | |
| 9 | 26.8 | 0.8 | 2ND VERTICAL | |
| 10 | 28.5 | 2.9 | 2ND LATERAL | |

* Unladen Trailer; Laden Trailer Frequency Reduced to 2 Hz
Twenty-Five Additional Higher Order Modes Observed

Table 3. Field Test Sample Sizes.

| | Truck Configuration | | | | | | |
|---|---|---|---|---|---|---|---|
| Test Site | 3S2 | | | 2S1 | 2SD | 2S1-2 | 2S1-2-2 |
| | COE | CON | TOTAL | | | | |
| US95 | 33 | 39 | 72 | 6 | 27 | 15 | 0 |
| APEX | 42 | 43 | 85 | 1 | 11 | 21 | 18 |
| SLOAN | 56 | 58 | 114 | 3 | 4 | 37 | 1 |
| TOTAL | 131 | 140 | 271 | 10 | 42 | 73 | 19 |

Table 4. Percentage of Axle Weights Within ± 10 Percent of Static Weight.

| SITE | COE | | | CON | | | ALL | | |
|---|---|---|---|---|---|---|---|---|---|
| | STEER | DRIVER | TRAILER | STEER | DRIVER | TRAILER | STEER | DRIVER | TRAILER |
| APEX | 71.4 | 33.3 | 46.5 | 70.4 | 33.3 | 40.1 | 81.4 | 88.5 | 88.2 |
| US95 | 65.8 | 85.3 | 55.9 | 79.3 | 40.0 | 78.0 | 74.7 | 90.5 | 68.0 |
| SLOAN | 54.1 | 84.6 | 73.1 | 74.7 | 92.9 | 73.2 | 65.1 | 89.0 | 73.4 |

Table 5. Distribution of Axle Weighing Error Statistics.

| | | CONVENTIONAL | | | COE | | | ALL |
|---|---|---|---|---|---|---|---|---|
| | | ALL | LEAF | AIR | ALL | LEAF | AIR | |
| STEER | MEAN | 3.00 | 6.07 | 1.63 | 5.86 | 7.49 | 4.82 | 4.35 |
| | SIGMA | 7.23 | 4.41 | 7.62 | 8.71 | 8.34 | 6.04 | 8.09 |
| DRIVER | MEAN | 1.12 | -1.89 | 2.47 | 1.36 | 1.53 | 0.44 | 1.23 |
| | SIGMA | 7.64 | 8.11 | 5.35 | 8.44 | 9.48 | 6.33 | 8.02 |
| TRAILER | MEAN | 0.01 | 0.03 | -0.17 | 4.49 | 4.71 | 4.12 | 2.12 |
| | SIGMA | 8.85 | 10.82 | 5.83 | 10.20 | 11.45 | 6.73 | 9.77 |

Table 6. Percentage of Gross Weights Within ± 5 Percent of Static Weight (3S-2).

| SITE | 3S-2 TRACTOR | | | ALL VEHICLES | ALL | |
|---|---|---|---|---|---|---|
| | COE | CON | TOTAL | TOTAL | DRIVER | TRAILER |
| APEX | 83.3 | 74.3 | 78.8 | 65.0 | 88.5 | 88.2 |
| US95 | 69.7 | 74.3 | 72.2 | 65.9 | 90.5 | 68.0 |
| SLOAN | 54.1 | 84.6 | 62.9 | 61.1 | 89.0 | 73.4 |
| ALL | 62.9 | 72.5 | 68.3 | 61.1 | | |

Table 7. Percentage of Vehicles Within ± 6 Inches Axle Spacing (3S-2).

| SITE | STEERING | | | DRIVER TANDEM | INTER TANDEM | TRAILER TANDEM |
|---|---|---|---|---|---|---|
| | CON | COE | TOTAL | | | |
| APEX | 30.8 | 51.3 | 42.7 | 84.9 | 44.3 | 88.1 |
| US95 | 18.2 | 34.3 | 26.5 | 77.6 | 16.7 | 86.3 |
| SLOAN | 22.5 | 26.8 | 24.7 | 58.8 | 30.6 | 60.7 |
| ALL | | | 31.3 | 71.9 | 44.8 | 80.6 |

Table 8. Test Site Characterisitics.

| Site | Location | Description | Condition | Roughness | |
|---|---|---|---|---|---|
| | | | | QI (inch/mile) | RMS (in) |
| A | Torey Pines Road | Concrete | Smooth/deteriorated | 166.5 | $0.586X10^{-2}$ |
| B | US 101 (MP 10.0) | Flexible | Rough | 178.4 | 0.191 |
| C | Mira Mesa Boulevard | Flexible | Smooth/new | 14.9 | $3.77X10^{-2}$ |
| D | US 101 (MP 7.5) | Flexible | Worn | 109 | 0.126 |

# WIM: The California Experience

*John Van Berkel, Jr., Office of Truck Studies*
*California Department of Transportation*

Three and one-half years ago, after the last Weigh-in-Motion (WIM) Conference in Atlanta, I was asked what I learned. My comment was that, if you rank the 50 states as far as what they have accomplished to date, California probably ranks about 48th. I think the situation is a little different today. In this presentation, I would like to briefly discuss why it is different today and where we plan to go with the Weigh-in-Motion Program in California; include a little background on how we got there since some of those things may be of benefit to others; briefly discuss some things we have learned from our program; and then define what we think still needs to be done.

For programming and budgeting purposes in California, we have four types of weigh-in-motion equipment. We have high-speed mainline; we have weigh-in-motion in our weigh stations; we have what we call mini-sites; and then like most other states, we have portable scales.

Currently there are seven high-speed mainline installations covering 22 lanes. All are connected via modem and telephone lines to a host computer in Sacramento. The cost of each installation was about $30,000 per lane for a turnkey operation which includes installation, roadside equipment and host computer software. Like all the rest of our systems, these installations report individual truck records. We do not "bin" the data, but want the capability to take a look at each individual record. Currently, all the systems we have are PAT bending plates, but there is nothing that says it has to be that way in the future. These installations are based upon performance specifications we have developed, and we would encourage every vendor to bid on future installations. We have developed a Master Plan for the high-speed mainline facilities which ultimately calls for about 120 sites. Currently, funding is available for about 70 sites in the next five years.

We currently have one WIM in a weigh station. It is in our Truckee Weigh Station. It's really a second generation of the Rusk, Wisconsin installation. The weigh station has two lanes in front of the weigh shack. The lane closest to the shack is the static lane and the further lane out is a 12' x 12' platform WIM. Each truck crosses the 12' x 12' platform WIM primarily because our Highway Patrol wants to give everyone a visual safety inspection. The WIM operates at five to ten miles per hour, and this is adequate for a visual safety review. Tied in with the WIM is an automated traffic control system. If the WIM detects the truck to be overweight, the traffic control system will automaticly route him around the racetrack and into the static lane for a reweighing. If the inspector wants to have a full safety inspection performed on the vehicle, he hits a "panic button" and the traffic control system will route the vehicle into one of the enclosed inspection bays. The philosophy is not to stop a legal operator because of an illegal or unsafe operation in front of him. Stopping the illegal operators and making them wait appears justifiable, but don't stop the legal operators.

In addition to our one installation in Truckee, we have three additional weigh station WIM retrofits under design which will be under construction this year. We have an additional five new or reconstruction weigh stations under design, and these will all have the weigh-in-motion feature in them. One of the more interesting retrofits is our Wheeler Ridge Station at the foot of the Grapevine on I-5. It has about 8,000 trucks per day with over 400 in the peak hour. In that weigh station, we will put in two lanes of weigh-in-motion in addition to the static lane, and for the Crescent Project, we are also going to add an AVI reader.

The third system we have is what is known as "mini-sites". These are really no more than wide spots in the road. We try to squeeze them in wherever we can and they each cost less than $250,000. The idea here is for the Highway Patrol to use a transportable WIM and have an instant, small weigh station.

The Highway Patrol will run the trucks across these WIMs and if they find somebody they want to statically weigh, they pull them ahead and use the static scales. The mini-sites provide a safe location along the roadside to conduct this operation. The Highway Patrol will probably operate these sites a couple of hours at a time, pick up, and move on to another site. We try to have everything prepared for them so it is a quick set up and a quick takedown. We want to create an enforcement presence and think we can do this with the mini-sites. Currently, we have 10 under construction in Los Angeles, 10 in design in San Francisco, and 10 in the planning stage in San Diego. As the Los Angeles sites get constructed/completed, the San Francisco sites begin construction, the San Diego sites begin design and the planning phase begins for the Sacramento sites. We anticipate about a five-year program for all sites statewide. On an adhoc basis, we have also approved such sites in new construction in the rural areas. Additionally, we plan to place the scale frames in the rest areas to create mobile weigh stations up and down the state. The only constraint, to date, is getting enough transportable WIMs for our Highway Patrol.

Briefly, that is our current program. So, how did we get there? Fortuitous timing is probably the biggest factor. A number of things have happened in the last three to four years that have emphasized the WIM program. We are in the middle of the Crescent Project both figuratively and literally. The commitment to put in weigh-in-motion for that demonstration probably more than anything got us into a weigh-in-motion mentality. The TMG requires us to put in 90 sites for the truck weighing portion. Our past Director was very supportive of the SHRP Project. We currently have 32 sites and the list is still growing. These sites, not necessarily at our TMG locations, also require significant weight data. There's supposedly a letter in Washington, D.C. urging us to do a better job of our urban weight enforcement. We also recently completed a cost allocation study which shows that overweights alone annually create $100,000,000 of pavement damage on the State highway system. That's an easy figure to remember, but it is also a figure that has some impact.

These were all issues which required us to do substantially more weighing than in the past. We used all of these issues to highlight the Weigh-in-Motion Program. We're a state where a successful administration is measured by the number of public employees on-board. The result is that we don't have the manpower to meet all these requirements with portable equipment. We came to the conclusion early on that we have to have permanent equipment. The Department bought this concept and we are moving forward with it. One of the things we have done in talking to our budgeting people is to compare our weigh-in-motion master plan to the roadway projects in our five-year highway program. If there is a highway project that is geographically close to a proposed WIM site and that project requires a roadway closure, the weigh-in-motion is made part of the roadway project. We have many roadway projects where the cost of traffic control is up to 50 percent of the total project. It is more cost effective if we can double up the projects for one roadway closure. One of the interesting ones coming up in the near future is on the Ventura Freeway (LA 101) rehabilitation project. We will be putting in six lanes of weigh-in-motion plus four lanes of classification, on a 270,000 ADT route. We would never be able to get the necessary traffic control on such routes just to put in WIM.

As far as the weigh stations are concerned, most of the new facilities were already under design. Truckee did show, however, that weigh station WIM allowed the Highway Patrol to do a better job of safety inspection while at the same time coming up with a better weight enforcement program than could be done with just static scales. The weigh station WIM is something that had benefits for everybody. Truckee, when it was first opened, recorded in the neighborhood of 15 percent overweights. Part of the reason for this high figure was that the WIM equipment could detect bridge violations which are not normally detected at static scales. That overweight figure has now stabilized at about 3 percent. This 3 percent is a pretty good detection rate for weigh station, but that is not the major point. The major point is not what you are getting but, in fact, what you are preventing. In the Truckee case, we have about 12 percent of the vehicles that are no longer coming through in an overweight condition. Since a goal of a the Highway Department is to prevent pavement damage, Truckee is certainly contributing to that goal.

It has be mentioned that the issue of overweights is really an economic issue. We agree with that and, from that perspective, we are putting a lot of emphasis on where weigh stations are placed. We try to block out a corridor. If somebody wants to bypass a scale, it is going to cost them. To bypass Truckee, for example, it is going to cost from four to six hours and about 200 miles. That is an economic impact and should have an impact on the number of overweights.

As for the mini-site program, we had some Federal urging to improve the operations in the urban areas. Weigh stations in the urban areas are of questionable value. Where we have them, we get complaints from the local agencies because the overweight trucks are using their facilities, and this results in negative publicity. We think the mini-site concepts, where the Highway Patrol can come in for a short period and quickly move on to another site, will discourage the overweights. If an overweight vehicle doesn't know where or when the enforcement is to occur, there is less likelihood of making that trip. We are also using the mini-sites in some of our rural areas. At a recent meeting on a rural weigh station, there was a concern that there might be a bypass route. A possible solution is to put in a mini-site on the potential bypass and operate it in conjunction with the weigh station.

What have we learned from all this? One thing is that data and information are not the same thing. We could have enough computer printout to fill a large room in less than a week. That is a lot of data, but it doesn't tell you much. You have to be able to analyze it. What is absolutely needed is a data management plan. You have to know who gets what data when and in what format. Some people need real-time data; some can get by with monthly or weekly summaries; others need individual records for each vehicle. You need a plan on how you are going to work with your data and who's going to receive and use it. We have talked to most of the individual Divisions within our Department. We have talked to the Highway Patrol and the Motor Vehicles Department. We think we have a pretty good idea of who needs what. This will also help us to define the kind of computer hardware we need and help define our collection schedule. There is a strong need to define a data program early in the process.

We have used this data, incidentally, for more than just the normal pavement design and pavement maintenance activities. We have used WIM data extensively to help us in policy issues related to the STAA access issue. For example, we found out that 99 percent of the doubles in California are less than 75' long. The 75' long double can legally operate in California and, therefore, it is not an STAA access issue. Until we got the WIM data, we really didn't know that. Related to that is the issue of semitrailer tractor length. We have determined that the tractors are getting longer. Twenty-five percent of the semi tractors in California operate at more than a 240" wheelbase. That is substantially longer than we have seen in the past.

There are many enforcement uses that can be made of this data. What we hope to do is to give the Highway Patrol a "next morning" summary of all the WIMs in operation to use in deploying their mobile enforcement people. We think that is a very valuable piece of management information. We have also found that remote weigh stations have a tendency to define their own enforcement standards. We have given the Highway Patrol management detailed data from our weigh-in-motion stations which they can compare to the weigh station data. They have used that data for their own weigh station management.

As far as WIM equipment installation and use, we believe we have learned a few things here also. One is that pavement smoothness is critical to a good WIM operation. We now have a policy that when we put in the mainline weigh-in-motion, we will grind the pavement on the approach to that site. We did a comparison of the same equipment and basically the same type of roadway. Previously, if the roadway smoothness at the WIM site still met our construction standards, we did not grind that pavement; we just left it as it was. Where the pavement did not meet the construction specifications, we would grind the pavement ahead of the WIM site. We found that the random error with pavement grinding was 2 to 3 percent better than where the pavement was not ground but did meet construction specifications. Pavement smoothness on the approach to a WIM is a critical issue.

On our mainlines where we do grind, our random error is in the 2 to 3 percent range. We think these are real good results. As far as the accuracy of the weigh station WIM is concerned, we had a situation a few weeks ago where a triple came into Truckee (triples are not legal in California). He was carefully weighed on the static scale, and we compared that to the WIM reading. Every one of the nine axles on the triple was within 200 pounds comparing the WIM to the static weight. We think that is pretty good accuracy.

Just a few words on calibration. Calibration is an issue that is still a problem. It is interesting how things grow up together around the country. We didn't know until a week ago that Arizona Department of Transportation was experimenting with a Falling Weight Deflectometer (FWD) for calibration. We have done some work in that area in the past and have had good results. The problem, at least theoretically, is that an FWD will only replicate one speed of the vehicle. We think the use of something like the FWD has the potential to substantially ease the calibration burden and is an area that needs to be explored further.

