NCHRP Web Document 13

(Project 20-34)
Contractor's Final Report

Developing Measures of Effectiveness for Truck Weight Enforcement Activities

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

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March 1998

ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Research Council.

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This report has not been edited by TRB.

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ACKNOWLEDGMENTS

Research undertaken in NCHRP Project 20-34 was accomplished through the efforts of many talented and dedicated individuals. The project Principal Investigator was Fred R. Hanscom, P.E. of the Transportation Research Corporation (Haymarket, Virginia).

The depth and breadth of consulting expertise provided by the following individuals enhanced the quality of the overall project effort. Dr. Thomas Gillespie, of the University of Michigan, provided experimental design input during early phases of the research. Dr. Olga Pendleton, of Pen-Hock Statistical Consultants, guided the Sampling Plan developmental effort that was completed with critical input from Statistician, Cindy Cornell of Chaparral Systems, Inc. Dr. Dan Middleton, of Texas A&M University conducted the WIM reliability study. Truck weight enforcement input was provided by Mr. George Edgerton, former Deputy Chief, Enforcement Services Division, California Highway Patrol. Robyn Champion of Howard/Stein-Hudson Associates, Inc. contributed to the Glossary and the listing of alternative truck weight enforcement strategies (to be subsequently reported in Phase II.)

The primary output of this research effort is a software product, TWEET (Truck Weight Enforcement Effectiveness Tool), programmed by Michael W. Goelzer. Pavement Design Consultant, Kenneth McGhee, developed the theoretical framework for the pavement deterioration portion of the software. Special thanks are due Mr. Ralph Gillmann (and his former superior, Mr. Perry Kent) of the Federal Highway Administration who critiqued the software throughout its development.

Success of the project is primarily owed to officials in the following state highway agencies who cooperated with our data collection effort or otherwise provided essential technical input.

California Department of Transportation, e.g., John Van Berkel, Jr.; Rich Quinley
Florida Department of Transportation, e.g., Harshad Desai; William Mickler
Georgia Department of Transportation, e.g., Robert Scott Knight
Idaho Department of Transportation, e.g., Scott Fugitt
Minnesota Department of Transportation, e.g., Curtis Dahlin
Ohio Department of Transportation, e.g., Tom Foody; Jeffery Gelety
Oregon Department of Transportation, e.g., Ken Evert; Milan Krukar
Texas Department of Transportation, e.g., Bert Lundell

Finally, we gratefully acknowledge the patience, guidance, and contributions of NCHRP Senior Program Officers, Dr. Ed Harrigan, Dr. Ronald D. McCready and Frank R. McCullagh, and the NCHRP Project 20-34 Panel.

ABSTRACT

This research addressed the determination of what is actually accomplished as the result of truck weight enforcement efforts. One project objective was to develop and validate truck weight enforcement measures of effectiveness (M.O.E.s). Traditionally applied measures, e.g., numbers of trucks weighed and citations issued, have simply provided indications of enforcement effort. These measures failed to provide results in terms of real enforcement objectives, e.g., to deter overweight truck and minimize pavement wear and tear.

M.O.E.s were developed in this project via a series of analytical procedures. They were subsequently validated in a comprehensive four-state field evaluation. Matched WIM data sets, collected under controlled baseline and enforcement conditions, were analyzed to determine the sensitivity of candidate M.O.E.s to actual enforcement activity. Data collection conditions were controlled in order to avoid contamination from hour-of-day, day-of-week, and seasonal effects. The following M.O.E.s were validated on the basis of their demonstrated sensitivity to truck weight enforcement objectives and the presence of enforcement activity: (1) Severity of Overweight Violations, (2) Proportion of Overweight Trucks, (3) Average ESALs, (4) Excess ESALs, and (5) Bridge Formula Violations. These measures are sensitive to legal load-limit compliance objectives of truck weight enforcement procedures as well as the potential for overweight trucks to produce pavement deterioration.

A second project objective was to document findings in a user guide formatted to explain appropriate data collection methods, how to apply these methods, and how to interpret their results. A software User Guide was developed which statistically compares calculated M.O.E.s between observed enforcement conditions. It also conducts an automated pavement design life analysis estimating, the theoretical pavement-life effect resulting from the observed enforcement activity.

SUMMARY OF FINDINGS

NCHRP Project 20-34 addressed the issue of determining what is actually accomplished as the result of truck weight enforcement efforts. Traditionally applied measures, e.g., numbers of trucks weighed and citations issued, have provided indications of enforcement effort. However, it is essential for valid measures of effectiveness (M.O.E.s) to provide measures of accomplishment in terms of actual enforcement objectives, i.e., deterring overweight truck operation and preventing pavement deterioration. This research project capitalized on WIM (Weigh-in-Motion) system capability and integrated a number of related scientific areas, i.e., pavement design principles and statistical applications, to develop M.O.E.s which directly interpret WIM findings in terms of actual enforcement objectives. Resulting M.O.E.s quantified the reduction in the number, proportion, and severity of illegally overweight trucks.

This report documents of the research project, the objectives of which were as follows:

1. To develop and validate truck weight enforcement measures of effectiveness (i.e., indicating what is accomplished as the result of enforcement activity).

2. To document findings in a user guide formatted to explain appropriate data collection methods, how to apply these methods, and how to interpret their results.

Specifically discussed aspects of this research activity are as follows: (1) M.O.E. development and validation, (2) truck weigh-scale diversion, (3) permit-issued trucks, (4) enforcement effects on pavement life, and (5) user guidelines.

M.O.E. Development and Validation

Candidate M.O.E.s were developed via a series of analytical procedures. The most promising candidate M.O.E.s were then validated in field studies via their application to actual truck weight enforcement procedures.

M.O.E. Development M.O.E.s were analytically developed in three steps. First, surveys of literature and state agency practice were conducted to establish existing enforcement evaluation procedures. Second, an expert panel developed candidate M.O.E.s on the basis of truck weight enforcement objectives and the sensitivity of candidate measures to those objectives. Third, these candidate M.O.E.s were evaluated and ranked by application of the following objective criteria: Practicality of Application, Measurement Reliability, Support of Statewide Random Sampling, Absence of Enforcement-Induced Bias, Data Collection Methods Capability, Sensitivity to Infrastructure Damage, and Applicability to Data Collection Future Technology.

The following M.O.E.s were thus established on the basis of their suitability to demonstrate truck weight enforcement effects: (1) Severity of Overweight Violations, (2) Proportion of Overweight Trucks, (3) Average ESALs, (4) Excess ESALs, and (5) Bridge Formula Violations. These measures are sensitive to legal load-limit compliance objectives of truck weight enforcement procedures as well as the potential for overweight trucks to produce pavement wear and tear.

M.O.E. Field Validation Analytically-developed M.O.E.s were empirically validated in a comprehensive four-state field evaluation. Matched WIM data sets, collected under controlled baseline and enforcement conditions, were analyzed to determine the sensitivity of candidate M.O.E.s to actual enforcement activity. Data collection conditions were controlled in order to avoid contamination from hour-of-day, day-of-week, and seasonal effects.

The field validation study design incorporated three essential measures-development methodological requirements: reliability, validity, and sensitivity. *Reliability* ensures that replicated applications will yield consistent results. In order to insure the reliability of recommended M.O.E.s, the field evaluation uniformly applied the M.O.E. sensitivity analysis to WIM truck weight data collected in four states representing northern, southern, eastern, and western regions of the United States. *Validity* of a measure refers to the degree to which it actually measures what it is designed to measure. The validity of tested measures in this study was established due to their relevance to truck weight enforcement objectives. *Sensitivity* requires that the applied measure produces a true indication of the sought attribute or condition. The applied context of the field studies, i.e., controlled baseline versus enforcement conditions, ensured M.O.E. sensitivity.

This four-state effort examined WIM data gathered in the presence of enforcement activities and compared it with data collected under non-enforcement affected flow conditions. Findings observed in each state are summarized as follows.

California The California Department of Transportation provided output from a WIM scale located on I-5. An analysis of 3,678 truck combinations exhibited lower gross weights with a smaller proportion of overweight axles during the time when the weigh station was open. A sub-sample of 2,370 tractor-semitrailer combinations demonstrated lower rear-tandem weights with fewer instances of Excess ESALs when the weigh station was open.

Georgia Mobile truck-weight enforcement operations, utilizing an obtrusive portable roadside weigh scale, were conducted at a rural interstate location. An analysis of 483 combination trucks revealed a number of M.O.E. validation effects associated with observed axle and tandem weights. Under conditions of visible (and unexpected) mobile enforcement operations, the observed sample exhibited lower steering-axle weights, lower rear-axle weights, and lower rear-tandem weights. Moreover, less severe Excess ESAL violations were observed during the enforcement period. During the surprise enforcement operation, a number of overweight trucks were observed to either park alongside the roadway or divert to alternate routes.

Idaho A large volume of WIM data, i.e., gathered on approximately 29,000 commercial vehicles, was provided by the Idaho Transportation Department. A comparison of baseline versus enforcement conditions during three different weekdays produced a number of significant findings. While no day-of-week effects were readily evident to indicate on which days enforcement effort would more likely be effective, all of the tested operational measures were shown to be sensitive to enforcement activity. The M.O.E.s most consistently demonstrating sensitivity were: (1) the truck proportion exceeding 80,000 pounds, (2) the truck proportion with overweight tandems, (3) rear-tandem weight violation severity, and (4) the truck proportion which exhibited Excess ESALs. While less frequently associated with enforcement activity, the following measures were also validated in the Idaho data: (1) higher average ESALs, (2) Bridge Formula violations, and (3) the truck proportion exhibiting Bridge Formula violations.

Minnesota Data sets representing two weeks of continuous traffic monitoring were provided by the Minnesota Department of Transportation. Bending plate WIM data were gathered approximately five miles from a permanent truck-weight enforcement scale during times when the scale was open and closed. While generally weak M.O.E. validation findings were seen in these data, one data set exhibited a tendency to lower Bridge Formula violations and the other set produced a lower proportion of overweight trucks and lower average ESALs.

A number of ancillary issues affecting truck weight enforcement were also investigated. First, a field study addressed the issue of overweight-truck weigh-scale diversion via usage of bypass routes. The applied methodology was to collect portable WIM scale data on bypass routes and compare these data with main line WIM data. Second, implications for permitted overloads, with regard to their potential to confound M.O.E. application, were studied via a literature reviews and highway agency surveys to examine state-of-art permit record systems. Third, pavement deterioration effects of overweight trucks were investigated. Pavement design principles were user to compare pavement life under specified axle loading conditions.

Truck Weigh Scale Diversion

This field study examined truck weight and travel trends on potential bypass routes which circumvented permanent weigh scales. WIM data were collected on both the main line and truck bypass routes in California and Florida. Similar truck overweight trends were observed in both states. Customary truck weight distributions, e.g., average gross and axle weights, did not statistically differ between bypass and main line routes. However, truck samples observed using bypass routes were consistently more likely to exhibit higher average ESALs and Excess ESALs. Similar time-related travel trends were observed between the two states; despite differing hours of mainline permanent scale operation. In Florida, in the presence of 24-hour and 7-day per week scale operation, the majority of overweight diversion activity occurred during the early morning hours, e.g., 6 a.m. to 9 a.m. In California, while time-of-day diversion travel was affected by permanent scale operation, a tendency was observed for early morning scale diversion, e.g., 3 a.m. to 8 a.m.

Permit-Issued Trucks

The presence of permitted overweight trucks in the traffic stream presents a formidable threat to any WIM-based truck weight enforcement evaluation procedure. That permitted overweight trucks in the traffic stream can not be detected by WIM systems confounds the observed compliance with legal weight limits. However, the literature has indicated that traffic observations are insightful regarding violations in the absence of permitted truck flow data.

Our survey of state highway agencies conducted during the course of this research established that existing record-keeping systems generally do not allow for adjusting collected WIM data to correct for permitted truck weight effects. Consequently, what is unknown at this time is the real effect of permitted overloads.

However, our investigation of this problem did reveal that the Texas Department of Transportation does maintain sufficiently detailed and current records to determine the extent of overweight violations accruing from the presence of permitted trucks. Nevertheless, due to the expense of associated hardware and operational costs, a solution that is sufficient to correct WIM-based truck weight surveillance for permitted truck presence is not generally available.

Enforcement Effects on Pavement Life

Appendix E of this report contains a comprehensive discussion of pavement design factors and resulting deterioration effects associated with various truck overweight conditions. This discussion estimated effects of overweight trucks via the application of pavement design principles that contrasted pavement life duration under specified axle loading conditions. Furthermore, the User Guide software includes an automated procedure to determine the pavement life effect of observed truck weight violations based on WIM-measured truck weights and existing pavement design characteristics.

User Guidelines

The primary product of this research consists of guidelines to instruct user highway agencies regarding M.O.E. applications in their determination of truck weight enforcement effectiveness. The guideline consists of two parts.

First, an M.O.E. Sampling Guide was included to assist highway agency personnel in determining data-collection site requirements. Data-collection site requirements depend upon the type of enforcement activity, i.e., regional enforcement program, corridor-specific enforcement campaign, or single-location enforcement activity. Site number requirements are given for specific traffic operational criteria, i.e., functional highway classification and proportion of trucks. Site-specific truck sample size requirements are also provided.

Second, an automated User Guide is provided with this report to analyze and interpret WIM data. A user-friendly Windows software package, Truck Weight Enforcement Effectiveness Tool (TWEET), allows users to directly determine the effectiveness of truck weight enforcement activities. The software calculates and statistically compares M.O.E.s between observed enforcement conditions. The user has the option of conducting an automated pavement design life analysis, whereby the program determines the theoretical pavement-life effect resulting from the measured ESAL-loading difference associated with the observed enforcement activity.

1.0 INTRODUCTION

This report addresses the need to evaluate truck-weight enforcement activities and provides the practitioner with procedures for conducting required studies. Users are first told what information needs to be gathered, i.e., Measures of Effectiveness (M.O.E.s). Application of the M.O.E.s is then detailed in study methods describing sampling procedures and data-analysis operations.

Candidate M.O.E.s were developed on the basis of truck weight enforcement objectives, and final M.O.E.s were determined via their ranked abilities to meet highway and enforcement agency needs. Developed M.O.E.s were then validated in a four-state study to confirm their sensitivity to actual enforcement activity.

M.O.E sampling procedures, applicable to evaluate statewide/regional truck weight enforcement programs, were developed via a statistical analysis of nationwide data (See Appendix F). The user is provided with the resulting sampling guidelines. Study site number requirements are estimated for specified highway-functional and truck-percentage categories. Site-specific sample size requirements are also designated. A software data analysis tool, i.e., the Truck Weight Enforcement Evaluation Tool (TWEET), is provided for the user to compare M.O.E. results between two conditions, e.g., with- and without-enforcement activity. The software also estimates pavement service life effects as a function of the enforcement activity.

This report is organized into three content sections. First, current truck weight enforcement monitoring practice is briefly reviewed with emphasis on effectiveness measurement requirements. Second, M.O.E.s are defined in the context of their developmental and field validation results. Finally, a User Guide provides practitioners with procedures to evaluate truck weight enforcement activity and applies validated M.O.E.s that were developed and tested in the current research project. The User Guide consists of two parts: sampling guidelines and a software data analysis tool.

Supporting information, experimental results, and analyses are provided in a series of appendices to this report as follows:

A - Literature Review
B - Development, Evaluation, and Ranking of M.O.E.s
C - M.O.E. Field Validation
D - Ancillary Enforcement Issues
E - Effects of Axle Weight on Pavement Life
F - M.O.E. Sampling Plan Development
G - User Guide Software Help Screens
H - Glossary of Terms

2.0 TRUCK-WEIGHT ENFORCEMENT EFFECTIVENESS MEASUREMENT

2.1 Background

Truck-weight enforcement programs are conducted to limit the amount of damage to the infrastructure and to improve public safety on the highways. These programs represent a considerable effort to protect this country's investment in its pavement infrastructure.

The level and value of truck weight enforcement activities are currently gauged by means of statistical measures such as: (1) the number of trucks weighed, (2) the number of violators detected, and (3) the amount of fines collected. Such measures indicate level of effort, but not what is actually being accomplished as a result of that effort in terms of overall compliance with weight laws.

A comprehensive examination of truck weight enforcement practice (U.S. DOT, 1993), over a four-year study period, noted that on average over 144 million trucks were weighed annually, resulting in over 681 thousand citations. However, this comprehensive nationwide examination of enforcement-activity concluded that *adequate information was not being collected to assess compliance trends.*

The DOT study documented a wide variation in the number of enforcement weighings between states, bearing no correlation with actual truck volumes. Moreover, sporadic changes in year-to-year enforcement activity further indicated the lack of uniform practice. Highlights of the study noting inconsistencies with regard to truck weight enforcement practice between states are summarized as follows:

1. Annual enforcement weighings ranged from less that 20,000 in certain states to more than 5 million.
2. Within the sample of states conducting more than 5 million weighings, truck weight-sampling rates varied from 287 to 1,864 weighings per million vehicle miles of estimated truck travel miles. Thus, the sampling rate was seen to vary from state to state by a factor of 6.5.
3. Within the above noted weighed-truck samples, citation rates varied between .66 and 6.3 trucks per thousand. Thus, citation rates were seen to vary from state to state by a factor of 9.6.

This wide divergence in enforcement practice confounds the problem of assessing compliance trends. It is not possible to gauge the impact of enforcement practice without a systematic data-sampling approach that is sensitive to the actual number of trucks in the traffic stream and to their degree of compliance with weight regulations.

2.2 Current Status

The effectiveness of the nation's truck weight enforcement activity is not measured via any systematic sampling of truck volume, weight, and violation data. As a result, the effect of truck-weight enforcement programs is not known in terms of: (1) actual impact on weigh-law compliance, (2) effect on safety of truck operations, (3) pavement service life effects, or (4) cost-effectiveness of enforcement activity, e.g., associated cost-benefit in terms of pavement preservation.

2.3 Effectiveness-Measurement Requirements

In order to determine what is actually achieved by truck weight enforcement efforts, it is first necessary to consider truck weight enforcement goals or objectives. Goals of state enforcement agencies, which operate truck weight enforcement activities, are the following:

1. Deter truck operation in an overweight condition and/or operating with inappropriate axle spacing,
2. Control pavement and bridge damage from overweight trucks,
3. Protect the public from safety risks associated with overweight trucks, and
4. Protect law-abiding truck operators from illegal competition.

Any benefit of the enforcement activity must then be recognized in terms of some, or all, of these goals. That is, a study to determine the effects of truck weight enforcement activities must be based on *measures that reflect goals* of the weight enforcement program. Typical output of a truck weight enforcement evaluation should indicate effects on compliance, e.g., instances and severity of overweight violations, and whether any enforcement benefit is achieved in terms of reduced pavement wear.

Moreover, it is necessary to *systematically* measure enforcement compliance in the context of actual truck exposure, e.g., total truck volume, so as to validly determine compliance (and consequences of non-compliance) within a given study area. Systematic observation procedures are required to ensure that the observed sample adequately characterizes the overall truck population.

3.0 TRUCK-WEIGHT ENFORCEMENT MEASURES of EFFECTIVENESS (M.O.E.s)

In response to the need for adequate truck-weight enforcement evaluation procedures, NCHRP Project 20-34 developed and validated applicable measures of effectiveness (M.O.E.s). The project effort also developed techniques to apply the M.O.E.s in a systematic sampling plan and to analyze the collected data.

A discussion of the M.O.E. development process is contained in Appendix B. The field validation procedure is detailed in Appendix C. Results of these efforts are summarized in the following two report sections.

3.1 M.O.E. Development

The first step in the M.O.E. development process was to consider an operational definition of truck weight enforcement M.O.E.s. Following this step, the project team developed a set of objective criteria against which to evaluate candidate M.O.E.s. The applied criteria were derived from M.O.E functional requirements. Candidate M.O.E.s were ranked according to their suitability to meet the designated performance criteria.

It is necessary to understand the definition of truck-weight enforcement M.O.E. A ***Measure of Effectiveness*** **(M.O.E.)** of weight enforcement activity is defined as a "determinable quantity *of what is achieved as the result of truck weight enforcement activity*". Its application should also be used to quantify the contribution that a particular activity makes toward achievement of one or more of the goals defined in Section 2.3. In order to quantify effectiveness there must be measures which show benefits in terms of: (1) compliance with operational weight and axle-spacing regulations, (2) pavement/bridge preservation, or (3) minimizing accidents, deaths, injuries, and property damage.

Initial truck-weight enforcement M.O.E. concepts were developed on the basis of an assessment of truck weight enforcement objectives (including results of a 50-state agency survey) and the anticipated sensitivity of resulting candidate measures to those objectives. A set of candidate M.O.E.s for field validation was derived from a systematic application of the following functional criteria:

1. *Practicality of M.O.E. application*, e.g., amenable to state agency data collection capability, cost requirements, and ease of measurement.
2. *Reliability of candidate M.O.E*, i.e., correctly represents a true distribution of weights, classification, percentage of overweight trucks, percent of bridge formula non-compliance, etc.
3. *Support random sampling*, i.e., designed to achieve representative sampling over designated study region.
4. *Absence of bias with regard to enforcement/monitoring procedure*, i.e., generally sensitive to prevailing truck characteristics regardless of enforcement activity.
5. *M.O.E. compatibility with agency data collection methods*, i.e., achieved in terms of measures that can be readily derived from existing or otherwise readily obtainable data-collection apparatus.
6. *Sensitivity to infrastructure damage,* e.g., considers that excessive axle-weight as opposed to excessive tandem-weight are more likely to result in pavement damage.
7. *Applicability to future technology,* i.e., data requirements are consistent with capabilities of emerging technologies.

Candidate measures were evaluated and ranked by an expert panel. The final set of designated candidate M.O.E.s for field validation, along with their definitions, is presented in Table 1.

3.2 M.O.E. Field Validation

A field validation study was conducted to confirm the sensitivity of candidate M.O.E.s to actual truck weight enforcement activity. Candidate M.O.E.s were tested in a four-state evaluation effort that applied matched sets of weigh-in-motion (WIM) data, collected under controlled baseline and enforcement conditions. Overall findings of the field validation effort confirmed the suitability of M.O.E.s listed in Table 1. State-specific findings are summarized as follows.

Table 1. Designated Measures of Effectiveness (M.O.E.s)
and their Definitions

Truck Weight Enforcement M.O.E.	**Definition**
Gross Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal gross weight limit.
Gross Weight Violation, Severity	The extent to which average measured gross weights for the observed sub-sample of gross weight violators exceeds the legal gross weight limit.
Single-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more axles which exceeds the legal single-axle weight limit.
Single-axle Weight Violation, Severity	The extent to which average measured single-axle weights for the observed sub-sample of single-axle weight violators exceeds the applicable legal limit.
Tandem-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more tandems which exceeds the legal tandem-axle weight limit.
Tandem-axle Weight Violation, Severity	The extent to which average measured tandem-axle weights for the observed sub-sample of tandem-axle weight violators exceeds the applicable legal limit.
Bridge Formula Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal Bridge Formula weight.
Bridge Formula Violation, Severity	The extent to which average measured Bridge Formula weights for the observed sub-sample of Bridge Formula violators exceeds the legal weight.
Excess ESAL[1]s, Proportion	The fraction (or percentage) of the total observed truck sample exhibiting Excess ESALs; i.e., ESALs attributable to the illegal portion the individual single or tandem axle group.
Excess ESALs, Severity	The average value of Excess ESALs observed for the truck sub-sample exhibiting Excess ESALs.

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[1] Equivalent Single Axle Load is defined in the Glossary (Appendix H) of this report.

California The California Department of Transportation provided output from a WIM scale located on I-5. An analysis of 3,678 truck combinations exhibited lower gross weights with a smaller proportion of overweight axles during the time when the weigh station was open. Data on a sub-sample of 2,370 tractor-semi-trailer combinations was further analyzed to examine M.O.E. sensitivity to the enforcement activity. The results confirmed the validity of the following M.O.E.s: Tandem-axle Weight Violation Severity, Bridge Formula Violation Proportion, and Excess ESAL Severity.

Georgia Mobile truck-weight enforcement operations, utilizing an obtrusive portable roadside weigh scale, were conducted at a rural interstate location. An analysis of WIM data gathered on 483 combination trucks revealed a number of M.O.E. validation effects associated with observed axle and tandem weights. Under conditions of visible (and unexpected) mobile enforcement operations, the observed truck sample exhibited lower steering-axle weights, lower rear-axle weights, and lower rear-tandem weights. During the surprise enforcement operation, a number of overweight trucks were observed to either park alongside the roadway or divert to alternate routes. The results validated the following M.O.E.s: Single-axle Weight Violation Proportion, Tandem-axle Weight Violation, and Excess ESAL Severity.

Idaho A large volume of WIM data, i.e., gathered on approximately 29,000 commercial vehicles, was provided by the Idaho Transportation Department. A comparison of baseline versus enforcement conditions during three different weekdays produced a number of significant findings. While no day-of-week effects were readily evident to indicate on which days enforcement effort would more likely be effective, all of the tested operational measures were shown to be sensitive to enforcement activity. M.O.E.s most consistently demonstrating sensitivity to enforcement activity were: (1) Gross Weight Violation Proportion, (2) Single-axle Weight Proportion, (3) Tandem-axle Weight Proportion, and (4) Excess ESAL Proportion. While less frequently associated with enforcement activity, the effectiveness of following measures were also validated in the Idaho data: (1) Gross Weight Violation Severity, (2) Single-axle Weight Violation Severity, (3) Tandem-axle Weight Violation Severity, and (4) Excess ESAL Severity.

Minnesota Data sets representing two weeks of continuous traffic monitoring were provided by the Minnesota Department of Transportation. Bending-plate WIM data were gathered approximately five miles from a permanent truck-weight enforcement scale during times when the scale was both open and closed. While generally weak M.O.E. validation findings were seen in Minnesota results, one data set did exhibit a smaller proportion of gross weight and tandem axle violations along with a tendency for less severe excess ESALs. The other set produced a tendency to lower Bridge Formula violations. The results validated the following M.O.E.s: (1) Gross Weight Violation Proportion, and (2) Tandem-axle Violation Proportion.

Summary All of the tested M.O.E.s. were shown to be sensitive to actual truck weight enforcement activities. A number of factors were seen to affect M.O.E. sensitivity to enforcement procedures, including actual truck weight/configuration characteristics, shipping commodity demands, observed truck sample size, and WIM equipment variables. Those measures most strongly supported by the field data (in descending order) are as follows: (1) Excess ESALs, Severity; (2) Tie – Gross Weight Violation, Severity, and Excess ESALs, Proportion; and (3) Tie – Gross Weight Violation, Proportion; Single-axle Weight Violation, Proportion; and Tandem-axle Weight, Severity.

4.0 M.O.E. USER GUIDE

This M.O.E. User Guide provides practitioners with techniques to evaluate truck weight enforcement activity and applies validated M.O.E.s that were developed and tested in the current research project. The user guide consists of two parts: sampling guidelines and a software data analysis tool.

> ***Sampling (Data Collection) Guidelines*** are applied to estimate the number of WIM data collection sites and required sample sizes required to measure an enforcement effect. This guideline provides users with estimates for specified roadway classification and truck percentage conditions.
>
> ***Software (Data Analysis) Tool*** calculates and statistically compares M.O.E. values between two observed enforcement conditions. This procedure also allows users to conduct an automated pavement design life analysis, estimating the theoretical pavement-life effect resulting from differences produced by the two observed enforcement activities.

It is important to distinguish between procedural *guidelines* and a methodological *tool.* A *guideline* (i.e., a method by which to undertake a course of action, which may be modified at the discretion of the user) provides the user in this case with the starting point for determining site number and data-collection sample sizes. However, final sampling requirements in the applied evaluation will depend upon observed data characteristics, due to statistical requirements for data stability (i.e., degree of measured variance).

On the other hand, a *tool* (i.e., an instrument to perform an operation in a specified manner) is to be strictly applied throughout the evaluation. In fact, the software tool in this case is designed to refine site-number requirements, on the basis of measured data characteristics, and to advise the user of final sampling requirements.

4.1 M.O.E Sampling (Data Collection) Guidelines

Sampling guidelines described in this section provide practitioners with straightforward data-collection requirements to measure enforcement effects using the validated M.O.E.s. This guideline provides users with estimates of observation site numbers and associated truck sample sizes. These estimates are provided for specified roadway classification and truck percentage conditions.

Statistical M.O.E. sampling requirements were based on an analysis of nationwide WIM data. This developmental analysis examined M.O.E. data generated for representative locations (i.e., exhibiting prerequisite highway functional classification and truck mix criteria) and determined the minimum number of observation sites required to produce representative M.O.E. distributions. Based on these results, M.O.E. sampling guideline procedures were developed to enable users to estimate equivalent sampling requirements.

Sampling guidelines are directed toward WIM database gathering. It must also be emphasized that the soundness of the WIM input data and its subsequent analysis to measure the effectiveness of truck weight enforcement is highly dependent on calibration and maintenance of that equipment.

Users of this Sampling Guide are not expected to apply expertise in the area of statistics. However, due to the fact that this guide was developed via the application of various statistical concepts that affect its output, two statistical concepts and their application in the guide's development are briefly explained as follows.

Sampling requirements contained in the guide utilized two statistical concepts, *Level of Significance*, and *Power of Test*. Each of these terms is defined as follows, only as a matter of information for users of this guide.

Level of Significance refers, in this case, to the probability that the user is willing to risk the error of rejecting a valid change in M.O.E. occurrence. In statistical terminology, the Level of Significance is the maximum probability with which we would be willing to risk a *Type 1 error*. A Type 1 error occurs when a true hypothesis is rejected, i.e., that baseline (no enforcement) versus enforcement M.O.E. variable sets are statistically different. The .05 Level of Significance was applied in the development of this guide.

Power of Test refers to the likelihood of making a correct statistical assessment, i.e., that the proper hypothesis is accepted, statistically speaking. The issue is to what extent is the user willing to risk accepting an invalid change in M.O.E. occurrence. In statistical terminology, the Power of a Test is the maximum probability with which we would be willing to risk a *Type 2 error*. A Type 2 error occurs when a false hypothesis is accepted, i.e., that baseline versus enforcement M.O.E. variable sets are not statistically different. The .80 Power of Test was applied in the development of this guide.

4.1.1. Sampling Observation Levels

Separate observation levels for sampling truck-weight violations were devised in order to meet the diverse evaluation requirements of varied truck weight enforcement operations. Three designated sampling observation levels are as follows: (1) statewide or regional, (2) highway corridor or local level, and (3) spot or location-specific. Figure 1 on the next page is a conceptual representation of the three designated observational levels.

At the broadest level, the implementation of revised regional or statewide policy may require sampling over a vast geographic area, covering hundreds of square miles. At the opposite end of the spectrum, spot truck-weight enforcement procedures are frequently required due to location-specific factors, e.g., pertaining to local hauling conditions. Finally, a major concern for enforcement and highway agencies is weight-law compliance along specific highway corridors. The critical nature of weight monitoring along corridors stems from a number of factors, including trucker avoidance of weight enforcement and costly pavement damage to local highways.

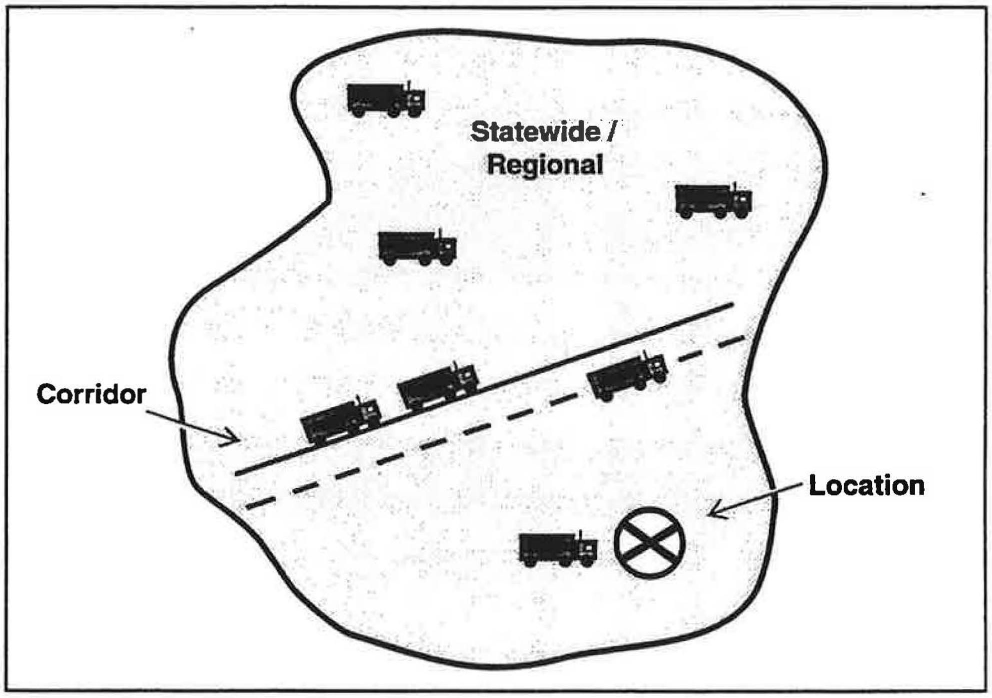

Figure 1. Illustration of Varied Data-sampling Observation Level Concept

4.1.2 Statewide or Regional M.O.E. Sampling

Statewide or regional M.O.E. sampling is applied to evaluate any truck weight enforcement program that affects large geographic areas which exceed the bounds of a definable highway corridor. The derivation of sampling requirements was based on actual observed statewide M.O.E. distributions; however, this guide is also applicable for smaller geographic regions. Site number requirements contained in this guide indicate minimum numbers to produce representative results for a designated region. Data collection site requirements are designated on the basis of regional characteristics, i.e., highway functional class and associated truck percentage combinations, which comprise the area under study. An example application of this procedure is shown in Section 4.1.3 of this report.

WIM Data Site Number Requirements Guidelines for determining the required number of observation sites for a statewide/regional study of truck weight enforcement effectiveness were determined on the basis of observed M.O.E. distributions[2] from representative

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[2] See Appendix F.

nation-wide locations. Site number requirements for a designated region were based on the region's composition in terms of specified highway functional classification and associated truck percentage criteria.

The user's determination of study site numbers shall commence via the application of the guidelines shown in Table 2, which specify site number requirements for each functional-class/truck-percentage category. Site numbers indicated in the table are intended as a starting point for establishing final regional observation site number requirements. The data-analysis software generated in this project is designed to refine site number requirement based on individual user's specific data characteristics.

Table 2. Minimum Site-number Guideline for Selected M.O.E.s in State/Regional Truck Weight Enforcement Evaluations

FUNCTIONAL CLASS And Truck Percentage	GROSS WEIGHT VIOLATIONS	TANDEM AXLE VIOLATIONS	SINGLE AXLE VIOLATIONS	EXCESS ESALs
Rural Interstate				
< 15 % Trucks	3	3	8	9
15 to 30 % Trucks	6	6	21	32
> 30% Trucks	3	3	13	32
Rural Primary Arterial				
< 9 % Trucks	3	3	11	2
9 to 30 % Trucks	7	7	24	15
> 30% Trucks	2	2	5	15
Rural Minor Arterial	3	3	9	9
Urban Interstate				
< 9% Trucks	2	2	2	10
≥ 9% Trucks	2	2	6	15
Urban Primary Arterial				
< 9% Trucks	2	2	7	10
≥ 9% Trucks	3	3	8	14

NOTE: The accompanying NCHRP Project 20-34 software generates site number requirements based on user's data.