We are also aware of the steer axle calibration issue. In California, the figures average 10,000 pounds for semi steer and 9,000 for double steer axle. We are not ready to calibrate a WIM using those figures. What we do use those figures for is to check the calibration. When a WIM station begins operation, we collect a week's worth of steer axle weights to establish a historical base for that specific location. Periodically, when we download a site, we run that data through a utility program, comparing that data set's steer axle values with the historical values for that site. From this, we determine if the system is still calibrated. You don't have to go out unnecessarily with a crew to check the equipment, it can be done from the office.

We do believe the whole issue of calibration needs to be much better addressed than it is today. Calibrating WIM scales using hundreds of actual vehicles is extremely expensive, both from an equipment time and personnel time prespective. We just don't have the time for this, especially, if we are looking at 100 or more sites. We hope the NCHRP 3-39 work goes a long way towards addressing this issue.

A second thing we think is needed is what we call a weigh-in-motion or WIM controller. We would like to take a single roadside computer and be able to plug it into any transducer. We think there are major benefits to such an approach. You would end up with a standardized data flow and format which would allow integrating data from different vendors' transducers, something we have a problem with today. From a maintenance perspective, if a WIM station goes out, you simply unplug the on-site computer and plug in a new "black box". You don't have to worry about having the right kind of box--you've got a standardized box. Also from a maintenance perspective, it is easier to have a maintenance technician working with one box he has to become familiar with than a whole multitude of boxes, each operating differently.

The other thing we need is better telecommunications. Several months ago, our commercial phone bill for the six Crescent sites was about $700. We download data from the roadside to our host computer at night to get the best rates and send the data in compressed binary format to minimize the transmission time. With 70 to 100 sites and this method of operation, we can still end up with an annual $100,000 phone bill. We also have a problem with our high-speed modem failing in the roadway environment. We think some work needs to be done there. The idea of fiberoptics for a telecommunication network is something that intrigues us and is something that we are pushing.

In summary, that's where California currently is in the weigh-in-motion. To use a California surfing term, we are on the crest of a wave, a lot of people created that wave, and we just hope we can ride it out smoothly to the shore.

# EVALUATION OF A WEIGH-IN-MOTION (WIM) DEVICE AT THE PAVEMENT TESTING FACILITY

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## Introduction

The Federal Highway Administration (FHWA) Pavement Testing Facility (PTF) consists of two 200 foot asphalt concrete pavements which are loaded by the Accelerated Loading Facility (ALF) machine. The ALF machine simulates truck traffic by modeling one-half of a single truck axle with dual tires. ALF can apply loads ranging from 9,400 lb to 22,500 lb (equivalent to 18,800-lb to 45,000-lb full axle loads) at a constant travel speed of 12.5 miles per hour, loading the pavement once every 9.5 seconds. The pavement itself is instrumented with strain gauges, moisture sensors, and thermocouples, and dynamic deflection is measured with a surface deflection beam. (1)

Tests at the PTF last from approximately 1 week to 6 months, depending upon the combination of the structure of the test pavement and the load applied. In a test lasting from May through October, 1988, a pavement constructed of 7 in of asphaltic concrete over a 12 in crushed aggregate base is being subjected to at least 800,000 applications of a 16,400-lb load, equivalent to approximately 5.4 million AASHO equivalent axle loads (ESALs). Because ALF models one-half of a dual-tired axle, this is equivalent to an axle weight of 33,200 lbs. Pavement performance studies are supported through collection of data to quantify effects of temperature, pavement roughness, location of loading along the transverse axis, and tire pressure.

The ALF is unique in its ability to apply controlled, variable magnitude loads to a pavement. Loads are changed by adding or removing steel plates from the trolley by means of a crane, an operation that takes less than 20 minutes per plate moved (there are five plates available in the load range). The trolley is fitted with four load cells to permit measurement of dynamic loads at any point in the loading path. Tire pressures are changed manually with a standard compressed air hose. Pavement primary responses (stress, strain, and deflection) are monitored through extensive instrumentation, and secondary responses (rutting, cracking, and deformation) are tracked at close intervals as they appear. As a laboratory facility, it is highly accessible to operations and research personnel. A drawing of the ALF trolley appears in Figure 1.

Within the framework of the main pavement testing experiment, a special experiment was conducted. In a project jointly sponsored by the Pavements Division of the Office of Highway Operations Research and Development, and the Demonstration Projects Division of the Office of Highway Operations, a low-cost vehicle weight and classification system was installed at the PTF. This device, manufactured by GK Instruments of Milton Keynes, England, uses piezoelectric cable sensors installed across the full width of a traffic lane. The sensors are connected by coaxial cable to a microprocessor unit which translates the signals into vehicle weights and determines the classification (FHWA Scheme F) of the passing vehicles in the traffic stream.

## Background

The FHWA has supported a number of projects in the past several years which have dealt with aspects of WIM and automatic vehicle classification equipment. The projects, sponsored under the Rural Technical Assistance Program (RTAP) have highlighted equipment testing and evaluation, as well as coordination of data for transportation and enforcement of vehicle weight limits.

One current project, Demonstration Project 76, included an activity for field testing a piezoelectric weight and classification system. Systems were installed in portland cement concrete pavement in Iowa and in asphalt concrete pavement in Minnesota. The researchers found differences in accuracy between the two field installations. Additional concerns were raised on the precision of the system. (2) As these were field installations, there were uncontrollable aspects, primarily in the traffic exposure received. One of the asphalt pavement installations had not performed well, requiring a change to the anchoring of the channel.

The extension of the project to add an experiment at the PTF served several functions. The protected setting was an ideal location to thoroughly check and evaluate the sensor installation procedure. As the ALF machine applies a constant, controllable load at a constant speed, it would complement the field experiments. The relatively heavy loads applied over a short period of time would provide a clearer picture of the physical aspects of the installation, and an opportunity to observe and document any deterioration of the pavement or of the sensor-pavement bond. Finally, the availability of a broad range of test and analysis equipment at the PTF would provide the researchers the opportunity to examine the interrelationships among the ALF, the pavement, and the WIM device in ways that would be impractical in a field setting.

## Research Approach

The purpose of our evaluation of a piezoelectric WIM at the PTF was threefold:

1. To determine the suitability of the ALF for controlled testing of a pavement-mounted WIM device under repeated constant loading and under variable loads, tire pressures, and transverse locations.

2. To assess the durability of the piezoelectric cable assemblies.

3. To determine the accuracy of the piezoelectric system under varying conditions of load, tire pressure, environment, and pavement distress.

As discussed above, the PTF has two unique testing capabilities appropriate to studying the performance of WIM systems. First, the ALF testing machine can simulate 20 years of normal highway traffic during a 6-month accelerated loading test. Using this capability, the durability of the piezoelectric cable assemblies and their installation could be determined. Second, the applied load, tire pressure, and lateral load location are easily changed, permitting evaluation of the accuracy of the WIM system. These evaluations could be conducted at various times during the life of the pavement to determine the effect of pavement distress on the accuracy of the system.

Initially, the research plan consisted of installing the WIM system at the beginning of an accelerated loading test, calibrating the system using five load levels, and studying the durability and accuracy of the system throughout the life of the pavement. Additional experiments were designed to study the effects of tire pressure, lateral load location, and temperature on the accuracy of the WIM system. This experimental design is shown in Table 1.

The initial plan to assess system accuracy was modified when a repeatable calibration factor for the WIM system could not be determined due to several factors, including modifications to the GK Instruments translation equipment and the particular test combination of a heavy axle on a relatively thin pavement. In an effort to understand the fundamental operation of the piezoelectric sensors themselves, their output, after amplification but prior to signal processing, was monitored. A series of tests was conducted to determine the effects of load, tire pressure, and lateral load location on the output of these sensors.

## Installation of the Piezo WIM

FHWA's Demonstration Projects Division provided the same system used in the Iowa and Minnesota projects, consisting of a pair of piezoelectric cables mounted in aluminum channels, a

Table 1: Planned Experimental Design

| | Load Levels | Tire Pressure | CL Offset | Air Temperature |
|---|---|---|---|---|
| Accuracy | 4* | 1 (100 psi) | 0 | min variation |
| Temperature Study | 1 | 1 | 0 | varies |
| Location | 1 | 1 | min 3 | min variation |
| Tire Pressure | 1 | up to 6 | 0 | min variation |

* 11.6, 14.0, 16.4, 18.9 kips

translation unit, a transformer, and coaxial cable. The equipment arrived at the PTF in the first week of May to coincide with the commencement of testing a new pavement section. Because the long-term physical integrity of the system was unknown, the cable channel sensors were placed near the end of the test pavement. The lead sensor would be placed 30 feet downstream of the trolley starting point, the second sensor, 34 feet downstream. In the event that the channels introduced localized distress, the 6-month performance experiment would not be significantly affected.

A high-quality installation is critical to the sensor's long-term durability, the maintenance of the pavement-sensor bond, and the ability of the sensor to read applied loads correctly. The sensor itself must be properly seated, and the support must be continuous along its length to prevent formation of stress risers in the pavement. With the exception of traffic control, obviously not necessary in a laboratory setting, the installation procedure was nearly identical to that performed in the field.

The pavement was marked and the outer edges of the planned sawcuts marked with masking tape. Sawing was done with a water-cooled, single blade saw. A gang saw would have speeded the operation, but was not available from local rental yards. Excess material was removed by hand-chipping to obtain the proper depth and width for the channel. The slots were cleaned with compressed air and dried with a heat gun. The edges of the slots were masked with duct tape to protect the pavement from possible damage resulting from removal of excess epoxy from setting the channels. Because the procedure was halted at this point by a thunderstorm, the cleaning, drying, and marking steps were repeated the next morning immediately prior to placing the channels. The free ends of the coaxial cables were brought into the PTF office trailer and tested for continuity.

A two-part epoxy system, such as is used to set traffic control loops, was used to set the channels. Short steel plates had been wired transversely to the longitudinal axis of the channel to allow the surface of the channel to mount flush with the pavement surface and not float above or below it upon the pool of epoxy. Holes were drilled in the pavement slots to accept 3-in long anchor rods attached to the underside of the channels to provide additional protection against transverse movement. Coaxial cables were connected to the channels and placed in the sawcuts. The epoxy was mixed immediately before placement, and was carefully poured into the slots. The channels were placed, beginning at the outside of the test lane to permit the slope of the pavement to set up a standing wave of epoxy from the highest to the lowest elevation (in the field, the installation would begin at the pavement centerline to obtain this effect). Excess epoxy was removed with drywall knives, and the channels weighted to maintain the top surface flush with the pavement. The placement operation took approximately 1 hour for each channel. Around 3 hours later, the epoxy was sufficiently hardened to permit the weights to be removed, and the protective tape with its coating of excess epoxy to be stripped. The installation was carefully checked for gaps between the channel bondbreaker (quarter-inch foam on the vertical faces of the channel) and the sawcuts. Gaps were filled with epoxy and high spots were filed down by hand. These initial repairs were recorded for later reference in case of future localized failures.

Once the coaxial cable sensor placement was checked, initial testing was begun. The piezoelectric cable channel sensor was struck with a mallet to verify that a loading signal would be generated and recorded. When the ALF was started, however, no readout was produced. The system's manufacturer indicated the ALF's single pair of dual tires constituted a half-axle, or "unicycle" configuration which was not recognized by the classification firmware. The manufacturer prepared and sent a replacement programmable read- only memory (PROM) chip to provide the ability to classify the ALF loading. An additional adjustment was made to reduce the sensitivity of the signal translation unit to enable it to deal with the deep deflection basin produced by the 16,400-lb ALF trolley traversing the 7-in asphaltic pavement.

### Calibration

While the overall experimental plan for this pavement section of the PTF called for ALF operation at a 16,400-lb load, the WIM evaluation required testing at different load levels at intervals in the pavement life. The initial test cycle took place during the period May 20 through June 3, 1988.

Weigh-in-motion systems are usually calibrated using static vehicle weights. Since the ALF trolley is instrumented with load cells to monitor dynamic load variation, the WIM system installed at the PTF could be calibrated using both static and dynamic loads. Our initial calibration plan was to obtain static and dynamic calibration factors at five load levels: 9,400 lb, 11,600 lb, 14,100 lb, 16,400 lb, and 19,000 lb. The calibration was performed using the procedure outlined in the Castle Rock Consultants (CRC) report on the Iowa and Minnesota tests (2). The procedure described the number of observations necessary to establish the calibration factor based on the standard deviation of the readings, the desired accuracy, and the confidence level. The load cells on the ALF trolley and the raw WIM readings were sampled simultaneously. The means and standard deviations of the load cells and the WIM readings were calculated. (See Table 2.) The static calibration factor was defined as the ratio of the static trolley weight to the mean of the WIM readings. Similarly, the dynamic calibration factor was defined as the ratio of the mean of the load cells to the mean of the WIM readings. These early calibrations showed accuracies similar to those obtained from flexible pavements under mixed traffic.

Table 2: Comparison of Static and Dynamic Calibrations

| Static Load, lb | WIM Mean, units | WIM SD | Load Cell Mean lb | Load Cell SD lb | Static Cal. | Dyn Cal. | Computed Static Wt, lb | Computed Dynamic Wt, lb | % Diff, Dyn vs Stat Wt |
|---|---|---|---|---|---|---|---|---|---|
| 9400 | 528 | 21 | 9471 | 28.6 | 1.78 | 1.79 | 9398.4 | 9451.2 | 0.56 |
| 11600 | 654 | 26 | 11795 | 42.6 | 1.77 | 1.80 | 11575.8 | 11772.0 | 1.69 |
| 14100 | 797 | 23 | 14525 | 69.6 | 1.77 | 1.82 | 14106.9 | 14505.4 | 2.82 |
| 16400 | 877 | 33 | 16449 | 66.0 | 1.87 | 1.88 | 16399.9 | 16487.6 | 0.53 |
| 19000 | 978 | 30 | 19224 | 88.2 | 1.94 | 1.96 | 18973.2 | 19168.8 | 1.03 |

* 9400-lb, 11,600-lb, 14,100-lb level calibrated 5/20, others 5/23

At this point, several potential sources of systematic measurement error were known. The sensitivity of the translation unit had been adjusted to deal with the particularly deep deflection basin produced by the ALF load-pavement thickness combination, and the classification software had been modified to deal with the ALF's "unicycle" loading pattern. We were also testing at the low end of the velocity range of the system: it is designed to operate between 9 and 140 mph, and the ALF trolley travels at 12 mph. Loads were to be applied at the centerline of the lane; in the field, loads are applied near the ends of the device, in the vehicles' wheeltracks.

For the first calibration at 9,400 lb, 400 passes were sampled. An analysis of this data indicated the standard deviation of the WIM readings and the load cells were small enough that only 100 readings would be needed to obtain an accuracy of 1% at the 95% confidence level. The ALF loading was then changed to 11,600 lbs and 14,100 lbs, and the calibration procedure was repeated at those levels later that day. The following week, the calibration procedure was run at the higher load levels, 16,400 lb and 19,000 lb, and also repeated at the lower levels. All calibration runs were made with the ALF at the centerline of the test section. The pavement temperature was recorded before and after testing. Data is presented in Table 3.