The statewide/regional M.O.E. sampling procedure involves two preparatory steps. First, the geographic area, e.g., jurisdictional territory, to be affected by the enforcement program under study must be clearly defined. Second, the highway network within the defined study region must be reviewed to determine its composition, in terms of route functional classification and associated truck percentage as a function of overall traffic volume, on each affected route.

The initial number of required study sites is then determined on the basis of corresponding site-number designations shown in Table 2, subject to revision by the associated software. The total number of study sites in a given region will be the sum of those applied in each functional class and truck-ratio which are represented in the region, as demonstrated in the next paragraph. Each functional class represented in the region under study must be included in the array of designated observation sites.

For example, when designating the primary M.O.E. of interest to be the "Proportion of Gross Weight Violations", then the number of required sites for each highway category will be derived from numbers shown in the left-most column of Table 2. That is, at least three data collection sites are required to represent Rural Interstates with less than 15 percent trucks, six to represent Rural Interstates with 15 to 30 percent trucks, etc. The total number of sites for the study region will be equal to the sum of site numbers for all functional-class/truck-percentage categories represented in the region, i.e., 36 sites. This procedure is illustrated in the example application of a regional sampling plan development shown in section 4.1.3.

It is important to note a number of user precautions and associated considerations underlying the development of site numbers contained in Table 2. These caveats relate to the analysis and application of nationwide representative data used to estimate requirements for conducting a regional truck weight enforcement evaluation.

First, the nationwide analysis determined that a *single* observation site, within selected functional-class/truck-percentage categories, was occasionally sufficient to statistically detect certain enforcement effects. However, application of sound sampling strategy to a regional enforcement study requires a significant degree of generality to ensure its validity; therefore, Table 2 mandates a minimum of two sites for each functional highway classification condition.

Second, site number requirements outlined in Table 2 were based on observed M.O.E percentage reductions found to be associated with enforcement activity[3]. However, for situations in which an observed enforcement activity is expected to produce greater or lesser percentage M.O.E differences, an appropriate adjustment to the number of observation sites would be required to statistically measure the effect. For example, in a given region where 7 data collection sites may be required to detect an 10-percent reduction in gross weight violations, only 5 sites would likely be required to detect a 20-percent reduction. Importantly, with the current application, the user will be appropriately informed of the level of affected M.O.E. change (and the associated number of required sites to validly observe this effect) via application of the software package accompanying this guide. The software application is explained in Section 4.2 of this report.

Third, site numbers designated in Table 2 were based on measured statistical M.O.E. distributions. By taking into account normal sample sizes and associated variability of these M.O.E.s, they indicate the number of observation sites required to capture representative M.O.E. distributions. However, a number of application-specific considerations are necessary in the user's interpretation of the table. Specifically, truck weight surveillance over a large geographical area may *logically* require larger site numbers than indicated in the table. For example, many cells in the table indicate the necessity of only 2 or 3 study sites, given certain highway classification and truck ratio conditions. Yet, in the case of a statewide enforcement program over a very large area, the limitation of 2 or 3 study sites may be considered inadequate.

Thus, the final designation of observation sites must consider prevalent conditions, e.g., specific hauling and commodity demands that affect truck-loading operations and the sub-regional areas to which they apply. Specifically, the user is cautioned against combining sites characterized by known non-homogenous loading conditions when applying the sampling procedure.

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[3] See Appendix F, Tables F-40 through F-42.

Finally, as previously noted, Table 2 is a *guideline* (i.e., a procedure by which to undertake a course of action, which may be modified at the discretion of the user) to provide the user with the starting point for determining site number and data-collection sample sizes. Its final application relies on engineering judgement in the context of specific study situations.

Designation of Data Collection Periods In view of known commodity shipping patterns, both weekend and weekday data collection periods are recommended in applied regional M.O.E. sampling efforts to evaluate truck weight enforcement programs. Importantly, designated data collection periods need to be sensitive to seasonal conditions, e.g., agricultural commodity hauling patterns. A minimum two-day data collection duration is required at each site for each observed enforcement condition.

Based on NCHRP Project 20-34 findings, the user is advised to expect maximum violation to occur during the early morning hours, e.g., 3 a.m. to 7:30 a.m. on weekdays, and during the late evening hours on Sundays.

Minimum site-specific truck sample sizes are shown in Table 3 for designated combinations of highway functional class and associated truck percentages for designated M.O.E.s. Sample size estimations shown in the table are based on the requirement to detect differences in truck proportions exhibiting the array of generally applied M.O.E.s at the .05 level of statistical confidence.

4.1.3 Example of a Regional M.O.E. Sampling Application

Consider the hypothetical example of a geographic region with a distribution of 100 WIM data collection sites as shown in Table 4. This distribution was estimated on the basis of traveled vehicle-miles by functional classification[4] with adjustments for traffic monitoring prioritization.

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[4] U.S. Department of Transportation, Bureau of Transportation Statistics, *National Transportation Statistics,* Washington, D.C. 1996

Table 3. Minimum Site-specific Number of Required Truck Observations

FUNCTIONAL CLASS and Truck Percentage	MINIMUM* SAMPLE
Rural Interstate	
< 15 % Trucks	175
15 to 30 % Trucks	300
> 30% Trucks	200
Rural Primary Arterial	
< 9 % Trucks	225
9 to 30 % Trucks	325
> 30% Trucks	100
Rural Minor Arterial	200
Urban Interstate	
< 9% Trucks	100
≥ 9% Trucks	200
Urban Primary Arterial	
< 9% Trucks	125
≥ 9% Trucks	100

* Over a minimum 2-day data collection period.

The assignment of available WIM sites to monitor an ongoing regional truck weight enforcement program, according to the scheme previously shown in Table 2, produces the sampling scheme shown in Table 5 on the next page.

Table 4. Available WIM Monitoring Locations in Example Sampling Application

FUNCTIONAL CLASS and Truck Percentage	AVAILABLE WIM DATA SITES
Rural Interstate	
< 15 % Trucks	4
15 to 30 % Trucks	8
> 30% Trucks	4
Rural Primary Arterial	
< 9 % Trucks	7
9 to 30 % Trucks	7
> 30% Trucks	14
Rural Minor Arterial	15
Urban Interstate	
< 9% Trucks	8
≥ 9% Trucks	18
Urban Primary Arterial	
< 9% Trucks	5
≥ 9% Trucks	11
TOTAL	100

An examination of Table 5 indicates that of the 100 available WIM-monitoring sites, only 36 sites are required for region-wide monitoring of two M.O.E.s, i.e., Gross Weight Violations, and Tandem Axle Violations, on all highway functional-class/truck-percentage categories. In order to obtain a non-biased estimation of truck weight enforcement effects, the user agency is advised to assign data collection locations in a *random* fashion (within appropriate functional-class/truck-percentage categories) when all available WIM installations are not statistically required for the evaluation.

A larger number of data collection sites is required within a region to statistically represent less-frequently-occurring M.O.E.s (See Appendix F Sampling Plan Development). Consequently, in the current example, the latter two M.O.E.s required more data collection sites within certain functional-class/truck-percentage categories than were available. In these instances, the percentage of available WIM sites is indicated in the appropriate cells of Table 5. For example, while 8 sites were previously suggested in the Table 2 Guide as the minimum number of sites to detect enforcement effects in terms of Single-Axle Violations, the 4 available sites comprise 50% of this requirement. In such instances, the regional evaluation is necessarily limited by WIM-site availability, and the issue site selection bias defers to applied site-location decision rationale.

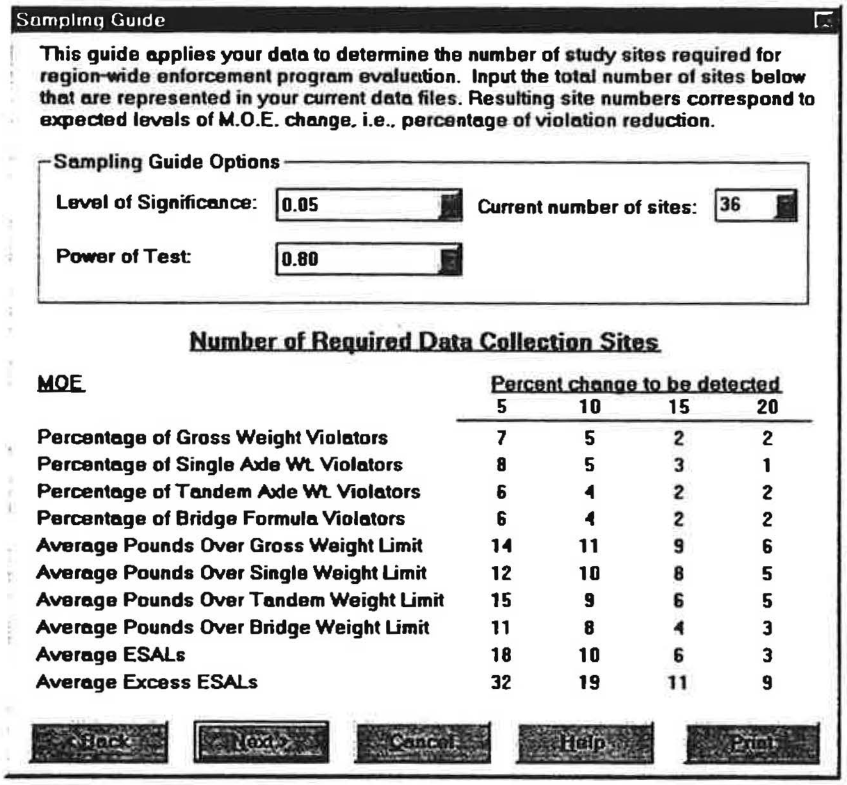
Table 5. Recommended WIM Data Collection Site Distribution
for Example State/Regional Sampling Scheme

FUNCTIONAL CLASS and Truck Percentage	GROSS WEIGHT VIOLATIONS	TANDEM AXLE VIOLATIONS	SINGLE AXLE VIOLATIONS	EXCESS ESALs
Rural Interstate				
< 15 % Trucks	3	3	4 (50%)	4 (44%)
15 to 30 % Trucks	6	6	8 (38%)	8 (25%)
> 30% Trucks	3	3	4 (31%)	4 (12%)
Rural Primary Arterial				
< 9 % Trucks	3	3	7 (64%)	2
9 to 30 % Trucks	7	7	7 (29%)	7 (47%)
> 30% Trucks	2	2	14 (58%)	14 (93%)
Rural Minor Arterial	3	3	9	9
Urban Interstate				
< 9% Trucks	2	2	2	8 (80%)
≥ 9% Trucks	2	2	6	15
Urban Primary Arterial				
< 9% Trucks	2	2	5 (71%)	5 (10%)
≥ 9% Trucks	3	3	8	11 (79%)
TOTAL	36	36	74	87

The non-availability of 100 percent of the Sample Guide's recommended site numbers does not necessarily mean than the region can not be evaluated in terms of the latter two M.O.E.s in this instance. Conversely, more sites may be needed in some instances than indicated by the Table 2 Guide. The reason is that the exact number of required sites is determined by the data variance that is actually measured. Again, we emphasize that site numbers indicated in Table 2 are guidelines, based on nationwide observations of expected M.O.E.s variances, and these estimates are prescribed as the starting point for development of the final sampling plan.

Precise site number requirements are determined via application of the data analysis software developed in this project, the Truck Weight Enforcement Evaluation Tool (TWEET), described in Section 4.2 of this report. This software computes customized site number requirements based on the user's collected data. Specifically, it performs site-number requirement calculations based on actual measured variances, as is statistically appropriate. Thus, this process provides the necessary site-number refinement calculation to define final sampling requirements. However, it can not replace the Table 2 Guide, as the user needs initial estimates for evaluation study planning purposes.

The data analysis software contains a "Sampling Guide" dialog box that computes site number requirements for various levels of statistical precision (see Figure 2). The example dialog box in the figure hypothetically considers data collected at 36 sites. This is the minimum number of prescribed sites in Table 2 assuming that the study region contains sites in all eleven functional-class/truck-percentage categories. This software sampling aid prescribes site-number requirements as a function of the specific enforcement-program effectiveness threshold, i.e., designated percent change in specific M.O.E.s, that the user wishes to consider. For example, looking at site-number requirement shown in the figure for Gross Weight Violators M.O.E., we see that if users want to detect an enforcement effect based on an expected 40-percent violation reduction, only two data collection sites are required. However, to apply a more rigorous statistical requirement, for example a statistical test that is sensitive to a ten-percent reduction, seven sites would then be required.



This guide applies your data to determine the number of study sites required for region-wide enforcement program evaluation. Input the total number of sites below that are represented in your current data files. Resulting site numbers correspond to expected levels of M.O.E. change, i.e., percentage of violation reduction.

Sampling Guide Options

Level of Significance: 0.05

Current number of sites: 36

Power of Test: 0.80

Number of Required Data Collection Sites

MOE	Percent change to be detected			
	5	10	15	20
Percentage of Gross Weight Violators	7	5	2	2
Percentage of Single Axle Wt. Violators	8	5	3	1
Percentage of Tandem Axle Wt. Violators	6	4	2	2
Percentage of Bridge Formula Violators	6	4	2	2
Average Pounds Over Gross Weight Limit	14	11	9	6
Average Pounds Over Single Weight Limit	12	10	8	5
Average Pounds Over Tandem Weight Limit	15	9	6	5
Average Pounds Over Bridge Weight Limit	11	8	4	3
Average ESALs	18	10	6	3
Average Excess ESALs	32	19	11	9

Figure 2. Sampling Guide Dialog Box Applied to Example Sampling Application

4.1.4 Corridor or Local-Level M.O.E. Sampling

Truck weight enforcement efforts often concentrate on a corridor surrounding a specific route, e.g., commonly used for commodity hauling. Applied enforcement strategies involve monitoring primary routes as well as potential diversion routes within the corridor.

Designation of WIM Data Collection Sites The corridor or local-level M.O.E. sampling procedure first involves designation of the potentially-affected roadways surrounding the primary route of interest. Routes in this area obviously need to be targeted (and WIM data sampled) by the corridor-specific enforcement program. Second, the highway network within the diversion area must be examined to determine the functional classification and associated truck percentage on each affected route. Initial numbers of required data collection sites on each functional class of highway within the region can then be determined via the application of guidelines in Table 6. While Table 6 is similar in appearance to Table 2, previously shown for wider-area regional truck weight enforcement programs, it does indicate routes on which a single observation site is suitable for collection of designated M.O.E.s. Unlike wider-area, regional weight-enforcement efforts, a single observation site may suitable for use in a corridor-specific enforcement activity evaluation.

Table 6. Recommended Minimum Site Numbers for Selected M.O.E.s
in Corridor-specific Truck Weight Enforcement Evaluations

FUNCTIONAL CLASS And Truck Ratio	GROSS WEIGHT VIOLATIONS	TANDEM AXLE VIOLATIONS	SINGLE AXLE VIOLATIONS	EXCESS ESALs
Rural Interstate				
< 15 % Trucks	3	3	8	9
15 to 30 % Trucks	6	6	21	32
> 30% Trucks	3	3	13	32
Rural Primary Arterial				
< 9 % Trucks	3	3	11	2
9 to 30 % Trucks	7	7	24	15
> 30% Trucks	1	1	5	15
Rural Minor Arterial	3	3	9	9
Urban Interstate				
< 9% Trucks	1	1	2	10
≥ 9% Trucks	2	2	6	15
Urban Primary Arterial				
< 9% Trucks	2	2	7	10
≥ 9% Trucks	3	3	8	14

Site number requirements contained in Table 6 were based on observed M.O.E percentage reductions, determined in Appendix F, to be associated with enforcement activity. As previously shown in the regional evaluation example, final sample size requirements will be confirmed via application of the TWEET software.

Designation of Data Collection Periods The same data-collection period sampling principles apply to the corridor and local-level M.O.E. application as were noted with regard to statewide and regional M.O.E. sampling strategy above. That is, truck observation periods should include both weekday and weekend periods. First, emphasis should be given to pre-dawn weekday and Sunday evening observation times. Second, scheduled data collection periods need to be sensitive to seasonal commodity hauling. Third, minimum data collection durations of two days are required for each enforcement condition. Finally, minimum site-specific sample sizes requirements are the same as previously indicated in Table 3.

4.1.5 Location-Specific M.O.E. Sampling

M.O.E. sampling to evaluate a specific enforcement activity can involve data collection at a single observation site. The site would be designated as a feasible permanent or portable WIM installation at a highway location affected by trucks subjected to the enforcement procedures under study. A minimum data collection duration of two days is required for each enforcement condition. Care must be taken that WIM instrumentation be installed and operated in an unobtrusive manner so as not to interfere with an objective evaluation procedure.

Ideally, such an evaluation would be conducted at a location where no potential overweight-truck diversion route is possible. However, at sites other than long desert highways, bridges between two islands, or a few select routes along the Florida Keys, enforcement agencies are advised to monitor any parallel highways for increased truck volume. Furthermore, as an internal validity check with regard to the enforcement evaluation effort, user agencies are advised to compare truck volumes, time-of-day flow rates, and violation percentages between enforcement and non-enforcement data collection periods. Direct application of the TWEET software accommodates this task.

4.2 M.O.E. Software (Data Analysis) Tool

This software guide consists of a user-friendly Windows program, Truck Weight Enforcement Effectiveness Tool[5] (TWEET), designed to aid users in determining the effectiveness of user-specified truck weight enforcement policies. It calculates and statistically compares M.O.E. values between two observed enforcement conditions. It also allows users to conduct an automated pavement design life analysis, estimating the theoretical pavement-life effect resulting from differences in the two observed enforcement activities. The software will be available to users on the Internet[6] and will automatically self-install on the user's computer.

The software works by reading WIM data that has been collected under different enforcement conditions and allowing the user to compare the data from each condition to determine the most effective method of enforcement. It presents the user with a variety of "dialog boxes", i.e., pop-up screens which enable the user to provide required input to run the software. The software is designed to be user friendly, e.g., in most cases the user will simply press the "Next" button to continue operation.

There are three discrete steps to the analysis process as follows: (1) User Input, (2) Calculation, and (3) Output.

1) The *User Input* phase of the program requires the user to enter such information as the type of units the program is to use (English or Metric), enforcement condition description, and data file format.

2) During the *Calculation* phase of operation, the program performs the necessary calculations on the data, including violation levels, Bridge Formula calculations, and M.O.E. calculations. The program performs this activity entirely automatically, and the user need not be concerned with this part of the program. During calculations a graphical percentage meter is displayed to indicate the program's progress.

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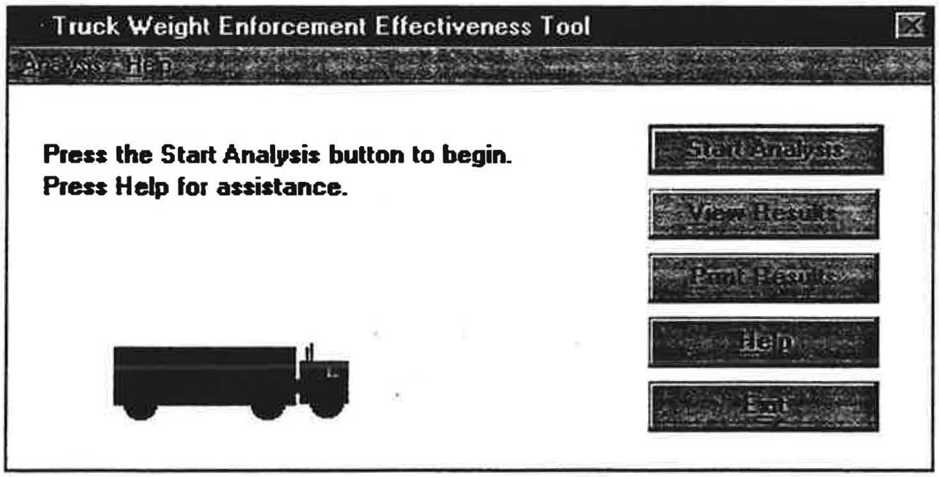
[5] More detail on this software package, including a description of the software's Help Screens, is shown as Appendix G to this report.

3) During the *Output* phase of the program, calculated results are displayed to the user. The data is displayed on-screen in a series of dialog boxes, each of which can be printed by the user. The program will automatically display the calculated values after finishing the calculations. Once the program has performed the calculations, the output can be viewed again by pressing the View Results button on the main window.

4.2.1 Starting the Analysis

To start a truck weight enforcement analysis, the user activates the program from the program's *Main Window* (Figure 3) dialog box. The button marked "Start Analysis" allows the user to start a truck-weight and enforcement-effects analysis.



Press the Start Analysis button to begin.
Press Help for assistance.

Figure 3. "Main Window" on M.O.E. Application Software

First the user will see the dialog labeled *Select Units* (Figure 4 on the next page). This dialog asks the user to select the system of units of measure to be used by the program. From this dialog box, the user selects the type of units to use (English or Metric) and presses "Next". This dialog box defaults to English units.

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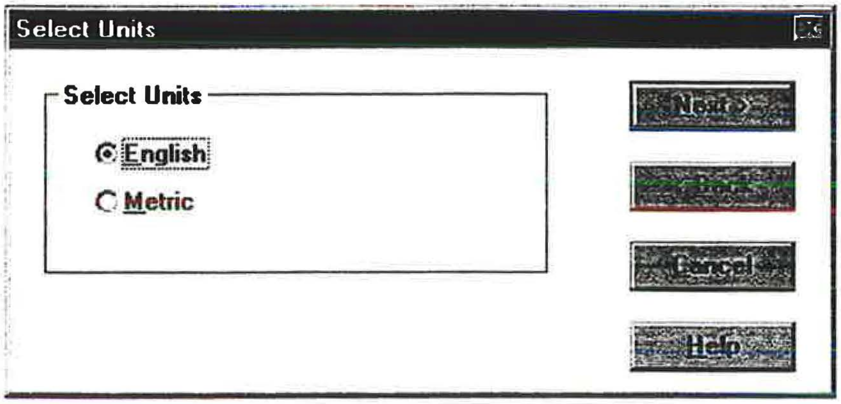
[6] Users are advised to check the NCHRP web site. The address is http://www2.nas.edu/trb/trbcrp.



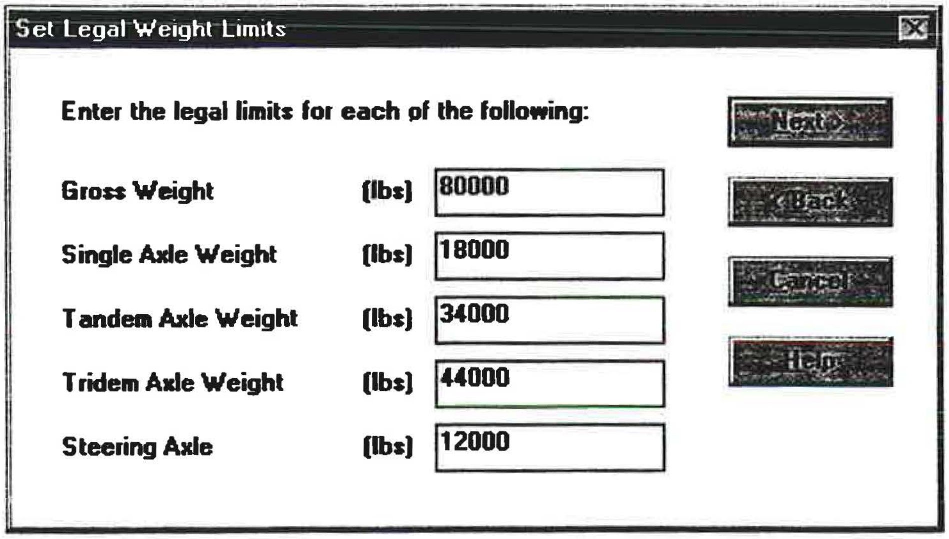
Select Units

● English

○ Metric

Figure 4. "Select Units" Dialog Box

The *Set Legal Weight Limits* dialog box appears next (Figure 5). This dialog box asks the user to enter the maximum allowable weights as defined by local regulations. There are five fields presented: Gross, Single Axle, Tandem Axle, Tridem, and Steering Axle Weights. Defaults in this dialog may be adequate for most users. Modification of these defaults may be necessary depending upon prevailing legal regulations.



Enter the legal limits for each of the following:

Gross Weight (lbs) 80000

Single Axle Weight (lbs) 18000

Tandem Axle Weight (lbs) 34000

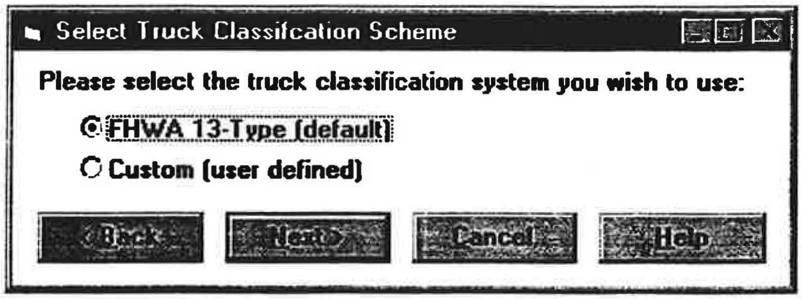
Tridem Axle Weight (lbs) 44000

Steering Axle (lbs) 12000

Figure 5. The "Set Weight Limits" Dialog Box

The *Select Truck Classification* dialog box (Figure 6) dialog box allows selection of the user's choice of truck classification system. Choices are FHWA 13-Type or Custom. The 1995 FHWA *Traffic Monitoring Guide* 13-Type scheme is a standard 13-type vehicle classification system that should be adequate for most users. At the time this

this software was developed, many states applied the FHWA Card-7 format. If data are in the FHWA Card-7 format, the user can click on the default standard 13-type classification option and the program will run normally.



Please select the truck classification system you wish to use:

● FHWA 13-Type (default)
○ Custom (user defined)

Figure 6. “Select Truck Classification Scheme” Dialog Box

The *File Conversion* dialog box (Figure 7) is designed to assist agencies whose data format does not conform to either the 1995 FHWA *Traffic Monitoring Guide* 13-Type scheme or Card-7 classification formats. If the user’s data are not in either one of these formats, the Convert button is applied to display the *TWEET Conversion Utility* dialog box which provides an efficient way to convert data files from other formats to the 1995 FHWA Truck Weight Record format. An associated dialog box will then prompt the user for specific information regarding customized input and output information required for operating the software given the user’s unique data format requirements.

TWEET requires all data files to be in either the 1995 FHWA Truck Weight Record format or Card 7. If your data files are in one of these standard formats already, press Next to continue. If your data files are in another format, press the Convert button below to run TWEET's conversion utility, which will convert your files to the proper format. Press Help for more information.

Figure 7. The “Data File Conversion” Dialog Box

The user then defines observed enforcement conditions providing input to the *Enforcement Condition 1 of 2* dialog box (Figure 8). For each condition, the user will be asked to enter the name, location, and dates of the enforcement effort. The user will also provide similar information to the above in response to the *Enforcement Condition 2 of 2* dialog box (not shown).

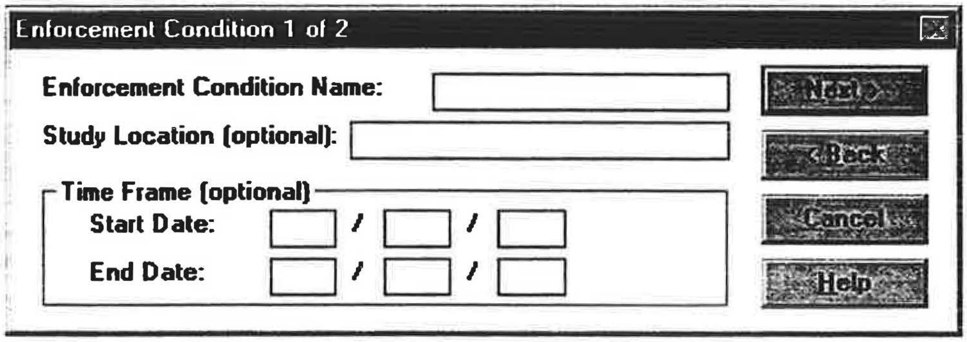
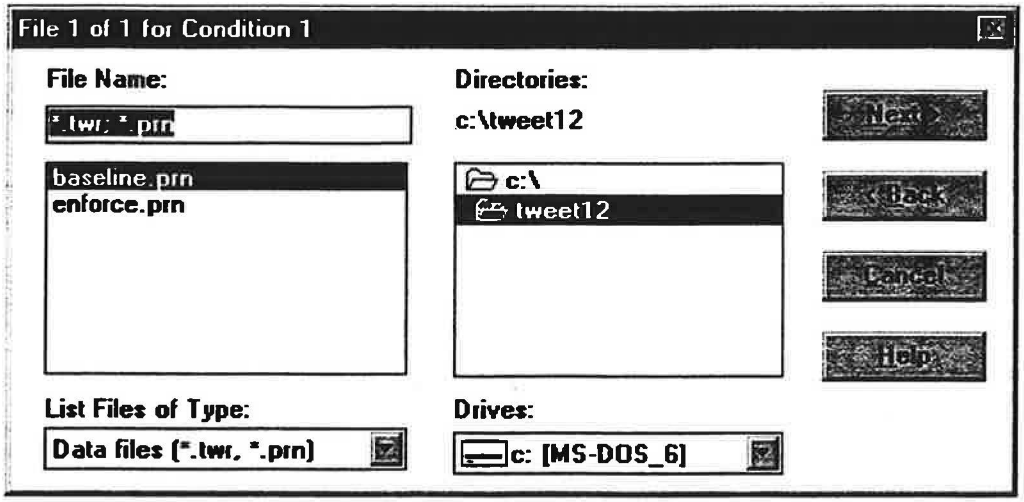


Figure 8. The "Enforcement Condition" Dialog Box

For each designated enforcement condition, a *Number of Files for Condition* dialog box asks for the identification of WIM data files that pertain to each condition. Up to four files can be utilized for each condition. Following this step, the *File 1 of 1 for Condition 1* dialog box (See Figure 9) asks the user to select a particular data file for the current condition.

The program will then ask the user to select (or name) the data files pertaining to each condition. The user is presented with a series of dialogs requesting the path of each data file labeled "Select Data File 'X' for Enforcement Condition 'Y". 'X' represents sequentially numbered data files and 'Y' is the number of the enforcement condition for which you are selecting data files.


File 1 of 1 for Condition 1

File Name: *.twr; *.prn

baseline.prn
enforce.prn

Directories: c:\tweet12

c:\
tweet12

List Files of Type: Data files (*.twr, *.prn)

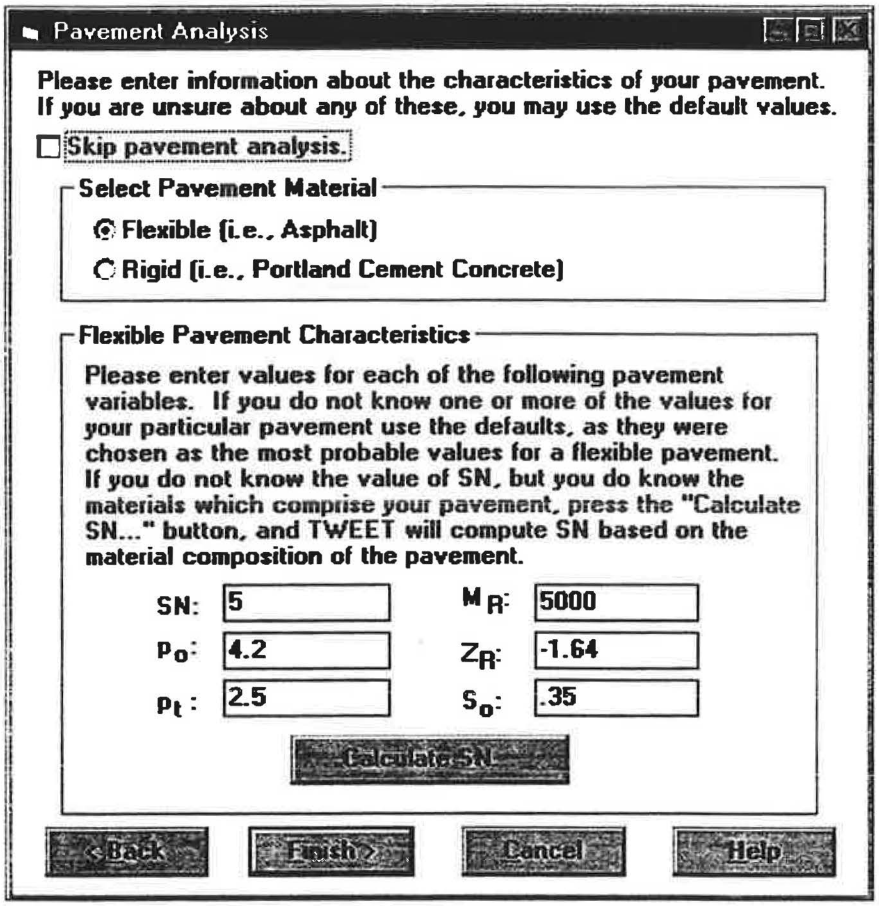
Drives: c: [MS-DOS_6]

Figure 9. The "Data File for Enforcement Condition" Dialog Box

The *Pavement Analysis* dialog box (Figure 10) provides the user with an option to conduct a pavement design-life enforcement-effects analysis. The program asks for specific (and detailed) pavement design data. Because of the complexity of the pavement design-life analysis, the user has the option of skipping the pavement analysis simply by clicking the 'skip pavement analysis' option.

Depending upon whether the user selects Flexible or Rigid pavement, different variables appear in the Pavement Characteristics portion of the dialog box. This box will prompt the user for appropriate pavement design parameters. A comprehensive "Help" screen associated with the Pavement Analysis Dialog boxes explains the design theory, including the AASHTO design equations, underlying the computations utilized in the software.

As further assistance to the user, Appendix E to this report contains a comprehensive explanation of relevant pavement design considerations and background references regarding overweight axle effects on pavement life.



Please enter information about the characteristics of your pavement. If you are unsure about any of these, you may use the default values.

☐ Skip pavement analysis.

● Flexible (i.e., Asphalt)

○ Rigid (i.e., Portland Cement Concrete)

Please enter values for each of the following pavement variables. If you do not know one or more of the values for your particular pavement use the defaults, as they were chosen as the most probable values for a flexible pavement. If you do not know the value of SN, but you do know the materials which comprise your pavement, press the "Calculate SN..." button, and TWEET will compute SN based on the material composition of the pavement.

SN: 5
M_R: 5000
p_o: 4.2
Z_R: -1.64
p_t: 2.5
S_o: .35

Figure 10. The "Pavement Analysis" (Flexible Example) Dialog Box

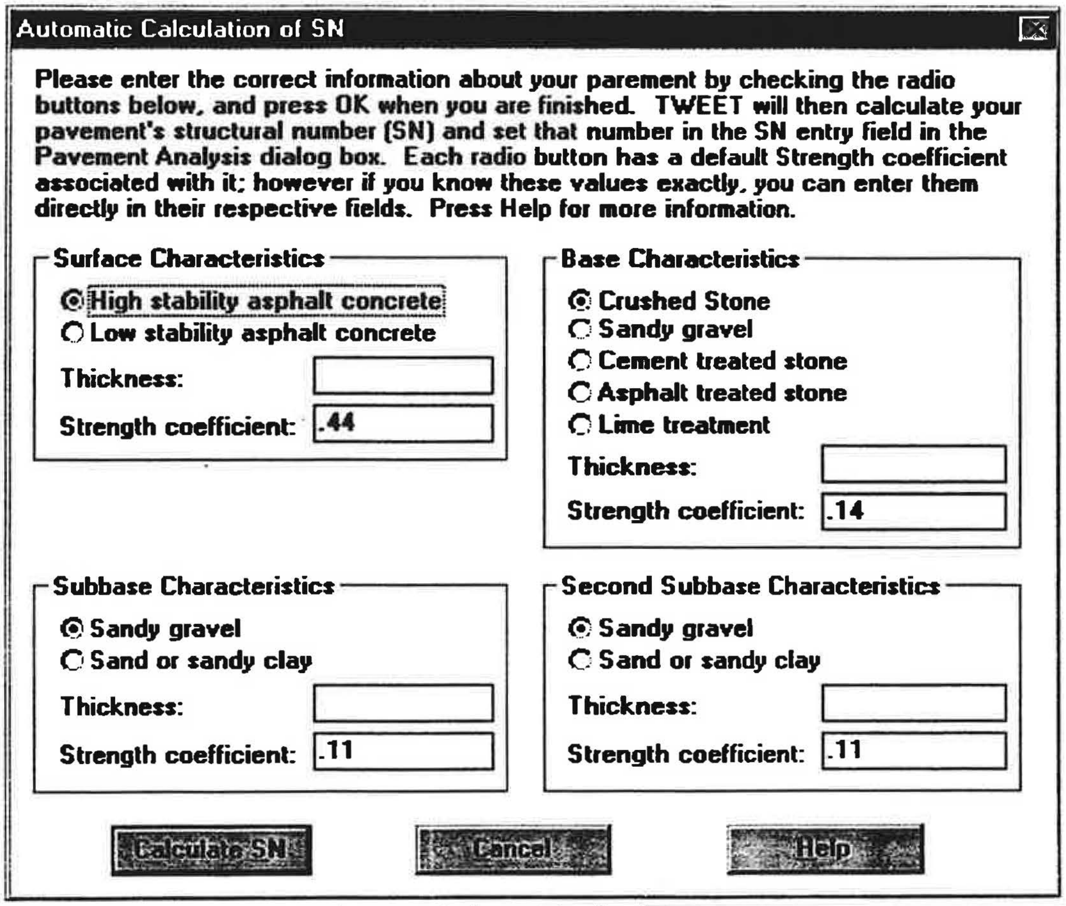
Flexible pavements are discussed first. Default values are shown on the dialog box for the following parameters.

SN	Pavement Structural Number. TWEET offers the option of computing this variable based on input values provided by the user.
p_o	Initial Serviceability Index
p_t	Terminal Serviceability Index
M_R	Default Resilient Modulus
Z_R	Standard Normal Deviate corresponding to design reliability
S_O	Standard Deviation associated with pavement performance prediction

The above parameters are defined and their design implications are explained in detailed 'Help' screens in the software.

Because of the importance of the pavement's Structural Number (SN), TWEET provides the user with alternative approaches to its calculation. First, the user may accept the commonly applied value shown as the default. Second, the user may apply a known value for SN, based on his knowledge of the site. Third, if the user knows the material composition of the pavement, TWEET can automatically calculate the SN value. In this case, the user clicks on 'Calculate SN', and the *Automatic Calculation of SN* dialog box appears as shown in Figure 11.

The dialog box shown in the figure allows the user to select the appropriate surface, base, and sub-base characteristics, i.e., pavement layer thickness (in inches), and strength coefficient. According to the specified material type, the program will suggest the most appropriate *default* Strength Coefficient. Pavement materials and design personnel who run this software have the option of overriding default values, depending upon their own knowledge of pavement materials and design procedures along with specific pavement characteristics associated with the truck weight enforcement location.



Please enter the correct information about your parement by checking the radio buttons below, and press OK when you are finished. TWEET will then calculate your pavement's structural number (SN) and set that number in the SN entry field in the Pavement Analysis dialog box. Each radio button has a default Strength coefficient associated with it; however if you know these values exactly, you can enter them directly in their respective fields. Press Help for more information.

Surface Characteristics

● High stability asphalt concrete
○ Low stability asphalt concrete
Thickness:
Strength coefficient: .44

Base Characteristics

● Crushed Stone
○ Sandy gravel
○ Cement treated stone
○ Asphalt treated stone
○ Lime treatment
Thickness:
Strength coefficient: .14

Subbase Characteristics

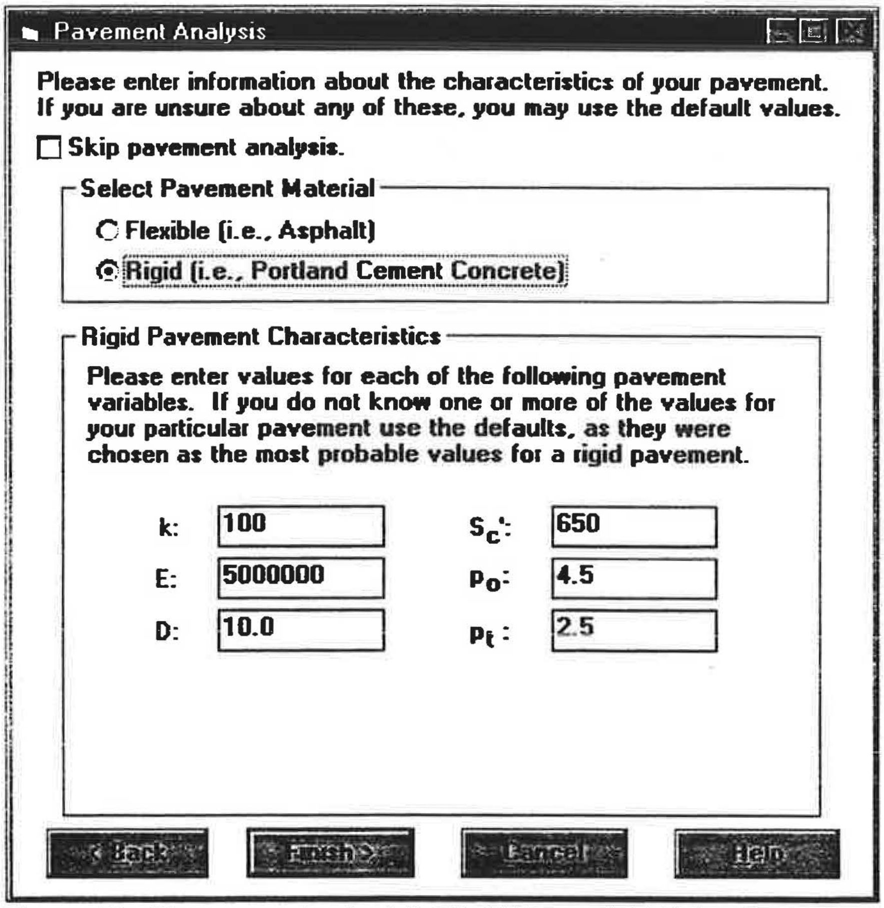
● Sandy gravel
○ Sand or sandy clay
Thickness:
Strength coefficient: .11

Second Subbase Characteristics

● Sandy gravel
○ Sand or sandy clay
Thickness:
Strength coefficient: .11

Figure 11. The "Automatic Calculation of SN" Dialog Box

In the event the user had selected Rigid Pavement, the *Pavement Analysis (Rigid Pavement)* dialog box would appear, as shown in Figure 12.



Please enter information about the characteristics of your pavement. If you are unsure about any of these, you may use the default values.

☐ Skip pavement analysis.

Select Pavement Material

○ Flexible (i.e., Asphalt)

● Rigid (i.e., Portland Cement Concrete)

Rigid Pavement Characteristics

Please enter values for each of the following pavement variables. If you do not know one or more of the values for your particular pavement use the defaults, as they were chosen as the most probable values for a rigid pavement.

k: 100
E: 5000000
D: 10.0
S_c': 650
P_o: 4.5
P_t: 2.5

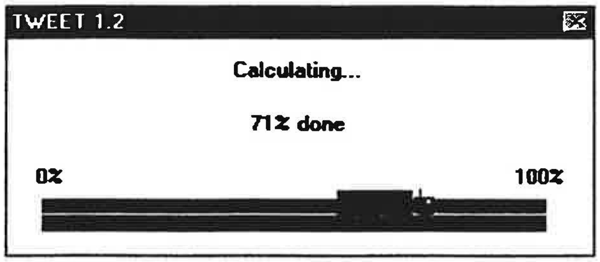
Figure 12. “Pavement Analysis” (Rigid Example) Dialog Box

This dialog box provides the following design values for user application:

k	Modulus of Subgrade Reaction
E	PCC Elastic Modulus
D	Slab Thickness (inches)
s'_c	Modulus of Rupture
p_0	Initial Serviceability Index
p_t	Terminal Serviceability Index

As was the case with the Flexible Pavement Characteristics box, the most likely default design values have been provided in the case of Rigid Pavements. The user has the option of manually entering values specific to the highway study site.

The program will then read the WIM data files and perform all calculations. Unless data files are extraordinarily large, these calculations should take no more than a few seconds. An animated graphic *Status* dialog box (Figure 13) will appear to advise of the program's progress on the computational process. The truck on the screen moves from left to right on the roadway section as the calculation is completed.



Calculating...

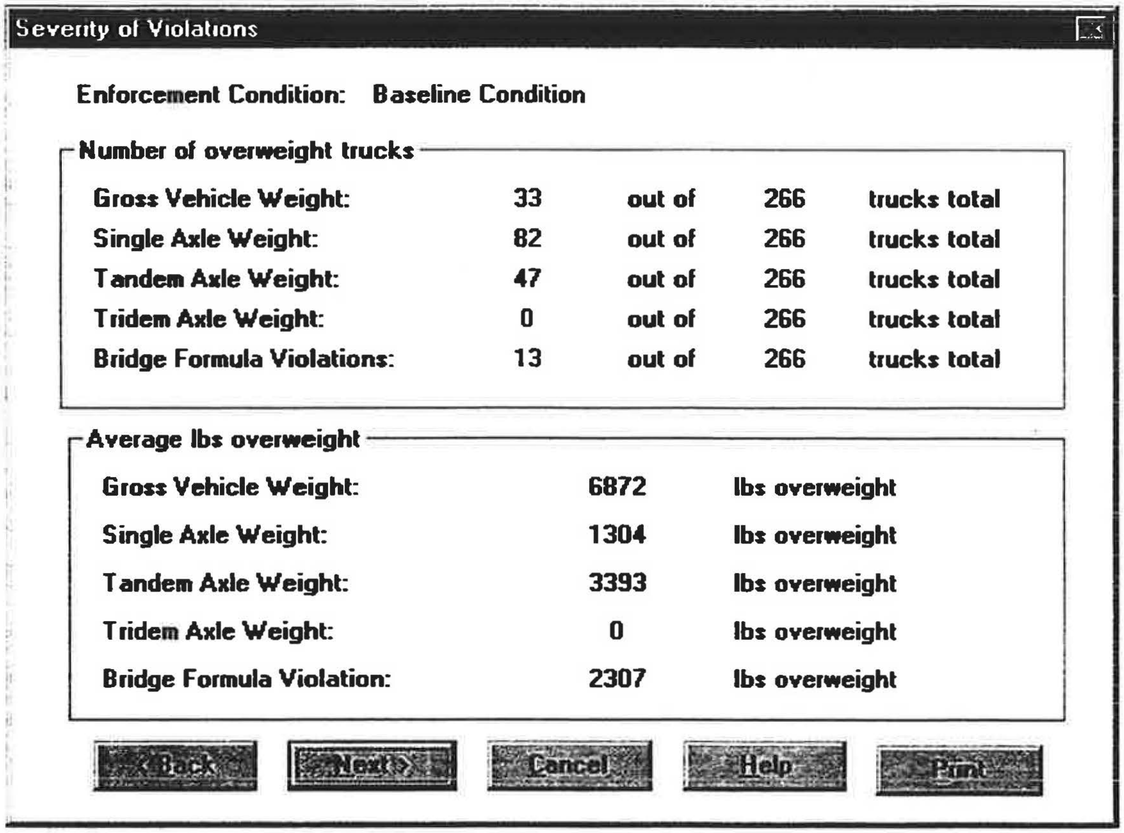
71% done

Figure 13. "Calculation Status" Dialog Box

4.2.2 Viewing Results of Calculations

Once the calculations are completed, the user will be presented with a series of "output" dialog boxes that display calculated values based on input data. The first M.O.E. output dialog box, *Severity of Violations* (Figure 14 on the next page), also reports summary information, i.e., enforcement condition, highway type, total vehicle, and truck sample. The first part of the dialog displays the observed number of violations, i.e., gross vehicle weight, single axle weight, tandem axle weight, tandem axle weight, and Bridge Formula violations. The second dialog displays the average number of overweight pounds (or Metric equivalent) for each grouping noted above.

The *Calculated Percentages of Overweight Trucks* dialog (see Figure 15 on the next page) displays the calculated percentages of overweight trucks in the sample. It lists four calculations based on the data files, i.e., (1) percentage of trucks over the legal gross weight limit, (2) percentage of trucks over the single axle weight limit, (3) percentage of trucks over the tandem axle weight limit, and (4) percentage of trucks violating the Bridge Formula.



Enforcement Condition: **Baseline Condition**

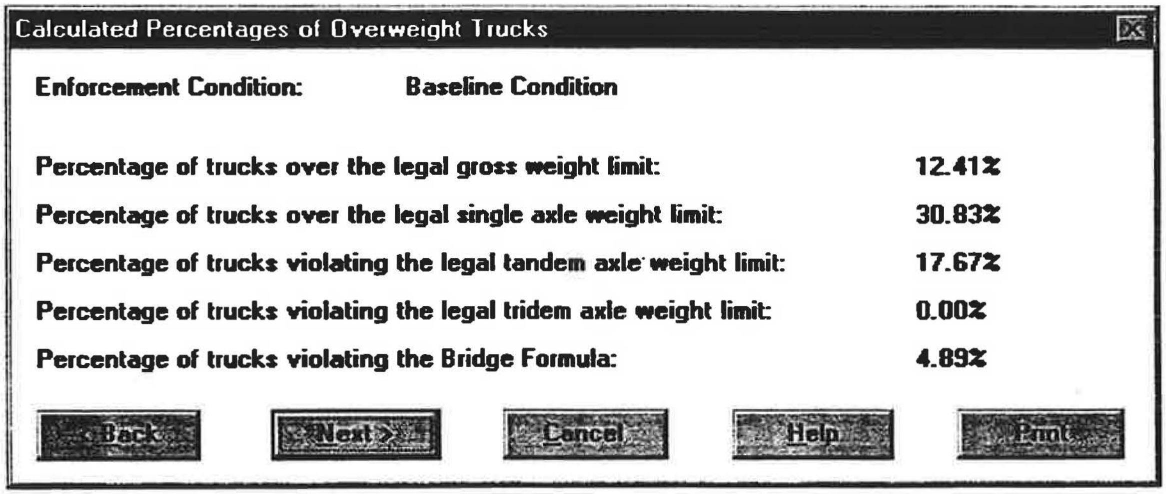
Number of overweight trucks

Gross Vehicle Weight:	33	out of	266	trucks total
Single Axle Weight:	82	out of	266	trucks total
Tandem Axle Weight:	47	out of	266	trucks total
Tridem Axle Weight:	0	out of	266	trucks total
Bridge Formula Violations:	13	out of	266	trucks total

Average lbs overweight

Gross Vehicle Weight:	6872	lbs overweight
Single Axle Weight:	1304	lbs overweight
Tandem Axle Weight:	3393	lbs overweight
Tridem Axle Weight:	0	lbs overweight
Bridge Formula Violation:	2307	lbs overweight

Figure 14. "Severity of Violations" Dialog Box

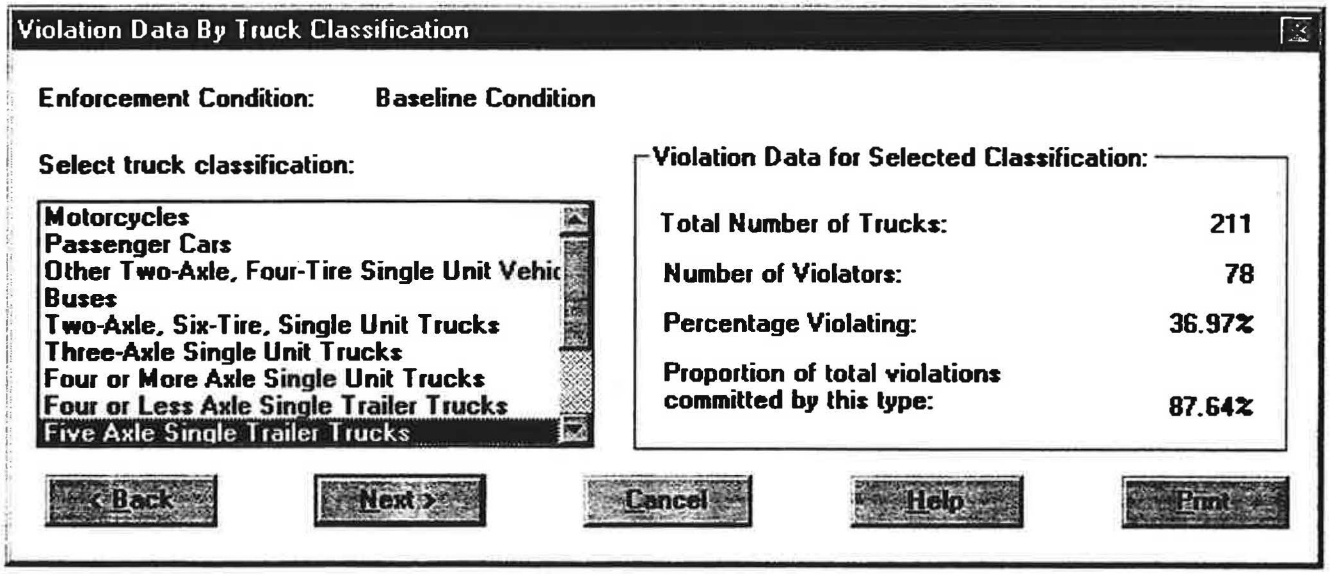


Enforcement Condition: **Baseline Condition**

Percentage of trucks over the legal gross weight limit:	12.41%
Percentage of trucks over the legal single axle weight limit:	30.83%
Percentage of trucks violating the legal tandem axle weight limit:	17.67%
Percentage of trucks violating the legal tridem axle weight limit:	0.00%
Percentage of trucks violating the Bridge Formula:	4.89%

Figure 15. "Calculated Percentage of Overweight Trucks" Dialog Box

The *Violation Data by Truck Classification* dialog box (Figure 16) indicates violators, by truck number and percentage, for each class of truck. This dialog box displays violation information, broken down by truck classification. This information is useful in determining violation distributions according to truck type.



Violation Data By Truck Classification

Enforcement Condition: Baseline Condition

Select truck classification:

- Motorcycles
- Passenger Cars
- Other Two-Axle, Four-Tire Single Unit Vehic
- Buses
- Two-Axle, Six-Tire, Single Unit Trucks
- Three-Axle Single Unit Trucks
- Four or More Axle Single Unit Trucks
- Four or Less Axle Single Trailer Trucks
- Five Axle Single Trailer Trucks

Violation Data for Selected Classification:

Total Number of Trucks:	211
Number of Violators:	78
Percentage Violating:	36.97%
Proportion of total violations committed by this type:	87.64%

Figure 16. "Violation Data by Truck Classification" Dialog Box

The dialog consists of two parts:

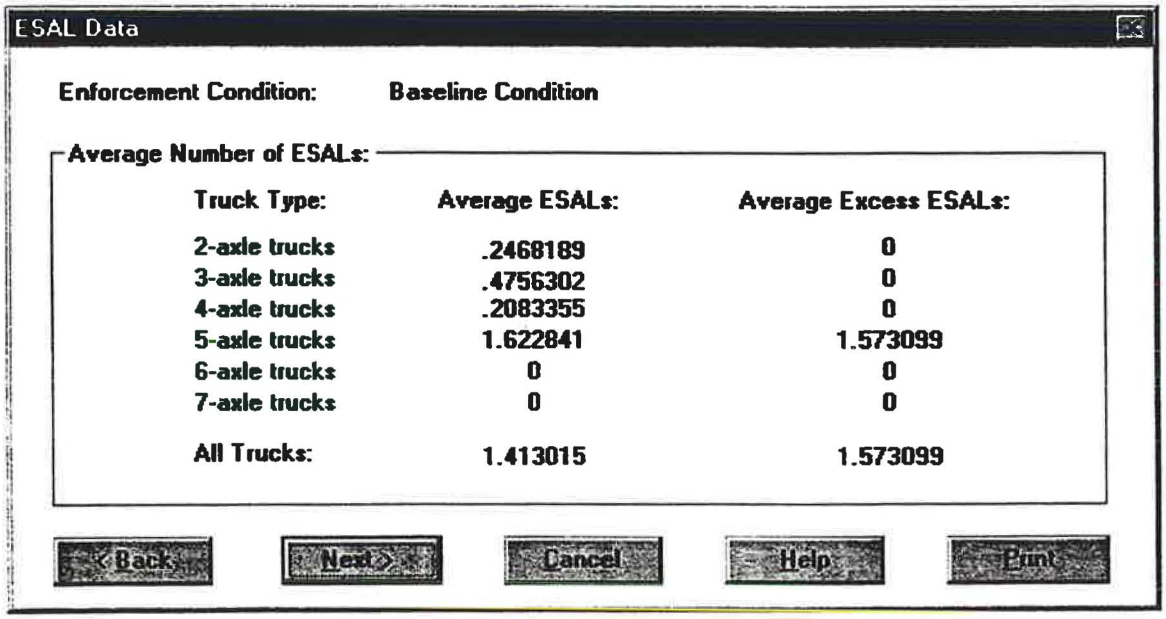
Truck Classification List Box This box lists all of the truck classifications which were input by the user during the beginning of the analysis, or if the default was selected, the FHWA 13-type classifications.

Violation Data This part of the dialog lists violation data for the currently selected truck classification. First, the Total Number of Trucks field displays the number of trucks of the selected type which were in the sample (regardless of whether they were violators). Second, the Number of Violators field lists the number of trucks of the selected type that violated the weight limits. Third, the Percentage Violating field lists the percentage of trucks of the selected type which were violators (this percentage is simply the Number of Violators divided by the Total Number of Trucks). Finally, the proportion of the total sampled violations represented by the selected truck class is indicated.

The ***Breakdown of Violations by Day-of-Week*** (not shown) dialog then displays the percentage of violations occurring on each day of the week. The dialog simply lists each day of the week, and next to it lists the percentage of all violations which occurred on that day.

The ***Breakdown of Violations by Time-of-Day*** (not shown) dialog then displays the percentage of violations occurring at different hours of the day. Because it would be overly complex to display the percentage of violations occurring at each of the 24 hours of the day, the five hours with the most violations are listed. If it is necessary to know what percentage of violations occurred at every hour of the day, the Print option will be of use. The printed copy of the data, unlike the on-screen display, does display the percentage of violations for each hour of the day.

The *ESAL Data* dialog box (Figure 17) indicates average ESAL calculations using the FHWA *Traffic Monitoring Guide* procedure according to the number of axles. This dialog also indicates computed Excess ESAL violations by truck axle-count.



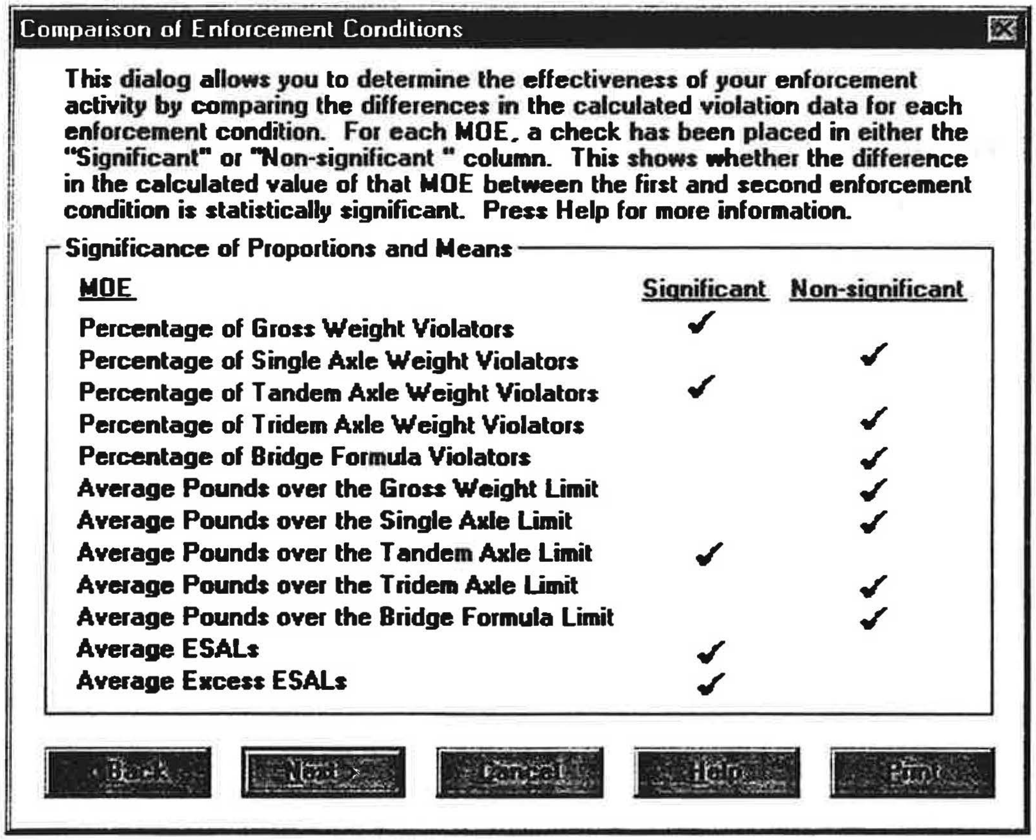
Enforcement Condition: **Baseline Condition**

Average Number of ESALs:

Truck Type:	Average ESALs:	Average Excess ESALs:
2-axle trucks	.2468189	0
3-axle trucks	.4756302	0
4-axle trucks	.2083355	0
5-axle trucks	1.622841	1.573099
6-axle trucks	0	0
7-axle trucks	0	0
All Trucks:	1.413015	1.573099

Figure 17. The "ESAL Data" Dialog Box

Now, TWEET begins its presentation of the data analysis results. The *Comparison of Enforcement Conditions* dialog (Figure 18) indicates to the user whether or not the observed M.O.E. differences are statistically significant. This dialog box contains results of applied statistical significance tests to the computed M.O.E.s and indicates to the user whether or not the observed differences are significant. Separate tests of statistical significance are applied to M.O.E.s depending upon whether the measure was calculated as a mean (i.e., average gross weight violation) or a proportion (i.e., proportion of gross weight violators). Significance tests are applied at the .05 level of statistical confidence.



This dialog allows you to determine the effectiveness of your enforcement activity by comparing the differences in the calculated violation data for each enforcement condition. For each MOE, a check has been placed in either the "Significant" or "Non-significant " column. This shows whether the difference in the calculated value of that MOE between the first and second enforcement condition is statistically significant. Press Help for more information.

Significance of Proportions and Means

MOE	Significant	Non-significant
Percentage of Gross Weight Violators	✓	
Percentage of Single Axle Weight Violators		✓
Percentage of Tandem Axle Weight Violators	✓	
Percentage of Tridem Axle Weight Violators		✓
Percentage of Bridge Formula Violators		✓
Average Pounds over the Gross Weight Limit		✓
Average Pounds over the Single Axle Limit		✓
Average Pounds over the Tandem Axle Limit	✓	
Average Pounds over the Tridem Axle Limit		✓
Average Pounds over the Bridge Formula Limit		✓
Average ESALs	✓	
Average Excess ESALs	✓	

Figure 18. "Comparison of Enforcement Conditions" Dialog Box

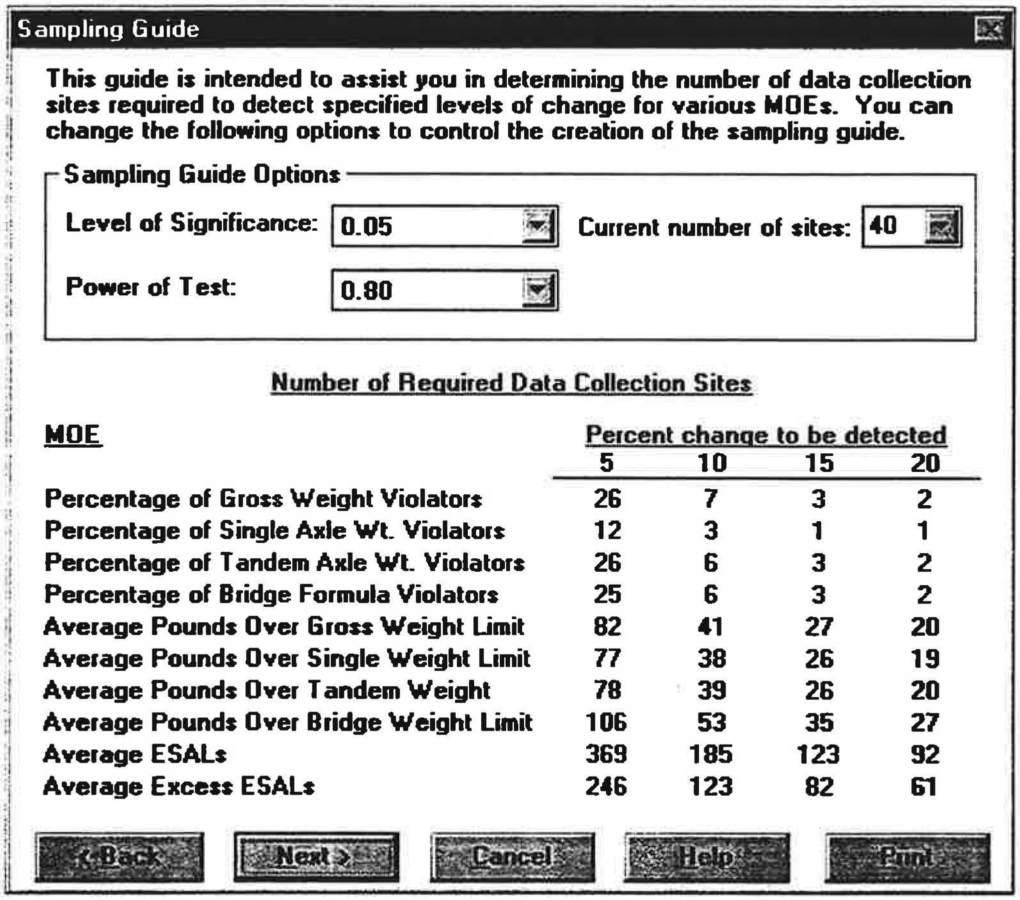
The *Sampling Guide* dialog box (Figure 19 on page 39) page is an aid to determine how many sites will be needed to be surveyed in order to detect regional changes for designated M.O.E.s given specified levels of statistical confidence. The user is first presented with a "Sampling Guide Options" table, allowing the option of specifying two parameters related to the precision of the statistical estimate. These are the desired *Level of Significance* and the *Power of Test*, explained as follows.

Level of Significance refers, in this case, to the probability that the user is willing to risk the error of rejecting a valid change in M.O.E. occurrence. In statistical terminology, the Level of Significance is the maximum probability with which we would be willing to risk a *Type 1 error*. A Type 1 error occurs when a true hypothesis is rejected, i.e., that baseline versus enforcement M.O.E. variable sets are statistically different. In practice, a significance level of .05 or .01 is customary.

Power of Test refers to the likelihood of making a correct statistical assessment. This is achieved when the proper hypothesis is accepted. At issue is the extent to which the user is willing to risk accepting an invalid change in M.O.E. occurrence. In statistical terminology, the Power of a Test is the maximum probability with which we would be willing to risk a *Type 2 error*. A Type 2 error occurs when a false hypothesis is accepted, i.e., baseline versus enforcement M.O.E. variable sets are not statistically different.

The main feature of the *Sampling Guide* dialog box is a table indicating the number of sites which are required for data collection if specified levels of M.O.E.s changes (i.e., 5, 10, 15, or 20 percent) are to be detected. These numbers are based on TWEET's analysis of the measured statistical characteristics (e.g., variance) of the observed M.O.E.s. The user will note that fewer sites are necessary for larger differences. This effect is due to the fact that smaller differences in real-world truck-weight enforcement compliance are subtler and therefore require more statistical rigor to detect.

The final dialog box (Figure 20 on the next page) presents results of the *Pavement Effects Analysis*. Results contained in this dialog box are based on a theoretical pavement design-life effect, associated with differential enforcement-related ESAL loading conditions. Had the user opted to include the pavement design-life effect computation, this screen would be displayed. Displayed information consists of the calculated pavement ESAL capacity, the estimated pavement life under both observed enforcement conditions, and estimated percentage pavement-life change due to the observed ESAL-loading difference associated with the enforcement activity.



This guide is intended to assist you in determining the number of data collection sites required to detect specified levels of change for various MOEs. You can change the following options to control the creation of the sampling guide.

Sampling Guide Options

Level of Significance: 0.05

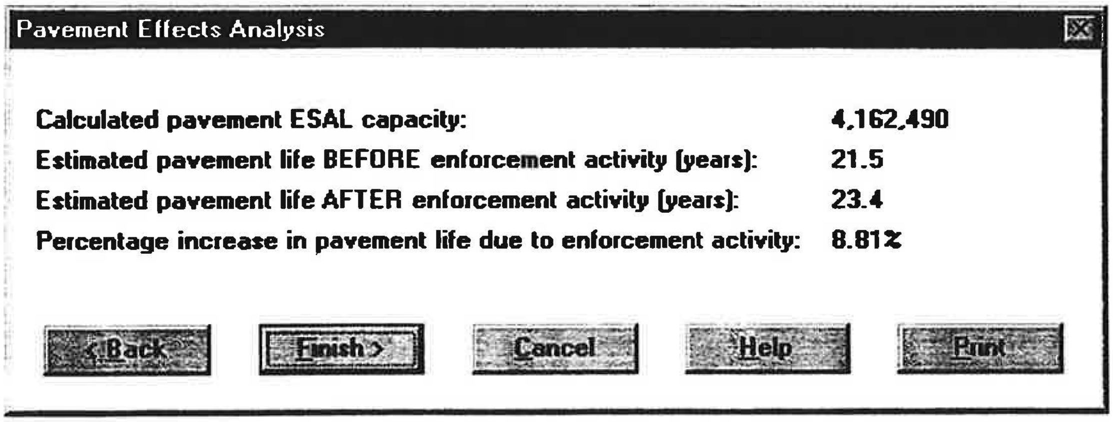
Current number of sites: 40

Power of Test: 0.80

Number of Required Data Collection Sites

MOE	Percent change to be detected 5	10	15	20
Percentage of Gross Weight Violators	26	7	3	2
Percentage of Single Axle Wt. Violators	12	3	1	1
Percentage of Tandem Axle Wt. Violators	26	6	3	2
Percentage of Bridge Formula Violators	25	6	3	2
Average Pounds Over Gross Weight Limit	82	41	27	20
Average Pounds Over Single Weight Limit	77	38	26	19
Average Pounds Over Tandem Weight	78	39	26	20
Average Pounds Over Bridge Weight Limit	106	53	35	27
Average ESALs	369	185	123	92
Average Excess ESALs	246	123	82	61

Figure 19. “Sampling Guide” Dialog Box



Calculated pavement ESAL capacity: 4,162,490

Estimated pavement life BEFORE enforcement activity (years): 21.5

Estimated pavement life AFTER enforcement activity (years): 23.4

Percentage increase in pavement life due to enforcement activity: 8.81%

Figure 20. The “Pavement Effects Analysis” Dialog Box

5.0 REFERENCE

U.S. Department of Transportation, Overweight *Vehicles – Penalties and Permits, An Inventory of State Practices for Fiscal Year 1991,* Report to the United States Congress, federal Highway Administration, Washington, DC, April 1993

APPENDIX A

LITERATURE REVIEW

State truck weight enforcement agencies generally measure their accomplishments in terms of actual enforcement activity, i.e., the number of trucks weighed, legalizations, etc. However, these measures can not address actual weight violation activity, i.e, number and severity of actual on-road overweight truck traffic. As a result, truck weight enforcement agencies currently have no way of gauging the real problem of overweight truck activity.