Table 3: Static Calibration Runs, sorted by load level

| Date | Load, kips | WIM Mean, readout units | WIM SD | Cal | Total Sampl | # Miss | % Miss | Usable Sample | Near Surface Temp | Avg Air Temp |
|---|---|---|---|---|---|---|---|---|---|---|
| 5/20/88 | 9.4 | 528 | 21 | 1.78 | 419 | 20 | 5 | 399 | 60 | 60 |
| 5/20/88 | 11.6 | 654 | 26 | 1.77 | 107 | 3 | 3 | 104 | 60 | 60 |
| 5/24/88 | 11.6 | 753 | 28 | 1.54 | 142 | 36 | 25 | 106 | 70 | 69 |
| 5/25/88 | 11.6 | 734 | 25 | 1.58 | 128 | 25 | 20 | 103 | 62 | 64 |
| 5/20/88 | 14.1 | 797 | 23 | 1.77 | 162 | 10 | 6 | 152 | 59 | 59 |
| 5/24/88 | 14.1 | 808 | 26 | 1.74 | 157 | 52 | 33 | 105 | 74 | 71 |
| 5/23/88 | 16.4 | 877 | 33 | 1.87 | 164 | 13 | 8 | 151 | 67 | 65 |
| 5/24/88 | 16.4 | 900 | 32 | 1.82 | 156 | 53 | 34 | 103 | 73 | 70 |
| 6/1/88 | 16.4 | 939 | 36 | 1.75 | 116 | 16 | 14 | 100 | 64 | 66 |
| 6/1/88 | 16.4 | 931 | 26 | 1.76 | 200 | 92 | 46 | 108 | 73 | 69 |
| 6/1/88 | 16.4 | 917 | 32 | 1.79 | 200 | 80 | 40 | 120 | 86 | 80 |
| 6/2/88 | 16.4 | 1031 | 30 | 1.59 | 116 | 16 | 14 | 100 | 57 | 63 |
| 6/3/88 | 16.4 | 917 | 23 | 1.79 | 108 | 6 | 6 | 102 | 55 | 59 |

The results of these initial tests show significant variation in the mean WIM readings and calibration factors over a short period of time, as well as with temperatures. To further quantify this variability, additional runs were made over a two-day period at the 16,400 lb load level. Again, all runs were made with the ALF at the centerline of the test section and with pavement temperatures recorded. ALF dynamic loads measured by the load cells have a fairly small standard deviation (25 lb to 100 lb) which varies with each load level. (See Table 4.) In the early tests, these values were highly predictable. Unfortunately, two of the four cells began operating erratically on May 24 and could not be relied upon to provide meaningful data during the remainder of the experiment. As a consequence, it was not possible to obtain additional dynamic calibration data.

Table 4: Statistics, ALF load cell readings

| Filename | Load(kip) | N | Min | Max | Mean | Median | SD |
|---|---|---|---|---|---|---|---|
| TestA001 | 9.4 | 399 | 9274 | 9600 | 9471 | 9468 | 28.6 |
| CalA001 | 11.8 | 97 | 11717 | 11887 | 11795 | 11788 | 42.6 |
| CalA002 | 14.4 | 149 | 14366 | 14783 | 14525 | 14530 | 69.6 |
| CalA003 | 16.4 | 147 | 16310 | 16589 | 16450 | 16464 | 66.0 |
| CalA004 | 18.9 | 150 | 19019 | 19377 | 19225 | 19224 | 88.2 |

Readings misinterpreted by the WIM device generated classifications of two-axle, and occasionally three- and four-axle, vehicles at higher pavement temperatures (generally above 75 degrees F ) and higher load levels (16,400 lb and 19,000 lb). No vehicle weights are displayed . As there is obviously no way to control the pavement temperature, the number of loading cycles was increased to obtain a minimum of 100 valid readings for a given test. The number of extra readings required was around 25 to 35 percent (125 to 150 total) at the 16,400-lb level. Total sample, "missed" readings, and computed calibration factors for different load levels on different dates also appear in Table 3. The frequency of misinterpreted readings seemed to be related to both the load level applied and the pavement temperature. The choice of methodology for adding an additional classification factor for the ALF trolley, while permitting the device to continue to classify the remaining 13 vehicle types, also played a role. This last issue is further explored in the section on secondary testing.

The 12 individual sets of calibration data were tested for normality using the univariate procedure in the Statistical Analysis System (SAS) software package (3). Applying the empirical rule at a 95 percent limit (two standard deviations from the mean), the data may be considered as near normal, but with a slight negative skew (4). While this could indicate a systematic error in the WIM unit towards under weighing, the separate and combined effects of the pattern and magnitude of pavement loading, and the hardware and software modifications in the tested device, may well have played a more significant role.

The observed inconsistencies in calibration factors from individual data sets collected at different load levels, as well as the issue of missed classification, emphasized the need for an alternative method to evaluate system accuracy.

## Secondary Testing: Sensor Response

There were several opportunities for inconsistencies to be introduced into the chain of signals between the sensor cables in the pavement and the LCD readout panel. The basic principle upon which the piezoelectric sensor operates involves translation of applied pressure to a voltage signal.

Pressure from the wheel load is converted to a voltage signal by the piezoelectric cable sensor. This voltage is transmitted from the sensor to the translation unit. Within the translation unit itself, these voltages are converted to vehicle weight-equivalent readouts. The transducer acts as a switch to classify vehicles based on the distance between axles, measured as a function of time. The weight-equivalent readouts were raw readings because we had elected not to set the calibration factor. A raw reading had to be multiplied by the factor to obtain the weight of the passing vehicle, or a vehicle-equivalent in the case of the ALF trolley. While a laboratory bench calibration gives a linear relationship between applied load and the resulting output voltage, the viscoelastic pavement response has the potential to delay, and ultimately change, the output.

Flexible pavements are viscoelastic. They return to nearly their original dimensions after being deformed by passing loads. They also accumulate permanent deformations over longer periods of time and numerous load applications which do not disappear after the loads are removed. Deformed pavements react differently to applied loads. The deformations themselves, generally rutting in the case of repeated loading apparatus such as the ALF, cause the loads to affect the pavement differently. Because flexible pavements are also viscous to a certain degree, the pressure is not instantaneous, but is subject to a small, but measurable, time delay. The response of the flexible, and viscous, pavement is slower than that of the stiff aluminum channel holding the cable sensor.

Although the ability to capture matched dynamic load and WIM readings had been lost with the malfunctioning of two load cells, we wished to make at least a rough comparison of differences in readings with variations in tire pressure. The first cycle was run at the performance-test inflation pressure. The inflation pressure was raised for the next cycle at the same load level. We found, to our surprise, that the inflation pressure had been considerably lower than the 100 psi it should have been for the main experiment. One of the tires on the ALF trolley had a slow leak that was traced to a cracked rim, which was repaired.

More significantly, we began to question if the readouts from the WIM device were dependent upon more than the static load of the axle running over the sensors.

Before this avenue could be pursued, it was necessary to bypass the portion of the translation unit (readout box) which converted the voltages to weights and classifications before passing them to the readout panel. Following the manufacturer's instructions, we located the point in the circuit where the voltage outputs produced by the piezoelectric cables entered the translation unit. We connected a second microcomputer with an external color monitor and a Keithley Instruments data acquisition system directly to that point. The Keithley system was configured to permit the computer to be used as a four- channel storage oscilloscope to enable us to visually monitor and digitally sample the voltages, and to store them for later playback and comparison.

A typical trace is shown in Figure 2. The time difference between the peaks represents the time to transverse the 4 ft between the cable sensors. While the difference in the amplitudes of the peak voltages of the two traces is very small, the minimum and maximum output voltage levels were noticeably different. According to the manufacturer's literature and the CRC report (2,5), weights are determined from the averaged outputs of the two sensors. As the lifting of the ALF trolley produces second-sensor output curves that are not smooth at the trailing end, all traces which follow are those of the first (leading) sensor.

The spikes in the trailing portion of the signals should be noted as well. According to the manufacturer, this signal noise may be read by the translation system as "ghost axles," and have been interpreted by the system as an expectation of a signal from a trailing axle. While the classification software had been modified to accept the ALF's "unicycle" loading, its ability to recognize the Traffic Monitoring Guide classifications had not. The system's recognition of a non-unicycle classification, when in fact the ALF was incapable of producing one, led to a missed reading, not to a misclassification, as had earlier been assumed. An alternative approach to modifying the classification software, where only the unicycle loading was recognized, would likely have avoided this problem. (6)

A series of load tests was performed at different tire pressures, different loads, combinations of load and tire pressure which produced equivalent values of contact area, and different lateral positions. The experimental cells comprising this series of tests are shown in Table 5. Limitations in the storage capacity of the individual software files permitted only four to five cycles of loading to be collected for each cell, but a careful qualitative comparison of the traces showed them to be highly consistent for a given test setup.

Table 5: Experimental Cells for Sensor Response Experiment

| | Test # | PSI | Load | Load/PSI |
|---|---|---|---|---|
| Effect of Tire Pressure at Constant Load | 10 | 76 | 16400 | 215.79 |
| | 14 | 100 | 16400 | 164.00 |
| | 12 | 140 | 16400 | 117.14 |
| Effect of Load at Constant Tire Pressure | 34 | 100 | 11600 | 116.00 |
| | 28 | 100 | 14100 | 141.00 |
| | 14 | 100 | 16400 | 164.00 |
| | 20 | 100 | 19000 | 190.00 |
| Effect of Load at Constant Contact Area | 32 | 76 | 14100 | 185.53 |
| | 14 | 100 | 16400 | 164.00 |
| | 22 | 120 | 19000 | 158.33 |
| Effect of Lateral Location | 14 | 100 | 16400 | 164.00 |
| | 16 | 100 | 16400 | 164.00 |
| | 18 | 100 | 16400 | 164.00 |

Time constraints did not permit a quantitative analysis of the traces, and, because the translation algorithms are part of a proprietary system, they could not be obtained from the manufacturer. From a qualitative standpoint, it may be noted that the general shape of the voltage traces is highly consistent for applications of constant loads. The shape of the trace changes with the magnitude of the applied load, with the rise and fall becoming steeper at both increased load levels and increased tire pressures.

A series of traces at four load levels, holding tire pressure constant at 100 psi, is shown in Figure 3. Under these conditions, the contact area of the tire will increase with increasing load. While the most noticeable difference among the curves is in their peak voltages, the minimum voltages at the beginning and end of the loading cycle show variations in magnitude as well. The rising slopes for the two heavier loads are less steep than those for the lighter ones.

Figure 4 illustrates the effect of changes in tire pressure while holding the load level constant. In this case, contact area increases with decreased tire pressure. Again, the condition providing the lowest contact area gave the highest amplitude voltage output. In this case, however, there is little difference in rising slopes of the three traces, and essentially none in the falling slopes. The period of the loading cycle decreased slightly at the higher tire pressures and their associated smaller footprints.

The traces in Figure 5 were produced from three combinations of loads and tire pressures which provided constant computed contact area. The rising and falling slopes showed a pattern most similar to those of the constant load/varying tire pressure combination in Figure 4. While the peak output voltage for the heaviest load is less than that of the intermediate load, the base-to-peak amplitude is slightly higher.

Effects of lateral load location are shown in Figure 6. A constant load of 16,400 lb with tire pressure of 100 psi was applied at the longitudinal centerline of the lane and at right and left offsets of 16.5 in. The peak amplitudes were nearly identical for the centerline and left offset loads, while the return traces were closest for the right and left offset loads. The amplitude of the right-offset trace was somewhat lower than for the other two.

It should be kept in mind, however, that the ALF applies load through a half-axle and the cable is deformed in a single deflection basin rather than the two transverse, parallel deflection basins produced by a full axle.

Figure 7 illustrates the superposition of the WIM voltage curve with the pavement deflection basin. The basin was measured with a deflection beam and sampled at the same time as the WIM sensors, but on an independently-operating microcomputer. The WIM voltage signal is located very deep within the deflection basin. The peak of the WIM signal also is ahead of the trough of the deflection basin, due to the slower reaction time of the viscous pavement and the stiff sensor channel. Another instance of the "ghost axle" spike may be noted toward the trailing end of the signal trace.

The area under the voltage curve is related to the magnitude of the passing load (6). Several methods may be used to determine the area under the voltage curve within the signal analysis and translation routines. The deflection basin curve may be extended, which provides the most complete picture of pavement-sensor interaction, but is the most complex from an engineering and mathematical standpoint. The deflection basin curve extension may be approximated with a line between the inflection point and the global minimum, or it may be chopped off at the inflection point with a horizontal line representing a low-pass filter. Both of these introduce a degree of systematic error because the voltage signal is not centered in the deflection basin of a flexible pavement. In a much stiffer pavement, such as a portland cement concrete or a very stiff asphalt, the signal would be more closely centered and the errors would be less. The fourth method would chop the signal at the baseline voltage. If the signal is at any depth in the deflection basin, this last method introduces very large errors.

Figures 8 and 9 illustrate the appearance of the WIM signals after subtracting the deflection basin, as described in the first method above. The trends illustrated by these sets of curves are similar to their counterparts in Figures 4 and 5. Figure 9 indicates a greater reliance on magnitude of load compared to that of contact area in the curve's peak amplitudes.

Table 6 shows a comparison of three computations of the areas under the voltage curves taken for a trolley load of 16,400 lb at tire pressures of 76, 100, and 140 psi. Method 1 utilizes the full deflection curve, Method 2, the straight line approximation, and Method 3, the signal chopped at the baseline voltage. The first line of each entry represents the area in volts x seconds, the second represents the ratio of the areas for each method, assuming the value at 76 psi to be the baseline. Excellent agreement was noted among the sets of three readings for Methods 1 and 2, as would be expected for a constant load. Method 3 provided very poor agreement.

These comparisons were extended to the amplitudes and areas of the curves to observe their relationships, if any existed, to tire pressure as well as load. These are illustrated in Figures 10 through 13. The strongest linear relationships were observed between amplitude and tire pressure (Figure 10) and between load and area (Figure 13). In the latter, the range of the amplifier may have been exceeded, causing the relationship to break down at the 19,000 lb load.

Table 6: Comparison of Areas Under Voltage-Time Curves:
16,400 lb load; 3 tire pressure levels

| | 76 psi | 100 psi | 140 psi | |
|---|---|---|---|---|
| Method 1 | 0.0558 | 0.0562 | 0.0578 | units |
| | 1 | 1.01 | 1.04 | ratio (base=76 psi) |
| Method 2 | 0.0515 | 0.0532 | 0.0540 | |
| | 1 | 1.03 | 1.05 | |
| Method 3 | 0.00591 | 0.0109 | 0.0183 | |
| | 1 | 1.84 | 3.10 | |

## Durability

The aluminum channels holding the cables seated themselves to conform to the contours of the pavement. Ruts reached a depth slightly over 1/2 in after 550,000 cycles. No localized distress was noted until 500,000 cycles (approximately 3.4 million ESALs) of loading, the same time cracking began in other areas of the test pavement. After approximately 725,000 cycles (4.9 million ESALs) the bonds broke between the second sensor and the pavement. The piezoelectric cable sensors continued to generate a consistent electrical signal. After this point, the pavement began to deteriorate more rapidly. An ellipsoidal cracking pattern developed along the major axis of both sensors. An examination of the voltage traces after approximately 763,000 passes ( 5.2 million ESALs) showed a significantly higher amplitude from the second sensor. This indicated that the deflection of the sensor was now independent of that of the pavement.

## Summary

A GK Instruments piezoelectric weight and classification system has been undergoing field testing in Iowa and Minnesota under Demonstration Project 76. The Demonstration Projects Division and the Pavements Division extended the project to include a series of controlled tests at the PTF/ALF located at the Turner-Fairbank Highway Research Center. The system was installed in May of 1988 and tested until October.

The original experimental plan called for a factorial design to determine the accuracy of the system under changing loads, tire pressures, and transverse loading locations. As several modifications had been made to the signal translation unit to permit it to accommodate the ALF's unicycle loading pattern, the plan was altered to concentrate on the output voltage signals themselves instead of the translated weight and classification readings.

There was no systematic pattern to calibration factors determined at different temperatures under constant weight. The source of this variation could not be determined. There were three potential sources: slight variation in the ALF loading pattern, variation in the manner in which the cables sensed loads, and variation in the translation of the voltages to weights and vehicle-class readouts. In addition, the signal analysis and translation system had been modified for this experiment. As noted above, the classification scheme was modified to handle the ALF's unicycle loading configuration, and the sensitivity level of the device had been reduced to deal with the deep deflection basin imparted by the ALF trolley to the pavement section. Finally, the ALF's travel speed of 12 mph is near the lowest range of the WIM device (9 to 140 mph).

Voltage data were collected directly from the piezo cable sensors instead of using the translated weight and classification readouts. These direct voltage plots have been quite consistent at constant loads, and have also shown systematic variation with changes in load. A second series of tests at different tire pressures showed variability similar to that observed in the early calibrations. A third series of tests at combinations of loads and tire pressures which provide a constant tire contact footprint appear to indicate that the system may be sensitive to the unit load as well as to total load. This leads to concern that different combinations of loads and tire pressures may not be properly weighed.

It was not possible to verify the techniques used to translate the voltage signals as this is part of the proprietary hardware and software developed by GK. GK had supplied a modification to the electronics necessary to classify the "unicycle" loading pattern of the ALF; we do not know if the translation algorithm for this loading pattern is the same as that used in the production units in the field.

The tests performed have provided a unique picture of the operation of this device. Use of the ALF to apply constant repeated loads and variable loads and tire pressures has been invaluable in assessing the WIM device. The testing was somewhat limited by the need to operate the ALF continuously over the planned time period for the pavement performance experiment.

## Conclusions

The ALF appears to be well suited for controlled testing under repeated constant loading and under variable loads and tire pressures. The range of applied loads as recorded by load cells on the ALF trolley is very small, on the order of 1.9 percent to 3.4 percent over the ranges tested. Care must be taken to place the sensors within the longitudinal range of constant loading to avoid the problems of trolley bounce at the ramp (load) end and temperature-affected variation in load transfer to the loading frame at the pick-up end. Because it was not known if the device would accelerate localized pavement deterioration, we were conservative in placing the sensors near the end of the test pavement section . Had the device introduced localized pavement distress within the middle portion of the test section, the entire planned 6 months of pavement performance testing would have been adversely affected.

The WIM cable assemblies installed in the pavement appear to be very durable. Even though the ALF's centerline, unicycle loading subjected the sensor channel to higher bending stresses than would normally be the case in a field operation, there was no pavement-sensor bond distress noted until after approximately 3.4 million ESALs of loading.

The determination of system accuracy is still in question. Additional time is needed to explore in more detail how the device translates the voltage signals into vehicle weights and how it combines weight readings to perform classifications.

More time is needed to evaluate the operation of the electronics and the weight and classification translation methods before the accuracy of the WIM unit can be assessed. For this reason, cable sensors will not be installed in the last test pavement during the current series of PTF tests. It was recommended that the WIM unit be installed in both flexible and rigid pavements during the second series of PTF tests to verify field results and to develop a higher degree of confidence in the operation of the system.

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6. Conversation with Mr. Steven Mears and Mr. Geoff Kent of GK Instruments, October 18, 1988.

## Acknowledgements

The authors wish to thank the following individuals who provided assistance in the performance of this study: Mr. Bill McCall, Director of Research at the Iowa Department of Transportation who assisted in the installation and provided guidance throughout the project; Mr. Perry Kent of the Office of Highway Information Management; Mr. Charles Stockfisch of the Demonstration Projects Division; and Mr. Charles Churilla, program manager at the FHWA Pavements Division. Graduate Research Fellow Ms. Debra Williams provided assistance in the evaluation of the statistical tests for normality of the data sets. Mr. Steven Mears and Mr. Geoff Kent of GK Instruments, designers of the AWACS device, reviewed our findings and provided technical comments.

This project was supported by the Demonstration Projects Division, Office of Highway Operations, Federal Highway Administration.