The objective of this literature search is to examine documented studies addressing relevant issues related to truck weighing effectiveness, i.e., potential in situ truck weight data sources and appropriate data-gathering technologies, required to establish a program for monitoring truck weight enforcement impacts.

BACKGROUND

General Truck Weight Enforcement Effectiveness

During the late seventies, the U.S. Government Accounting Office sent a questionnaire (*1*) to all states asking for information on truck weight laws, enforcement programs and methods, and background data on their State Highway System. The final report, summarizing the states' responses, referred to enforcement program effectiveness only in terms of numbers of trucks weighed and citations issued.

A 1981 NCHRP Synthesis (*2*) addressed criteria for evaluating truck weight enforcement programs. Various findings are cited as follows:

1. One purpose of truck weighing programs is to enforce legal load limits and to prevent trucks from damaging highways and bridges. Although all states have truck weight enforcement

programs, none has established criteria for evaluating these programs. However, each state periodically reviews operations, evaluates and purchases equipment, requests revisions to laws, and adjusts its organization in an effort to improve enforcement.

2. Comparing truck population with the number of vehicles being weighed is part of determining the effectiveness of a truck weighing program. Also needed are data on the overloaded truck routes and volumes, types of movements (interstate or intrastate), vehicle classifications, types of cargo, and distances traveled.

3. Essential to truck weight enforcement is the effective combination and deployment of the various types of scales (permanent, portable, and semiportable). Through the use of data collected in truck traffic studies, permanent scales can be located where there are many overloaded trucks, and these scales can be supported by roving portable-scale crews. Greater use of the semiportable scales should be carefully considered and may eliminate the need for a new permanent weigh station. Improved instrumentation for weigh stations and semiportable stations is needed.

4. In most states, overweight violations are misdemeanors and are processed through the courts. In several states, an overweight violation is a civil offense, and penalties are collected at the weigh site or within 15 days after the citation is issued unless a hearing is requested. Most states have unloading requirements for an overload violation. Many enforcement officers believe that the off-loading requirement is the most effective deterrent in a truck weight enforcement program.

5. Some of the problems in truck weight enforcement can be attributed to insufficient personnel, usually the result of an insufficient number of budgeted positions for proper operation of permanent and portable scales. The hours of operation of scales are related to the available personnel. Most permanent stations are operated continuously only on routes with large volumes of truck traffic.

6. Each state needs to evaluate its truck weight enforcement program, beginning with cooperation within and among the agencies involved. The state needs to determine the most effective enforcement procedures possible under the law in light of the existing facilities and

available personnel and with minimal expenditures for additional facilities and equipment. Long-range goals for changing state laws and improving site operations also are necessary, as are methods for measuring the effectiveness of state truck weight enforcement programs. Some of the possible methods are simple and can be implemented with little more than an evaluation of existing data. Other methods require a different use of existing equipment, additional equipment, or a change in operations.

A deterrent to truck weight enforcement effectiveness is that overweighing can prove to be economically beneficial for truckers. Paxson (*3*) demonstrated benefits to truckers of overweighing by means of an incremental approach (decrease in transport cost per unit with increase in cargo weight) and by using specific cargo movements to calculate the incentives to overweight. The fine and penalty structures of various states were examined and were combined with the probability of being weighed to calculate the expected value of being weighed to the trucker. The net benefit of overweighing to the trucker was then shown by comparing the costs with the incentives. Finally, actual permit costs were examined in relation to the cost of additional pavement damage caused by overweight trucks. Paxson concluded that (a) economic incentives often exceed the expected costs of overweighing to the trucker, (b) current enforcement programs in some states are not effective, (c) fine structures should take account of both the amount of truck overweight and the number of miles traveled, and (d) the cost of overweight permits does not reflect the additional pavement damage caused by overweighing.

A Canadian study published by TRB (*4*) also addressed the economic disincentive of weight enforcement activity. The object of this research was to assess the effectiveness of a truck weight enforcement program. Truck weight regulations and trucking activity in the Province of New Brunswick, Canada, were used as a case study. The methodology compared incremental revenues that can be earned by overloading a particular truck configuration with the expected cost of getting caught, taking into account the fine regime and the level of enforcement. The results of the research demonstrated that fines are not structured in New Brunswick to be an effective deterrent for would-be violators. Alternative enforcement programs were postulated and the deterrent effect was evaluated.

One strategy to improve the effectiveness of truck weight enforcement effectiveness was suggested in the Wisconsin study by Stein (*5*). This study recommended that weigh-in-motion data be utilized as a tool for prioritizing weight enforcement efforts. The suggested prioritization indicated patrolling Interstates first, followed by U.S. numbered highways, then state trunk and town roads.

Current Weigh-In-Motion Programs

Our survey of state enforcement agencies indicated that -- states conduct weigh-in-motion efforts. Most states collect truck classification and weight data in conformance with the Traffic Monitoring Guide (*6*).

Two example programs documented in the literature are Florida and Wisconsin.

Hazen (*7*) reported that Florida has 20 years of experience in running continuous weighing-in-motion stations. Florida currently has 13 continuous WIM stations in operation which provides a "wealth" of data. Research investigated optimum number of WIM sites required to address pavement management systems requirements. WIM data was examined for also seasonal patterns or other patterns for allocating a continuous WIM station to a pattern group. Florida found little or no seasonal patterns. There was some indication of patterns by geographic area of the State. Daily ESAL values are more variable than originally thought. The Florida study recommended one week of data collection at stable sites, two-one weeks at moderately stable sites at semiannual intervals, and four-one weeks at unstable sites spread over the quarters of a year.

Beginning in 1983, the Wisconsin Department of Transportation collected truck weight data utilizing Bridge Weigh-In-Motion equipment at 21 sites distributed among 7 highway functional classifications. A study by Stein (*5*) focused on data gathered between 1983 and 1986 on the Rural Interstate and Rural Principal Arterial highway systems for the 5 Axle Combination Truck with Trailer, the common eighteen wheeler and test data collected at Rural Interstate and Rural Principal Arterial sites in 1987.

General findings and recommendations of the Wisconsin study were as follows.

1. Composite data from all highway systems indicate approximately 14% of the 5 Axle Combination Trucks with Trailer were operating with at least 1 possible weight violation and over 6% had gross weight violations. On the Rural Interstate, 15% had possible weight violations with individual stations ranging from 2% to 30%. On the Rural Principal Arterial system, 17.6% had possible violations with the individual stations ranging from 16% to 20%.

2. Forty percent of the ESALs observed on the Rural Interstate are attributable to excess axle loadings. The range of observations at individual stations was 17% to 55% excess ESALs. On the Rural Principal Arterial, 29% were excess with a range of 17% to 38%.

3. The test data indicated that 10% of the trucks had a possible violation while the basic data indicated 15% were possible violators on the Rural Interstate. These figures tend to confirm the validity of the basic data with respect to the extent of possible violators.

4. Confirmation of the magnitude of excess ESALs is less conclusive. However, the excess ESAL comparison in Illustration 10 of 29% for the basic data and 14% in the test data tends to be supportive of the legitimacy of the basic data.

5. The basic data exaggerate the magnitude of the severity of violations (ESALs) while not significantly impacting on the data with respect to the number of probable violators.

6. Future analysis of truck weight data for highway systems within Wisconsin comparing data collected utilizing one weighing system and one calibration method will remove considerable ambiguity from the results and better establish the magnitude of the severity of the overloaded truck. In the interim, the basic data should be utilized for highway design and enforcement planning.

Specific finding of the Wisconsin study having implications for pavement design are as follows:

1. An examination of data collected utilizing Bridge Weigh-In-Motion equipment illustrated that ESAL load factors based on data collected at enforcement scales were significantly underestimated.

2. Load factors should be based on flexible pavement with a Structural Number of 5 and terminal serviceability of 2.5 and rigid pavement with a thickness of 9-inches and a terminal serviceability of 2.5.

3. Load factors should be maintained using current ESAL values attained utilizing weigh-in-motion systems.

Benefit/Need for Truck Weighing Programs

Truck weight enforcement programs are both necessary and beneficial. Specific discussed aspects of this issue are the current truck overweight problem, economic impact of truck weight, pavement damage, and safety effects of increased weight.

Current Truck Overweight Problem The most definitive study of the overweight problem was conducted in Wisconsin (*5*). Its findings are as follows:

1. Scope of overweight truck population. Composite data from all highway systems indicate approximately 14% of the 5 Axle Combination Trucks with Trailer were operating with at least 1 possible weight violation and over 6% had gross weight violations. On the Rural Interstate, 15% had possible weight violations with individual stations ranging from 2% to 30%. On the Rural Principal Arterial system 17.6% had possible violations with the individual stations ranging from 16% to 20%.

2. Magnitude of excess ESALs. Forty percent of the ESALs observed on the Rural Interstate are attributable to excess axle loadings. The range of observations at

individual stations was 17% to 55% excess ESALs. On the Rural Principal Arterial, 29% were excess with a range of 17% to 38%.

Economic impact of truck weight A New Jersey study (*8*) to estimate the total overweight truck population suggested that total pavement damage attributable to all overweight trucks may approach $20 million dollars per year. It was therefore concluded that a substantial increase in the revenue generated by overweight trucks may be appropriate.

Pavement-related costs that might be affected by changes in truck weights include costs for (a) new and reconstructed pavements; (b) resurfacing and other forms of pavement rehabilitation; (c) routine maintenance, such as cleaning and filling cracks and patching potholes; and (d) effects of users caused by changes in pavement condition.

For existing pavements, increases in traffic loadings would affect pavement rehabilitation costs in two ways. First, an increase in traffic loadings would shorten the time interval to the next resurfacing. Moving resurfacing expenditures nearer to the present would increase the real cost for resurfacing because of the time value of money (incurring a $1,000 cost today is worse than incurring a $1,000 cost one year from today, because in the latter case, the money could be invested productively for a year). If the funds required to resurface highways sooner were not available to highway agencies, the condition of the road when resurfacing is carried out (referred to as the "terminal serviceability") would be reduced and, as discussed below, highway users would be subjected to added cost and discomfort. Second, at the time resurfacing is required, higher traffic loadings would either increase overlay thicknesses or require more frequent resurfacing in the future.

A cost-analysis methodology applied in TRB *Special Report 225* (*9*) to estimate the impacts of alternative truck weight regulatory scenarios has implications for the development of truck weight enforcement M.O.E.s. This methodology consisted of three steps:

1. The added costs to highway agencies for new and reconstructed pavements and for pavement rehabilitation were estimated assuming a 10 percent increase in traffic loadings (as measured in ESAL-miles) on the nation's highways. Separate estimates were developed for flexible and rigid pavements and for each of the seven regions

and four highway classes (Rural Interstate, Rural Non-Interstate, Urban Interstate, and Urban Non-Interstate) used in the productivity analysis.

2. For each truck weight regulatory scenario, the committee used the forecast of 1995 truck miles by region, highway system, truck type, and operating weight that was developed as part of the productivity analysis to calculate the percentage change (relative to the base case) in ESAL-miles by region, highway system, and pavement type.

3. The percentage changes calculated in Step 2 were used to scale the estimates of cost impacts developed in Step 1; for example, a 5 percent increase in traffic loadings would produce half the impact estimated in Step 1 for a 10 percent increase.

Pavement Damage Wheel loads of heavy trucks contribute to various forms of pavement distress. Of the various types of damage, fatigue (which leads to cracking) and permanent deformation (rutting) are of great importance and are the primary focus of this study.

A previously cited NCHRP Synthesis (*2*) noted that without dedicated, persistent truck weight enforcement officers, the highway system would have deteriorated long ago.

However, an opposing perspective regarding the effect of truck weight on pavement damage was published by the New Jersey D.O.T. (*8*). This study was undertaken to quantify the magnitude of the pavement damage done by overweight trucks in New Jersey. This was accomplished using the AASHTO 18-Kip Equivalent Axle Load parameter, established engineering-economic procedures, and data obtained from the New Jersey State Police. Questions specifically addressed include:

1. How much pavement damage is attributable to overweight trucks?
2. What are the costs associated with this damage?
3. Are these costs adequately covered by the revenues collected from the overweight violators?
4. Is mandatory off-loading (requiring violators to immediately lighten their loads at the ticketed location) justifiable?

It was found that detected overweight trucks cause a relatively small shortening of pavement life and, had overweight trucks been successfully off-loaded, a negligible savings would have resulted.

However, there is serious concern expressed in the New Jersey study that the number of overweight trucks actually detected represents a small fraction of the total number of violators.

A Pennsylvania study (*10*) produced analytical guidelines for the posting of load limits. The analysis evaluated a variety of loading conditions (i.e, various load magnitudes and configurations) for different pavement thicknesses and material properties. It was found that axle configuration (i.e., single-, tandem-, and triple-axle assemblies) did not significantly affect pavement response, provided that the load per tire remained the same. A performance model based on present serviceability index was developed that related pavement performance to calculated subgrade strain. The program generates information concerning predicted years to failure for different load limits. Results indicate more damage responsibility for heavy loads on thin pavements than on thick pavements, as would be expected. However, the study concludes that cost allocation based on marginal pavement damage can be misleading if the initial cost of construction is not considered. The load-limit analysis procedure presented in this study can be a valuable tool in the evaluation of axle load limits and axle damage.

The most recent and comprehensive study of pavement effects of heavy-truck effects on pavements was conducted at UMTRI by Dr. Tom Gillespie (*11*). Under NCHRP Project 1-25(1), the mechanics of truck-pavement interaction were studied to identify relationships between truck properties and damage (fatigue and rutting). Computer models of trucks were used to generate representative wheel load histories characteristic of the different trucks and operating conditions. Rigid and flexible pavement structural models were used to obtain pavement "influence functions," which characterize the pavement response to tire loads at any location on the roadway.

Fatigue damage to rigid and flexible pavements is most directly determined by maximum axle loads and pavement thickness. Fatigue damage varies over a range of 20:1 with typical variations in axle loads and over the same range with typical variations in pavement thickness. Other vehicle properties have a smaller, but still significant, influence on fatigue. The relationships between damage and certain truck properties of interest are as follows:

1. Axle loads - Fatigue damage is dominated by the most heavily loaded axles. The first-order determinant of overall fatigue damage for a vehicle combination is the sum of the Equivalent Single-Axle Loads (ESALs) for each axle. Assuming a fourth-power damage relationship, a 22-kip axle is 23 times as damaging as a 10-kip axle.

2. Tandem suspensions - Theoretically, tandem axles have the potential to be no more damaging to roads than single axles with equivalent load per axle (i.e., a 36-kip tandem can be no more damaging than two 18-kip singles). In practice, certain deficiencies in the performance of tandem suspensions preclude these benefits:

    a. Inequalities in static load sharing cause disproportionate fatigue from the heavily loaded axle.

    b. Most tandem suspensions produce dynamic loads comparable to their single axle equivalents.

3. Axle spacing - Aside from the suspension effects discussed above, locating axles at a close spacing does not contribute to pavement damage. Damage on flexible pavements is largely insensitive to axle spacing down to the limits dictated by current tire diameters.

Pavement Cost Implications of Enforcement Effectiveness

The literature review addressed the documented sensitivity of various pavement impacts (e.g., damage, cost) to seek implications for effects of truck weight enforcement effectiveness.

The methodology applied in *TRB Special Report 225 (9)* examined the impact of alternative truck weight regulation scenarios various pavement issues. Projections of heavy-truck miles by type of truck, region of the country, highway functional class, and operating weight were developed for a base case and alternative truck weight regulatory scenarios, i.e., referred to herein as "truck-weight cases". These projections were used to estimate impacts on truck costs, pavements, bridges, and safety. The study procedure is described as follows:

> "In-depth interviews with a cross section of firms selected to represent major segments of the trucking industry were a key input to the development of forecasts for the alternative scenarios. The analytical procedure used for the forecasting process is based on the assumption that all carriers would shift toward use of the most economical type of equipment, taking into account purchase price, operating costs, and the productivity improvements that might be realized by each type of equipment. The procedure takes into account all important constraints on the operation of each type of equipment, such as regional truck size and weight limits, the mix of commodities carried and types of operations involved, the proportion of time the equipment is weight-limited or volume-limited, and limitations of docks or storage capacity.
>
> Quantitative estimates of truck traffic for alternative scenarios were developed using a base case derived from FHWA forecasts of 1995 vehicle miles by state, vehicle configuration, and highway functional class. Although the estimates are derived using forecast 1995 traffic volumes, they actually are designed to represent the steady-state response of the industry to any change in weight limits; that is, they represent the situation that would exist in 1995 if the new limits had been in effect long enough for the industry to have acquired a fleet that had been optimized for operation under the new limits. Much of the estimated savings resulting from higher weight limits are likely to be obtained within 2 or 3 years of any change. However, carriers operating particularly expensive equipment and those with operations that can benefit only marginally from the new limits could be expected to take appreciably longer to modify their fleet to take full advantage of the new limits."

Pavement impacts were estimated on the basis of costs for new pavements, reconstructed pavements, and pavement rehabilitation. Pavement rehabilitation costs, accounting for the greatest impact, were estimated using (a) projections of truck miles by vehicle type and operating weight, (b) AASHTO load-equivalence factors (used to calculate equivalent axle loads for different vehicles on flexible and rigid pavements), (c) data on highway miles and paved area from the FHWA

Highway Performance Monitoring System (HPMS), and (d) the Pavement Rehabilitation Cost Model, which was developed for TRB by Deacon (*12*).

Deacon (*12*) developed sensitivity analyses using the pavement rehabilitation costs for pavements with widely varying levels of soil condition, traffic, and other variables. These sensitivity analyses indicated that, for pavements of a given width, there is surprisingly little variation in the added pavement rehabilitation cost associated with a 10 percent increase in traffic loadings. Depending primarily on soil condition, the added cost for 10 percent more ESALs on flexible pavements ranged from $12 per foot-mile on a very good soil (roadbed soil resilient modulus of 1,250 psi). On rigid pavements, the range was somewhat greater - from $7 per foot-mile on very good soil to $26 per foot-mile on very poor soil. For simplicity, a single-unit cost, $16 per foot-mile, has been chosen for use with both flexible and rigid pavements in estimating the pavement rehabilitation cost impacts of a 10 percent increase in traffic loadings.

Pavement area by highway class and region was tabulated from FHWA's Highway Performance Monitoring System (HPMS) data base for flexible and rigid pavements. Local roads and other highways carrying less than 10,000 ESALs per year were excluded from these tabulations, because pavement costs for these roads are not likely to be significantly affected by the scenarios under consideration in this study.

For each region and highway class, the added pavement rehabilitation cost per year associated with a 10 percent increase in traffic loadings was calculated by applying the unit cost of $16 per foot-mile to pavement area for the region and highway class. For the nation as a whole, the added pavement rehabilitation cost for a 10 percent increase in traffic loadings would be $344 million per year - $293 million for flexible pavements and $51 million for rigid pavements.

The added cost (Z) for each truck-weight case was then estimated for each region and highway system:

Z = X (Y/10 percent)

where X is the added cost for a 10 percent increase in traffic loadings and Y is the increase (or decrease) in traffic loadings, for each truck weight case expressed as a percentage of base case traffic loadings.

Safety Implications of Enforcement Effectiveness

The literature review addressed the documented sensitivity of accident occurrence (in terms of both frequency and severity) with truck weight to seek implications for safety effects of truck weight enforcement effectiveness.

Campbell et al. (*13*) analyzed data based on fatal accident involvement ratios by gross weight for loaded single-unit trucks and combination vehicles on limited-access highways. Their findings suggest a moderate accident rate increase for higher gross weights. A caveat to this finding does exist, however, due to the relatively small number of data points and high degree of scatter.

Fancher et al. (*14*) used the same data base to investigate relationships between fatal involvement rates and GVW for five-axle van tractor-semitrailers by crash type. That study found that:

1. Fatal involvement rates in rollover and ramp-related crashes increased with increased GVWs.

2. For curve-related crashes and crashes in which trucks rear-ended other vehicles, increased GVWs may increase fatal involvement rates, although the trends were not as conclusive as those for the rollover or ramp-related crashes.

3. For jackknifes and sideswipes, increased truck gross weights do not affect the fatal involvement rates.

Base accident rates used to estimate the impacts of alternative truck weight regulatory scenarios on safety as derived Campbell et al. (*13*) and other research were presented in *TRB Special Report 225 (9)*. These base accident rates have implications for determining the effectiveness of truck weight enforcement activity and are shown in Exhibit 1 on the next page.

BASE ACCIDENT RATES USED TO ESTIMATE SAFETY IMPACTS OF SCENARIOS

	Type of Accident (per 100 million vehicle-mi)		
Vehicle	Fatal	Injury	Property Damage Only
Single-unit trucks	7.7	185	499
Tractor-semitrailers	10.2	245	595
Doubles	11.2	269	653

Source: TRB *Special Report 225*

Exhibit A - 1

The effect of truck weight on the severity of truck-car crashes has been extensively researched, with generally good agreement among past studies. In a truck-car crash, the primary determinant of the severity sustained by occupants of the car is the magnitude of the change of velocity (V) of the car at impact (*15*). V, in turn, increases dramatically with increased mass ratios between the truck and the car (*16*). The weight ratios of most existing medium or heavy trucks to passenger cars range mainly from 7.0 to 30.0, and further increases in truck weight are not likely to result in significantly different V-values for cars or severity sustained by occupants of passenger cars in truck-car crashes.

The base accident rates as reported in *TRB Special Report 225 (9)* were adjusted for changes in GVW using the following equation:

$$R' = R(1 + kG'/G)$$

where R and R' are base and adjusted accident rates, G and G' are average GVWs for the base case and the alternative scenario, and k is a constant.

The constant k reflects the extent to which changes in average GVW are expected to affect accident rates. For example, a k of 0.0 would imply that accident rates are unaffected by gross weight; a k of 0.5 would imply that a 10 percent increase in average gross weight would cause a 5 percent increase in accident rates.

Because data for producing reliable estimates of k are not available, the TRB Truck Weight Study Committee (9) judged that 0.5 and 0.0 are reasonable upper and lower bounds for k.

Key findings from *TRB Special Report 225 (9)* on the effects of truck operating weight and configuration on accident rates are as follows:

1. Without making changes to truck dimensions, number of axles, and vehicle and component designs, increased truck weights would increase accident involvement rates of trucks, particularly for rollover and ramp-related crashes for multiple-trailer combinations. In addition, the rates of fatal involvements in crashes on curves or crashes in which trucks rear-end other vehicles may also be adversely affected.

2. Severity of truck accidents is not sensitive to truck configuration, and given that a truck accident occurs, the probabilities of fatalities or injuries are not sensitive to changes in truck weight.

TRUCK WEIGHT ENFORCEMENT OPERATIONS

The weight and size of commercial vehicles is regulated and enforced for the following two reasons: (1) to avoid excess damage to roadway structures caused by overweight and overheight loads, and (2) to assure that operating safety of the roadway is not compromised by loads or vehicles that occupy an unsafe proportion of the roadway. A designated agency is generally responsible for enforcing the size and weight of commercial vehicles on state highways and in other jurisdictions. If a citation is issued to a commercial vehicle driver for carrying a load that is either overweight or oversized, the driver must pay the fines to the local court system. Commercial vehicles are required to stop at weigh stations or ports-of-entry, when they are open. For the most part, safety regulations nationwide are prescribed by the Federal Motor Carrier Safety Regulations (FMCSR) and administered through the Motor Carrier Safety Assistance Program (MCSAP) and state safety programs (*17*).

The literature review addressed aspects of truck weight enforcement activity which pertain to assessing weight enforcement effectiveness. Specifically searched literature topics were: general weight enforcement procedures, application of automated weight monitoring procedures, relevant evidence enforcement, effect of enforcement on compliance, weigh scale avoidance by trucks, and enforcement agency effectiveness evaluation.

General weight enforcement procedures

Documented research studies have addressed truck size and weight enforcement operation in terms of specific truck weighing practices which have implications for NCHRP Project 20-34. For example, NCHRP *Synthesis of Highway Practice 68* (*18*) pointed out that significant differences exist between states in almost all aspects of enforcement. These differences include levels of enforcement activity, tolerance, actions taken toward violators, fine schedules for violations, and court actions. The study makes recommendations as follows:

1. Assign all size and weight enforcement activity to a special operations unit that is adequately staffed. Establish program needs for use of various scales to ensure reasonable coverage of state systems and apprehension of violators.
2. Take effective action against violators with appropriate fine schedules with deterrent effect. Coordinate legislative and regulatory action.

3. Coordinate programs and develop model systems with the assistance of the Federal Highway Administration, the American Association of State Highway and Transportation Officials and the National Governors' Association.

4. Study problem of difference in permit issuance, which has greater impact than enforcement, and those affected are possibly even more numerous. The problem stems partially from the fact that not all states have similar views on permit issuance. Specific aspects of problem are permit limits, application and issuance methods, routine issuance definitions, types of permits, permit restrictions, escort practices, and motor vehicle accessory requirements. States should cooperate to issue permits for interstate movements. One such compact needs to be examined because it has not

had anticipated results. Because of adverse effects of current practice, the permit situation badly needs correction.

A Texas report (*19*) described Texas state regulations affecting motor vehicle sizes and weights, agencies involved directly or indirectly in the enforcement of these regulations, characteristics of oversize-overweight vehicle movements within the state (both legal and illegal movements), and the cost of these vehicle movements. The characterization of oversize-overweight movements was emphasized. To study the economic effects to the state, a 100 percent compliance case was developed to compare with the actual case. The study showed that, while current oversize-overweight movements may save the trucking industry up to 1.4 billion dollars over the next twenty years at current conditions, these movements are estimated to cost the state an additional 261 million dollars over the same twenty-year period. Similarly, enforcement of state laws is estimated to result in only 84 million dollars if the current fine and permit fee structure is maintained. It is recommended that the current fine and fee structure be revised so that violators would pay for their share of the estimated damage to highways.

Application of Automated Weight Monitoring Procedures

Three Oregon papers describe innovative procedures for automating truck weight enforcement activities. The first addresses screening of overweight trucks in the vicinity of Ports of Entry, the second describes an automated management tool for deploying enforcement personnel, and the third relates application of automated vehicle identification technologies.

Krukar and Evert (*20*) reported on the Oregon Department of Transportation's automation of the Woodburn port-of-entry (POE), located on Interstate Highway 1-5 southbound at milepost 274.40. Automation of the Woodburn southbound POE interfaced six components: (1) weigh-in-motion sorter scales, (2) automatic vehicle identification (AVI) system, (3) electronic static scales, (4) supervisory computer (SC), (5) various software interfaces, and (6) motor carrier data base. Reported advantages of the procedures were to minimize manpower tasks; improve weight, size, and safety enforcement; provide more data for planning and design purposes; maximize enforcement agency resources; improve tax collection and audit capabilities; and save time for the trucking industry. Findings indicated improvements and cost savings in (1) weighmaster functions, (2) performance measures, (3) POE operations and functions, (4) human resources deployment, (5) data collection, (6) tax audit trails, (7) tax collection, and (8) to the private motor carrier industry.

An earlier paper by Krukar and Evert (*21*) described Oregon's Integrated Tactical Enforcement Network (ITEN). ITEN is an automated management tool for deploying enforcement personnel in a more effective and efficient manner. The foundations for this network are the automated ports-of-entry, the data collection weigh-in-motion systems coupled with automatic vehicle identification systems, automatic classification systems, computers, communication network, and custom software.

A 1986 paper by Krukar and Evert demonstrated the use of WIM, AVC, AVI, and DBFCA equipment in the collection of traffic and truck weight data, applied in Oregon. Nine integrated, yet separate elements, involved the automatic identification, tracking, classification, and weighing of trucks traversing U.S. Interstate Highway 5 northbound from the Oregon-California border to the Oregon-Washington border, a distance of 310 miles, both on and off the Interstate System.

Relevant Evidence Enforcement

Relevant evidence truck weight enforcement is an application of civil rather than criminal law in enforcing truck weight. The procedure involves inspection of relevant documents (receipts, bills-of-laden) comprising records of origin, destination, weight and composition of shipments. When these records indicate vehicles have violated weight laws, suits are initiated. Advantages are: (1) numerous violations can be cited in a single suit thereby rendering this procedure highly effective against habitual violators, (2) the procedure is unobtrusive and not route-specific, and (3) no on-enforcement activity is required. Disadvantages are: (1) administration of the procedure can be costly, and (2) the procedure's sensitivity is limited to gross weight violations.

A number of states, i.e., Minnesota, Montana, and Texas, and the Province of Alberta, Canada, apparently favor Relevant Evidence enforcement. While little literature was found regarding Relevant Evidence, it is well documented that Minnesota has demonstrated benefits of its

Relevant Evidence procedures, by virtue of their 1991 review of 428,000 bills of lading which resulted in 529 overweight loads being detected.

Under Minnesota state statute, Relevant Evidence is defined as:

> "A document evidencing the receipt of goods issued by the person consigning the goods for shipment or 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 document required to be kept indicating a unit of measure that, when converted to weight and combined with the weight of the empty vehicle, indicates a gross weight 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. The forgoing provisions cannot limit the introduction of other competent evidence bearing upon the question of whether or not there is a violation of the prescribed maximum weight limitations permitted by this chapter."

Minnesota statute also requires that records be kept for certain overweight loads, and established penalties, by stating:

> "**Record-keeping.** A person who weighs 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 loading or receipt, the name and address of the shipper, the total number of axles on the vehicle or combination of vehicles, and the registration number of the power unit or some other means of identification by which the shipment was transported. The

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[1] Report to Congress from the Secretary of Transportation. *Overweight Vehicles - Penalties and Permits. An Inventory of State Practices for Fiscal Year 1991.* Publication FHWA-MC-93-001. Federal Highway Administration. Washington, D.C., April 1993

> record shall be retained for 30 days and shall be open to inspection and copying by a state law enforcement officer or motor transport representative, except state conservation officers, upon demand. No search warrant is required to inspect or copy the record. This subdivision does not apply to a person weighing goods who is not involved in the shipping, receiving and transporting of those goods, or to a person weighing raw and unfinished farm products transported in a single unit vehicle with not more than three axles or by a trailer towed by a farm tractor when the transportation is the first haul of the product.
>
> **Evidence.** Except for records relating to the loading and unloading of the first haul of unprocessed or raw farm products and the transportation of raw and unfinished forest products, a record kept and maintained as provided in subdivision 1 that shows that a vehicle has exceeded a gross weight limit imposed by this chapter is relevant evidence of a violation of this chapter. The foregoing provisions do not limit the introduction of other competent evidence bearing upon the question of whether or not there is a violation of the prescribed maximum weight limitation permitted by this chapter.
>
> **Penalty.** A person who fails to keep, maintain, or open for inspection and copying, those documents as required in subdivision 1 is guilty of a misdemeanor. A person who does not accurately record the information required to be contained in those documents required in subdivision 1 is guilty of a misdemeanor."

An ongoing internal study by the Wisconsin D.O.T. will evaluate the effectiveness of Relevant Evidence laws in Minnesota, Montana, and Alberta. We have discussed this effort with the consultant performing the study. Results are scheduled to be available on August 1, 1994. Our discussion with the consultant indicated that enforcement agencies in northern climates re-assign personnel to examine appropriate records during inclement weather. No conclusion had been reached by the consultant regarding the effectiveness of Relevant Evidence laws. We shall follow-up on the current study as part of our Task 5 effort.

Effect of Enforcement Level on Compliance

A Canadian study (*22*) reports that little is known about the effect of the level of enforcement on the degree of compliance with the weight limits. To fill this gap in the literature, the authors present the context, methodology and tentative results of three studies of the effect of enforcement on compliance carried out on provincial highways in Saskatchewan. Analysis of data from 12 permanent weigh scales situated on primary highways indicated that as the inspection rate (apprehension probability) increased to about five percent, the violation rate decreased rapidly. Increasing apprehension probability beyond five percent had little impact on violation rate. The data from 18 mobile patrol units confirmed this trend. Data from before and after type studies at two specific locations were used to study the effect of continuous and/or zero enforcement. One location was selected to be representative of a short-haul situation. The other location was selected to represent long-haul truck movements incorporating interprovincial and intercity truck haul with relatively little local haul. Enforcement levels were employed over a length of time necessary to ensure the trucking industry was aware of the change. The long-haul study showed that the rate of violation of gross weight limits decreased to a low of 2.8% at continuous enforcement from 5.6% at normal enforcement. The violation rate increased to 18.6% at zero enforcement. A statistical analysis utilizing the t-test indicated that there is a significant difference between the number of overweight trucks at the various enforcement levels. The short-haul study also indicated a significant difference between zero and normal enforcement.

A sophisticated mathematical modeling approach to economic theories of compliance was documented by Hildenbrand et al., (*23*). The authors note a general acceptance of the notion that the costs associated with complete compliance are excessive. At the same time, the nature of public highways is such that enforcement is required. The theoretical model provides a strategic framework for analyzing the economic outcome of different levels of fines and enforcement efforts. The economic tools of "game theory" are used to model the conflict between truckers and the highway enforcement officials. Truckers have two choices: to comply with the law, or to overload their truck. The regulation enforcers also have two choices: they may have the scale open and weigh passing trucks, or they may close the scale. Assuming a randomized operation of scales and random overloading by truckers, the game theory model establishes the equilibrium level of weight regulation compliance, given a set of enforcement parameters. The game theory model is developed to estimate the equilibrium levels of enforcement and compliance. The paper concludes with a discussion of the model results and its implications for highway transport policy.

Weigh Scale Avoidance by Trucks This behavior is a major concern to operational truck weighing operations. Two reported studies were undertaken in Virginia and Wisconsin.

The most comprehensive work on truck avoidance has been documented by the Wisconsin Department of Transportation (*24*). Three levels of enforcement were conducted as follows:

Level 1 - Mainline scale only
Level 2 - Mainline scale and patrol on a major bypass
Level 3 - Mainline scale and patrol on major and secondary bypasses.

Avoidance of overweight is indicated by truck volume (see Exhibit A - 2 and by highway wear, expressed in ESALs (see Exhibit A - 3).

The study revealed that the rate of overweight trucks on the mainline decreased 6% during Enforcement Level 1, while the rate of overweight trucks on the major bypass increased 140 percent. In Enforcement Level 2, the rate of overweight trucks on the mainline was 27 percent below baseline, while the rate of overweight trucks was still up 70 percent over baseline on the major bypass. During Enforcement Level 3, the rate of overweight trucks on the mainline declined still more below baseline to 34 percent, but the associated rate of overweight trucks on the major bypass had also declined to 13 percent below baseline.

ESAL's were computed from individual axle weights and as well as axle weight groupings. Although ESAL's were down 14 percent on the mainline during Enforcement Level 1 (about the same percentages truck volume), the Enforcement Levels 2 and 3, ESAL's were down 6 percent and 9 percent more than truck volume. Increased enforcement also meant scattered ESAL's: 40 percent of diverting ESAL's used the major bypass route during Enforcement Level 1, but only 8 percent used it during Enforcement Level 2 with a patrol there, and no ESAL's diverted to the major escape route in Enforcement Level 3. It is significant that trucks, overweight trucks and ESAL's all diverted in the same pattern.

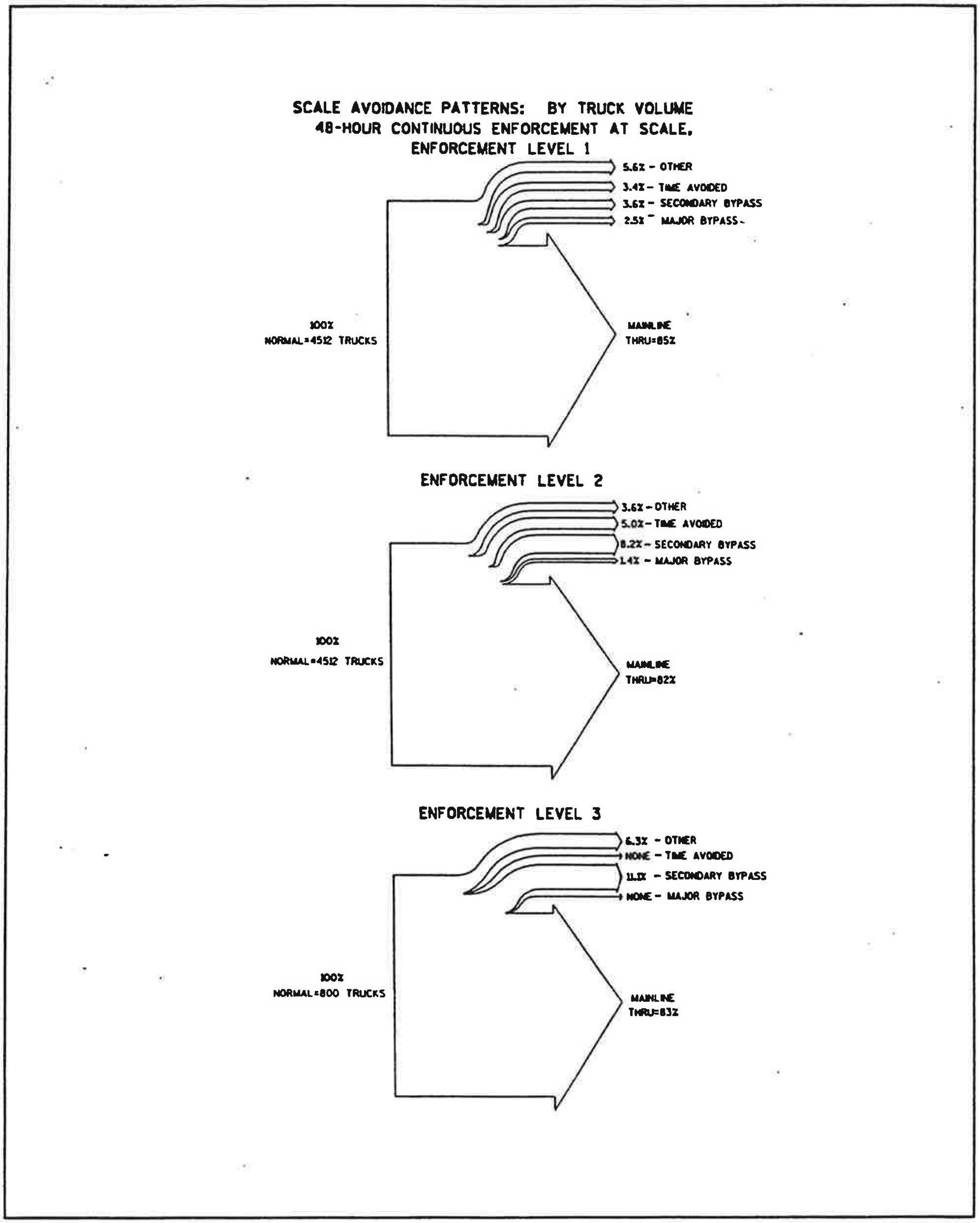


Exhibit A - 2

Observed Wisconsin Scale Avoidance Patterns by Truck Volume

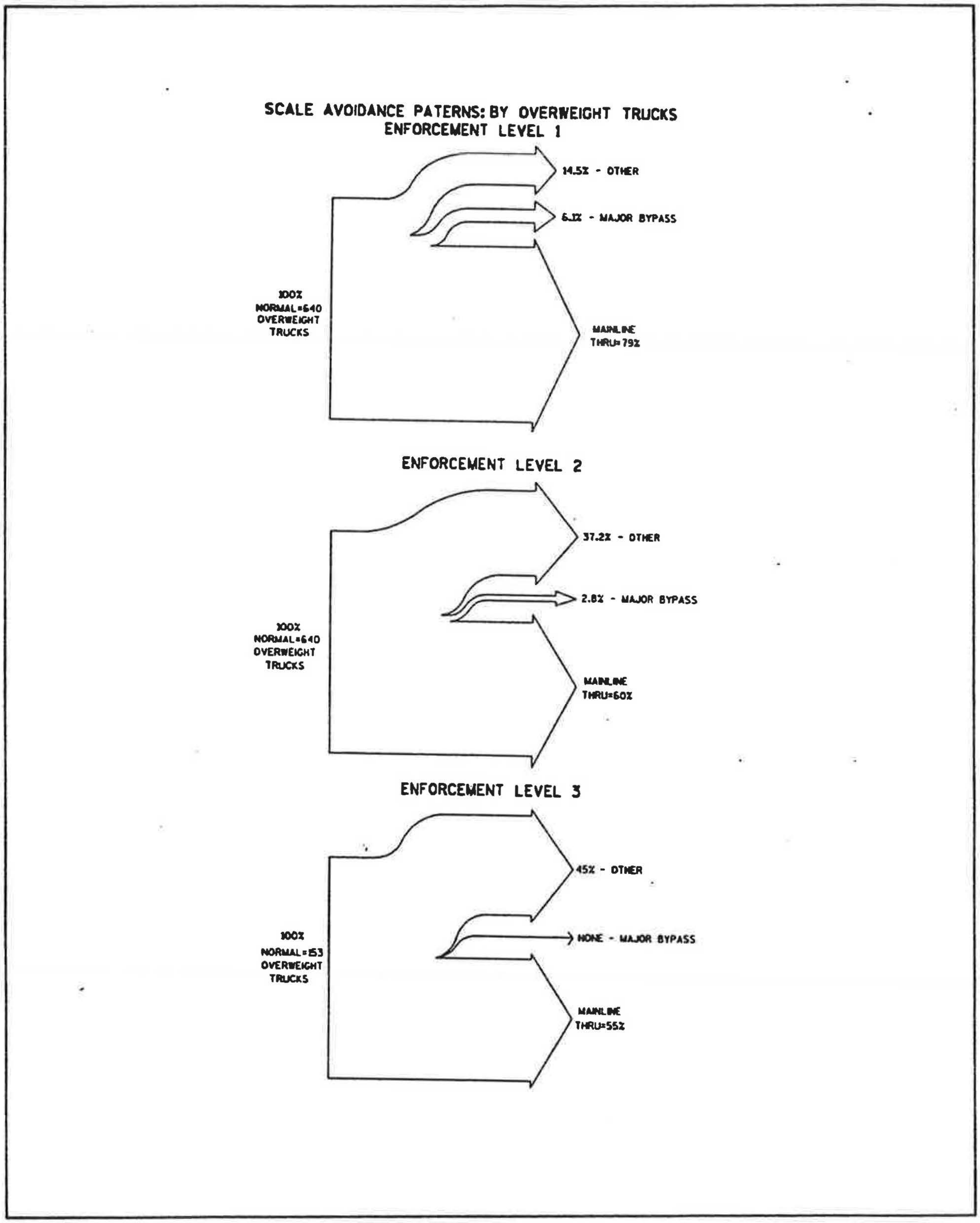


Exhibit A - 3

Observed Wisconsin Scale Avoidance Patterns by ESAL

The overall Wisconsin D.O.T. study was conducted from various tasks, producing 11 key findings as follows.

"1. Truck avoidance of enforcement scales was found to range:

- 15-18% by truck volume;
- 21-45% by overweight trucks;
- 6-34% by the rate of overweight trucks; and
- 14-26% by ESAL's (the engineering standard unit for pavement fatigue).

Of these measures, ESAL diversion is equatable to added pavement deterioration or wear.

2. At 15-18%, avoidance by truck volume was considerably under the 30% diversion that was expected. Avoidance broke down as follows:

- 5-11% was geographical-based (took an alternate route);
- 3-5% was time based (waiting at rest stops for scale to close); and
- 4-6% was unknown (beyond the monitored routes).

3. Concentrated enforcement meant scattered truckers. As enforcement was incrementally increased each phase, truckers diverted by routes progressively farther away from the scale.

4. Although ESAL's must be calculated and are therefore intangible, they are the most important basis by which to evaluate and modify weight enforcement activity since ESAL's are a direct measure of the wear trucks inflict on pavements. Accordingly, the state patrol should develop an ability to gauge their truck weight enforcement effectiveness based on ESAL's. A logical first step would be more portable weighing activity on the bypass routes coordinated with scale operation. This means optimizing operations with existing weighing equipment, buying more WIM or other portable weighing equipment, and employing more inspector personnel.

5. Scale avoidance effects, assuming the scale in operation 34% of the time, include reduction of 2 years in the pavement life of the major bypass route and an increase of 1 year in the pavement life of the mainline. Effects on other routes are uncertain, but should be quantified through first, a full inventory of bypass routes surrounding each scale and second, more WIM or other weighing equipment monitoring.

6. Of the trucks diverting around the Rusk Scale:

   - 51% had safety violations (MCSAP);
   - 24% had driver violations (predominantly hours of operation);
   - 8% had weight violations;
   - 4% had registration violations; and
   - 13% had no violations whatsoever.

7. During Rusk Scale operations, the likelihood of weight violations was 8 times greater on the major bypass route than at the scale. Driver violations were 65% higher on the major bypass route than at the scale. Safety violations were 14% higher on the major bypass than at the scale. The likelihood of legal trucks on the major bypass was 1/3 that of the scale.

8. After enforcement cessation, truckers waiting in rest stops and restaurants quickly returned to the mainline, within 1-8 hours. This traffic normalization pattern may have implications for enforcement strategy: e.g., conduct weighing at rest stations simultaneous with scale operation.

9. Although most truckers returned to the mainline 9-16 hours after scale closure, some continued to bypass even 24 hours after scale closure. This traffic normalization pattern suggests that enforcement should continue to monitor bypass routes the first 8 hours after scale closure. It also suggests that some truckers decide many hours in advance and far away to avoid the scale, although their disappearance off the mainline is not recorded until later.

10. ESAL factors (average ESAL's by truck class) used by Wisconsin pavement design engineers as a standard since 1987, are adequate to accommodate diversion on scale bypass routes, since these standards slightly exceed ESAL factors found in our field study. ESAL factors found differed significantly by highway type.

11. Portable or pad weigh-in-motion (WIM) equipment accuracy was found to be +13.3% on gross truck weight at the 95% confidence level. Accuracies by axle weight were found to range +19-26% at the 95% confidence level. The portable WIM was 3 times more reliable than bridge WIM (BWIM) equipment: it lost 5% of total truck traffic due to malfunctions compared to a 14% loss for BWIM."

A significant issue raised in the Wisconsin study was the relative effect of pavement wear between the mainline and diversion routes resulting from truck avoidance of weight enforcement. Based on the computed ESALs, it was determined that pavement service life of the routes used for diversion was shortened by two years.

A Virginia study (*25*) also studied weigh scale avoidance by overweight trucks. In addition, secondary study objectives were: (1) to determine the magnitude of overweight truck activity on selected routes, and (2) to compare traffic loading data collected using static scales with enforcement with data collected using weigh-in-motion without enforcement.

Two weigh stations on one Interstate route were studied for weigh station avoidance. It was found that 11 and 14 percent of the trucks on routes used by trucks to bypass the two stations were overweight. However, at one station, 50 percent of the runbys were trucks which passed the weigh station because the entrance lane to the station was filled. The study also found that between 12 and 27 percent of trucks on two primary routes and one other Virginia Interstate route were overweight.

Regarding the second study objective, traffic loadings collected with WIM without enforcement are 30 to 60 percent higher than loadings collected using static scales and enforcement.

Enforcement Agency Effectiveness Evaluation

NCHRP Synthesis of Highway Practice 82 presented criteria for an enforcement agency to evaluate the effectiveness of its program. The synthesis points out that comparing truck population with the number of vehicles being weighed is part of determining the effectiveness of a program, e.g., these steps are generally followed by enforcement agencies as part of their periodical FHWA certification programs. Data on overloaded trucks, truck routes and volumes, types of movements, vehicle classifications, types of cargo and distances traveled are also applied in this evaluation. The effective combination and deployment of various types of scales is essential for effective operations. In most states, overweight violations are misdemeanors and are processed through the courts. Some of the problems in truck weight enforcement are attributed to inefficient personnel. Each state needs to evaluate its truck weight enforcement program beginning with cooperation within and among the states. This synthesis report describes data collection and its application to the truck population, site selection and equipment, weight laws, enforcement. The report recommends various short- and long-term self-evaluation program steps.

Another study (*4*) also developed a method for assessing the effectiveness of a truck weight enforcement program. The procedure compared incremental revenues earned by overloading a particular truck with the expected cost of getting caught, taking into account the fine structure and the level of enforcement. Results demonstrated that fines are not structured to be an effective deterrent for would-be violators.

An ongoing study undertaken by the Wisconsin D.O.T. is thoroughly evaluating the Wisconsin's truck safety and weight enforcement program. Objectives of the study are: (1) to compare Wisconsin's program with programs in other states, (2) to develop specific objectives and measures of success for the program, and (3) to prepare and evaluate strategies to meet the objectives. Results of this study will not be available until August; although we have been advised by the consultant, Cambridge Systematics, Inc., that they concluded from their review of Federal and state reports that "no one is measuring the right thing to determine the effectiveness of truck weight enforcement, nor have appropriate proxy measures been developed". An applied truck weight enforcement M.O.E. in the Wisconsin study is the estimated enforcement "coverage", taken as a proportion of scale capacity to truck traffic on the road.

STATE DATA SOURCES FOR MONTIORING TRUCK WEIGHT EFFECTS

A review of the literature has demonstrated a number of potentially available data sources which state highway agencies can apply to monitor the effectiveness of truck weight enforcement activities. These are SHRP's Long-Term Pavement Performance (LTPP) Program WIM sites, Pavement/Bridge/Safety Management Systems, the Highway Performance Monitoring System, and *Traffic Monitoring Guide* data collection sites. A brief explanation of each is as follows.

SHRP Long-Term Pavement Performance (LTPP) sites

The Strategic Highway Research Program (SHRP) was a 5-year, $150 million dollar research program funded through a set-aside of state-apportioned Federal highway aid funds. The Long-Term Pavement Performance (LTPP) Program was designed as a 20-year program. With the completion of the first 5 years of the research under SHRP, the LTPP Program was transitioned to the FHWA.

Objectives of the LTPP Program are to:

1. Evaluate existing design methods.
2. Develop improved design methods and strategies for the rehabilitation of existing pavements.
3. Develop improved design equations for new and reconstructed pavements.
4. Determine the effects on pavement distress and performance of loading, environment, material properties and variability, construction quality, and maintenance levels.
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.

Information from the LTPP studies is available from the LTPP Information Management System (IMS), a data base developed under SHRP. The LTPP Program will collect data on in-service pavement sections throughout the country for a 20-year period.

Data collected under the LTPP Program are classified into the following seven modules:

1. Inventory
2. Materials Testing
3. Climatic
4. Maintenance
5. Rehabilitation
6. Traffic
7. Monitoring

The most relevant data modules for application to truck weight enforcement monitoring are the maintenance and traffic modules.

The maintenance module consists of 9 tables that store data recorded on 17 data sheets; one of the data sheets is used to record historical maintenance activities. This module is primarily used to record maintenance activities performed on the test section after inclusion in the LTPP Program. This module also records maintenance-related information such as placement of seal coats, patches, joint resealing, milling, and grooving.

The traffic module will store annual traffic summary statistics for a study lane for each year since the road was opened to traffic. The specific items for the study lane will include automobile and truck volumes, axle weight distributions by axle configurations (single, tandem, tridems, etc.) and weight range(s) that are usually in 1000- to 2000-lb (454- to 908-kg) increments, estimated Equivalent Single Axle Loads (ESALs) using American Association of State Highway and Transportation Officials (AASHTO) procedures, and an indication of the statistical variability of the data.

Highway Performance Monitoring System (HPMS)

The HPMS is a nationwide inventory system that includes all of the nation's public road mileage as certified by the States' Governors on an annual basis. In concert with recent highway legislative mandates and regulations, this mileage includes all facilities both on and off the state highway systems. Each state furnishes on an annual basis all data requirements specified in the HPMS Field Manual. The provision of data is a cooperative effort with the state highway agencies

(SHAs), local governments and the metropolitan planning organizations (MPOs) working to assemble and report the necessary information. The FHWA identifies the data to be collected, establishes efficient collection methods, develops improved analytical techniques, and analyzes the data. Collectively, these activities facilitate informed highway planning, policy making, and decision making.

Data provided by state agencies falls into two primary sample classifications. These are "standard" and "donut area" samples:

- A **standard sample** section record contains the universe data plus additional data items related to the physical characteristics, condition, performance, use, and operation of the sampled sections of highway. These sample data provide detailed information which is used as the basis for evaluating change over time, and provides the basic input to the HPMS Analytical Process (models).

- **Donut area samples** are unique in that their sole purpose is to enhance the precision of travel estimates outside of the adjusted urbanized area(s) boundary but within the NAAQS nonattainment areas designated by the Environmental Protection Agency (EPA). Consequently, donut sample data item additions are limited to identification, AADT and an expansion factor.

Annual area-wide HPMS data reporting requirements are summarized immediately below:

1. System Length and Daily Vehicle Travel Summary Data.
2. Minor Collector and Local Functional System Length Data.
3. Fatal and Injury Motor Vehicle Accident Data.
4. Travel Activity by Vehicle Type Data.

Vehicle classification data requirements which are relevant to NCHRP Project 20-34 are as follows:

1. Two-Axle, Six-Tire, Single-Unit Trucks -- All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., having two axles and dual rear wheels.

2. Three-Axle, Single-Unit Trucks -- All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., having three axles.

3. Four-or-More Axle, Single-Unit Trucks -- All vehicles on a single frame with four-or-more axles.

4. Four-or-Less Axle, Single-Trailer Trucks -- All vehicles with four-or-less axles consisting of two units, one of which is a tractor or straight truck power-unit.

5. Five-Axle, Single-Trailer Trucks -- All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power-unit.

6. Six-or-More Axle, Single-Trailer Trucks -- All vehicles with six-or-more axles consisting of two units, one of which is a tractor or straight truck power-unit.

7. Five-or-Less Axle, Multi-Trailer Trucks -- All vehicles with five-or-less axles consisting of three-or-more units, one of which is a tractor or straight truck power-unit.

8. Six-Axle, Multi-Trailer Trucks -- All six-axle vehicles consisting of three-or-more units, one of which is a tractor or straight truck power-unit.

9. Seven-or-More Axle, Multi-Trailer Trucks -- All vehicles with seven-or-more axles consisting of three-or-more units, one of which is a tractor or straight truck power-unit.

An important data item provided by the HPMS sample with regard to our assessment of candidate measures in "road roughness". One intent of the HPMS is to provide a measure of pavement condition that has nationwide consistency and comparability and is as realistic and practical as possible, a uniform, calibrated roughness measurement for paved roadways. The details and reporting requirements were established by an HPMS Pavement/ Roughness Working Group.

Roughness is defined (in accordance with ASTM E 867-82A) as "The deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage." After a detailed study of various methodologies and road profiling statistics by the FHWA/State Pavement/Roughness Working Group, the International Roughness Index (IRI) was chosen as the HPMS standard reference roughness index. The IRI was chosen because it facilitates correlation to a variety of roadmeter vehicles over a range of surface types.

The summary numeric (HPMS data reporting unit) is the IRI in in/mi or m/km. IRI is computed from elevation data ("known profile") in a wheel-path for use as a profile numeric for profile measuring methods. The primary advantages of the IRI include:

1. It is a time-stable, reproducible mathematical processing of the known profile.

2. It is broadly representative of the effects of roughness on vehicle response and user's perception over the range of wavelengths of interest, and is thus, relevant to the definition of roughness.

3. It is identical to the Reference Quarter Car Simulation (RQCS) inches per mile statistic derived in the National Cooperative Highway Research Program (NCHRP) 228 Report (*26*).

4. It is compatible with all profile measuring equipment currently available, and projected, in the U.S. market.

5. It is independent of section length and amenable to simple averaging.

6. It is directly consistent with recently established international standards, and able to be related, through published correlations to other U.S. and foreign roughness measures.

Truck Weight Data The proposed HPMS truck weight sample is a subset of the vehicle classification sample. This process eliminates duplication and directly ties the estimates on weight, classification, and volume. Since automatic vehicle weighing equipment classifies and counts, and the recommended period of measurement is the same (48 hours), sample sections in the weight sample do not require a separate classification or volume count. This combination further reduces the level of effort required by the recommended program.

The stratification categories remain the same as those in the vehicle classification scheme. As in the classification element, the distribution of the sample within the combined strata will remain proportional to traffic volume measures. The minimum recommended reporting strata are:

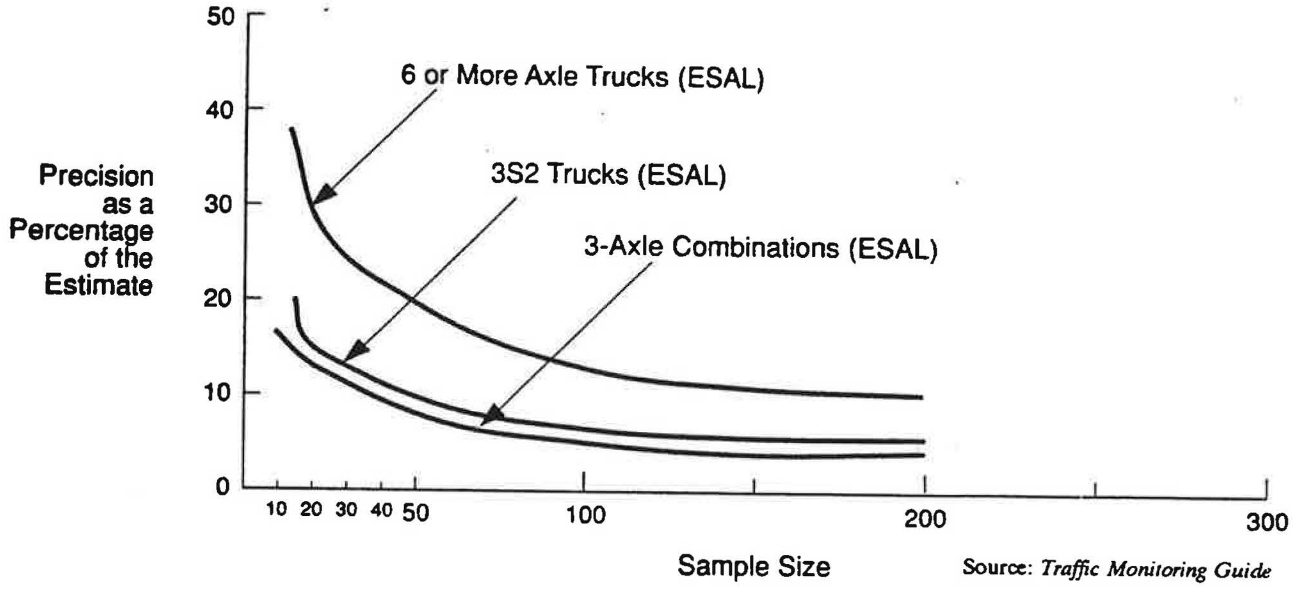
1. Interstate
2. All other roads

The estimation of sample size for the truck weight sample is based on the characteristic Equivalent Single Axle Loadings or Loads (ESAL).

Exhibit A - 4 illustrates the sample size and precision relationships at the 95 percent confidence level for the total Interstate system.

The analysis conducted shows that about 30 measurements (over a 3-year cycle) are needed to estimate equivalent single axle loadings (ESAL) on the Interstate system for 3S2 trucks (18-wheelers) with a precision of +/- 10 percent with 95 percent confidence. The 3-year cycle acts to further reduce the sample needed annually. If the reporting strata were Interstate Rural and Interstate Urban, and the same precision levels were desired in each, then a sample of 60 locations, 30 rural and 30 urban, would be needed.

Interstate Sample Size vs. Precision
(Equivalent Single Axle Loads at the 95% Confidence Level)



Source: *Traffic Monitoring Guide*

Exhibit A - 4

Pavement/Bridge/Safety Management Systems

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 required states to develop and implement systems for managing: Highway pavement of Federal-aid highways; bridges on and off Federal-aid highways; highway safety; traffic congestion; public transportation facilities and equipment; and intermodal transportation facilities and systems. In addition, this legislation requires states to develop and implement a traffic monitoring system for highways and public transportation facilities and equipment.

These requirements went into effect on a designed National Highway System (NHS) on October 1, 1995, and on non-NHS Federal-aid highways on October 1, 1997.

Pavement management system (PMS) means a systematic process that provides, analyzes, and summarizes pavement information for use in selecting and implementing cost-effective pavement construction, rehabilitation, and maintenance programs.

Mandated data elements to be included in the PMS include:

1. An inventory of physical pavement features including the number of lanes, length, width, surface type, functional classification, and shoulder information.

2. A history of project dates and types of construction, reconstruction, rehabilitation, and preventive maintenance.

3. Condition surveys that include ride, distress, rutting, and surface friction.

4. Traffic information including volumes, classification, and load data.

5. A data base that links all data files related to the PMS. The data base shall be the source of pavement related information reported to the FHWA for the HPMS in accordance with the HPMS Field Manual.

Applications of Pavement Management Systems The state-of-the-art is Pavement Management Systems (PMS) application is aptly described by Novak and Kuo (*27*) as "an application software system that analyzes and processes data from the designated data base for use by policy makers who are then able to do such things as control long-term network condition and funding requirements [via maintenance, rehabilitation, and reconstruction (MR&R) program development constraints] to reduce the total cost of pavement preservation, and to have decisions flow from the top down."

Various highway agencies and researchers have recently developed efficient methods for maintenance planning. PMSs have been implemented in numerous states. Three illustrative examples studied describing their application are cited in Michigan, Maryland, and Virginia.

UMTRI's Novak and Kuo (*27*) noted that pavement management systems are typically designed to select projects and treatments on the basis of which alternatives have the lowest project life-cycle cost.

Network life-cycle cost analysis is based on the remaining service life and strategy analysis concepts, which are not in wide use. Therefore, these methods are explained briefly. Conceptually, network and project life-cycle cost analysis are similar in that for network analysis, the lane-mile length of each alternative program is used in place of each alternative project, and each alternative program's average design service life is substituted for alternative project treatments.

Novak and Kuo also illustrated procedures to use project life-cycle cost analysis to increase the total cost of network preservation. They also proposed that the policy level use network life-cycle cost analysis to minimize the total cost of network preservation. Economic analysis would then be a three-step process: network life-cycle cost analysis, to establish program development constraints that minimize the total cost of preservation; program analysis, to select the combination of projects and treatments that meet policy constraints and maximize program benefits; and engineering analysis, to minimize project cost.

A Maryland study noted that PMS and Maintenance Management Systems frequently neglect effects on user costs, which can greatly exceed the maintenance costs. Wei and Schonfeld (*28*) conducted a comprehensive literature review and questionnaire survey, to argue that the concept of combined cost for highway maintenance and traffic operation is relatively unfamiliar. Recognizing existing deficiencies, the authors proposed a maintenance planning methodology to evaluate various economic and safety factors and to analyze technical trade-offs between different maintenance strategies. A quantitative optimization model will then be developed for determining the best maintenance plan. The ultimate objective of the plan is to help decision makers to reduce user costs and improve maintenance operations efficiency.

Virginia has published a series of reports on the progression of their pavement management system (*29*). Among the issues discussed are the development of an adequate data base and the implementation of a condition rating system.

Among the major findings are the following:

1. The applied condition inventory method differentiates among candidate projects for the establishment of maintenance replacement priorities.
2. A 5% random sample of pavements is adequate for condition monitoring purposes.
3. A significant portion of the interstate system is below par in structural capability as a result of truck traffic and axle loads and age.
4. Continued increases in traffic and axle loads will significantly reduce the service life of traditional overlays.
5. The condition rating system will provide management with an objective approach to pavement management including documentation of the funding required for maintenance replacement.

Bridge management system (BMS) means a decision support tool that supplies analyses and summaries of data, uses mathematical models to make predictions and recommendations, and provides the means by which alternative policies and programs may be efficiently considered. A BMS includes formal procedures for collecting, processing, and updating data, predicting deterioration, identifying alternative actions, predicting costs, determining optimal policies, performing short- and long-term budget forecasting, and recommending programs and schedules for implementation within policy and budget constraints.

Bridge management systems are to include a data base and an ongoing program for the collection and maintenance of the inventory, inspection, cost, and supplemental data needed to support the BMS.

States were to complete the BMS design process by October 1, 1995, and the BMS is to be fully operational by October 1, 1998.

Application of Bridge Management Systems A Bridge Management System (BMS) can help transportation agencies evaluate current and future conditions and needs and determine the best mix of maintenance and improvement work on a road network over time with and without budget limitations.

AASHTO guidelines (*30*) established minimum requirements of a BMS capable of providing this type of evaluation. At the minimum, a BMS should consist of both procedures for coordinating various organization units and technical inputs and a computerized database and decision support tool. The BMS must serve to facilitate allocating funds to bridges on a network in order to protect safety, preserve the national investment in bridges, and serve commerce and the motoring public.

A BMS decision report (*31*) cited the BMS function of assisting the bridge manager in the cost-effective assessment of bridge infrastructure needs. Typical decision support that a comprehensive BMS should provide include: easy data storage, access and retrieval of bridge related information, assessment of bridge needs, evaluation and cost estimating of relevant, alternate strategies for possible timely inclusion in optimized capital and maintenance programs as well as network and project level forecasting and trend analysis.

An example BMS application was documented by the Pennsylvania D.O.T. (*32*). PennDOT has developed and implemented a comprehensive BMS. This system has been operational since December 1986. Pennsylvania's BMS has the ability to store a wide range of bridge inspection data. The BMS also has the ability to analyze the data using individual subsystems in order to provide decision support for Department managers. A Bridge Rehabilitation and Replacement Subsystem provides cost estimating and prioritization of bridge improvement projects to support long range planning and programming decisions. This BMS provides cost estimating and prioritization of bridge maintenance activities for assistance in developing annual maintenance programs. A Modeling Subsystem that utilizes deterioration curves for bridge condition and bridge load capacity enables Department managers to predict future bridge improvement needs using different funding scenarios. An Automated Permit Rating and Routing Subsystem is being developed to provide decision support in the load rating, routing and issuance of permits for overweight and oversize vehicles. Finally, a Reports Subsystem is available to provide both standardized and customized report generation capabilities for any subset of data in the BMS.

Highway Safety Management System (SMS) means a systematic process that has the goal of reducing the number and severity of traffic crashes by ensuring that all opportunities to improve highway safety are identified, considered, implemented as appropriate, and evaluated in all phases of highway planning, design, construction, maintenance, and operation and by providing information for selecting and implementing effective highway safety strategies and projects.

SMS data requirements include:

(1) Data necessary for identifying problems and determining improvement needs. Data bases and data sharing shall be integrated as necessary to achieve maximum utilization of existing and new data within and among the agencies responsible for the roadway, human, and vehicle safety elements. These records consist of information pertaining to: crashes, traffic, pedestrians, enforcement activities, vehicles, bicyclists, drivers, highways, and medical services;

(2) Analysis of available data, multi-disciplinary and operational investigations, and comparisons of existing conditions and current standards to assess highway safety needs, select countermeasures, and set priorities; and

(3) Evaluation of the effectiveness of activities that relate to highway safety performance to guide future decisions.

The SMS was scheduled to be fully operational by October 1, 1996.

Traffic Monitoring Systems The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 specifies "requirements for development, establishment, implementation, and continued operation of a traffic monitoring system for highways (TMS/H) in each State in accordance with the provisions of 23 U.S.C. 303 ".

TMS/H means a systematic process for the collection, analysis, summary, and storage of highway traffic data, including public transportation on public highways and streets.

Highway traffic data must be sufficiently comprehensive when used to develop estimates of the amount of vehicular travel and associated vehicle characteristics for a system of highways. These data must support an estimation of traffic volume, vehicle classification, and vehicle weight. Specific weight requirements noted in the legislation include "the weights of such vehicles including the weight of each axle and associated distances between axles on a vehicle".

TMS/H data elements include the following:

a. Annual average daily traffic (AADT). The estimate of typical daily traffic on a road segment for all days of the week, Sunday through Saturday, over the period of one year.

b. Annual seasonal factors. The set of 12 factors, one for each month of the year, that is used to adjust coverage counts to estimates of AADT. Annual seasonal factors make use of the full year's data collected by continuous counters.

c. Automatic traffic recorder. A device that records the continuous passage of vehicles across all lanes of a given section of roadway by hours of the day, days of the week or months of the year.

d. Continuous counter. An automatic traffic recorder that operates continuously for all hours of a year.

e. Coverage count. A traffic count taken as part of the requirement for system-level estimates of traffic. The count is typically short-term and may be volume, classification, or weigh-in-motion.

f. Functional classification. The grouping of streets and highways into classes or systems, according to the character of service they are intended to provide. The recognition that individual roads do not serve travel independently and most travel involves movement through a network of roads is basic to functional classification.

g. Functional system. Highways of a similar type as determined by functional classification.

h. Highway traffic data. Estimates of the amount of person or vehicular travel, vehicle usage or vehicle characteristics associated with a system of highways or with a particular location on a highway. These types of data include estimates of the number of vehicles traversing a section of highway or system of highways during a prescribed time period (traffic volume), the portion of such vehicles that may be of a particular type (vehicle classification), the weights of such vehicles including weight of each axle and associated distances between axles on a vehicle (vehicle weight), or the average number of persons being transported in a vehicle (vehicle occupancy).

i. Traffic data collection session. The collection of highway traffic data for a defined period of time at a specific highway location.

Applications of State Highway Agency Truck Weight Sampling

A number of state have documented their truck weight monitoring procedures. Two examples are Wisconsin and Minnesota.

Truck weight sampling procedures used by the Wisconsin Department of Transportation were described by Gardner (*33*). The TRB paper addressed determining the number and locations of truck study sampling stations. The purpose of the described Wisconsin program is to collect representative trucking characteristic data for use in pavement design, highway cost allocation, motor carrier enforcement, and other planning and research activities. The use of weigh-in-motion technologies and the emphasis on the collection of basic weight data permit random selection of weigh stations and a comprehensive sample of truck traffic. The sampling plan developed relies heavily on user needs and statistical criteria to help ensure a valid and meaningful sample. By using data from the 1980-1981 highway performance monitoring system Wisconsin truck weight case study, the number of required stations is calculated on the basis of the average variability of truck weights in the state. Stations are distributed across recommended road types in proportion to the size of the total population (truck vehicle miles of travel) on each road type. Stations by road type are assigned to counties by using a weighted random procedure. Corridor and specific station locations are designated via application of established criteria.

The Minnesota Department of Transportation (*34*) has operated permanent continuous weigh-in-motion stations since 1981. At present, 16 sites are collecting volume and weight data by vehicle type for use in transportation planning and design. Questions that can be answered from an analysis of this data can provide useful information. For example, gross weight trends of big trucks in Minnesota have been speculated on with great interest. Are trucks on the highways getting heavier? With a number of years of accumulated data from the first WIM sites and several years from succeeding locations available, we have the means to answer this question.