Figure 1: Schematic of ALF dual wheel trolley assembly

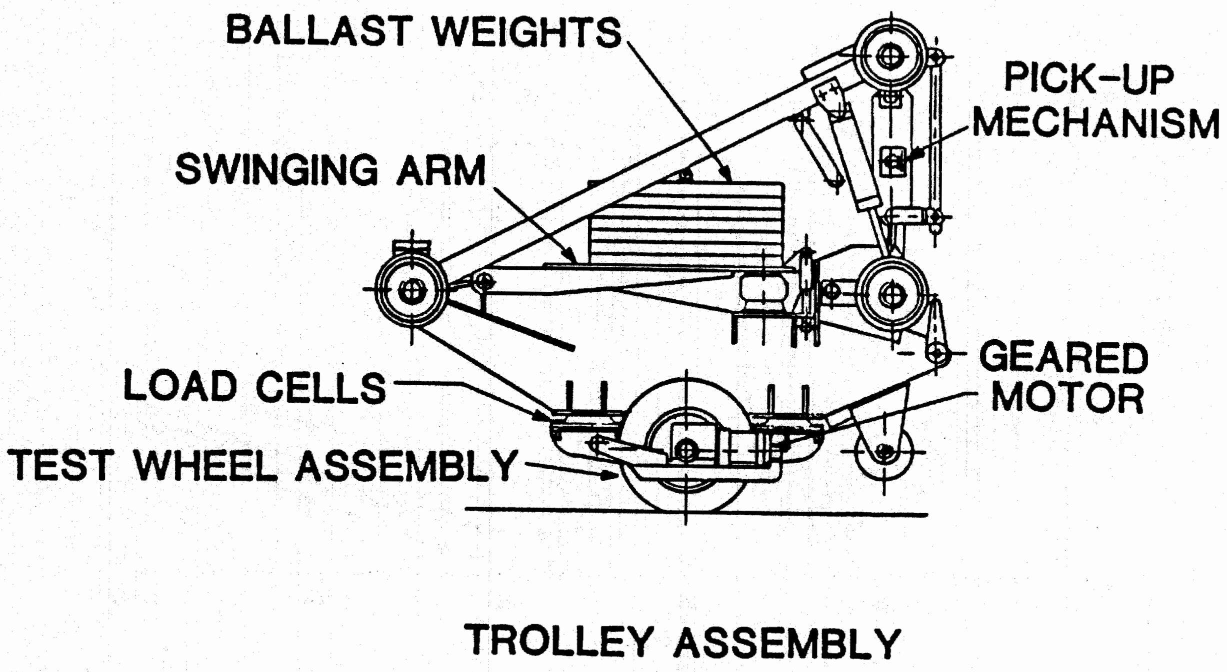


Figure 2: Typical voltage output trace from WIM cable sensors

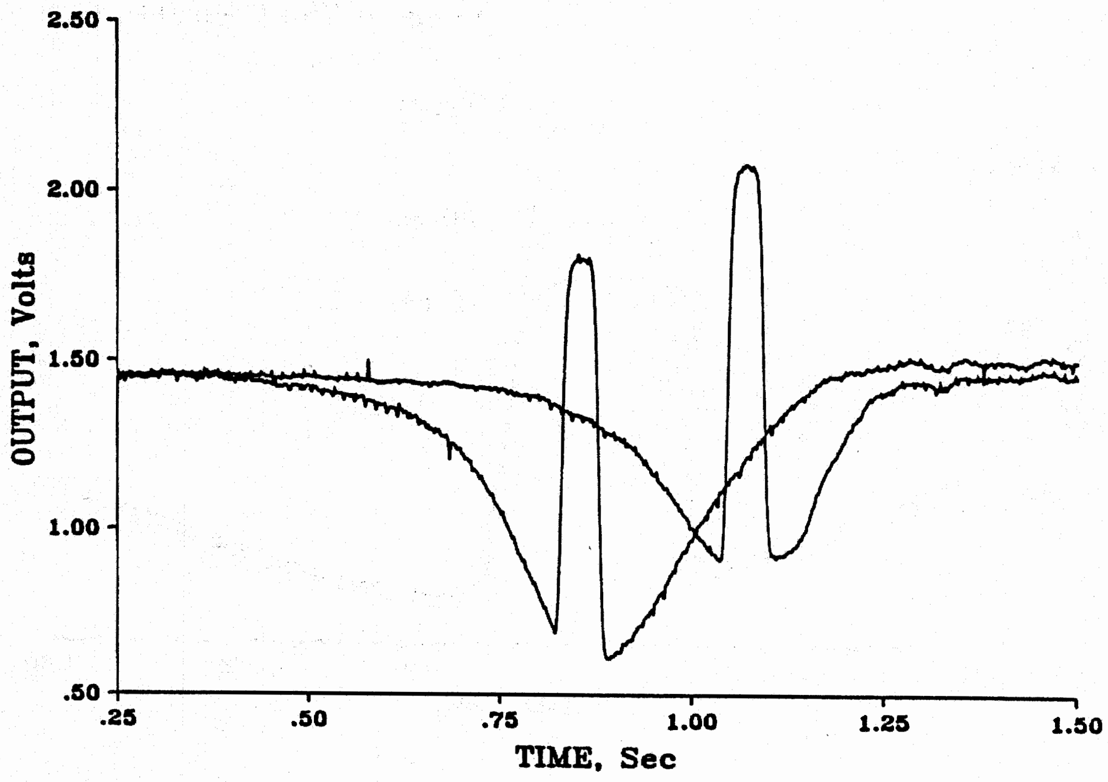


Figure 3: Effect of load on WIM sensor voltage output

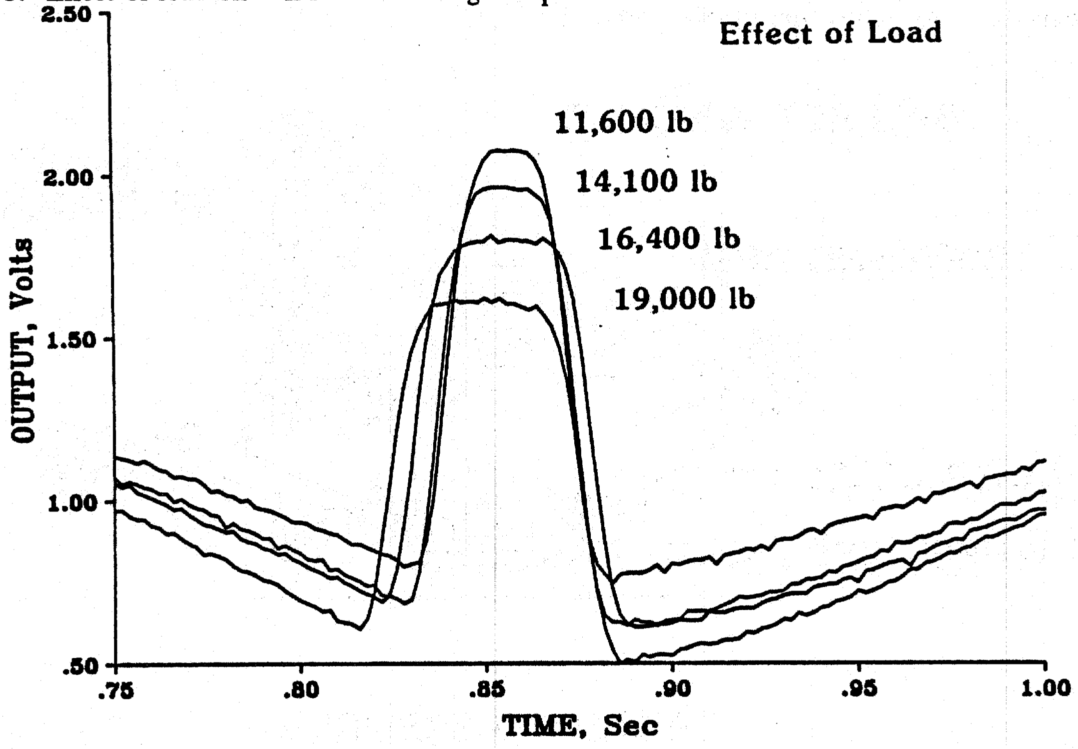


Figure 4: Effect of tire pressure on WIM sensor voltage output

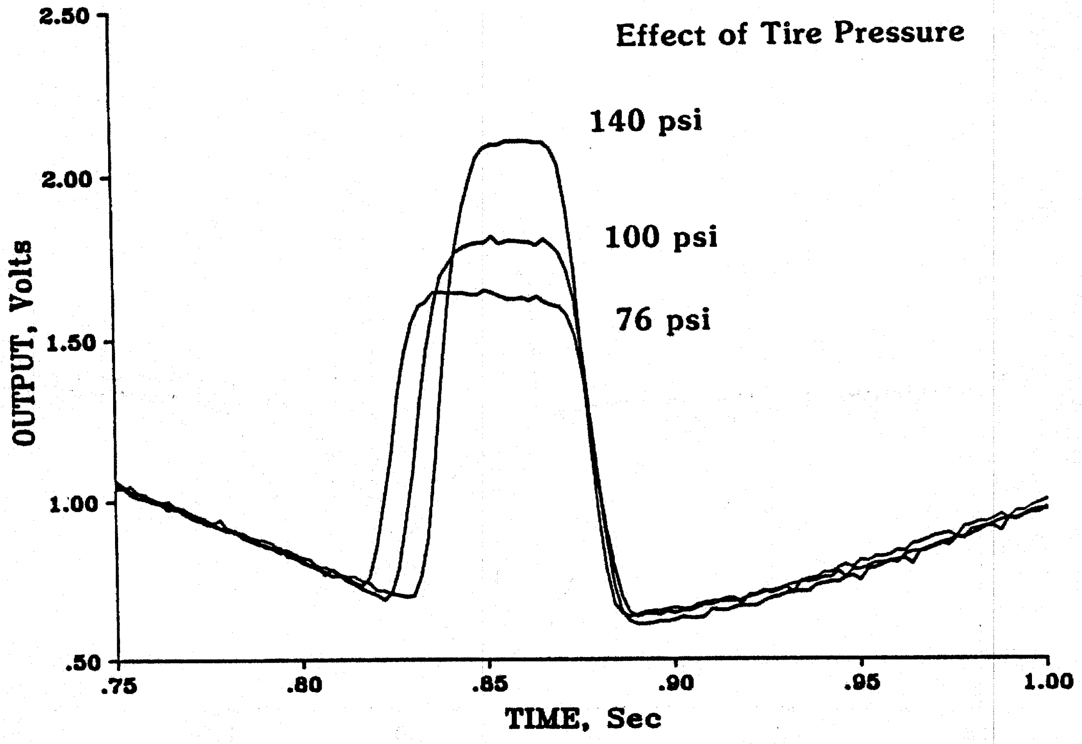


Figure 5: Effect of load and tire pressure on WIM sensor voltage output

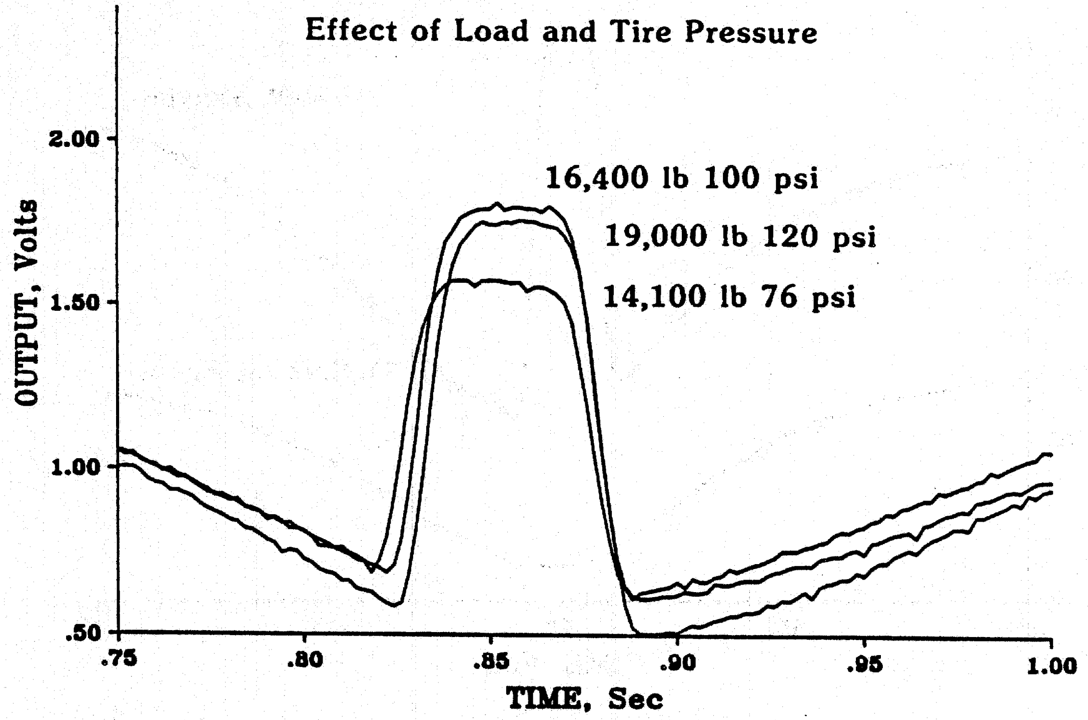


Figure 6: Effect of lateral offset loading on WIM sensor voltage output

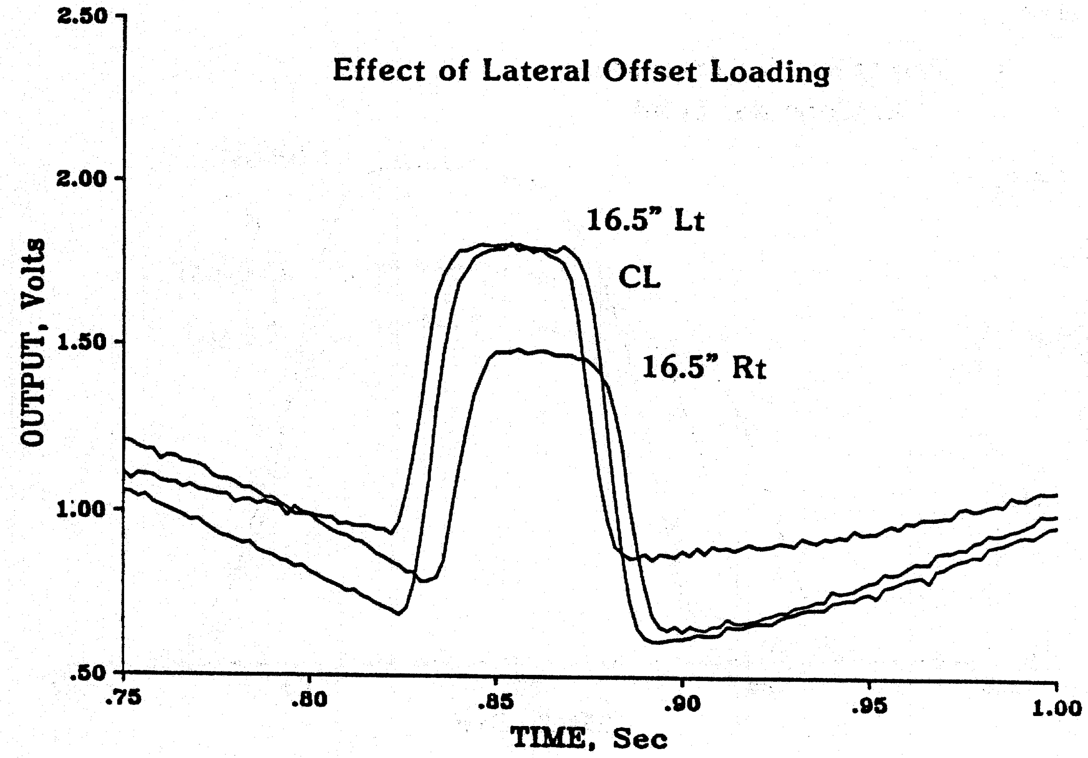


Figure 7: Superposition of voltage output curves from WIM sensor and pavement deflection beam

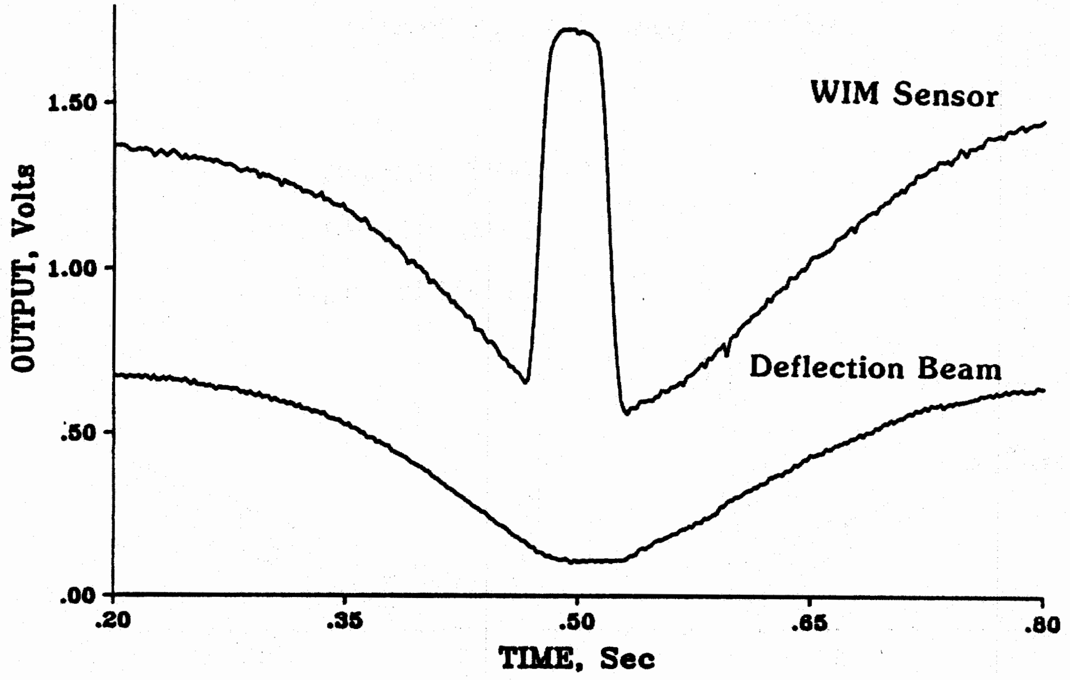


Figure 8: Effect of tire pressure at constant load, deflection basin subtracted

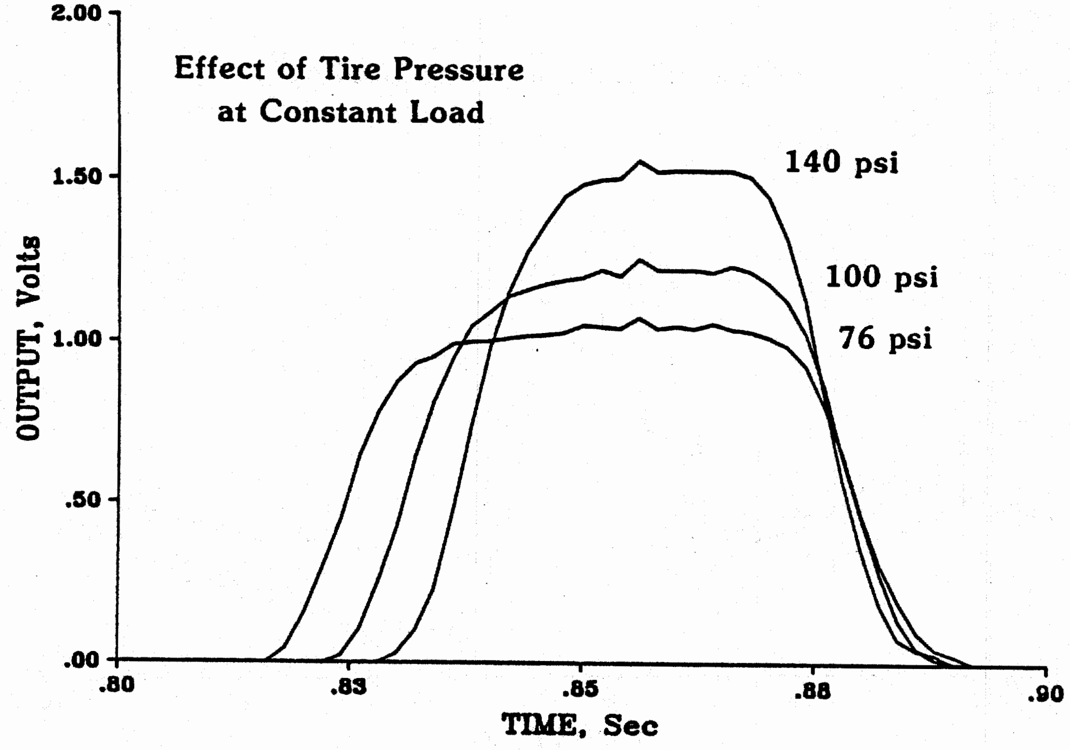


Figure 9: Effect of loads and tire pressure (constant contact area), deflection basin subtracted