Typically, 5-axle tractor semi-trailers contribute 60 to 90 percent of the Equivalent Single Axle Load (ESAL) damage on many highways. For example, 5-axle semis in the right eastbound lane of Interstate 494 in Bloomington contributed over 70 percent of the rigid ESALs and about 65 percent of the flexible ESALs in 1989, yet they totaled just over nine percent of the traffic flow. Similarly, on the U.S. Highway 2 Bemidji Bypass, 5-axle semis, 11 percent of the traffic in the right eastbound lane, contributed about 80 percent of all ESALs in 1989.

Although both weight and volume of trucks are crucial to issues such as pavement damage, safety, etc., a particularly sensitive relationship exists between truck weights and ESALs. For example, a four percent increase in axle weights produces about a 16 percent increase in ESALs.

This study analyzed gross weight data of 5-axle semis at five WIM locations. The amount of data available for analysis ("good data") varied from year to year at each site.

Three measures, average gross vehicle weight, average gross vehicle weight of all-but-empty trucks, and percentage of trucks operating over legal weight limits, were used to determine weight trends. The data have been developed from tables of gross weight distribution by vehicle type, aggregated by week for each site for a year. All five of the sites were on designated 10-ton routes where 80,000 pounds is the maximum allowable gross weight. Two sets of average gross weights of all 5-axle semis were given at each location. Average gross weight of all-but-empty 5-axle semis was also used in this study.

The Traffic Monitoring Guide

The Federal Highway Administration's *Traffic Monitoring Guide (6)* provides a method for states to apply a statistically-based procedure to monitor traffic characteristics such as traffic loadings. The TMG provides detailed directions for the monitoring of traffic characteristics. Traffic characteristics are those obtained through a coordinated program of traffic counting, vehicle classification, and truck weighing.

Truck Accident Data Programs

While not a source of truck weight data, a number of federal agencies, along with states, the motor carrier industry, and highway safety groups maintain truck accident data. These data sources may provide useful information in evaluation of truck weight enforcement activities. Therefore, Exhibit II - 5, assembled by TRB's Committee for the Truck Safety Data Needs Study *(26)* summarizes existing truck accident data programs.

SUMMARY OF EXISTING TRUCK ACCIDENT DATA PROGRAMS

Data Base	Agency	Time Frame	Features and Strengths	Limitations
FARS	NHTSA	Since 1975	Census of fatal crashes; has good quality control	Does not include nonfatal crashes; limited detail on truck and operation
TIFA	UMTRI	Since 1980	Census of fatal truck crashes; rich detail on truck, carrier, and driver; good quality control	Does not include nonfatal crashes
GES	NHTSA	Since 1988[a]	Based on a probability sample of fatal and nonfatal crashes	Limited detail on truck and operation; based solely on police reports
CARDfile	NHTSA	Since 1982	Large sample of fatal and nonfatal crashes	Not based on a probability sample; limited detail on truck and operation; no road class; based solely on police reports
Computerized Motor Carrier Accident Reports (50-T)	Office of Motor Carriers, FHWA	Since 1973	Rich details on trucks	Lacks data on intrastate carriers; based solely on self-reporting
SAFETYNET	Office of Motor Carriers, FHWA	Since 1990	Census of reported truck crashes (interstate carriers)	No truck configuration, driver, or crash type; based solely on police reports
State accident data	Individual states		Census of reported fatal and nonfatal crashes	Data elements and reporting thresholds not uniform among states; based solel on police reports
NTSB reports	NTSB		Rich details on contributing factors	Number of crashes investigated is extremely small and not randomly selected

Exhibit A – 5

Source: TRB *Special Report 228*

In order to maximize the utility of provided information, data from these sources is structured into components as follows:

> *Monitoring Systems:* These systems assemble data on truck accidents and travel on an ongoing basis nationwide. Sufficient details on the vehicle, roadway, region, driver, and accident circumstances are included to allow users to discern significant differences in truck safety trends with respect to factors relevant to truck safety performance and to spot potential safety problems.
>
> *Data Systems for Accident-Causation Research and Other Special Studies:* These data are needed to answer specific, well-defined research questions. The data may be collected on a one-time basis, or be tailored to meet the needs of individual studies.
>
> *Management Information Systems:* This kind of system provides day-to-day support for agency or company programs that affect safety. Management information systems allow users to identify components that may be inefficient or to redirect resources. The level of detail and kind of information to be collected depend on the particular operations that the data are intended to support. Management information systems should be an integral part of the programs that they are supporting.

APPLICABLE DATA-COLLECTION TECHNOLOGIES FOR TRUCK WEIGHT ENFORCEMENT M.O.E. DEVELOPMENT

The development of truck weight enforcement M.O.E.s is largely dependent on available technologies for detecting truck weights, classification, axle configuration, and vehicle identification. Three primary technologies for such application are: (1) Weigh-in-Motion (WIM), (2) Automatic Vehicle Identification (AVI), (3) and Automatic Vehicle Classification (AVC). While WIM applications have been frequently documented, all three have been experimentally applied, e.g., Krukar and Evert (*35*), H.E.L.P., Inc. (1994).

Primary Technologies

Primary technologies designated for truck weight enforcement M.O.E. development are described as follows.

Weigh-in-Motion (WIM) Utilizing WIM systems, truck axle and gross weights of vehicles can be obtained while they are traveling along the highway using in-pavement sensors. Various systems are available ranging from slow-speed WIM through a range of full highway speed systems, each with a different level of capability and cost. WIM is now an established technology throughout the world.

Various types of WIM systems are as follows.

Bending plate systems
Bridge systems
Capacitive mat systems
Deep Pit scales
Piezo-electric systems
Shallow weigh scales

Automatic Vehicle Identification (AVI) refers to techniques that uniquely identify vehicles, as they pass specific points on the highway. On board transmitters emit a uniquely identifiable signal requiring no action on the part of the driver or an observer. Recent advances in vehicle detection and the processing of data have made AVI application technically and economically feasible.

AVI systems consist of three subsystems: a vehicle-mounted transponder; a roadside detector, with associated antennas; and a system for the transmission, analysis and storage of data. Applicable technologies comprising these systems are the following.

Inductive loops
Optical and infrared systems
Radio frequency and microwave systems

Automatic Vehicle Classification (AVC) AVC systems have application in providing vehicle classification information which is widely used in the design, maintenance and management of highway networks. AVC systems consist of the following.

Sensors - indicating vehicle presence.

Detectors - which receive and condition signals from sensors and then transmit the signals to the processor.

Processors - which perform calculations to determine wheel base, number of axles, etc., to determine vehicle classification.

Recorders - to store and present data.

Limited application of these technologies was noted in the literature. Krukar (*35*) documented Oregon D.O.T.'s experience with WIM, AVC, and AVI and described: (1) the historical perspective on truck weighing in Oregon, (2) the Oregon experiment with WIM and AVI equipment, (3) present selection criteria, installation and testing, (4) costs and limitations of the present system, (5) WIM/AVI results, and (6) conclusions, recommendations, and future directions.

The Heavy Vehicle License Plate (HELP) program comprised the first formal multi-state demonstration of the technologies noted above. This extensive evaluation effort, known as the Crescent Evaluation Team (*36*), identified various applications of these technologies. The Crescent evaluation concluded that application of the technologies produces the following services which have direct application in the evaluation of truck weight enforcement effectiveness.

Roadside Dimension and Weight Compliance Clearance - Allows state authorities to check the size and weight of commercial vehicles without stopping them. Benefits include reduced trip time for compliant trucks and more effective enforcement (capture) of non-compliant trucks by the states.

Pre-Clearance of Vehicles with Proper Documents - Electronic checking of vehicle documents, by storing the data in a transponder in the vehicle or in state databases that can be quickly checked when the vehicle's identity is automatically determined, could reduce unnecessary vehicle stops, improve enforcement, and reduce trip time for compliant trucks.

Government Audit of Carrier Records - Electronic monitoring of vehicles could improve the accuracy and reduce the costs of state audits of: carrier mileage records, number and location of vehicles, fuel tax payments, and certification of fleet maintenance inspections.

Government Processing of Commercial Vehicle Operator Documents Electronic administration of documents is both required for other services to be effective (for example, pre-clearance of vehicles with proper documents may require that the documents be electronically filed) and could reduce the time and paperwork currently involved in issuing/acquiring/certifying permits, credentials, and inspections.

The Crescent evaluation included measures of the equipment and system performance (for example, WIM accuracy and availability), operations adequacy (for example, site layout), and adequacy of the applied technologies. A number of states participated in the evaluation. These are: Arizona, California, Colorado, Idaho, Iowa, Minnesota, Nevada, New Mexico, Oregon, Pennsylvania, Utah, Virginia, and Washington.

The "Western States Transparent Borders" project, part of a national effort to achieve a more efficient transportation system, is aimed at developing technologies and systems that provide a less expensive and more efficient operating environment for commercial vehicle operations (CVO), and ultimately, one which will allow unimpeded passage of trucks across state boundaries.

Goals and objectives of the Transparent Borders project are as follows:

"Provide documents for each participating state that describe the current regulatory and administrative organizational frameworks within that state as they relate to the creation of transparent state borders for interstate commercial vehicle operations.

> Develop, within each participating state, an interagency working group that will guide the implementation of systems and technologies related to the transparent borders concept. These technologies will be designed to improve the efficiency of both governmental agencies and trucking firms operating in the state.
>
> Identify the areas where use of IVHS technologies will provide the most significant benefits for each state.
>
> Develop working relationships between these groups on an interstate level.
>
> Determine a potential course of action for each state to implement IVHS technologies to improve commercial vehicle operations."

The Transparent Borders Project final report (*37*) summarizes the first part of the Transparent Borders Project, a seven-state study to identify the institutional barriers to implementation of various Intelligent Vehicle Highway Systems (IVHS) technologies for CVO.

The report describes the current practices within state and federal agencies and organizations that affect CVO in Washington.

Documented Weigh-in-Motion Application Numerous literature items were cited which describe and evaluate truck weigh-in-motion (WIM). An early NCHRP synthesis (*38*) described how WIM scales can be used to collect data on truck weights, what uses those data have, and the advantages and disadvantages of using WIM systems to collect the data. The history of WIM development was briefly described, and WIM data needs and uses were reviewed.

A subsequent evaluation of low-cost WIM alternatives (*39*) cited data requirements for pavement and bridge design, truck size and weight enforcement, and the development of administrative policy and legislation. This study was the first to cite current technologies for low-cost WIM systems. One of these, piezoelectric cable, was investigated in a joint research effort with Iowa, Minnesota, Washington, the FHWA and several European countries. A second technology, an inexpensive capacitive weighmat WIM sensor and associated electronics, was developed for the

FHWA. A third alternative is a reduced cost configuration of the bending plate WIM transducer manufactured and distributed by the PAT Equipment Corporation. Each of these was evaluated in this study to determine its usefulness in providing effective truck weighing devices at a cost that would allow widespread implementation of in-motion truck weighing programs in Texas.

A subsequent Texas study (*39*) was conducted to evaluate piezo film WIM sensor technologies, produce an electronic data collection unit, and integrate the different assemblies with appropriate software to produce a low cost piezoelectric film WIM system.

Numerous applications of WIM have been applied to instrument highway bridges. One study (*40*) described the background and history of the bridge weigh-in-motion system, the personnel training provided, and the operation of the system including bridge selection, traffic control, installation and take-down, calibration, and problems. Results are given regarding the accuracy of the bridge weigh system in three areas: classification, axle spacing and speed, and vehicle axle and gross weights. Enforcement effectiveness is also evaluated. The cost effectiveness of the system was discussed, and conclusions were presented.

A number of studies were cited to compare WIM accuracy with permanent truck weighing scales in an attempt to establish the reliability of WIM systems. Two such studies are noted as follows.

The first study by Dahlin and Novak (*41*) analyzed WIM data collected by continuously operating systems at three sites on the same route. The analysis examined the gross weight distribution of 5 axle semis. Truck loading pattern differences were studied for both travel directions on the same route. One observed result of consistent patterns was that, on selected routes where long-haul loading characteristics (origin-destination, commodities hauled, etc.) are known, data users can confidently apply weight data collected at one location and to predict patterns for another location on that route. A second result is that these repeating patterns make it possible to monitor the calibration of WIM systems. A shift in the weight distribution at one site, while remaining constant at the other two, indicates a possible change in calibration. These changes in calibration are readily observable. The authors conclude that the demonstrated techniques can also be used in analyzing data collected at WIM sites which may be distant from other WIM sites.

The majority of current WIM data collection throughout the United States is conducted at SHRP Long-Term Pavement Performance (LPTT) sites.

Emerging Technologies

Significant emphasis during the conduct of NCHRP Project 20-34 will address future applicable technologies for monitoring and communicating collected truck weight/classification data. Therefore, a review of literature was conducted which pertained to IVHS application and telecommunications technology.

Intelligent Vehicle Highway Systems (IVHS) The previous discussion of Crescent-evaluated (H.E.L.P., 1994) AVI and AVC technologies comprised IHVS application. In addition, the Crescent project evaluated an integrated communications system and database.

The Crescent computer system enabled data from WIM, AVI, and AVC technologies to be integrated and analyzed. This data link provided various state and motor carrier users with the following services:

"1. To enable "one-stop-shopping", the database includes motor carrier credential and permit information, allowing all agencies and states to share the information rather than require motor carriers to acquire documents in each state and agencies to re-enter data.

2. Weigh stations can check credential and permit data from the database for each truck identified by the AVI equipment for pre-clearance of vehicles with proper documents.

3. AVI and WIM/AVC data are captured by the database and can be accessed by states and motor carriers, by terminal or hard copy:

    A. State taxation agencies can use the data to audit carrier records.

    B. State planning agencies can use traffic volume and weight data for road planning.

C. Motor carriers can use AVI data for vehicle and driver administration (location, estimated time-of-arrival, time on duty, average speed)."

The Transparent Borders project (*42*) applied AVI and WIM in the design of a continuous data collection program for vehicle classification and weight.

Hallenbeck and O'Brien note that Intelligent vehicle-highway system (IVHS) initiatives offer substantial improvements in the operational efficiency of public agencies that regulate, administer, and interact with commercial vehicle carriers. The IVHS technologies combine with changes in data collection methods, information sharing, and organization to form a new concept, referred to as "transparent borders." The transparent borders concept was developed to:

1. reduce motor carrier costs,
2. reduce regulatory costs for public agencies,
3. improve competitiveness among motor carriers,
4. improve motor carrier safety and compliance, and
5. eliminate unnecessary delays for both public agencies and the motor carrier industry.

Hallenbeck and O'Brien also note that although many IVHS technologies are already commercially available, substantial barriers prevent their immediate implementation. These barriers may include the following:

1. physical limitations at existing facilities,
2. resource constraints,
3. political concerns (e.g., job security, authority),
4. antiquated computer systems and manual record keeping, and
5. administrative and legislative restrictions on the collection and dissemination of information and money (including privacy issues).

Telecommunications Devices The Oregon State Highway Division has developed an Integrated Tactical Enforcement Network or ITEN. Management has on-line real-time access to field personnel for immediate deployment when and where the need arises based on histograms of truck traffic and violation trends.

The district weighmaster supervisor has a master computer which will, upon command, dial the various permanent weigh stations and highway monitoring systems in that district. This gives the supervisor real-time access to site data. Using split screens, with the capability of using graphics, the supervisor can obtain information in real-time view mode and past-time histograms on what is occurring at that site with respect to daily and hourly truck volumes, their gross and axle weights, and possible violations. Crews can then be deployed to maximize their enforcement efforts for efficiency and effectiveness. At other remote sites where there are no permanent weigh stations, the supervisor can deploy his portable scale crews to maximize their enforcement efforts. This could be done on an hourly basis and crews could be deployed to meet the changing truck traffic.

With the weighmaster being asked to take on additional responsibilities and do more with less, there is a real need to deploy their available human resources efficiently and effectively. Management needs a tool which will help them achieve these goals.

Moreover, a wide variety of new maintenance management technologies designed for acquisition, recording, transmission, receipt, and field verification of field data was evaluated under NCHRP contract (*43*). The evaluated electronic devices applied telecommunications technologies to offer new and better ways to provide accurate and timely information, allow quick transfer of data from field to office and vice versa, and improve the productivity of the maintenance organization.

The applied technologies included portable hand-held computers, electronic clipboards with handwriting recognition, bar-code scanners, voice recognition systems, satellite Global Positioning System (GPS), digitized maps, radio frequency transponders, facsimile machines, and telecommunications including regular and cellular telephones. Maryland, Connecticut, and Arizona DOTs all agreed to participate in the development, testing, and evaluation of the technology applications and options.

CANDIDATE TRUCK WEIGHT ENFORCEMENT M.O.E. DEVELOPMENT

Reviewed literature contained a number of implications for development of candidate truck weight enforcement M.O.E.s. Prior to citing documents which contain implications for specific measures, the related issue of data acquisition requirements is addressed. Reviewed literature is then cited which pertains to overweight truck presence and resulting pavement-wear effects. Following this, candidate M.O.E.s suggested in the state survey are noted. Finally, we note two promising courses for M.O.E. application: the Federal Highway Administration Truck Weight Study, and the *Traffic Monitoring Guide (6).*

Data-monitoring method

Implicit in the development of M.O.E.s is consideration of the applied *methodology* required to determine the measures. TRB Special Report 228 (26), *Data Requirements for Monitoring Truck Safety,* cited methodological needs recommended to monitor truck safety. However, an adaption of this methodology can be specifically geared to truck weight enforcement requirements. Thus, data requirements derived to monitor truck weight enforcement M.O.E.s are as follows.

1. Monitoring Systems: These systems would assemble data on truck volume, classification, and weight on an ongoing statewide basis. Sufficient detail on the vehicle classification, axle loading, ESALs, and Bridge Formula compliance, would be included to allow the state agency to discern significant differences in truck compliance trends with sufficient sensitivity (or statistical confidence) to spot potential pavement damage, bridge structural, or safety problems.

2. Data Systems for Pavement/Bridge Damage and Safety Research: These data are needed to answer specific, well-defined research questions related to deleterious effects of overweight trucks. The data may be collected on a one-time basis, or be tailored to meet the needs of individual studies.

3. Management Information Systems: This kind of system provides day-to-day support for agency programs related to truck weight monitoring/enforcement. The level of detail and

kind of information to be collected will depend on the developed M.O.E.s. Management information systems are an integral part of the programs that they are supporting.

WIM has obvious and essential application for monitoring truck weight enforcement effectiveness. The primary issue regarding WIM applicability is weight accuracy. Recent research (*11,44*) has demonstrated improve accuracy with multiple sensors.

Recent WIM system cost estimates (*44*) indicate that dual piezoelectric sensor systems can be installed for $9,500 per lane. Four-year life cycles were estimated with a 25% sensor failure rate at the end of three years. Sensor replacement cost is $2,000.

Candidate M.O.E. Development

A number of documents were cited in the literature review which give rise to consideration of specific candidate M.O.E. concepts.

Excessive Truck Weight Due to the fact that pavements are designed to withstand specific loading during their lifetime, overweight trucks are a critical factor in pavement deterioration. Literature previously cited in this review have elaborated on this point. For example, Gillespie (*11*) studied the mechanics of truck-pavement interaction to identify relationships between truck properties and damage (fatigue and rutting). Stein (*5*) documented excessive truck weights in the traffic stream as follows.

1. Forty percent of the ESALs observed on the Wisconsin Rural Interstate System were attributable to excess axle loadings.

2. Data indicated that 10 to 15 percent of trucks were potential violators. (It was not possible in effort this to discern overweight violators from overweight permitted trucks.)

3. Due to this presence of observed overweight trucks, Stein recommended that Weigh-In-Motion data be utilized as a tool for prioritizing weight enforcement efforts.

While Pavement Management Systems do contain information which may be useful for M.O.E. application, their applicability to the development of truck weight M.O.E.s is limited. Research by Hallenbeck and Kim (*45*) has demonstrated that states' current application of Pavement

Management Systems are not sensitive to truck weight. The Transparent Borders project team examined nine states' pavement management systems. These states included: Arizona, Arkansas, California, Florida, Idaho, Minnesota, Nevada, Ohio, and Washington.

In all of these states, some measure of traffic was used in the pavement management system. However, in none of these systems did truck volumes or an estimate of actual equivalent single axle loads (ESAL) play a leading role in the determination of expected pavement deterioration rates or pavement rehabilitation prioritization.

The Transparent Borders project indicated that expected pavement life was predicted in years, not ESALs, and was usually a predetermined function based on standard deterioration curves adjusted (in some cases) to reflect actual pavement performance. In none of the examined PMS were the deterioration rates based directly on ESAL estimates measured on individual road segments.

The Transparent Borders Project literature review demonstrated that traffic and/or truck volume estimates were used only peripherally in pavement management systems. Application of traffic measures served to categorize the expected deterioration rate (e.g., high, medium, or low rates of deterioration). However, in no reviewed case was the pavement management system sensitive to expected ESAL loading changes based on monitoring of actually applied loads or traffic volumes.

The use of pavement condition to determine expected pavement life within the structure of PMSs, rather than the use of cumulative ESALs, was in part due to the lack of valid truck data available when time these PMSs were implemented. Deterioration rates were used partly because the PMSs lacked accurate loading data and partly because the use of actual deterioration rates allowed the PMS to account for a variety of causes of pavement deterioration (e.g., poor quality construction). However, the study demonstrated the critical impact of truck weight in terms of ESALs as it affects pavement deterioration.

A frequent cause of "premature" pavement failure was found to be significant underestimation of actual level of traffic loading. The underestimated load results in a pavement that actually meets its design life in ESALs but fails prematurely in terms of the number of years it lasts. For example, if a pavement is designed to withstand 1 million ESALs per year for 7 years, but actually receives 2 million ESALs per year in loads, the pavement will fail in 3.5 years. The perception is that the pavement failed prematurely, when in actuality, the pavement met its design criterion (7 million ESALs).

Thus, Transparent Borders project underscored the need for truck weights, preferably in ESALs, to be applied as an estimate of pavement wear due to excessive truck weight.

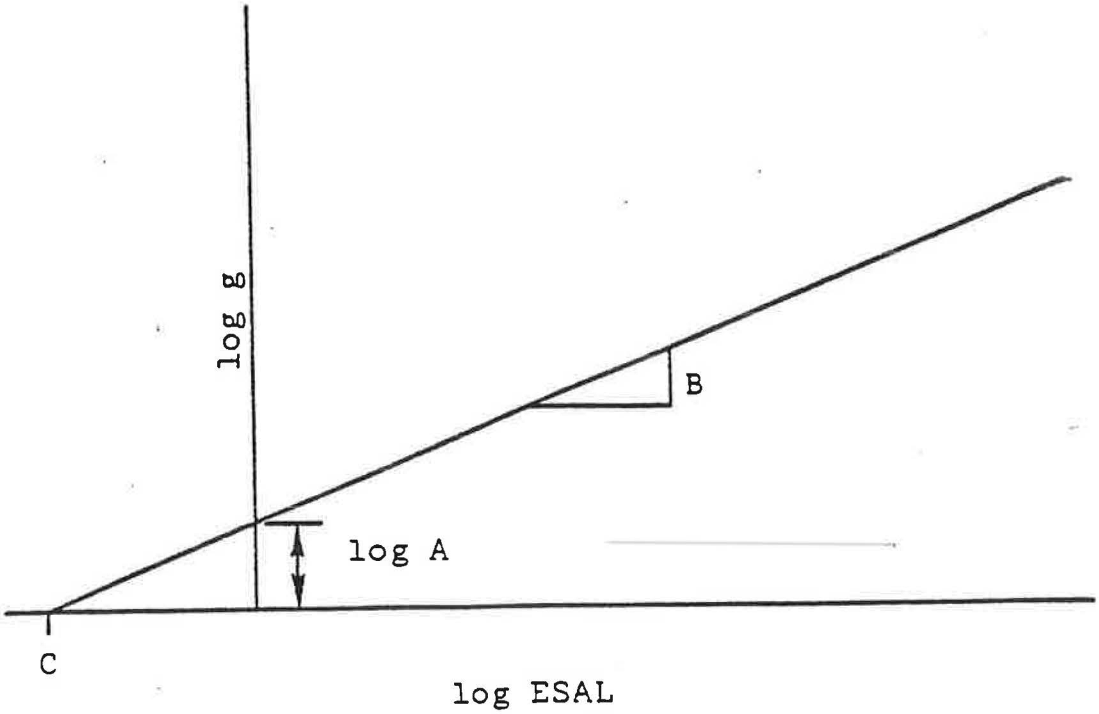
Pavement Distress Index Grivas et. al. (*46*) presented a methodology for determining a pavement distress index (PDI) needed for pavement management purposes. The authors concluded that the developed index is a viable single measure of pavement surface condition useful for pavement management purposes.

Pavement Distress Index formulation is based on two types of information, namely, (a) individual distress ratings along nominal lengths of pavement, and (b) a set of weighing values associated with the various distress types and severity-extent combinations. The PDI is used as a condition measure in various other analytical methodologies within the pavement management system. Application of the PDI has been practiced by the New York State Thruway Authority.

A useful application of pavement distress in developing a potential truck weight enforcement M.O.E. was documented in Virginia by McGhee (*29*). This study incorporated the AASHTO pavement distress function, g, related to Equivalent Single Axle Loadings in the Exhibit A - 6 plot shown on the next page.

This straight line function intercepts the horizontal axis at C, the point at pavement distress is said to occur. A possible confounding factor in application of a pavement distress function as a truck weight enforcement M.O.E. is unreliability of pavement deformation due to variations in properties of materials. This factor will be investigated in the Task 5 M.O.E. evaluation study.

Pavement Roughness While pavement roughness can be considered as a candidate M.O.E., McGhee (*29*) that, due to the generally good ride quality and low pavement roughness associated with Virginia highways, that pavement roughness is not useful in prioritizing pavement rehabilitation projects. Therefore, the sensitivity of this measure to overweight truck traffic must be carefully evaluated.



Distress function vs. traffic.

Source: McGhee, 1984

Exhibit A - 6

Ride Quality AASHTO (*47*) reports that one of the major accomplishments of their 1956-1960 Road Test to develop a concept for evaluating the performance of a pavement. Ride quality was used as a measure of how well pavements could serve the public. Studies made, after completion of the Road Test, have consistently indicated that ride quality can be correlated to pavement roughness. It has also been shown that roughness is not only a measure of user satisfaction (or dissatisfaction), but can also be related to user costs; i.e., vehicle operating costs and speed profiles.

The report notes that road roughness should be considered as a fundamental requirement for a pavement management system. There are a wide range of methods of measurement to evaluate road roughness, either subjectively (ride quality) or objectively (roughness). For state highway administrations the use of automated measuring devices to measure and record roughness is considered preferable to subjective ratings. Local government agencies, which do not have access to automated devices, have found subjective estimates of ride quality to be a useful measure of functional performance.

Methods for measuring roughness and interpreting roughness vary and are constantly changing as both equipment and analytical capabilities improve. Both response type roughometers, designed to measure vertical movement between the axle and frame of a vehicle (or trailer) and profilometers, designed to measure the longitudinal profile, have been used to evaluate roughness.

Within any particular agency, any of the response or profilometric equipment can be used. The pros and cons of each need to be carefully considered since the reliability of the measurement and utility of the data (correlation to ride quality) will vary.

For comparison between agencies, the conversion to the International Roughness Index (IRI) could be considered as a useful means of summarizing roughness measurements (10).

Physical Distress AASHTO (*47*) reported that physical distress is a measure of the road surface deterioration caused by traffic, environment and aging.

There are no national standards for procedures to be followed or equipment to be used for identifying pavement distress. It is, however, acknowledged that the type and cost of maintenance, rehabilitation and reconstruction will be significantly influenced by the type, extent and severity of distress.

The types of distress can generally be categorized into three classes: fracture (cracking), distortion (rutting, corrugations, faulting), or surface wear or deterioration (raveling, spalling). Specific descriptions of distress related to asphaltic or portland cement concrete pavements may vary depending on the types of distress encountered in a particular area.

Methods for evaluating distress can vary widely, ranging from "windshield" surveys from a moving vehicle to automated equipment designs to measure and record distress in a prescribed way. The choice of method should be made as an integral part of the PMS development. The primary factors to consider are: applicability, cost, productivity, quality and quantity of the information obtained. The most important of these considerations are applicability, quality and quantity. For example, is there a sufficient amount of the right kind of information and does the information represent field conditions?

Currently Applied M.O.E.s

The survey of states, conducted as part of the NCHRP 20-34 effort, revealed little application of truck enforcement M.O.E.s.

Twenty-three surveys were returned from state enforcement agencies, and 36 were returned from state highway planning agencies. Appendices B and C, respectively, to this report provide response summaries for the enforcement and planning questionnaires. **Bold face** appendix entries on questionnaires display both the number of agency responses and the corresponding percentage of the nationwide sample. Responses are indicated in the appendices as follows.

"1. Does your state conduct an on-going truck Weigh-In-Motion (WIM) program?

Yes **18 (36%)** No **5 (10%)**"

The above example signifies that 18 responding enforcement agencies (or 36.0 percent of all sampled agencies) conduct on-going WIM truck weighing activity. The state survey queried M.O.E. information both from state enforcement agencies and state highway planning agencies.

M.O.E.s Suggested by State Enforcement Agencies Exhibit A -6 lists state truck weight enforcement agency responses to question numbers 6 and 7, stated as follows.

"6. What measures (e.g., reduction in the number, proportion, and severity of overweight trucks) are <u>currently</u> applied to evaluate truck weight enforcement effectiveness? Please explain if not included in documentation.

7. What measures (e.g., reduction in the number, proportion, and severity of overweight trucks) are <u>planned</u> for future application to evaluate truck weight enforcement effectiveness? Please explain."

Arkansas	None.
Colorado	Vehicle Compliance Ratios.
Georgia	None.
Idaho	1. Severity of overloads 2. Proportion of enforcement action v. number weighed
Illinois	Suggested Relevant Evidence helpful, but would likely not pass legislation.
Iowa	Monthly activity reports are compared to proposed goals Weight Enforcement plan submitted to FHWA.
Kansas	None.
Michigan	None.
Montana	None.
Nebraska	None.
New Jersey	Total overweight compliance; monthly comparison with previous year.
New York	No current. Planned monthly statistics re: vehicles weighed, dangerously overloaded vehicles.
North Carolina	No current. Plans for: (1) severity of overweight trucks, (2) reduction in violations.
Oklahoma	None.
Oregon	1. Truck Weighings, annual count 2. Statewide average weight violation trends, by roadway classification. 3. Legalizations, by type (cargo shift, off-load)
Pennsylvania	Truck volume, amount overweight, trip distance.
Virginia	Did not complete questionnaire, due to current transition in enforcement procedures.
Washington	Compliance ratio, severity of violation, WIM monitoring.
Wyoming	Routine weight monitoring

Exhibit A - 6. Candidate Truck Weight Enforcement M.O.E.s
M.O.E.s reported by State Enforcement Agencies

Of the responding states, nine indicated some applied or planned measure(s) of truck weight enforcement effectiveness. These are listed below.

1. Severity of violation. Four states.
2. Vehicle Compliance Ratios, i.e., the number of citations as a proportion of total number of weighed vehicles. Three states.
3. Routine weight or WIM monitoring. Three states.
4. Reduction in violations.
5. Truck Weighings, annual count
6. Statewide average weight violation trends, by roadway classification.
7. Legalizations, by type (cargo shift, off-load)
8. Comparison of monthly activity to FHWA enforcement plan goals
9. Relevant Evidence findings

Despite the fact that an introductory letter explaining the nature of the project was sent to state enforcement agencies, it is nevertheless obvious from the above list that certain of the suggested candidate M.O.E.s miss the point of determining what is actually accomplished by the enforcement effort rather than merely indicating a level of enforcement effort.

M.O.E.s Based on Pavement/Bridge/Safety Management Systems In order to assist in the development of candidate M.O.E.s the state survey asked the following question of state highway planning agencies. Exhibit A - 7 lists responses from 36 states.

> "7. What measures are gathered (or planned for future data collection) in your state's Pavement/Bridge Management System? If convenient, enclose appropriate documentation portions."

Responses shown in the exhibit contain measures shown in the literature review to be considered as candidate M.O.E.s.

Alabama	AADT, Percent Commercial Vehicles, Truck Weight
Arkansas	None at this time.
Arizona	None reported
Colorado	Pavement - Traffic, Rut depth, Cracking, Skid, GPR, Weight Bridge - Traffic, NBI, Weight, PONTIS (System aid to optimization of budgets and programs)
Connecticutt	Overload permit records anticipated in PMS
Florida	Final decision on variables not determined, as yet
Georgia	None yet
Illinois	Extensive list of geometric and locational data provided
Kentucky	Traffic volume, classification, ESALs at 64 counting stations
Kansas	Pavement - Portable WIM data Bridge - SHRP data
Louisiana	None provided
Iowa	ESALs at 18 sites; volume, classification, speed at 24 sites; volume, speed at 43 sites.
Maryland	None reported.
Michigan	90 TMG WIM and 30 SHRP sites.
Minnesota	Volumes, vehicle classifications, ESALs, roadway and structure information, condition ratings, etc.
Nebraska	None reported.
Nevada	None reported.
New Hampshire	IRI for pavements; 15 WIM sites

Exhibit A – 8

Measures available from Pavement Management Systems

Reported by State Highway Agencies

Application of FHWA's Truck Weight Study

As has been noted in this review, many states collect massive WIM data from relatively unobtrusive WIM stations for the purpose of monitoring pavement performance. The Federal Highway Administration has developed software and distributed it to states to the purpose of reducing and analyzing the WIM data. Data from approximately one-half of the states is maintained in files stored at the FHWA. Summary data obtained from this source can potential be applied to monitor long-term truck weight enforcement effectiveness.

Application of Traffic Monitoring Guide (TMG) Variables

Cottrell (*25*) developed a sampling plan involving the systematic deployment of portable WIM devices at TMG sites. Cottrell concluded that use of the TMG and WIM systems together provide improved monitoring of truck weight sampling procedure using the TMG and WIM systems. Four alternatives from the TMG that were based on differentschemes for multiple measurements at permanent WIM sites were evaluated. A truck weight sampling plan was developed for the preferred alternative. Truck weight sampling sites, data collection procedures, cost and resources estimates, data from permanent WIM sites, and data management information are included in the plan.

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APPENDIX **B**

DEVELOPMENT, EVALUATION, AND RANKING OF MEASURES OF EFFECTIVENESS (M.O.E.s)

Implicit in the development of M.O.E.s is the definition of various terms and concepts related to truck weight enforcement. Consideration is first given to truck weight enforcement goals and procedures. The M.O.E. concept is then discussed as it relates to truck weight enforcement.

Truck Weight Enforcement Goals and Procedures

Truck weight is enforced for two reasons: (1) to avoid excess damage to the roadway and structures caused by overweight loads, and (2) to assist the safe operation of trucks and other vehicles in the vicinity of trucks.

Goals of state enforcement agencies that operate truck weight enforcement activities are the following:

1. to deter truck operation in an overweight condition and/or operating with inappropriate axle-spacing,
2. to control pavement and bridge damage from overweight trucks,
3. to protect the public from safety risks associated with overweight trucks, and
4. to protect law-abiding truck operators from illegal competition.

Truck weight enforcement **procedures** involve **activities** and **programs** by which weights are monitored. An individual **activity** is designated by the specific type of hardware used, operating schedule, or other strategy affecting the driver's knowledge that his vehicle will be weighed when using the highway.

General classes of enforcement **procedures** are:

1. Permanent roadside weigh scales (highly visible facility, hours of operation may be scheduled or random)
2. In-pavement weigh-in-motion (visible, but unobtrusive; full or part-time operation)
3. Bridge or culvert weigh-in-motion (invisible, full or part- time operation)
4. Unscheduled roadside truck inspections with portable scales (period of effectiveness is quite brief because of communications via the trucking network)
5. Relevant evidence prosecutions (effective all the time, affecting only part of the trucking fleet)

An area-wide weight enforcement **program** involves monitoring trucks using a network of activities such as those listed above. A program is more comprehensive and considers applied procedures, operating schedules, required enforcement staff, type of road where deployed, route and diversion routes where enforcement is deployed, and other characteristics.

Truck Weight Measure of Effectiveness (M.O.E.s)

The "measure of effectiveness" of a weight enforcement activity is defined as a "a determinable quantity, i.e., of what is achieved as the result of truck weight enforcement activity". Its application should also be applied to quantify the contribution that activity makes toward achievement of one or more of the goals defined above. In order to quantify effectiveness there must be measures which show benefits in terms of: (1) compliance operational weight and axle-spacing regulations, (2) pavement/bridge preservation, or (3) minimizing accidents, deaths, injuries, and property damage.

Historically, measures of effectiveness have used indices such as the number of trucks weighed, number of overweight trucks pulled off the road, size of the overloads detected, amount of fines imposed, number of prosecutions, trends with time, and compliance ratios. In many cases, these indices do not express the effectiveness in meaningful terms that relate to overall goals, e.g., the number of overweight trucks detected does not relate to preservation, punishment or prevention.

Development of Candidate Measures

The designation of candidate measures addressed one central question: what needs to be measured (and how) in order to reliably determine overweight violations?

Task 2 activity first involved the identification of candidate M.O.E.s based on the Task 1 literature review and the collective expertise of the project team. Following the identification of candidate M.O.E.s, the measures were ranked on the basis of designated criteria. These criteria were designated prior to the initiation of work in NCHRP Project 20-34.

The initial set of candidate measures was identified through independent contributions of NCHRP Project 20-34 team members. These individuals, and the basis for their M.O.E. development assessments, are as follows.

> *Fred R. Hanscom, P.E.* Principal Investigator. The basis of Mr. Hanscom's M.O.E. development assessment consisted of: (1) his review of the literature in those areas identified in Task 1; and (2) his 23 years of traffic operational research experience, including the conduct of numerous truck operational safety studies, in addition to WIM reliability determinations and WIM data collection activities.
>
> *Thomas D. Gillespie, Ph.D.* Director of The University of Michigan's Transportation Research Institute. The basis of Dr. Gillespie's measures development assessment consisted of his 28 years of highway safety research experience which has emphasized heavy vehicle characteristics and their effects on pavements. Dr. Gillespie is also published in the area of WIM reliability assessment.
>
> *Benjamin H. Cottrell* TMG/HPMS Truck Measures Consultant. The basis of Mr. Cottrell's measures development input is his 15 years of experience in traffic engineering research which includes specific research addressing the development of a truck weight sampling plan using the *Traffic Monitoring Guide.*

The development of candidate measures first considered the primary truck weight objective, i.e., to deter truck operation in an overweight condition. Second, the question of candidate M.O.E. development then addressed manpower and equipment resources available to enforcement and highway agencies. Finally, a list of potential measures was based on current and foreseeable data-gathering capabilities, given likely agency resources, and what measures are most efficacious given these resources.

Candidate M.O.E. Evaluation and Ranking Procedures

The initial list of developed candidate M.O.E.s considered a variety of applications; i.e., effectiveness determinations for truck weight enforcement site-specific activities, corridor enforcement, and program application. The developed candidate M.O.E.s, described in this report section, are amenable to any of these operations. Their specific application with regard to site-specific versus program effectiveness determination, for example, will be subsequently addressed in this NCHRP project's development of M.O.E. data sampling plans.

The evaluation of derived candidate M.O.E.s was conducted via application of the following criteria:

A. *Practicality of M.O.E. application* Of primary importance is state agency data collection ability, efficiency, cost requirements, and ease of measurement as applied to each candidate M.O.E. For example, high priority was given to M.O.E.s which can be readily derived from existing data sources, e.g., WIM devices, shipping records.

B. *Reliability of candidate M.O.E.* Reliability refers to measurement precision, e.g., confidence that repeated measurement will yield consistent results. A reliable M.O.E. is one which correctly represents the true distribution of weights, classification, percentage of overweight trucks, percent of bridge formula non-compliance, etc. within the study region. This concept is of paramount importance in assessing the performance of technologies applied in truck weight measurement and classification activity.

C. *Support statewide random sampling.* Traffic monitoring in the vicinity of weigh stations (including alternate truck routes) presents a limited perspective of overweight hauling practices. Therefore, monitoring procedures, designed to achieve statewide random weight sampling and consistency with Safety and Pavement Management System technologies, was designated to gather M.O.E. data. It was therefore necessary that designated M.O.E.s be comprised of variables which can be derived from these systems.

D. *Absence of bias with regard to enforcement/monitoring procedure.* It is imperative that the applied M.O.E. data-gathering procedure not be biased with regard to either a weight enforcement program or a particular traffic monitoring method. Applied M.O.E.s must be generally sensitive to prevailing truck characteristics regardless of enforcement activity. Furthermore, care must be taken to ensure that overweight truck presence is not influenced by specific traffic-monitoring or weight-enforcement installations. Therefore, M.O.E. selection criteria considered the susceptibility of candidate M.O.E.s to potential bias.

E. *M.O.E. compatibility with state agency data collection methods.* The designated procedure for states' measurement of enforcement effectiveness must be achieved within the state's data collection capabilities. Therefore, emphasis was placed on emerging technologies, i.e., Safety and Pavement Management Systems, in order that the developed M.O.E. assessment procedure have future applicability. SHRP WIM installations were considered a primary data source, therefore variables collected by this system were given high priority.

F. *Sensitivity to infrastructure damage* One objective of truck weight enforcement is to control pavement and bridge damage from overweight trucks. Certain truck loading conditions, e.g., excessive axle-weight as opposed to excessive tandem-weight are more likely to result in pavement damage. This consideration is important with regard to assessing the merits of candidate M.O.E.s.

G. *Applicability to future technology* The use of Pavement Management Systems, Bridge Management Systems, Maintenance Management Systems, and Safety Management Systems present an emerging technology in many states. An objective of

NCHRP Project 20-34 is to enable highway agencies to efficiently assess the effectiveness of truck weight enforcement programs. Therefore, designated M.O.E.s included those measures which can be determined via use of these systems.

Each candidate M.O.E. was evaluated on the basis of each of the above criteria. In order to rank candidate M.O.E.s, a numerical rating scheme was applied in the evaluation process. As each criterion was applied to each candidate M.O.E., the suitability of the M.O.E. was assessed on the basis of each criterion using the numerical scale indicated in Table 1 below.

Table 1. Applied Numerical Rating Scheme to Evaluate Candidate M.O.E.s

Numerical Score	Assessment Criterion
0	No value whatever
1	Insignificant Worth
2	Some Utility
3	Moderately Useful
4	Significantly Valuable
5	Superior Merit

Using the above scale, the average rating across the six criteria was assigned to each M.O.E. to determine the final ranking.

Candidate M.O.E.s

The development of this M.O.E. was guided by two principles. First, derived measures should be consistent with capabilities of potential data sources, e.g., commercially available WIM equipment and SHRP LTPP data output. Second, derived measures should be functionally capable of apprising enforcement agencies of target truck characteristics. Due to the fact that existing data sources are not fully compatible with M.O.E. sensitivity requirements, two classes of traffic operational measures are listed. *Direct* M.O.E.s are those to be evaluated; however, due to the fact that highway/enforcement agencies are currently dependent on data collection procedures which do not directly generate these precise measures, a list of *indirect* measures, i.e., those required to derive the direct measures set, was also generated.

Indirect measures - These measures consist of data output gathered by WIM systems. These data must be recorded in ASCII or similar computer readable files for subsequent manipulation into *direct* Traffic Operational M.O.E.s listed below.

1. Total truck sample data, generated by WIM system, e.g.,

    a. Total truck volume.
    b. Grouped by weight-regulation and axle-configuration classification.
    c. Grouped by specified time interval.

2. Vehicle-specific data, generated by WIM system, i.e.,

    a. Total truck weight, in pounds and ESALs
    b. Individual axle weights, in pounds and ESALs
    c. Axle-grouping configuration, i.e., tandem, tridem
    d. Axle-grouping weight, in pounds and ESALs
    e. Spacing between axles/axle-groupings.

Direct M.O.E.s - These measures are derived from WIM system output. Commercially available equipment from manufactures such as Golden River, International Road Dynamics, PAT, Inc. directly supports most of the developed M.O.E.s. All of the following seven candidate M.O.E.s can be derived from software programming of output from this equipment.

1. ***Proportion of Overweight Trucks in Sample*** - The fraction (or percentage) of the truck sample exceeding the applicable weight limit based on any of the parameters listed below, based on a statistically valid sample size.

    a. Gross Vehicle Weight
    b. Individual Axle Weight
    c. Individual Axle-grouping Weight
    d. Truck Type(FHWA 13-classification scheme)

The M.O.E. significance of each of the above parameters is as follows. The impact of trucks on pavement deterioration varies according as to how the stress is applied. Therefore, gross truck weights, as well as weights exerted by individual axles and axle-groupings, are important. Furthermore, whether a particular classification of truck is more (or less) prone to overweight violations may be of assistance to enforcement agencies due to visual characteristics associated with specific truck types.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 5 Superior. Commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Significantly valuable. Commercially available equipment is becoming increasingly reliable.

C. Supports Statewide Random Sampling

Ranking: 4 Significantly valuable. Commercially available WIM equipment is commonly applied in statewide sampling procedures.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 2 Some Utility. This measure may be associated with pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

2. ***Severity of Overweight Violation*** - The extent to which collected data on any of the parameters listed below exceeds the allowable legal weight limit, expressed as a percentage exceeding the allowable legal weight, grouped by range to indicate 5, 10, 20, 30, and 40+ percent overweight).

a. Gross Vehicle Weight
b. Individual Axle Weight
c. Individual Axle-grouping Weight
d. Truck Type(FHWA 13-classification scheme)

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 5 Superior. Commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Useful. Commercial equipment is becoming increasingly reliable, yet this M.O.E. demands precision.

C. Supports Statewide Random Sampling

Ranking: 4 Significantly valuable; Commercial WIM equipment applied in statewide sampling procedure, yet this M.O.E. demands precision.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 5 Superior. Severity of overweight violations is highly sensitive to pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

3. ***Distribution of Overweight Trucks in Sample*** - While the two M.O.E.s noted above are essential to describe the overweight truck problem to enforcement and highway agencies, simple distributions, e.g., the *numbers of overweight trucks* and associated *excess loading* over legal limits, are necessary for dispatching enforcement personnel to locations in which enforcement operations can be conducted in the most cost-effective manner.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 5 Superior. Commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Significantly valuable. Commercially available equipment is becoming increasingly reliable.

C. Supports Statewide Random Sampling

Ranking: 5 Superior. Commercially available WIM equipment is commonly applied in statewide sampling procedures.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 2 Some Utility. The proportion of overweight trucks is marginally sensitive to pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

4. ***Bridge Formula Violations*** - Axle-spacing information, in combination with individual-axle and axle-grouping weights, applied to spacing criteria specified by the applicable Bridge Formula.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 4 Significantly valuable. Much commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Significantly valuable. Commercially available equipment is becoming increasingly reliable for axle-spacing data.

C. Supports Statewide Random Sampling

Ranking: 4 Significantly valuable. Commercial WIM equipment applied in statewide sampling procedure, yet this M.O.E. demands measurement specificity.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 5 Superior. By definition, the Bridge Formula is sensitive to pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

5. ***Equivalent Single Axle Load (ESAL)*** - This measure is defined as a unit of measurement equating the amount of pavement consumption caused by an axle or group of axles, based on the loaded weight of the axle group, to the consumption of a single axle weighing 18,000 pounds. This M.O.E. provides a direct measure of pavement wear exhibited by a single truck. The usefulness of this measure derives from the fact that pavement design life is determined in terms of ESALs.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 5 Superior. Commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Significantly valuable. Commercially available equipment is becoming increasingly reliable.

C. Supports Statewide Random Sampling

Ranking: 5 Significantly valuable. Commercially available WIM equipment is commonly applied in statewide sampling procedures.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 5 This measure is highly sensitive to pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

6. ***Excess ESALs*** The definition of excess ESALs as determined by the Wisconsin study (Stein, 1988) is "excess ESALs equal the sum of the total ESALs attributable to the illegal portion of the individual single or tandem axle group." The significance of application of this M.O.E. is that forty percent of observed ESALs on Wisconsin's Rural Interstate System were attributable to excess ESALs. This M.O.E. is to be gathered by vehicle class.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 5 Superior. Commercially available WIM equipment generates data for easy computation of this measure.

B. Reliability of Candidate M.O.E

Ranking: 4 Useful. Commercial equipment is becoming increasingly reliable, yet this M.O.E. demands precision.

C. Supports Statewide Random Sampling

Ranking: 4 Significantly valuable. Commercial WIM equipment applied in statewide sampling procedure, yet this M.O.E. demands precision.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Subject to the same bias as any weighing operation.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 4 Significantly valuable. This measure is compatible with emerging technology.

F. Sensitivity to Infrastructure Damage

Ranking: 5 This measure is highly sensitive to pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 5 Superior. This measure is highly amenable to emerging technology.

7. ***Projected Distance Traveled by Overweight Truck*** - Total pavement wear is obviously more severe for overweight trucks traveling longer distances. Application of WIM surveillance devices on corridors of known truck travel patterns will enable

enforcement agencies to prioritize enforcement operation in a manner to minimize regional pavement wear.

This M.O.E. was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 3 Useful. Commercially available WIM equipment generates data useful for computation, however manually generated travel distance factor must be applied.

B. Reliability of Candidate M.O.E

Ranking: 2 Some Utility. Application of travel distance factor comprises a reliability threat, e.g. not possible to determine travel distance for entire truck sample; estimated from planning data.

C. Supports Statewide Random Sampling

Ranking: 2 Some Utility. Estimation requirement presents problem.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 2 Some Utility. Subject to more bias than other weighing operations.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 2 Some Utility. This measure requires integration of WIM technology and travel estimation techniques, a process which produces a barrier to its application.

F. Sensitivity to Infrastructure Damage

Ranking: 2 Some Utility. Distance traveled has secondary impact on pavement/bridge damage.

G. Applicability to Future Technology

Ranking: 2 Some Utility; Applicable emerging technology, e.g., AVI, is slow to materialize and may induce bias with regard to this measure.

8. ***Distribution of Above Measures by Day-of-Week, Hour-of-Day*** The Issue of whether to collect temporal distributions of the above M.O.E.s was based on the ability to assist enforcement agencies with manpower-allocation decisions to facilitate the optimization of resources.

This M.O.E. collection strategy was evaluated in terms of receiving a ranking (using the scheme given in Table 1) for each of the previously discussed M.O.E. evaluation criteria. Results of the ranking procedure are discussed for each criterion as follows.

A. Practicality of M.O.E. Application

Ranking: 4 Significantly valuable. Most applicable data collection methods, e.g., automated devices, rely on temporal observations.

B. Reliability of Candidate M.O.E

Ranking: 4 Significantly valuable. Commercially available equipment has proven reliable in terms of temporally recording data.

C. Supports Statewide Random Sampling

Ranking: 4 Significantly valuable. Random sampling with commercially available WIM equipment is readily applied in statewide sampling procedures.

D. Absence of Bias with Regard to Enforcement/Monitoring Procedures

Ranking: 3 Useful. Temporal observation is not expected to complicate any bias problem.

E. M.O.E. Compatibility with State Agency Data Collection Methods

Ranking: 5 Superior; Commercially available WIM equipment readily generates data by day-of-week and hour-of-day.

F. Sensitivity to Infrastructure Damage

Ranking: 2	Some Utility. Pavement/bridge damage is marginally affected by temporally-related usage.

G. Applicability to Future Technology

Ranking: 5	Superior. This measurement strategy is highly amenable to emerging technology.

Ranking of Candidate M.O.E.s

The six M.O.E. evaluation criteria were defined earlier in this discussion. Applied criteria were as follows.

A. Practicality of Application
B. Measurement Reliability
C. Supports Statewide Random Sampling
D. Absence of Enforcement-induced Bias
E. Data Collection Methods Capability
F. Sensitivity to Infrastructure Damage
G. Applicability to Future Technology

Ranking of M.O.E.s was achieved by assessing the applicability of each M.O.E. to truck weight enforcement procedures. This procedure was achieved by assigning a point value to each M.O.E. based on the following criterion.

No points	No value whatever
1 point	Insignificant worth
2 points	Some utility
3 points	Moderately useful
4 points	Significantly valuable
5 points	Superior merit discussed in Chapter 3.

The average rating across the six criteria was assigned to each M.O.E. to determine the candidate M.O.E.'s final ranking.

Numerical results of the applied rating procedure and M.O.E. rankings in each category are shown in Table 2 on the next page. The list of measures shown in the exhibit generally comprised proposed M.O.E.s for field validation. The single exception was that, due to practical considerations that precluded its current application, the "Distance Traveled" measure was not evaluated in the current project. However, this measure is retained for subsequent consideration where applicable, i.e., AVI monitoring procedures.

Final M.O.E. Definition

In accordance with project objectives and in compliance with the NCHRP Project 20-34 Problem Statement, a final M.O.E. list was developed. This final list consisted of M.O.E.s that were suitable for field evaluation. The list of final M.O.E.s, along with their definitions appears as Table 3 on page 20.

REFERENCE

Stein, P. et al, *The Overweight Truck in Wisconsin: Its Impact on Highway Design, Maintenance, Enforcement, and Planning,* Wisconsin Department of Transportation, Lansing, WI, October, 1988

Table 2. Ranking of Candidate M.O.E.s

EVALUATION CRITERIA

CANDIDATE MEASURES	Practicality of Application	Measurement Reliability	Supports State-wide Random Sampling	Absence of Enforcement-induced Bias	Data Collection Methods Capability	Sensitivity to Infrastructure Damage	Applicability to Future Technology	TOTAL SCORE	FINAL RANKING
Excess ESALs	5	4	4	3	4	5	5	30	1
Severity of Overweight Violation	5	4	4	3	4	5	5	30	2
Equivalent Single Axle Load (ESAL)	5	4	4	3	4	4	5	29	3
Bridge Formula Violation	4	4	4	3	4	5	5	29	4
Proportion of Overweight Trucks	5	4	4	3	4	2	5	27	5
Distribution of Violation by day-of-week, hour-of-day	4	4	4	3	5	2	5	27	6
Projected Distance Traveled by Violator	3	2	2	2	2	2	4	17	7

Table 3. Designated Measures of Effectiveness (M.O.E.s)
and their Definitions

Truck Weight Enforcement M.O.E.	Definition
Gross Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal gross weight limit.
Gross Weight Violation, Severity	The extent to which average measured gross weights for the observed sub-sample of gross weight violators exceeds the legal gross weight limit.
Single-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more axles which exceeds the legal single-axle weight limit.
Single-axle Weight Violation, Severity	The extent to which average measured single-axle weights for the observed sub-sample of single-axle weight violators exceeds the applicable legal limit.
Tandem-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more tandems which exceeds the legal tandem-axle weight limit.
Tandem-axle Weight Violation, Severity	The extent to which average measured tandem-axle weights for the observed sub-sample of tandem-axle weight violators exceeds the applicable legal limit
Bridge Formula Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal Bridge Formula weight.
Bridge Formula Violation, Severity	The extent to which average measured Bridge Formula weights for the observed sub-sample of Bridge Formula violators exceeds the legal weight.
Excess ESALs, Proportion	The fraction (or percentage) of the total observed truck sample exhibiting Excess ESALs; i.e., ESALs attributable to the illegal portion the individual single or tandem axle group.
Excess ESALs, Severity	The average value of Excess ESALs observed for the truck sub-sample exhibiting Excess ESALs.

APPENDIX C

FIELD EVALUATION OF CANDIDATE MEASURES

Methodological Approach

The field study conducted during Task 5 of the NCHRP Project 20-34 efforts evaluated candidate M.O.E. sensitivity to actual truck weight enforcement operations. This study has defined weight enforcement M.O.E.s as..

> *"..determinable quantities of what is achieved as the result of truck weight enforcement activity. Their application also quantifies the contribution that activity makes toward achievement of one or more of the enforcement goals."*

The following M.O.E.s (See Table 1) were based on their suitability to demonstrate truck weight enforcement effects. These measures addressed legal load-limit compliance objectives of truck weight enforcement procedures as well as the potential for overweight trucks to produce pavement wear and tear.

Having developed a set of proposed truck weight enforcement M.O.E.s to be evaluated, specific methodological considerations were implemented with regard to the Task-5 evaluation study plan. In order to assess the M.O.E.s, it is essential to include three fundamental measures-evaluation related concepts: reliability, validity, and sensitivity. An understanding and application of these concepts are necessary for an M.O.E. assessment.

Reliability This concept addresses measurement repeatability, i.e., confidence that replicated applications will yield consistent results. In order that a measurement technique be

Table 1. Designated Measures of Effectiveness (M.O.E.s)
and their Definitions

Truck Weight Enforcement M.O.E.	**Definition**
Gross Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal gross weight limit.
Gross Weight Violation, Severity	The extent to which average measured gross weights for the observed sub-sample of gross weight violators exceeds the legal gross weight limit.
Single-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more axles which exceeds the legal single-axle weight limit.
Single-axle Weight Violation, Severity	The extent to which average measured single-axle weights for the observed sub-sample of single-axle weight violators exceeds the applicable legal limit.
Tandem-axle Weight Violation, Proportion	The fraction (or percentage) of the total observed truck sample with one or more tandems which exceeds the legal tandem-axle weight limit.
Tandem-axle Weight Violation, Severity	The extent to which average measured tandem-axle weights for the observed sub-sample of tandem-axle weight violators exceeds the applicable legal limit
Bridge Formula Violation, Proportion	The fraction (or percentage) of the total observed truck sample which exceeds the legal Bridge Formula weight.
Bridge Formula Violation, Severity	The extent to which average measured Bridge Formula weights for the observed sub-sample of Bridge Formula violators exceeds the legal weight.
Excess ESALs, Proportion	The fraction (or percentage) of the total observed truck sample exhibiting Excess ESALs; i.e., ESALs attributable to the illegal portion the individual single or tandem axie group.
Excess ESALs, Severity	The average value of Excess ESALs observed for the truck sub-sample exhibiting Excess ESALs.

dependable, it must be reliable. Reliability refers to the degree of stability exhibited when a measurement is repeated under identical conditions.

Concern for reliability comes from the necessity for dependability in measurement. Synonyms for reliability are: dependability, stability, consistency, predictability, accuracy. With regard to truck weight enforcement M.O.E.s, reliability is necessary for the uniform application of enforcement procedures across regions of the country or within a state.

In order to ensure the reliability of recommended M.O.E.s, the Task 5 evaluation uniformly applied the M.O.E. sensitivity analysis to WIM truck weight data collected in four states representing north, south, east, and western regions of the United States.

Validity The validity of a measure refers to the degree to which it actually measures what it is designed to measure. Validity is a complex subject, but it is particularly important in behavioral research. It is possible to study reliability without inquiring into the meaning of variables. It is not possible to study validity, however, without inquiring into the nature and meaning of one's variables.

The validity of the tested measures in this study was established based on their relevance to truck weight enforcement objectives, i.e., examine compliance with legal weight limits (e.g., axle, axle-grouping, and gross weights) and infrastructure considerations. Therefore, no further consideration was necessary to ensure validity in the field study.

Sensitivity A key element of the Task 5 Field Studies was to assess the sensitivity of candidate M.O.E.s to actual truck weight enforcement operations.

In behavioral studies, the concept of sensitivity is as follows. When an instrument, e.g., measure, is used to classify individuals as having or not having a specific attribute, the *sensitivity* of the measure is the proportion of correct results among people who actually have the attribute. That is, sensitivity is an indication that the applied measure produces a true indication of the sought attribute or condition. With regard to truck weight M.O.E.s, it was necessary to seek assurance that application of the M.O.E. provided a true indication of truck weight enforcement effects.

The sensitivity of the candidate M.O.E.s to actual truck weight enforcement activities was experimentally determined in this field study through the controlled (matched day-of-week, time-of-day, and seasonal) comparison of measures between "baseline", i.e., no enforcement activity, and "enforcement" conditions, i.e., on-going truck-weighing operations. Both permanent weigh scale operations and portable roadside truck weighing procedures were observed as enforcement conditions.

Results

Candidate M.O.E.s were evaluated in this field study on the basis of matched WIM data sets representing controlled enforcement and non-enforcement time periods. Data collection periods were controlled so as to avoid time-of-day, day-of-week, and seasonal confounding effects. Applied WIM data were gathered in California, Georgia, Idaho, and Minnesota. Enforcement procedures and results are discussed as follows for each of the four study states.

California M.O.E. validation results, based on field observations in California, are discussed in this section. The analyses compare WIM data collected during baseline (non-enforcement) and enforcement conditions.

The California Department of Transportation provided output from a WIM scale located approximately three miles north of the Santa Nella weigh scale on I-5. The data sample consisted of a 24-hour observation period containing 3,678 semi- and full-trailer truck combinations. The permanent truck-weight enforcement scale was open during the observation period for seven consecutive hours (4 a.m. to 11 a.m.). This data set afforded an adequate sample size of uniform truck weights (e.g., no day-of-week or seasonal effect contamination) to support a one-shot determination of enforcement effects.

The analysis depicted in Table 2 below is based on sample of 2,370 Type 9 (Tractor with semi-trailer) trucks. Given observed samples of 416 and 1,954 trucks, respectively, during the enforcement and baseline conditions, lower gross weights (i.e., 55,948 versus 59,547 pounds) were observed during times when the weigh station was open. A further examination of axle-specific weight differences between conditions revealed that rear-tandem weights were lighter during enforcement conditions. While lower average ESALs were observed during the enforcement period, the difference was not statistically significant. However, it is worth noting that while no trucks exhibiting Excess ESALs were observed during the period when the scale was open, a small (.36) Excess ESAL average was observed when the scale was closed.

Table 2. California Measures Sensitivity Experiment

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	5.9%	10.1%	No
Gross Weight Violation, Severity	2,567	2,266	No
Single-axle Weight Violation, Proportion	2.9%	3.1%	No
Single-axle Weight Violation, Severity	438	879	No
Tandem-axle Weight Violation, Proportion	6.8%	6.5%	No*
Tandem-axle Weight Violation, Severity	2,016	1,607	Yes
Bridge Formula Violation, Proportion	44.3%	40.2%	Yes
Bridge Formula Violation, Severity	7,400	9,780	No
Excess ESALs, Proportion	.1%	0	No*
Excess ESALs, Severity	.36	0	Yes

Note: Weight units are pounds

* = *Non-significant tendency*[1]

An examination of Type 9 truck weights exceeding 80,000 pounds revealed only slightly lower average gross weights (i.e., 82,266 versus 82,567 pounds) during periods

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[1] The designation, "Non-significant tendency", indicates a numerical difference which suggests a possible observed enforcement effect; however, the difference is not sufficiently strong to be statistically significant.

when the scale was open. The proportion of trucks exceeding 80,000 pounds was higher (i.e., 10.1 percent versus 5.9 percent) when the scale was open.

The presence of Bridge Formula violations was examined for both the baseline and enforcement conditions. A smaller proportion of the truck sample (i.e., 40.2 versus 44.3 percent) was seen to exhibit Bridge Formula violations during periods when the weigh scale was open implying a favorable enforcement effect. Nevertheless, the degree of violation was more severe (i.e., 9,780 versus 7,400 pounds) during this enforcement period.

An examination of single-axle violations first examined steering axle weights and compared these to the California legal limit of 12,500 pounds. During the baseline condition, 2.9 percent of the weighed steering axles exceeded the legal limit by an average of 438 pounds. During the enforcement period, 3.1 percent exceeded the limit by an increased average weight of 879 pounds. Second, an examination was conducted for individual axles throughout the tandems. During the baseline period, 1.2 percent exceeded the California legal limit by an average of 1, 279 pounds; and during the enforcement period, 4.8 percent exceeded the limit by an average of 1,664 pounds. Thus, no enforcement was observed with respect to single axle weights.

Tandem weight distributions were compared between baseline and enforcement conditions. A favorable enforcement effect was noted with regard to rear tandem violations. The severity of violation was significantly decreased (i.e., from 2,016 pounds to 1,607 pounds, and the proportion of violations fell slight from 6.8 percent to 6.5 percent during the enforcement period.

In addition, we applied one candidate measure that had been considered as an M.O.E., i.e., the 95th-percentile gross weight, to the data set. A slightly lower 95th-percentile, i.e., 80.1 kips versus 81.2 kips, was found for the "scale closed" truck sample. This difference was not statistically significant.

California M.O.E. Validation Summary The California Department of Transportation provided output from a WIM scale located on I-5. An analysis of 3,678 truck combinations exhibited lower gross weights with a smaller proportion of overweight axles during the time when the weigh station was open. Data on a sub-sample of 2,370 tractor-semi-trailer combinations was further analyzed to examine M.O.E. sensitivity to the enforcement activity. The results confirmed the following M.O.E.s: Tandem-axle Weight Violation Severity, Bridge Formula Violation Proportion, and Excess ESAL Severity.

Georgia Mobile truck-weight enforcement operations, utilizing an obtrusive portable roadside weigh scale, were conducted at two locations in Georgia: a rural arterial, State Route 300 in Crisp County; and a rural interstate, Interstate 20 in Taliferio County. WIM equipment problems, i.e., failure to generate data for a representative truck sample, precluded use of data gathered at the rural arterial location. Data gathered at the interstate location did produce a suitable vehicle sample; however, the WIM equipment proved to be "over-calibrated", i.e., generating higher than expected truck weights, thus requiring a "Quality-Control" analytic procedure. A brief explanation of the applied Quality Control procedure follows.

Chaparral Systems of Santa Fe, New Mexico has developed a software package to analyze 'raw' WIM data and apply a series of quality control corrections, e.g., factors to compensate for WIM-calibration error. The software examines truck weight distributions and notes distributional 'peaks' due to the presence of empty and loaded trucks in the traffic stream. The QC software then applies correction factors based on expected peaks for loaded and empty trucks. This public-domain software is ready available[2], and can be operated using Windows and SAS software.

Truck weight data collected on I-20 in Talifero County demonstrated problems due to apparent WIM equipment over-calibration. Therefore, two follow-on steps were taken

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[2] Interested users should contact Statistician, Cindy Cornell, at Chaparral Systems, 649 Harkle Road, Santa Fe, New Mexico 87501 .

with regard to the Georgia data. First, data files were supplied to Chaparral Systems so they could conduct a Quality Check analysis. Second, the M.O.E. sensitivity analysis was conducted with regard to the existing data to examine for enforcement effects. This analysis tested the sensitivity of 'uncorrected' data to enforcement effects. This step is important in the M.O.E. assessment process in order to address the requirement to preliminarily conduct quality control steps prior to applying any M.O.E. evaluation procedure.

The applied Quality Check (QC) analysis generated the plot, Figure 1on the next page, comparing baseline (06JUN95, broken line) with enforcement (13JUN95, solid line) conditions. It is important to note that plotted data have been corrected for the calibration error through the application of correction factors.

Results follow for M.O.E. computations based on data generated directly from the SHRP WIM equipment and not subjected to the QC analysis. We feel that it is important to examine calculations based on these data, as these are the form of data initially generated as the result of WIM data-collection procedures. Any M.O.E. analysis tool that can be validated with "raw" data will be more easily applied by states than if a QC analysis is necessary.

Analysis of uncorrected WIM data An analysis of "uncorrected" Georgia data, i.e., Quality Control correction factors were not applied, yielded a number of results which supported M.O.E. development. Although no promising difference was observed for average gross weight difference (e.g., gross weights exhibited a larger variance in the enforcement condition), lower rear tandem weights were evident during the enforcement period. The most significant M.O.E.-developmental effects were noted for the proportion of overweight trucks and associated axles. The proportion of overweight trucks was significantly lower (at the .05 significance level) during the enforcement period. This finding also held for the examination of compliance proportion associated with each axle comparison.

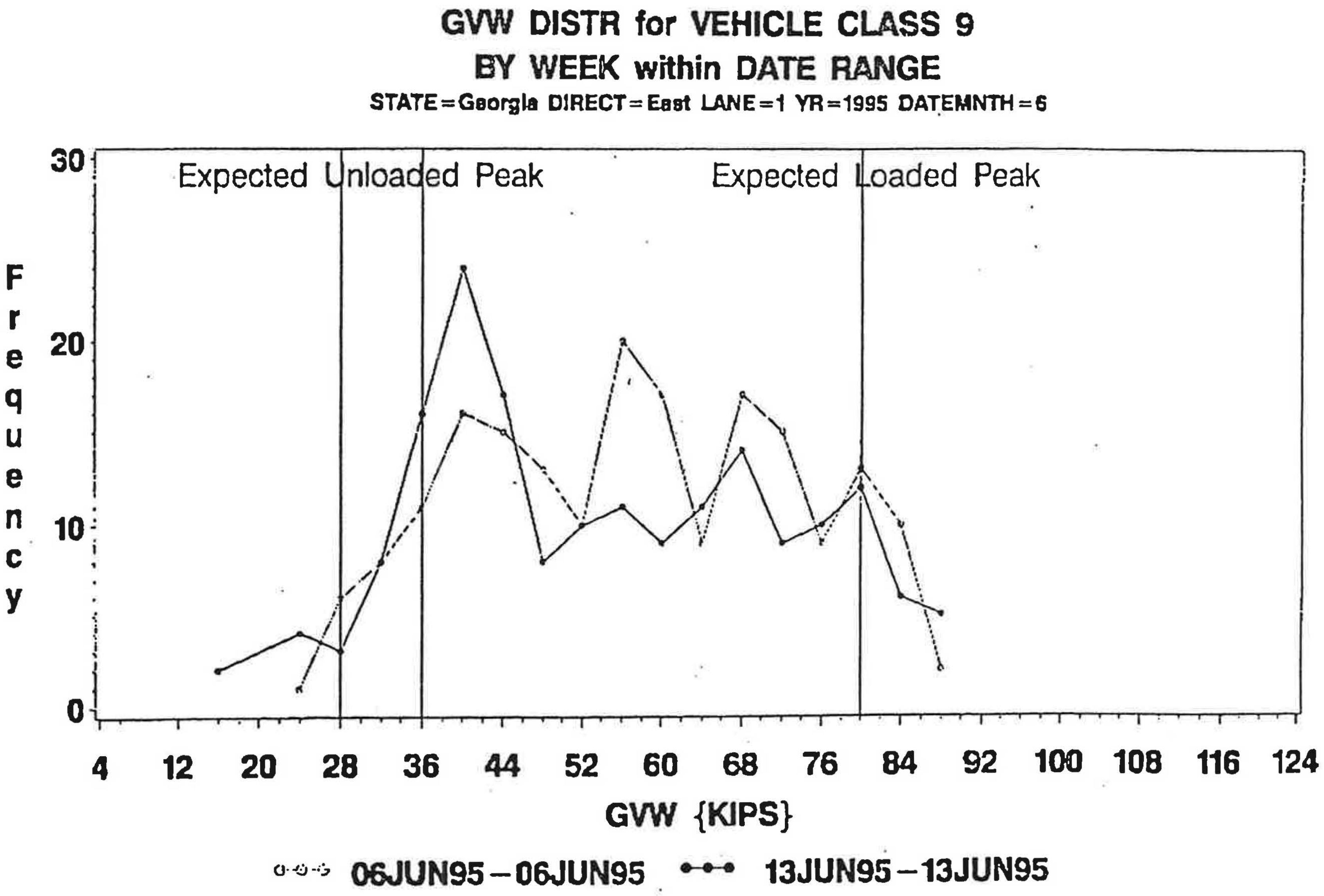

Figure 1. Plot of QC-corrected data versus uncorrected data.