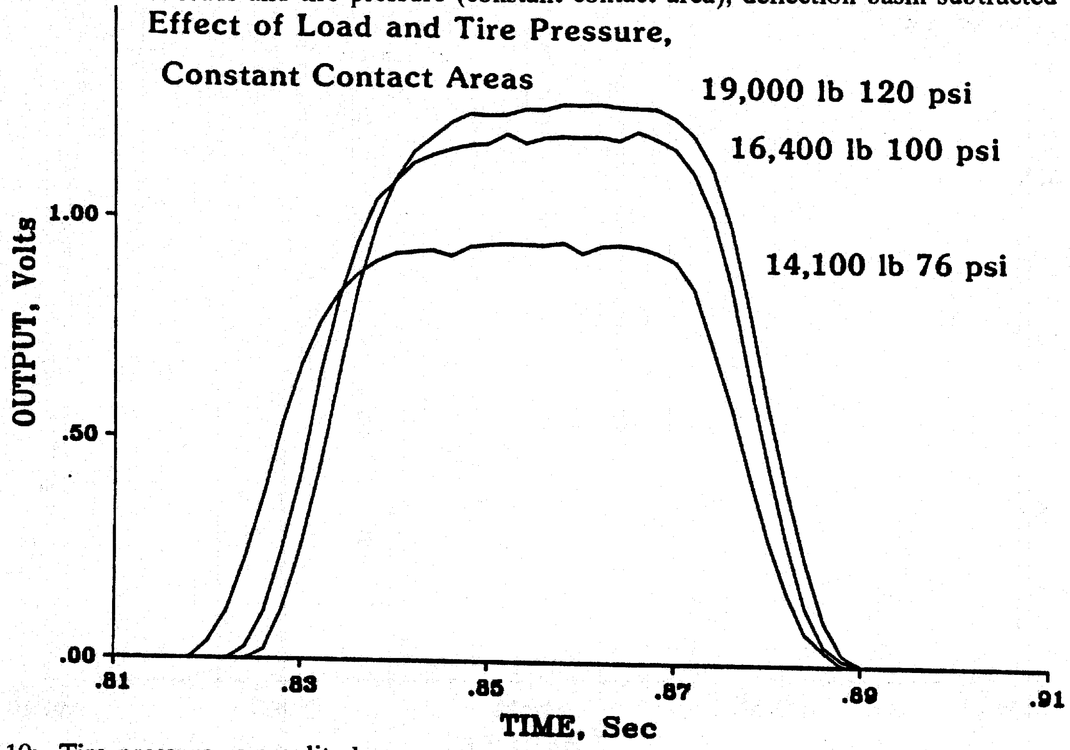


Figure 10: Tire pressure vs amplitude

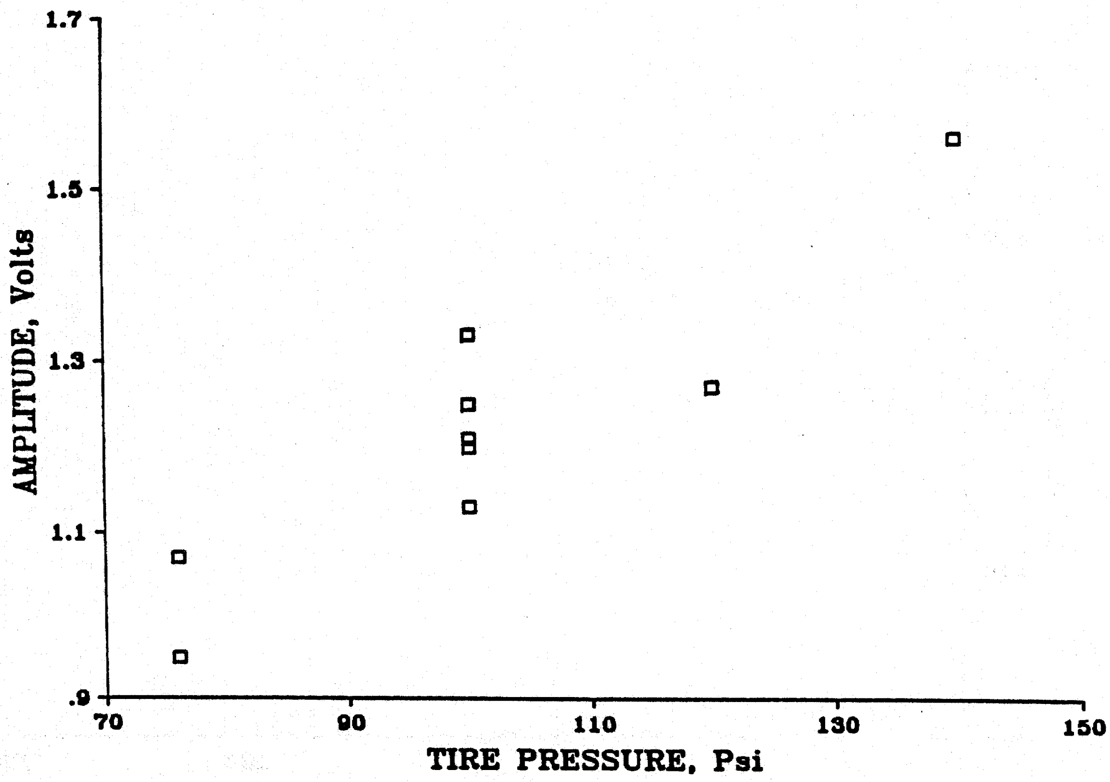


Figure 11: Load vs amplitude

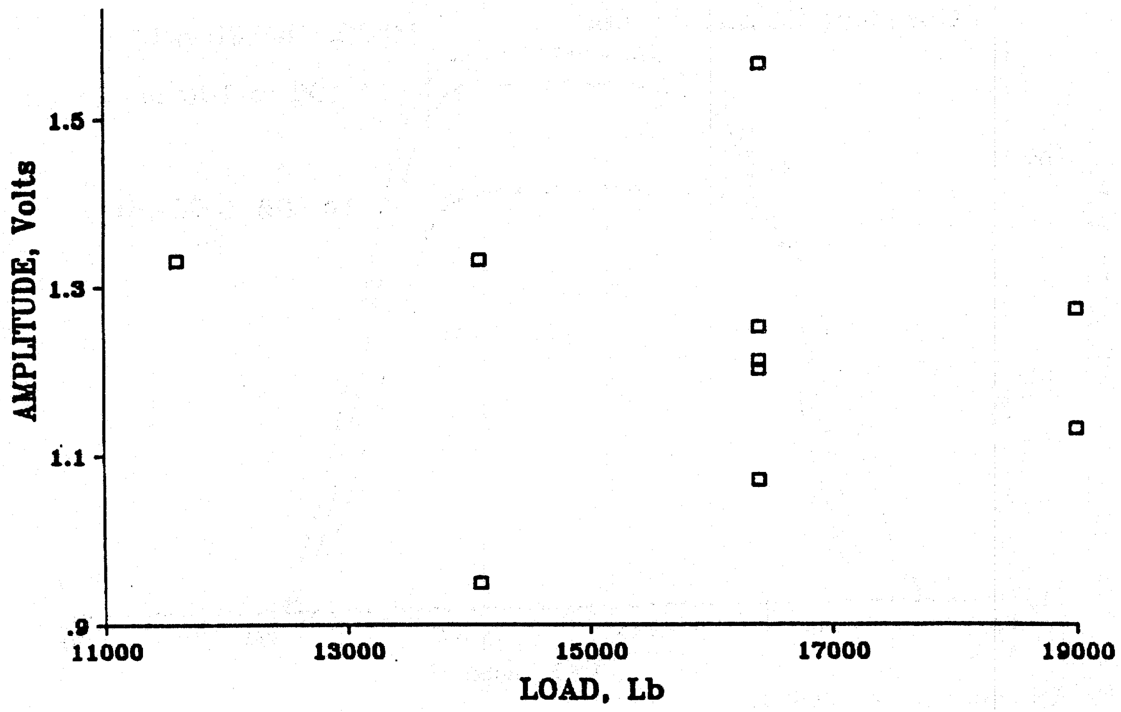


Figure 12: Tire pressure vs area

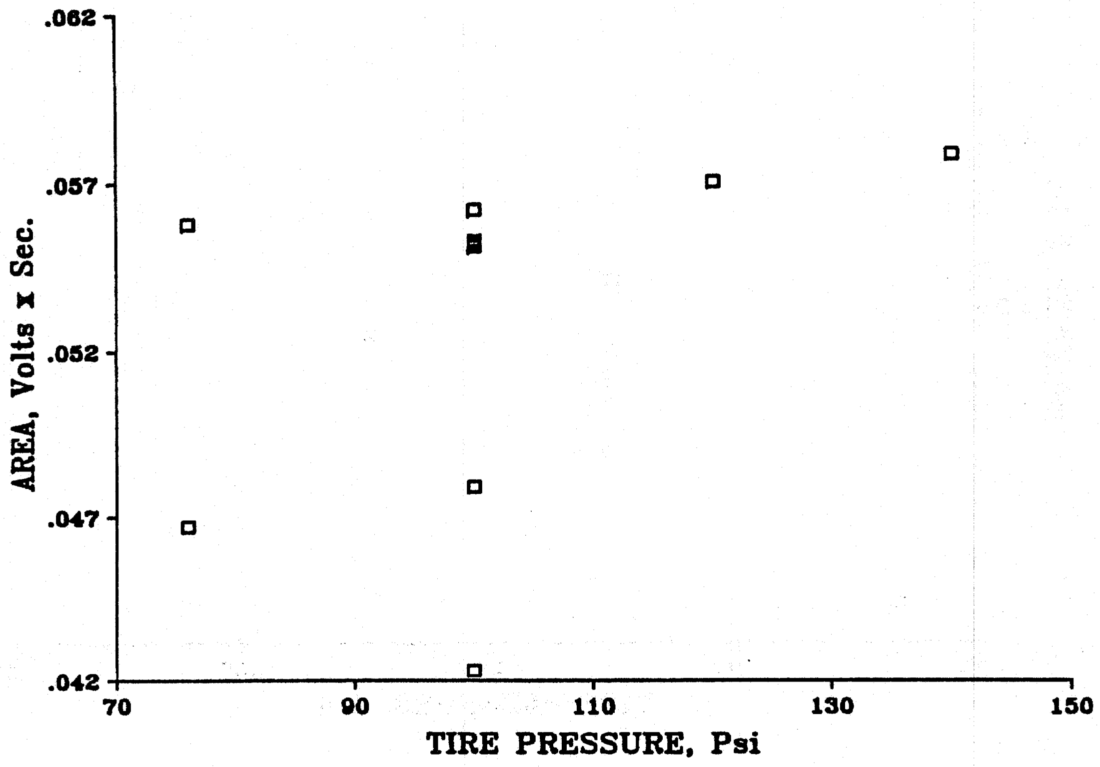
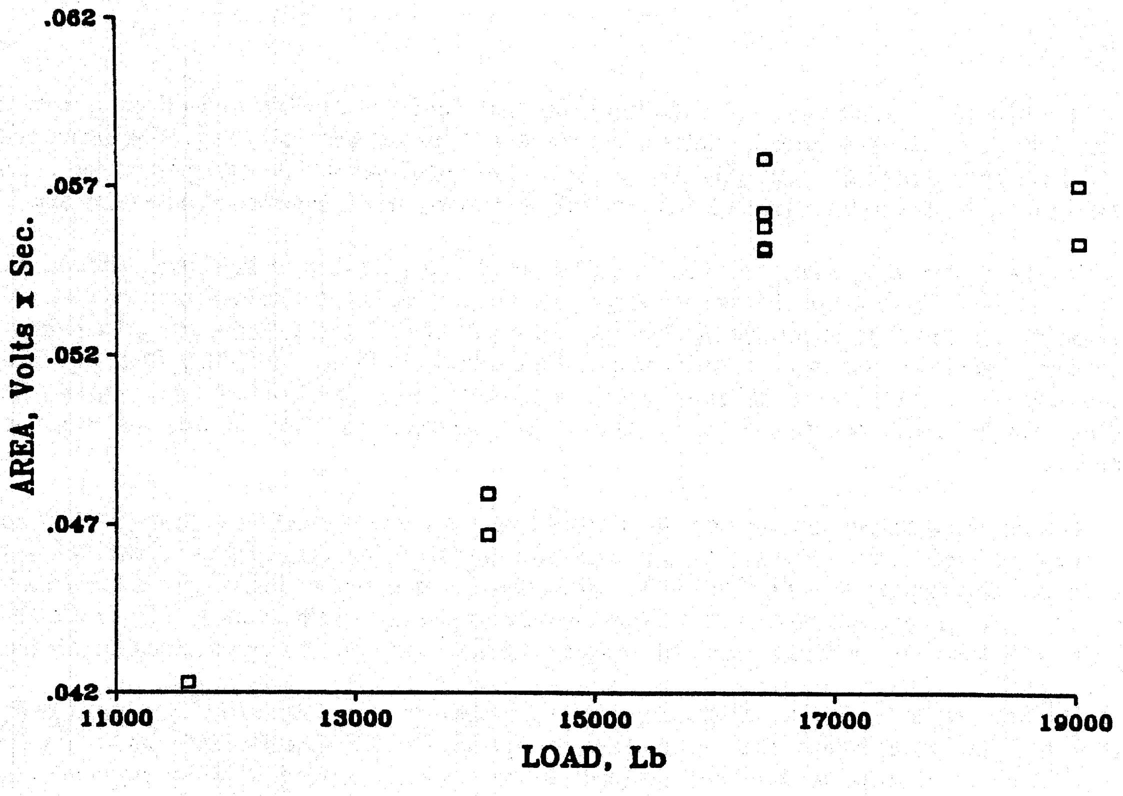


Figure 13: Load vs area



# FUTURE WEIGH-IN-MOTION (WIM) TECHNOLOGIES

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## Introduction

This paper has been prepared for the third National Conference in Weigh-in-Motion, to be held in St. Paul, Minnesota, October 1988. It contains an overview of current and upcoming WIM developments in the US and overseas, concentrating primarily on the field of **enforcement**. The final part of the paper seeks to take a longer-term look into the WIM crystal ball, addressing **traffic monitoring** functions also.

On the **enforcement** side, the paper describes work being performed by Castle Rock Consultants (CRC) for the UK Transport and Road Research Laboratory (TRRL), to evaluate a piezo-electric weigh-in-motion sorter. This current project involves an assessment of both the accuracy and effectiveness of the piezo sorter, installed half a mile upstream from a weighstation in Wylye, Wiltshire, England. One of the primary aims of the study is to establish whether the utilization of such a low-cost piezo sorter can lead to more overweight trucks being selected by enforcement officers, compared to existing visual selection techniques.

Another **enforcement** application is the Port-of-Entry slow-speed weigh-in-motion (SWIM) feasibility study recently completed for Arizona Department of Transportation (ADOT) by Castle Rock. In this project, the technical performance of a specific SWIM system was assessed at the Ehrenberg Port-of-Entry on the AZ/CA state line. Legal and institutional issues relating to issuing SWIM citations for overweight trucks were also addressed. Recommendations and necessary further work are also summarized in this paper.

The first section provides a brief outline of piezo-electric technology, which has been incorporated in the piezo WIM sorter system under evaluation in England. Some background information on UK truck weight enforcement practice has also been included. Details of the two-lane piezo WIM system are presented, including the sensor array, site layout, method of operation and system output. Tests carried out with the system are described, for which full results will be available next year.

## 1. PIEZO WIM SORTER

One of the key developments in weigh-in-motion in recent years has been in the domain of piezo-electric cable technology. Extensive research programs in England, France, West Germany, the Netherlands and Scandinavia established the feasibility of utilizing piezo sensors for weighing and classification. In 1986, the Iowa and Minnesota Departments of Transportation and the FHWA awarded a contract to CRC to translate these international research development efforts into an operational system for low-cost truck classification and weighing, designed to meet the needs of state and federal highway agencies.

Piezo-electric cable is a 3 mm diameter cable (approximately 1/8" diameter) with copper inner and outer electrodes. Between the electrodes is a compressed piezo-electric powder. During manufacture, the powder is poled by a radial electric field applied between the inner and outer conductors, producing a piezo-electric response to radial stress. The response of the cable is a charge, essentially dependent upon a constant of proportionality, the change of applied pressure and the length of cable over which it operates (Davies and Sommerville, 1985).

Research into the behavior of the cable identified that the method of mounting was particularly important. Depending on the mounting adopted, the performance of piezo cable sensors can range from being virtually useless to being very suitable for use as an inexpensive axle load sensor. Findings from the authors' work showed that, as well as aiming to reduce or eliminate stresses produced by bending of the pavement, mountings need also to eliminate variations in output with loaded width which are inherent in unmounted cable. A preferred mounting design has since been developed which was successfully utilized in the Iowa/Minnesota AWACS project. This same design has also been adopted in the WIM sorter project described in this section of the paper.

Signal processing for piezo-electric weight sensors is currently performed in one of two ways. The first of these uses analog voltage measurements to determine the peak output from high impedance amplifiers connected to the sensors. However, although this approach is valid for systems in which the whole axle load is located on the weight sensor at one time, such as capacitive weighmats, for piezo-electric sensors and other similar 'strip' sensors it can lead to considerable errors in the axle weights produced. This is because the output of narrow cable or strip sensors is related to the tire contact area, as well as the contact pressure.

The second approach takes account of the relationship between output and tire contact area by digitally integrating the output from the piezo-electric sensors after charge amplification. This approach to signal processing has a much sounder theoretical basis, as is borne out by the improved results it has produced in the AWACS project (Davies, et al, 1988).

### UK Truck Weight Enforcement

In the UK, the enforcement of truck weight laws is carried out by the UK Department of Transport, County Trading Standards Departments and the police. Checks are performed regularly using either slow speed axle weighing equipment (less than 2.5 mph) or static scales. Slow speed weigh-in-motion is widely adopted for enforcement applications in the UK because it offers a number of advantages over conventional static platforms. For example, a higher thruput can be achieved and individual axles can be measured more accurately, due to the elimination of errors caused by load transfer from one axle to another when the vehicle is stopped.

UK enforcement officers usually only carry out weight checks during the normal working day, although special checks are occasionally undertaken at night. Vehicles are selected from the traffic stream by the enforcement officer and directed to a weighstation nearby. The selection is at the discretion of the enforcement officer who will either be positioned at the roadside or riding in a police patrol car. Not all trucks selected are subsequently weighed. Some may be found to be empty on closer inspection, while others will be checked for other violations such as mechanical defects.

Utilizing this strategy, the enforcement agencies in the UK typically find about 15% of all vehicles weighed are overloaded. It is widely believed that the overall incidence of overloading may be significantly higher than this percentage. In an attempt to improve the selection efficiency and make more efficient use of scarce resources, the UK Department of Transport instigated this study of a low-cost piezo-electric WIM sorter through its research laboratory, TRRL.

### System Description

The weigh-in-motion system selected by TRRL for this project was a piezo-electric cable system from Trevor Deakin Consultants (TDC) of Trowbridge, UK. Castle Rock worked with TDC to advise on signal processing and to supply and install the sensors. The system was installed in two lanes of the A303, the main London to Exeter road, at Wylye, Wiltshire, close to Stonehenge. Initially, one full-length piezo sensor, one short piezo sensor and one inductive loop were installed in each lane. A recent upgrade to the system has involved the addition of a further full-length sensor in each lane.

The sensors have been positioned approximately half a mile upstream of a Department of Transport weighstation (Figure 1). Charge amplifiers and other electronics for signal processing are housed in a roadside cabinet next to the sensors. Processed signals are transmitted to a control unit located at the weighstation, where they are displayed on the control unit monitor and also sent to a microcomputer. The microcomputer runs a TRRL program which further processes the WIM outputs by applying calibration adjustments, and compiles summaries of axle weights, axle damage factors, and overloaded vehicles and axles. Summary data are stored on a microcomputer disk at preset intervals, allowing detailed data analysis to be carried out later.

As a vehicle crosses the sensor array, the axle weights are displayed on the microcomputer monitor a few thousandths of a second later. When all axles of a vehicle have crossed the sensor, the gross vehicle weight is calculated by summing the individual axle weights. For each axle and gross vehicle weight, the TRRL program checks whether they are overloaded by comparing the respective weight with the maximum allowable weight. Because of the complexities of the truck weight regulations in the UK and the lack of vehicle classification in the system, these checks are not stringent. Nevertheless, this approach does provide a reasonable indication of overloading. Where an axle or vehicle overload is identified, the weight value is shown in red on the monitor and an audible warning is also given. A sample of the WIM output on the PC monitor is presented below (Table 1), with weights given in tonnes.

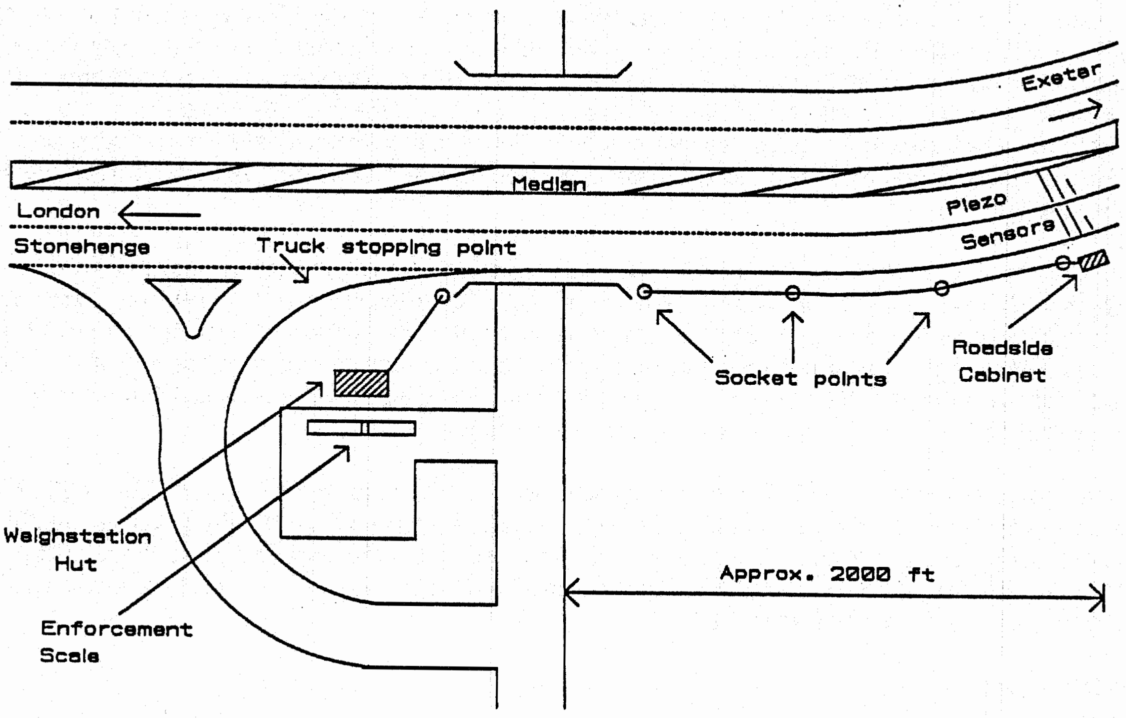

Figure 1 - Site Plan of Wylye WIM Sorter Installation

| Lane | W1 | W2 | W3 | W4 | W5 | W6 | W7 | Max. | GVW | Aol | Gol | Wf4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7.2 | 8.0 | 8.1 | 7.5 | | | | 8.1 | 30.80 | 2 | 2 | 5.70 |
| 1 | 9.1 | 9.2 | 4.5 | | | | | 9.2 | 22.80 | 2 | 2 | 5.70 |
| 1 | 3.4 | 4.8 | 4.4 | | | | | 4.8 | 12.64 | 2 | 2 | 5.70 |
| 1 | 8.6 | 11.3 | 5.9 | | | | | 11.3 | 25.80 | 2 | 2 | 5.70 |
| 2 | 2.6 | 8.2 | | | | | | 8.2 | 10.80 | 1 | 3 | 4.97 |
| 2 | 4.8 | 3.5 | 2.1 | 5.7 | | | | 5.7 | 16.10 | 1 | 3 | 4.97 |
| 2 | 5.6 | 8.2 | | | | | | 8.2 | 13.83 | 1 | 3 | 5.00 |
| 2 | 5.1 | 5.8 | | | | | | 5.8 | 10.90 | 1 | 2 | 5.00 |

Table 1 - WIM Output Displayed on PC

An additional part of the system is a small hand-held unit which connects to the control unit or the microcomputer. This remote control unit has a liquid-crystal display for indicating the gross vehicle weight and the maximum axle weight of a truck. It can be connected to the devices at the weighstation and at any one of five sockets mounted along the cable run between the sensors and the control unit. This enables enforcement officers at the roadside to see the WIM weights of approaching trucks.

### Test Procedures

Evaluation of the piezo WIM system was divided into three main parts, reflecting the study objectives. The first of these concerned an examination of the effectiveness of operating the WIM sorter in different modes for selecting trucks for enforcement check weighing. The second aspect involved monitoring the stability of the system calibration and accuracy under normal operating conditions. The final part was to obtain weight data for use in planning future enforcement activities.

The assessment of the sorter's effectiveness has been carried out through the adoption of four truck selection strategies by the enforcement officers. These are as follows:

1. WIM sorter only;
2. WIM sorter + camera;
3. WIM sorter + remote control unit; and
4. No WIM sorter.

Strategy One involves the enforcement agencies utilizing only the WIM sorter to select trucks for weighing. An enforcement officer at the weighstation monitors the WIM output on the microcomputer screen and, when an overweight truck is identified, informs the police at the roadside, via a radio link, to stop the truck in question for an enforcement check. Close liaison between the police and enforcement officer is necessary to ensure the correct truck is stopped. The police officer has approximately 20 seconds in which to identify the truck before it arrives at the stopping point.

The second strategy is similar to the first, except for the addition of a camera system. A video camera is located next to the sensors and the picture is relayed to a TV monitor at the weighstation. The enforcement officer is then able to observe the vehicles crossing the sensors as well as obtain an indication of the weights. This makes the identification process much easier and provides the enforcement officers with more information on which to base their selection.

Strategy Three utilizes the WIM remote control unit. This unit is operated by the enforcement officer responsible for vehicle selection at the roadside. Again, this approach allows visual observations to be matched with the WIM sorter output. The enforcement officer can use the remote unit at the point where the trucks are halted or at a point close to the sensors.

The final strategy is effectively a control strategy as it does not involve operation of the WIM sorter at all. Trucks are selected for check weighing using purely manual observations. It was important to include this to provide some means of determining changes in the selection efficiency caused by utilization of the WIM equipment.

Over the twelve-month evaluation period it is proposed to use the above strategies at 24 of the regular enforcement sessions. Each strategy is to be implemented on at least four occasions, with the remaining sessions devoted to those strategies which required further appraisal. This evaluation process is now approximately 60% complete.

At each enforcement session the study team has been collecting data necessary to establish the effectiveness of the system. This has included recording the number of overweight trucks, the total number of trucks selected and the number of potentially-overweight trucks not stopped. The latter has been determined by asking the enforcement officer, for each truck, what action would have been taken if the WIM equipment was not being used. This provides further information on the system's effectiveness. Without this extra information an accurate assessment cannot be made since the selection efficiency (the number of overweight trucks as a proportion of the total number of trucks selected) could be maximized simply by selecting only those trucks which appear to be grossly overweight.

Tests to establish the calibration and accuracy of the system have been performed in conjunction with the evaluation of the alternative selection strategies. The WIM weights of trucks selected for check-weighing have been recorded, together with the corresponding weights obtained from the enforcement scale. Further data were also obtained from several 12-hour axle weight surveys at the site, which involved interviewing the drivers as well as weighing and photographing the trucks.

Analysis of the WIM data for each test session has allowed the calibration and accuracy to be monitored over a significant period of time. In addition, system calibration has also been monitored by examining the output of a self-calibration feature in the TRRL software.

When not in operation by the enforcement agencies, the WIM sorter has been left to continuously record axle load data. These data will be utilized to construct a picture of variations in the proportion of overloaded trucks at the site on an hourly, daily and weekly basis over the evaluation period, for planning the deployment of enforcement resources at the site in future years.

## 2. SLOW-SPEED WIM ENFORCEMENT (SWIM)

A second WIM development project recently completed by Castle Rock Consultants involves an appraisal of the SWIM system commonly used in Britain and several other countries for issuing truck weight citations. Both technical performance and legal/institutional issues were included in the scope. Recommendations are summarized here and presented in full in the project report (Castle Rock Consultants, 1988).

At present, enforcement scales in the United States are almost invariably static. Typically, vehicles stop with each axle on the scale, pulling forward several times to complete a weighing operation. Each time the vehicle is moved, redistribution of its load takes place within the suspension system, reducing the accuracy of the final result. Although the scales themselves may be highly accurate, their method of utilization introduces errors such that a margin has to be allowed before any citation is issued.

An alternative approach provides very long, segmental scales, with segment lengths matched to the axle spacings of typical trucking rigs. Installations of this type may cost up to $1 million per site, including hardware and installation. Maintenance and calibration costs are significant, while segmental configurations may rapidly be superseded by changing truck dimensions.

As already outlined, some European countries, particularly the United Kingdom, adopt a different approach to enforcement weighing. Vehicles pass over a high accuracy, slow-speed WIM scale at a constant, minimum speed in bottom gear, allowing an increase in throughput of vehicles of around three times relative to static installations. With appropriate equipment and smooth approach aprons, accuracies similar to that of static weighing can be achieved.

Although an effective system of truck weighing based on high accuracy SWIM equipment is already known to be technically feasible, recommendations on a preferred technical system's specification must be accompanied by consideration of what new laws, if any, would be required for widespread implementation of the SWIM technology.

A feasibility study was therefore initiated to particularly examine the Arizona legal and institutional position with regard to the adoption of SWIM equipment for enforcement weighing. Detailed testing of a SWIM system, supplied by CMI Dynamics Inc, was undertaken at the Ehrenberg Port-of-Entry on I-10. This was carried out to provide the necessary data to verify the accuracy and consistency of SWIM systems under representative US operating conditions.

## Objectives

Within the overall framework of the project, the following detailed objectives were identified:

1. To evaluate the feasibility of slow speed weigh-in-motion devices for the enforcement of truck weight and bridge formulas.

2. To identify which state and federal standards are applicable and whether new laws will be required to allow weigh-in-motion to be used in preference to static weigh scales.

3. To plan and coordinate a state testing program for the accuracy evaluation of SWIM equipment at the Ehrenberg Port-of-Entry, including the analysis of data and the development of recommendations.

4. To consider an implementation program and make recommendations on the nature and direction of future work.

5. To prepare a final report detailing the technical, legal and institutional appraisals and summarizing recommendations on the use of the system for truck weight enforcement in Arizona.

The system resulting from this project could have far-reaching effects on the cost and scale of weight limit enforcement. The use of slow-speed weigh-in-motion offers many benefits over the conventional means of static weighing. Some of these are:

- Automated weighing offers improved weigh station efficiency, potentially benefitting both the state and trucking industry;
- Truck throughput may be greatly increased;
- Waiting lines and back-ups can be reduced or eliminated, thereby improving both safety and economy;
- Manpower requirements are potentially reduced;
- Trucking industry relationships with states may be improved through more efficient operations of PoEs;
- SWIM equipment promises to be cost effective to install and operate;
- Monitoring and control of oversize and overweight vehicles may be significantly improved;
- Load/frequency data could become more reliable, through widespread use of WIM consistent with the objectives of the HELP program; and
- Long term forecasts of trends in truck characteristics such as size, weight and axle configuration can be based on more reliable information.

### Legal review

A review of legal issues relating to the use of SWIM for enforcement was carried out under subcontract to CRC by an Arizona licensed attorney. The review showed that it is not absolutely necessary to amend either statutes or regulations for the use of SWIM scales for enforcement purposes in Arizona.

One possible exception identified by the attorney would be the Arizona Administrative Rule and Regulation R4-31-207(D) concerning the installation of scales. This regulation must be complied with as far as specifications on vehicle scales installation. If SWIM scale installation is in accord with this regulation, no modification would be necessary. If it is not, this regulation might be amended by revision, an exception to this regulation for SWIM scales could be added, or a separate regulation for SWIM scales could be provided.

There is no reference to either the type of scale necessary, or any requirements for certification found in Title 28 of the Arizona Revised Statutes. Title 41 of the Arizona Revised Statutes adopts Handbook 44. A.R.S. Section 41-2064(8) exempts government scales from licensing. If it is assumed that no licensing is required and there is no independent requirement for certification, it is safe to assume no certification is required. Arizona Regulations R4-31-104 allows the weights and measures division to inspect the weighing devices of the state, but does not require and/or establish any particular standards.

One problem envisioned is that in the prosecution of an overweight ticket, as in all criminal forms of certification of accuracy, even though only by custom and usage as it currently exists, an enterprising defense attorney could easily convince many trial courts that certification is a necessary element of the

State's case. A system of certification of SWIM scales should therefore be adopted, even if there is no formal requirement. To overcome this potential problem, the State of Arizona could create a SWIM handbook and utilize the same as a standard for SWIM scales and certification thereof and, in essence, do nothing more in the way of statutory or rule and regulation revision.

Lastly, there appears to be nothing in federal law or regulations which prevent the use of SWIM scales for state weight enforcement, and the federal authorities seem to encourage the same.

## System performance

Before performance tests on the SWIM equipment began, Arizona DOT carried out a leveling survey of the approach and exit concrete slabs to the SWIM scale. Results of this survey show that both slabs were constructed with a cross-fall for drainage. The levels have been plotted and are shown graphically in Figure 2.

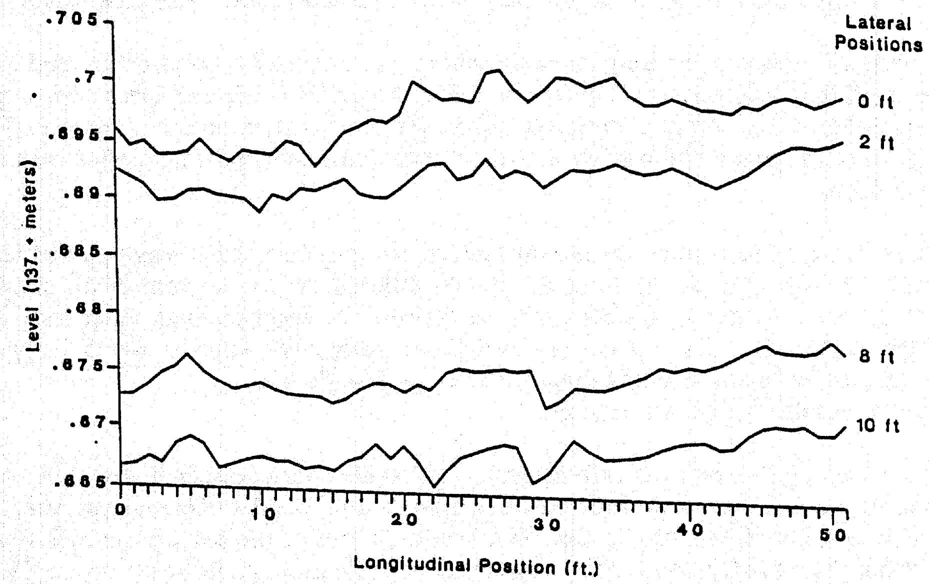

**Figure 2** Assessment of SWIM Scale Levels

Excluding the level variation due to the cross-fall, Figure 2 reveals that in a few places the concrete apron does not conform to the recommended tolerance of ± 1/8 inch. For example, at the zero line the tolerance is nearer to ± 3/16 inch. The resulting scale performance should be interpreted with these facts in mind.

Static calibration checks by Arizona Weights and Measures Division indicated that the system calibration was out by around 160 lbs. This difference remained fairly constant with increasing load. Adjustment of the calibration could not readily be undertaken. For the system to be certified, a high tolerance on the static calibration is essential, for unless the system can consistently weigh static weights traceable to national standards, its credibility for determining dynamic weights would be impaired. CRC recommends that in static calibration tests the SWIM output should agree with the static weight to within a tolerance of ± 15 lbs over the entire weight range.

The calibration did not appear to change over the wide temperature range observed. The majority of the tests were performed at high temperatures, however. It is therefore desirable that some evaluation of low temperature effects be considered before the SWIM system became widely adopted.

The tests with random vehicles have shown that there appears to be no significant difference between vehicles crossing the scale at the recommended speed of 2.5 mph and those crossing at speeds up to 4 mph. A similar result was found in the UK by Surrey Trading Standards Department when they evaluated a Weighwrite system in 1976. Closer examination of the speed effect would be desirable prior to full-scale implementation of this technology.

Results obtained by operating the system at a speed of 4 mph suggest that there was a gradual deterioration in the calibration, in terms of an increasing systematic error over the test period. This suggests that it is essential to regularly examine the calibration. UK practice is to verify the scale every six months with three test vehicles. However, UK SWIM scales are not utilized on a continuous basis as would be the case with a system at a port-of-entry. Therefore, it would be desirable to check the scale more frequently, for example every three months, until the stability of the calibration had been established.

With trucks continuously crossing the scale, whether or not the system is being used for enforcement, there may be significant changes in the levels of the approach and exit platforms over a period of time. Frequent monitoring of the levels is desirable to ensure they remain within tolerance. The verification procedure needs further consideration to ensure that it meets current standards, is effective and is not unduly expensive to perform.

The main series of tests were carried out using randomly selected trucks weighed statically and on the SWIM scale. The standard deviation of the weight differences (the random error) ranged between 211 lbs and 255 lbs (1.4% - 1.7%) for individual axles/axle groups. The corresponding range for gross weights was 339 lbs - 381 lbs (0.6% - 1%). 95% of the axle weights therefore lie within ± 414 lbs to ± 500 lbs of the mean. For gross weights the 95% limits range between ± 664 lbs and ± 747 lbs. Typical results are shown in Table 2.

To utilize the SWIM scale for enforcement, a tolerance must be specified within which the system should operate. In the UK the operational accuracy limits are ± 220 lbs (100 kgs) per axle. Examination of individual vehicle weights reveals that in the January session, out of the 392 axle groups weighed, only 275 (70%) were within this specification and 117 outside the specification. Adjustment of the SWIM calibration by an increase of 160 lbs would increase the proportion within the specification to 91%. The corresponding analysis of gross weights indicates that almost all vehicles are within the specifications.

Based on the data collected, it would be necessary to use a tolerance of ± 660 lbs per axle to ensure all individual axles were within specification. This high margin would probably be unacceptable to the enforcement community. The recommended alternative is therefore to correct the calibration and take steps toward improving the concrete apron profile.

The random vehicle tests tend to confirm the view that the type of suspension on the trucks does influence the output. Air suspensions appear more efficient than mechanical suspensions, leading to more reliable and consistent results from the SWIM scale.

The interaction between the suspension and the height of the approach platforms was also shown to be particularly important with mechanical suspensions. Large changes in the SWIM output were produced by raising the relative scale level by only a small amount, especially for tandem and triple axle groups with mechanical suspensions. This indicates that the specification suggested by the manufacturer, ± 1/8 inches, must be strictly adhered to if high tolerances are required. An example of the response trend is shown in Figure 3.

| Sample | Systematic Error | | Random Error | |
|---|---|---|---|---|
| | Axle | Gross | Axle | Gross |
| All vehicles | -1.7%<br>(-264) | -1.5%<br>(-784) | 1.4%<br>(211) | 0.6%<br>(339) |
| Overspeed | -1.8%<br>(-248) | -1.5%<br>(-686) | 1.4%<br>(198) | 0.6%<br>(324) |
| Correct Speed | -1.7%<br>(-267) | -1.5%<br>(-804) | 1.4%<br>(214) | 0.6%<br>(339) |

Table 2. Measurement accuracy - January data

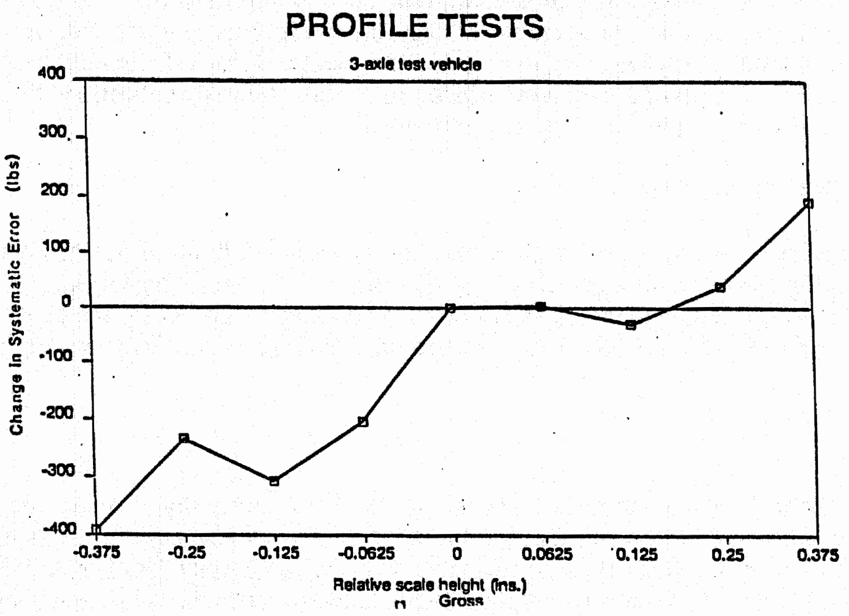

FIGURE 3 Profile Tests

## Conclusion

The obvious case for the use of SWIM is the efficiency derived from the short period of time taken to determine axle weights and gross weight of any vehicle type. For example, a vehicle with a 50 foot wheelbase travelling at 4 mph can be weighed in approximately 11 seconds, regardless of the number of axles. In practical terms, the use of SWIM should reduce weighing time to about one third of that required using current practices.

A less obvious case, but one of equal importance, is accuracy. To stick to the letter of the Federal Highway Administration requirements for an effective weight enforcement process, individual axle loads should be measured, rather than tandem and triple axle loads as are usually measured for axle groups. The Standards and Tolerance Committee of the National Conference on Weights and Measures in a report presented several years ago noted the following.

"The measurement of individual axle loads statically is subject to much potential error, due to weight distribution shifts between axles caused by starting/stopping, brakes being applied, etc. Weighing of axle loads in motion largely eleminate these errors and will in general be more accurate than static weighing, at least at low speed."

Overall, the use of slow speed weigh-in-motion scale for port-of-entry operations offers many benefits over the conventional means of static weighing, notably:

- Improved weigh station efficiency
- Increased truck throughput
- Reduced queues and delays
- Improved axle weighing accuracy

As a result, there may be lower personnel requirements and improved relationships with the trucking industry. The results of the recent test program at the Ehrenberg port-of-entry indicate that slow speed weigh-in-motion is potentially cost effective to install and operate. Some refinements to the system tested would be required before it could be routinely utilized in a port-of-entry application. CRC recommended ADOT work with vendors to perfect the system it requires.

## 3. FUTURE DEVELOPMENTS

This final section of the paper briefly gazes into the future of weigh-in-motion to try to spot the likely areas of further development. We considered calling this section "The WIM Crystal Ball," following on from the introduction, but feared someone would say we were describing yet another piece of new technology for estimating truck weights. We believe upcoming systems will beat the occult, and by statistically significant margins.

### Near term

Two areas currently attracting the attention of the WIM fraternity include **output formats** and **calibration methods. Standardized output formats** for WIM data are a goal central to the aims of the heavy vehicle electronic license plate (HELP) program. The technical lead state DOT, CALTRANS, has been particularly active in seeking to agree data output formats between different WIM systems which satisfy the needs of all participants while allowing easy exchange of data. The culmination of this work will be seen in the Crescent Demonstration Project, a 2500 mile coordinated WIM/AVI system on Interstates 5 and 10.

Improved **calibration methods** represent another area of considerable significance in future WIM developments. NCHRP3-39 is concerned with evaluation and calibration procedures for weigh-in-motion systems. Some of the techniques which may come out of this project and others relating to calibration include:

- better site evaluation procedures, including pavement surface condition assessment, pavement profile and construction materials;
- improved laboratory testing procedures for pre-installation calibration under a wide range of environmental conditions;

- field simulation of traffic-induced forces on WIM transducers, including static loading techniques and new dynamic methods such as the use of a modified falling weight deflectometer (FWD);
- instrumented vehicle techniques to measure the actual forces imposed by test vehicles while crossing the WIM sensor array;
- standard field testing procedures, using statistically-valid samples of randomly-selected vehicles; and
- better definition of the role of test vehicles (each with its own unique suspension dynamics) within the overall calibration process.

**Self-calibration** is a final approach which is now becoming more widely accepted following its demonstration in the AWACS project and elsewhere. Much still remains to be done to learn about the practical applications of the technique at a wide range of sites.

The principle of self-calibration is that the loads on certain axles of specific truck classes show relatively little variation, regardless of the loading condition of the truck. Therefore, provided that the WIM system includes automatic vehicle classification, a database can be built up by the system consisting of axle load measurements for these particular axles. If the mean weight of these axles is calculated after the addition of each new set of measurements to the database, the system calibration factor can be adjusted to force the mean weight to agree with the known long-term population mean.

One particular axle category is particularly suitable for use as the basis for a self-calibration feature. This is the steering axle of 3S2 trucks. The vehicle dimensions of 3S2's are such that the kingpin is usually located close to the center of the first tandem axle. Therefore, the loading of the vehicle should have relatively little effect on the steering axle load.

To test this hypothesis, a database of US vehicle dimensions and weights, collected during a biennial Truck Weight Study (TWS) in Arizona, was initially analyzed by CRC. For the self-calibration technique to be practical, only classes of vehicle which commonly occur in the normal traffic stream can be used and so for this analysis only 3S2's were selected. Of the 1500 vehicle entries in the database, over one third were the class being analyzed. The vehicle weights in the database had been obtained from portable static weighing scales, accurate to ± 2%, and collected during a period when no enforcement weighing was in progress.

A computer program has been written to analyze the database by firstly selecting only the vehicle type under consideration and then examining the axle weight of the steering axle. Each of the weights examined was sorted into classes of 400 lbs in the range 6400 lbs to 14000 lbs (Figure 4). In total, 512 vehicles were used in the analysis, having a mean axle weight of 9950 lbs, with an associated standard deviation of 1126 lbs.

More recently, we have repeated these analyses with much larger truck samples collected in Iowa, Minnesota and the United Kingdom. These samples have shown a remarkable degree of consistency in both means and standard deviations of lead axle weights for specified vehicle types. This has proved to be true for different time periods, between sites and even between countries. These results strongly confirm our view that self-calibration will be a key evaluation and calibration technique of the future.

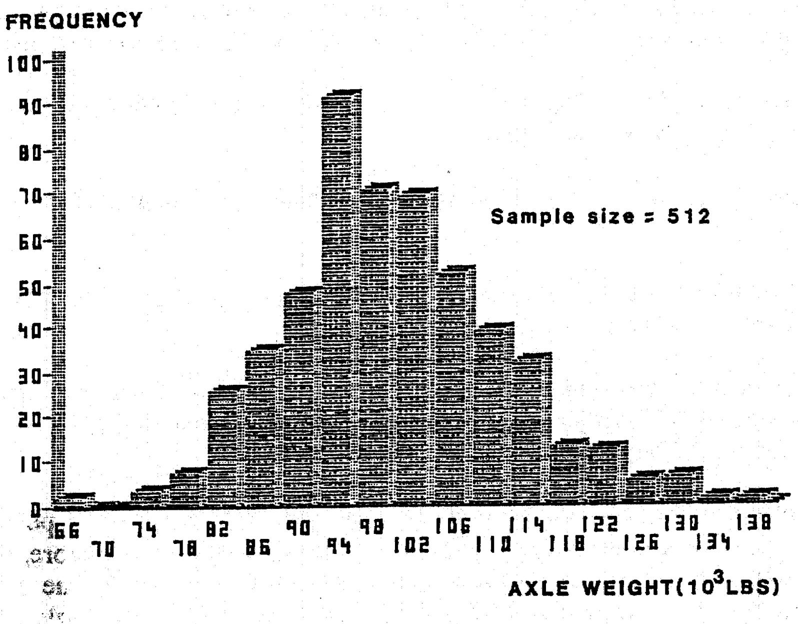

**Figure 4** Analyzed Steering Axle Weight Data

For self-calibration, if the assumption is made that the standard deviation of the sample is representative of the population as a whole, it is possible to determine the sample size required to give a specified standard error of the mean for a given confidence level. For example, for 95% confidence limits of ± 100 lbs in 10,000 or approximately ± 1%, the required sample is given by:

SEM (Standard error of mean) = $\frac{\sigma}{\sqrt{n}}$ where $\sigma$ = standard deviation
n = sample size

95% confidence = 1.96 SEM = ± 100 lbs

SEM = 51 lbs

$$51 = \frac{1126}{\sqrt{n}}$$

n = 487

An alternative requirement of a calibration correct to ± 200 lbs yields n = 132.

From the analysis of the data now available, it appears that the use of steering axle weight data from 3S2's for self-calibration purposes is a very practical proposition, although a number of issues still need to be finally resolved. In particular, the reliability of the data used to determine the population mean and standard deviation needs to be carefully assessed. It is possible that the data employed for these analyses are biased, caused by a proportion of illegally overloaded vehicles bypassing the weighing location even though no citations were being brought. The data may also be time dependent in the long-term as the construction and use of the vehicles changes. This could be readily investigated given appropriate data for different sites and years, abut will need to be monitored in the future. The accuracy of the vehicle classification, particularly for the class used in this technique, is a further consideration for the method to be effective and need careful examination for each WIM system.

Because of the problems above, the technique will not totally eliminate the need for individual site calibration on a regular basis, but could be used in several different ways to improve the accuracy of axle weight measurements between calibrations. For example, successive sample means can be calculated in turn or a long-term moving average of the samples can be derived. When there is a significant difference between the sample means and the population mean, the system could just record the fact and do nothing, or could alert operating personnel that the equipment is in need of recalibration. Alternatively, the system could automatically re-adjust the calibration factor by a small increment in the required direction. These fluctuations in the calibration factor could go unrecorded, or more likely, would be recorded so that the weight data could subsequently by "unadjusted" should the need arise.

The concept of self-calibration offers the potential of greatly improved long-term accuracy for WIM systems. However, before the technique can be fully implemented, further detailed analysis of weight and classification data will be necessary, together with practical testing at several locations to further confirm the concept.

## Longer term

In the longer term, the WIM story has many exciting chapters still to be written. Both commercial considerations and unavoidable ignorance make it difficult to be more specific. It is always tempting for researchers to believe that their particular contribution represents the "ultimate" development within an area of work. We believe there are WIM breakthroughs still to be made which will make current techniques look primitive in the extreme.

Some possibilities to be mentioned in the presentation (time permitting!) include:

- new WIM sensors, including better mountings, improved installation techniques and better/lower cost cable such as **Vibetek**;

- new WIM sensor layouts, culminating in the concept of dynamic monitoring/compensation to iron-out vehicle bounce and produce quasi-static equivalent weights at full highway speeds.

## Conclusion

The recognition of the TRB WIM Task Force as a fully-fledged TRB Committee this year is indicative of the fact that WIM has finally come of age-- institutionally, at least. Technically and operationally, however, we believe that there are still great strides to be made. Our dream is that one day, WIM will be as functional and routine as traffic counting or truck safety checks. The past decade has seen some exciting new developments. In fact, we've come a long way...but...just keep watching.

See you in three years' time.

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