Two critical M.O.E.s, the proportion of Single Trailer trucks exhibiting Excess ESALs (i.e., .72 and .67, respectfully, for the baseline and enforcement conditions) and the proportion of trucks exhibiting Bridge Formula violations (i.e., .69 and .63) did not differ between baseline and enforcement conditions.

Analysis of QC-corrected data Results of the M.O.E. Sensitivity Experiment data analysis based on data to which the Quality Control factor was applied are summarized in Table 3 below.

Table 3. Georgia Measures Sensitivity Experiment

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	6.1 %	6.7 %	No
Gross Weight Violation, Severity	2,370	4,709	No
Steering Axle Weight Violation, Proportion	9.4 %	7.5 %	Yes
Steering Axle Weight Violation, Severity	695	545	No*
Tandem Weight Violation, Proportion	5.4 %	3.7 %	Yes
Tandem Weight Violation, Severity	1,675	1,545	No*
Bridge Formula Violation, Proportion	1.0 %	3.8 %	No
Bridge Formula Violation, Severity	390	223	Yes
Excess ESALs, Proportion	9.4 %	8.8 %	No*
Excess ESALs, Severity	1.0	.65	Yes

Note: Weight units are pounds ** = Non-significant tendency*

Observed gross weight differences failed to provide M.O.E. field validation. More severe average gross weight violations (4,709 versus 2,370 pounds) were noted during the enforcement period. However, it is also noteworthy that proportions of trucks exhibiting gross weight violations did not significantly differ between enforcement and baseline conditions.

The analysis of specific axle and tandem weights revealed enforcement-effect differences as follows. An analysis of single axle weights indicated a reduction in steering- and rear- axle violations. For example, lower overall steering-axle weights were evident via a smaller proportion (7.5 versus 9.4 percent) of violations during the enforcement condition. Also, given the sample of trucks exhibiting steering axle violations, there was a statistically non-significant tendency toward less severe violations. While there was an observed tendency for lower tandem-axle violations during the enforcement period, the observed difference was not statistically significant.

Two additional M.O.E.s were validated on the basis of the field observations. First, less severe Bridge Formula violations were observed during the enforcement period. Second, while a non-significantly smaller percentage (8.8 versus 9.4) of Excess ESAL violations was observed during the enforcement period, the level of severity was reduced by a small (.65 versus 1.0 ESALs) but statistically significant level.

M.O.E. differences between QC-corrected and non-corrected data sets

The comparison between Georgia enforcement and baseline conditions involved two examining data sets, one on which WIM-calibration corrections (i.e., Quality Control or QC analyses) had been applied and another on which corrections had not been applied. This comparison was conducted to determine the suitability of non-corrected data sets for M.O.E. evaluation.

The QC-corrected set indicated significantly lower steering-axle weights during the enforcement condition, i.e., indicating a valid enforcement effect. This effect was not evident in the non-corrected data set. Other less consequential difference were as follows: the non-corrected data set indicated greater variability on steering-axle ESALs during the baseline condition, less variability on second-axle ESALs during the baseline condition, and greater variability in third tandem weights during the enforcement condition.

In general, the QC-corrected data set was more sensitive to ESAL variability differences between the baseline and enforcement conditions, and it detected lower third tandem weights during the enforcement condition. Moreover, the QC-corrected data set discerned Excess ESAL differences between baseline and enforcement conditions.

Agreement between the two data sets was noted with regard to certain M.O.E. differences, e.g., lower rear-axle weights during the enforcement condition. The most serious divergence in detected differences between the data sets related to a critical measure, total weight violation severity. The non-corrected data set failed to statistically distinguish between baseline and enforcement samples on the basis of this measure. The QC-corrected data set did discriminate between conditions, unfortunately noting larger gross weight violations during the enforcement period.

The foregoing analysis concludes that it is generally recommended to conduct a QC check of WIM databases prior to application of an M.O.E. evaluation. However, we must note that this finding is based on "poor case" scenario, i.e., the required correction factor was .5 due the over-calibration severity of the applicable WIM system. Obviously, data collected by a recently-calibrated WIM system does not require application of a QC check prior to an M.O.E. analysis.

It is also noteworthy that during the surprise enforcement period, a number of overweight trucks were observed to either park alongside the Interstate or divert to alternate routes. Alert enforcement personnel were able to administer citations to a number of drivers exhibiting this behavior.

Georgia M.O.E. Validation Summary Mobile truck-weight enforcement operations, utilizing an obtrusive portable roadside weigh scale, were conducted at a rural interstate location. An analysis of 483 combination trucks revealed a number of M.O.E. validation effects associated with observed axle and tandem weights. Under conditions of visible (and unexpected) mobile enforcement operations, the observed truck sample exhibited lower steering-axle weights, lower rear-axle weights, and lower rear-tandem weights. During the surprise enforcement operation, a number of overweight trucks were observed to either park alongside the roadway or divert to alternate routes. The results confirmed the following M.O.E.s: Single-axle Weight Violation Proportion, Tandem-axle Weight Violation, and Excess ESAL Severity.

Idaho A large volume of WIM data was provided by the Idaho Transportation Department. Data were collected at a WIM site located two miles north of the Cotteral Port of Entry, near milepost 232 on I-84, approximately 40 miles north of the Idaho-Utah border. WIM data represented traffic flow in both directions during 24-hour observation periods for approximately two weeks in March and April 1996. The available 29,000-truck database was divided into sub-samples in order to achieve necessary experimental control required to examine specific day-of-week effects and separate weekend from weekday violation trends.

Table 4 illustrates the enforcement schedule, i.e., days/hours of operation of the Port of Entry during dates for which data were supplied.

Data analysis periods were designated to permit observation of enforcement effects while controlling for time-of-day and day-of-week. Seasonal variation was not a consideration as all data were collected within a six-week time frame. The large amount of data provided by the Idaho Transportation Department supported a determination of enforcement effects for various times during the week. This consideration is important due to enforcement agencies' manpower-scheduling requirements. The data analysis below contains separate enforcement analyses for enforcement activity conducted on a Sunday, Tuesday, and Thursday.

Sunday enforcement effects A baseline condition, i.e., no enforcement, was established for data collected on Sunday, April 7, 1996 in the northbound direction. Data were compared for an enforcement condition in effect on March 3. On that date, the Port of Entry was operated during both the Day and Swing shifts, thus allowing data comparison for the corresponding period and traffic direction on April 7.

The applied database for this enforcement-effects comparison consisted of 393 trucks for the baseline condition and 957 trucks for the enforcement condition, which were observed during equal time periods. Due to the fact that the Measures Sensitivity analysis required a large sample of equivalent truck-loading axle-configuration characteristics, this

Table 4. Idaho Port of Entry Operation and WIM Data Collection Schedule

Idaho Transportation Dept.
Cotterel Port Of Entry
I-84 Milepost 232 40 miles North Of Idaho-Utah Border

March 1996

	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Descending (North Bound)	Swing Day	Day Swing	Day Swing	Day Swing	Day Swing	Swing Day	Swing Day	Swing Day	Swing Day	Day Swing	Day Swing	Day Swing	Swing Day	Swing Day
Ascending (South Bound)	Closed	Closed	Day	Day	Day	Day	Closed	Closed	Closed	Closed	Closed	Closed	Closed	Closed

D - Day Shift 6:00 AM to 4:00 PM
S - Swing Shift 3:30 to 1:30 AM

April 1996

	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Descending (North Bound)	Closed	Swing Day	Day Swing	Day Swing	Day Swing	Swing Day	Closed	Closed	Swing Day	Day Swing	Day Swing	Day Swing	Swing Day	Closed
Ascending (South Bound)	Closed	Closed	Swing	Swing	Swing	Closed	Closed	Closed	Closed	Swing	Swing	Swing	Closed	Closed

D - Day Shift 6:00 AM to 4:00 PM
S - Swing Shift 3:30 PM to 1:30 AM

analysis was conducted for Type 9 trucks, i.e., five-axle semi-trailer combinations. The baseline and enforcement condition samples consisted of 348 and 846 Type 9 trucks, respectively.

Table 5 summarizes results of the M.O.E. analysis for this experiment. A smaller percentage of the sample, 4.1 versus 11.2 percent, was observed to exceed the 80,000-pounds gross weight limit during the enforcement period. However, gross weight violation severity, average truck weights in excess of 80,000 pounds, was greater during the enforcement period. This effect may be due in part to the presence of permitted vehicles in excess of 80,000 pounds. Nevertheless, the enforcement sample demonstrated lower gross weights on average, i.e., 57,379 pounds versus 63,953 pounds, with the difference being distributed over all axles.

Table 5. Idaho Measures Sensitivity Experiment (Sunday Enforcement Effects)

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	11.2 %	4.1 %	Yes
Gross Weight Violation, Severity	3,744 lbs.	8,089 lbs.	No
Single-axle Weight Violation, Proportion	13.5 %	2.1 %	Yes
Single-axle Weight Violation, Severity	1,019 lbs.	2,306 lbs.	No
Tandem-axle Weight Violation, Proportion	7.2 %	3.8 %	Yes
Tandem-axle Weight Violation, Severity	1,767	2,534	No
Bridge Formula Violation, Proportion	2.8 %	2.5 %	No *
Bridge Formula Violation, Severity	3,512 lbs.	3.435 lbs.	No
Excess ESALs, Proportion	14.9 %	5.0 %	Yes
Excess ESALs, Severity	1.18	0.61	Yes

Note: Weight units are pounds ** = Non-significant tendency*

An examination of axle-specific violations revealed slightly reduced violation proportions for all axles during the enforcement condition. The largest violation reduction, from 13.5 to 2.1 percent, was observed for rear axles. However, the average severity of rear-axle violations increased from 1,019 pounds to 2,306 pounds during the enforcement period.

A number of tandem-weight differences were observed between the baseline and enforcement conditions. For example, lower average drive and rear tandem weights were observed during the enforcement condition. While average observed drive-tandem violations were greater during the enforcement period, this trend was not evident for rear tandems. However, significantly lower proportions of trucks with overweight tandems (drives and rear combined) were observed during the enforcement condition. Thus, the observed proportion of trucks with tandem violations was determined to be an enforcement-related M.O.E.

During the enforcement period, observed average ESALs per truck were significantly lower than those observed during the baseline condition. Also, lower average axle-specific ESALs were observed for the second through fifth axles.

A significantly smaller proportion of the truck sample (5.0 versus 14.9 percent) exhibited Excess ESALs during the enforcement period. Moreover, this sub-sample exhibited lower average Excess ESALs than were observed for the baseline condition.

Tuesday enforcement effects This data comparison is based on WIM data collected in the southbound direction on consecutive Tuesdays, i.e., March 5 and March 12.

A baseline condition, i.e., no enforcement, was established for data collected on Tuesday, March 12. Data were compared for an enforcement condition in effect on March 5. On that date, the Port of Entry was operated during the Day shift, thus allowing data comparison for the corresponding time period one week later. The database using for this enforcement-effects comparison consisted of 539 trucks for the baseline condition and 546 trucks for the enforcement condition. The analyzed baseline and enforcement condition samples consisted of 492 and 500 Type 9 trucks, respectively.

During the enforcement period, observed trucks did demonstrate significantly lower gross weights on average, i.e., 61,684 pounds versus 63,563 pounds. However, the sample proportion exceeding gross-weights of 80,000 remained essentially the same as during the baseline condition.

Table 6 summarizes results of the M.O.E. finding for this experiment. By comparison with the Sunday analysis, a lesser number of findings was available to support the development of truck weight enforcement M.O.E.s. as follows.

Table 6. Idaho Measures Sensitivity Experiment (Tuesday Enforcement Effects)

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	10.1 %	9.8 %	No *
Gross Weight Violation, Severity	2,262	2,240	No *
Single-axle Weight Violation, Proportion	9.4%	4.0%	Yes
Single-axle Weight Violation, Severity	9,324	7,896	No
Tandem-axle Weight Violation, Proportion	9.2 %	6.8%	Yes
Tandem-axle Weight Violation, Severity	2,622	2,699	No*
Bridge Formula Violation, Proportion	4.1 %	3.2 %	No*
Bridge Formula Violation, Severity	1,918	2,538	No
Excess ESALs, Proportion	12.6 %	12.2 %	No*
Excess ESALs, Severity	1.23	1.31	No

Note: Weight units are pounds ** = Non-significant tendency*

An examination of axle-specific violations revealed slightly reduced violation proportions for all axles during the enforcement condition. The largest violation reduction, from 9.4 to 4.0 percent, was observed for the forth axle (lead axle on rear tandem). However, the severity of axle violations increased during the enforcement period, averaging 9,324 pounds per axle as opposed to 7,896 pounds per axle in the baseline condition. A similar analysis of tandem-axle violations revealed reduced proportions of violators in the enforcement period, characterized by a reduction of rear tandem from 9.2 percent to 6.8 percent, and slightly increased average tandem violation severity during the enforcement period.

No significant differences were observed with regard to Excess ESAL or Bridge Formula violations.

Thursday enforcement effects This data comparison is based on WIM data collected in the southbound direction on consecutive Tuesdays, i.e., March 7 and March 14.

A baseline condition, i.e., no enforcement, was established for data collected on Tuesday, March 14. Data were compared for an enforcement condition in effect on March 7. On that date, the Port of Entry was operated during the Day shift, thus allowing data comparison for the corresponding time period one week later. The applied database for this enforcement effects comparison consisted of 474 trucks for the baseline condition and 512 trucks for the enforcement condition. The analyzed baseline and enforcement condition samples consisted of 439 and 473 Type 9 trucks, respectively.

Table 7 summarizes results of the M.O.E. finding for this experiment. A large number of the M.O.E.s were validated in this data set. During the enforcement period, a smaller percentage of trucks violated the 80,000-pound gross weigh limit; and given the sub-sample of violators, the severity of the violations was decreased.

Table 7. Idaho Measures Sensitivity Experiment (Thursday Enforcement Effects)

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	12.5 %	5.5 %	Yes
Gross Weight Violation, Severity	2,493	1,765	Yes
Single-axle Weight Violation, Proportion	10.3 %	5.0 %	Yes
Single-axle Weight Violation, Severity	6,874	5,188	Yes
Tandem-axle Weight Violation, Proportion	14.8 %	8.5 %	Yes
Tandem-axle Weight Violation, Severity	1,621	834	Yes
Bridge Formula Violation, Proportion	3.4 %	3.8 %	No
Bridge Formula Violation, Severity	1,854	3,361	No
Excess ESALs, Proportion	16.2 %	8.2 %	Yes
Excess ESALs, Severity	.42	.33	No*

Note: Weight units are pounds

* = *Non-significant tendency*

An examination of axle-specific violations revealed reduced violation proportions for all axles during the enforcement condition. The largest violation reduction, from 10.3 to 5.0 percent, was observed for the forth axle (lead axle on rear tandem). Moreover, the average severity of axle violations decreased during the enforcement period; i.e., from 5,188 pounds per axle, as opposed to 6,874 pounds per axle in the baseline condition.

This experiment produced M.O.E. validation with respect to the Excess ESAL measure. Lower average ESALs were observed for the enforcement truck sample and a smaller proportion of this sample exhibited Excess ESALs.

Idaho M.O.E. Validation Summary A large volume of WIM data, i.e., gathered on approximately 29,000 commercial vehicles, was provided by the Idaho Transportation Department. A comparison of baseline versus enforcement conditions during three different weekdays produced a number of significant findings. While no day-of-week effects were readily evident to indicate on which days enforcement effort would more likely be effective, all of the tested operational measures were shown to be sensitive to enforcement activity. M.O.E.s most consistently demonstrating sensitivity to enforcement activity were: (1) Gross Weight Violation Proportion, (2) Single-axle Weight Proportion, (3) Tandem-axle Weight Proportion, and (4) Excess ESAL Proportion. While less frequently associated with enforcement activity, the following measures were also validated in the Idaho data: (1) Gross Weight Violation Severity, (2) Single-axle Weight Violation Severity, (3) Tandem-axle Weight Violation Severity, and (4) Excess ESAL Severity.

Minnesota Data sets provided by the Minnesota Department of Transportation were applied in this measures sensitivity experiment. Bending plate WIM data were gathered approximately five miles from a permanent truck-weight enforcement scale during times when the scale was open and closed. Data collection periods were designated to conform to the weigh station-operating schedule. The weigh station is routinely closed one weekend per month, thus providing opportunity to obtain data sets for open versus closed periods while controlling for day-of-week and season of year effects.

During the research team's November 1995 meeting with Minnesota D.O.T. officials, we requested data sets representing designated study days during November, December, and January in order to support the Measures Sensitivity experimental design. However, November data were not provided due to problems with the WIM scale. Data collected over twelve days were provided for designated days in December 1995 and January 1996.

Due to truck shipping trends affected by the holidays, we were limited regarding the applicability of certain of the data sets. However, a number of non-confounded data comparisons were possible to support the Task 5 Measures Sensitivity experiments.

Two comparisons are discussed herein which compare candidate M.O.E.s between periods of enforcement versus non-enforcement. The first comparison, carefully controlling day-of-week effects, is based on data sets collected on consecutive Tuesdays. In general, no enforcement effect was found with regard to candidate M.O.E. differences. The second comparison based on consecutive business days of operation, contrasting on the last two days in 1995 with the first *business* day in 1996, thereby eliminating New Year's Day traffic, did reveal some differences. Each of these two comparisons is now separately discussed.

Consecutive-Tuesdays Comparison The first comparison was based on two samples of Type 9 (Five-axle, Semi-trailer combination) trucks. Data were controlled for both seasonal and day-of-week effects. Each data set was collected on a Tuesday during late December 1995 and early January 1996. The "Enforcement" condition, i.e., scale-open, sample contained 1,915 trucks, and the "Non-enforcement" condition, i.e. scale-closed, sample contained 1,357 trucks. Observed differences between the data sets did not reveal differences that support the operational validation of truck weight enforcement M.O.E.s. Table 8 summarizes the observed M.O.E. comparison between conditions.

Table 8. Minnesota Measures Sensitivity Experiment One

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	1.55 %	1.90 %	No
Gross Weight Violation, Severity	2,043	2,000	No*
Single-axle Weight Violation, Proportion	6.0 %	4.4 %	No
Single-axle Weight Violation, Severity	1,338	1,231	No*
Tandem-axle Weight Violation, Proportion	7.2 %	8.3 %	No
Tandem-axle Weight Violation, Severity	3,566	5,900	No
Bridge Formula Violation, Proportion	.15%	.36 %	No
Bridge Formula Violation, Severity	2,200	1,700	No*
Excess ESALs, Proportion	9.13%	10.70 %	No
Excess ESALs, Severity	.52	.55	No

Note: Weight units are pounds

* = *Non-significant tendency*

Truck weights were heavier on average, 48,228 pounds versus 46,166 pounds, with an insignificant increase, 1.90 versus 1.55 percent, in gross-weight overload violations during the enforcement period. The distribution of axle-specific overload violations was consistent with the noted gross-weight violation rate. A slight increase in average ESALs per truck, .99 versus .85, was noted during the enforcement period. The only observed difference, supportive of M.O.E. development was that larger Bridge Formula violations did occur during the non-enforcement period; however the sample sizes were too small to be statistically significant. Of the 1,915 trucks observed during the enforcement period, a single Bridge Formula violation, i.e., 1,700 pounds, was detected. Of the 1,357 trucks observed during the non-enforcement period, only two Bridge Formula violations, i.e., averaging 2,200 pounds, were detected.

An examination of axle-specific violations revealed non-significant differences with the exception of an increased proportion of Axle 3 (rear axle in drive tandem) of 6.0 versus 4.4 percent in the enforcement condition. The average severity of axle violations was slightly reduced, i.e., 12,306 versus 13,379 pounds during the enforcement period; however, this reduction was not statistically significant.

Slight but statistically non-significant increases in the proportion of overweight tandems were associated with enforcement activity. The most pronounced difference was seen for driver tandems, whereby the proportion of violators increased from 7.2 to 8.3 percent. The severity of the associated tandem violations increased from an average of 3,566 pounds during the baseline condition to 5,900 pounds during the enforcement period.

In addition to the 3,272 Type 9 (five-axle semi-trailer) trucks noted above, a similar analysis for 260 Type 10, 11, and 12 (multi-trailer) trucks revealed similar results. No differences were observed to support the development of M.O.E.s. Specifically, Bridge Formula violations noted for the Type 9's were not replicated. The likely explanation is that there were significantly fewer of the latter truck types observed.

In summary, this data set revealed no statistically significant truck weight effects to support M.O.E. validation.

Consecutive Business-days Comparison The second comparison revealed slightly more promising results in terms of establishing the applicability of candidate truck weight enforcement M.O.E.s. Based on two samples of Type 9 (Five-axle, Semi-trailer combination) trucks, data were controlled for seasonal effects due to the close time proximity between enforcement and non-enforcement conditions, i.e., this sample pair contrasted the last two days in 1995 with the first business day in 1996, again omitting New Year's Day. The enforcement sample contained 1,915 trucks, and the non-enforcement sample contained 1,671 trucks. Table 9 on the next page summarizes the observed M.O.E comparison between conditions.

Truck weights were marginally lower on average, 48,228 versus 50,646 during the enforcement period. During the enforcement period, the average overload violation was

Table 9. Minnesota Measures Sensitivity Experiment Two

CANDIDATE M.O.E.	Baseline Condition	Enforcement Condition	M.O.E. Validation
Gross Weight Violation, Proportion	4.19 %	1.90%	Yes
Gross Weight Violation, Severity	2,323	2,000	No*
Single-axle Weight Violation, Proportion	6.9 %	3.9 %	Yes
Single-axle Weight Violation, Severity	1,054	1,230	No
Tandem-axle Weight Violation, Proportion	11.6 %	8.3 %	Yes
Tandem-axle Weight Violation, Severity	1,311	1,314	No
Bridge Formula Violation, Proportion	0.21 %	0.43 %	No
Bridge Formula Violation, Severity	1,650	1,700	No
Excess ESALs, Proportion	11.4 %	10.7 %	No*
Excess ESALs, Severity	0.57	0.55	No*

Note: Weight units are pounds

* = *Non-significant tendency*

lower, i.e., 2,000 pounds compared with 2,323 pounds during the non-enforcement period; however this difference was not statistically significant. There was a significant decrease in the proportion (1.90 versus 4.19 percent) of gross-weight overload violations during the enforcement period. Also, a comparison of axle-specific violations revealed a greater proportion of overloads on the steering and last axles during the period of non-enforcement.

Decreased average ESALs were observed during the enforcement period; however, axle-specific analyses demonstrated that the decrease could not be associated with specific axles. The proportion of trucks exhibiting Excess ESALs, and their associated severity, while exhibiting tendencies to demonstrate valid enforcement effects, did not significantly differ between the enforcement and non-enforcement conditions.

Generally smaller proportions of single-axle violations were observed during the enforcement condition, with the most pronounced difference being a reduction from 6.9 to 3.9 percent for the forth axle. Very small differences (1,054 versus 1,230 pounds) in the severity of average axle violations were observed between the baseline and enforcement conditions.

Smaller proportions of tandem violations were observed during the enforcement condition, with the most pronounced difference being a reduction from 11.6 to 8.3 percent for the drive tandem. No statistical effect was associated with severity of the tandem violations, as nearly identical average tandem violations (1,311 and 1,314 pounds) were observed between baseline and enforcement conditions.

A very small number of Type 9 trucks were observed to exhibit Bridge Formula violations. Four (of 1,915 trucks) during the enforcement condition and seven (of 1,617 trucks) during the non-enforcement condition were in violation. The level of observed violation, i.e. 1,700 and 1,650 pounds was also quite small. These violations did not statistically differ between the enforcement and non-enforcement conditions.

In summary, this data set revealed a few truck weight effects (i.e., a lower proportion of overweight trucks and lower average ESALs) which support the M.O.E. validation effort.

Minnesota M.O.E. Validation Summary Data sets representing two weeks of continuous traffic monitoring were provided by the Minnesota Department of Transportation. Bending-plate WIM data were gathered approximately five miles from a permanent truck-weight enforcement scale during times when the scale was both open and closed. While generally weak M.O.E. validation findings were seen in Minnesota results, one data set did exhibit a smaller proportion of gross weight and tandem axle violations along with a tendency for less severe excess ESALs, and the other set produced a tendency to lower Bridge Formula violations. The results confirmed the following M.O.E.s: (1) Gross Weight Violation Proportion, and (2) Tandem-axle Violation Proportion.

Summary of Measures-Sensitivity Field Validation Study Candidate M.O.E.s were developed during the course of NCHRP Project 20-34 based on their suitability to demonstrate truck weight enforcement effects: Proportion and Severity of Gross Weight Violations, Proportion and Severity of Single-axle Weight Violations, Proportion and

Severity of Tandem-axle Weight Violations, Proportion and Severity of Bridge Formula Violations, and Proportion and Severity of Excess ESAL Violations. These measures addressed legal load-limit compliance objectives of truck weight enforcement procedures as well as the potential for overweight trucks to produce pavement wear and tear. However, a field study was necessary to examine the sensitivity of these measures to actual field truck weight enforcement operations.

This four-state effort examined WIM data gathered in the presence of enforcement activities and compared it with data collected under non-enforcement affected flow conditions. Data collection periods controlled for day-of-week, time-of-day, and seasonal effects. Findings for each state are summarized as follows.

California The California Department of Transportation provided output from a WIM scale located on I-5. An analysis of 3,678 truck combinations exhibited lower gross weights with a smaller proportion of overweight axles during the time when the weigh station was open. Data on a sub-sample of 2,370 tractor-semi-trailer combinations was further analyzed to examine M.O.E. sensitivity to the enforcement activity. The results confirmed the following M.O.E.s: Tandem-axle Weight Violation Severity, Bridge Formula Violation Proportion, and Excess ESAL Severity.

Georgia Mobile truck-weight enforcement operations, utilizing an obtrusive portable roadside weigh scale, were conducted at a rural interstate location. An analysis of 483 combination trucks revealed a number of M.O.E. validation effects associated with observed axle and tandem weights. Under conditions of visible (and unexpected) mobile enforcement operations, the observed truck sample exhibited lower steering-axle weights, lower rear-axle weights, and lower rear-tandem weights. During the surprise enforcement operation, a number of overweight trucks were observed to either park alongside the roadway or divert to alternate routes. The results confirmed the following M.O.E.s: Single-axle Weight Violation Proportion, Tandem-axle Weight Violation, and Excess ESAL Severity.

Idaho A large volume of WIM data, i.e., gathered on approximately 29,000 commercial vehicles, was provided by the Idaho Transportation Department. A comparison of baseline versus enforcement conditions during three different weekdays produced a number of significant findings. While no day-of-week effects were readily evident to indicate on which days enforcement effort would more likely be effective, all of the tested operational measures were shown to be sensitive to enforcement activity. M.O.E.s most consistently demonstrating sensitivity to enforcement activity were: (1) Gross Weight Violation Proportion, (2) Single-axle Weight Proportion, (3) Tandem-axle Weight Proportion, and (4) Excess ESAL Proportion. While less frequently associated with enforcement activity, the following measures were also validated in the Idaho data: (1) Gross Weight Violation Severity, (2) Single-axle Weight Violation Severity, (3) Tandem-axle Weight Violation Severity, and (4) Excess ESAL Severity.

Minnesota Data sets representing two weeks of continuous traffic monitoring were provided by the Minnesota Department of Transportation. Bending-plate WIM data were gathered approximately five miles from a permanent truck-weight enforcement scale during times when the scale was both open and closed. While generally weak M.O.E. validation findings were seen in Minnesota results, one data set did exhibit a smaller proportion of gross weight and tandem axle violations along with a tendency for less severe excess ESALs, and the other set produced a tendency to lower Bridge Formula violations. The results confirmed the following M.O.E.s: (1) Gross Weight Violation Proportion, and (2) Tandem-axle Violation Proportion.

Overview A large number of factors were seen to affect M.O.E. sensitivity to enforcement procedures, including actual truck weight/configuration characteristics, shipping commodity demands, observed truck sample size, and WIM equipment variables. Table 10 on the next page summarizes which M.O.E.s were shown to be sensitive to actual truck weight enforcement actives in each of the states. It is highly evident that all M.O.E.s will not discriminate between enforcement conditions at every site.

Table 11. Measure Sensitivity Summary by State

CANDIDATE M.O.E.	CA	GA	ID	MN
Gross Weight Violation, Proportion	❽		❽	
Gross Weight Violation, Severity	☠		❽	❽
Single-axle Weight Violation, Proportion		❽	❽	
Single-axle Weight Violation, Severity			❽	☠
Tandem-axle Weight Violation, Proportion		☠	❽	
Tandem-axle Weight Violation, Severity	❽		❽	
Bridge Formula Violation, Proportion	❽	☠	☠	
Bridge Formula Violation, Severity		❽		☠
Excess ESALs, Proportion	❽	☠	❽	
Excess ESALs, Severity	❽	❽	❽	

Legend: ❽ *= Significant effect*; ☠ *= Non-significant tendency*

APPENDIX **D**

ANCILLARY ISSUES

A number of ancillary issues affecting truck weight enforcement were investigated. First, a field study addressed the issue of overweight-truck weigh-scale diversion via usage of bypass routes. The applied methodology was to collect portable WIM scale data on bypass routes and compare these data with main line WIM data. Second, implications for permitted overloads, with regard to their potential to confound M.O.E. application, were studied via a literature review and highway agency surveys to examine state-of-the-art permit record systems.

TRUCK SCALE DIVERSION STUDY

Methodological Approach

The applied study procedure was to measure truck diversion patterns on potential bypass routes (as suggested by local officials) which circumvent operational permanent weigh scales. The experimental design was twofold: first, to detect truck diversion tendencies by day-of-week and hour-of-day; and second, to examine the magnitude of truck overload variation as a function of main line enforcement activity. Portable WIM scales were deployed on potential scale bypass routes during periods when permanent main line scales were open and closed. The applied data analysis addressed day-of-week and time-of-day patterns for potential overweight violations on bypass routes.

Results

Results are separately discussed for field studies conducted in California and Florida.

California The selected permanent weigh scale is located in northern California on Interstate 5, north of the Santa Nella Village interchange. The diversion route circumventing the weigh station is indicated on the map shown (See Figure 1) on the next page.

Data were collected using portable IRD WIM equipment deployed by a field data collection team from Texas A&M University. Data were collected on the scale bypass route from October 2 to October 10, 1995 allowing for seven consecutive business days of observations. No weekend data were collected due the fact that main line enforcement stations were closed on weekends, hence truck scale diversion ceased to be an issue during those periods.

Table 1 on page 4 summarizes portable WIM data output obtained on the bypass route. The table indicates truck sample sizes, average truck weights, and average axle-weights. The proportion of overweight trucks and overweight axles are then listed by truck type. The "Average ESALs" row lists average of total truck-specific ESALs (summed over all axles). "Excess ESALs" are then computed as the excess over the legal limit for each truck type. The table concludes with average observed Excess ESALs for violators, the proportion of violators for trucks exhibiting Excess ESALs and Bridge Formula violations. The table contains separate data summaries for FHWA Vehicle Class trucks, defined as follows:

Type 9 Five-Axle Single Trailer Trucks
Type 11 Five or Less Axle Multi-Trailer Trucks

A comparison between California main line and diversion route WIM data indicated insignificant differences in terms of observed average gross weights, including the proportion of overweight trucks. However, trucks on the bypass route exhibited higher average ESALs and Excess ESALs. It follows that a larger proportion of trucks on the diversion route was seen to exhibit higher Excess ESALs. These findings were consistent with bypass route overweight trends observed in subsequently discussed Florida data.

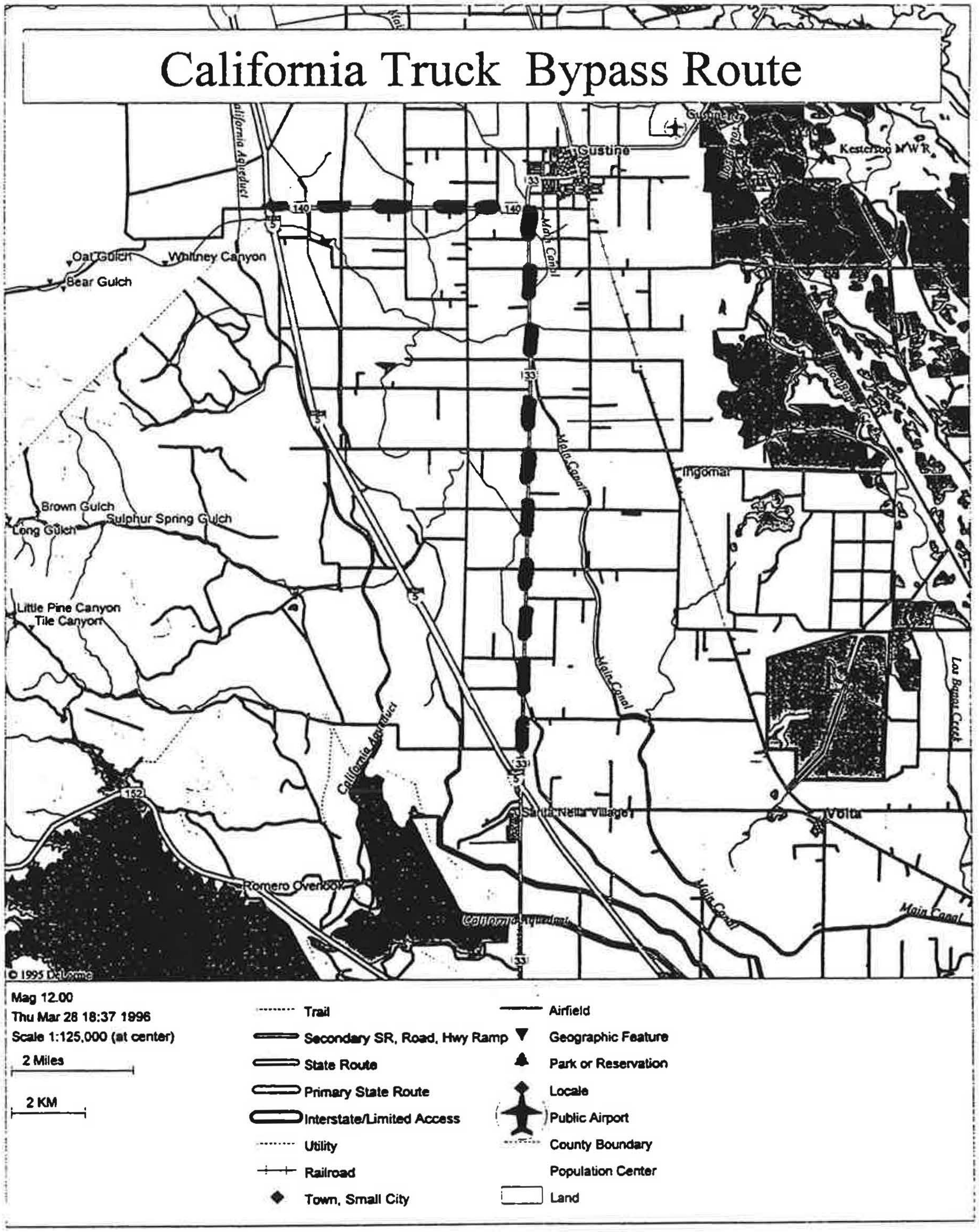

Figure 1. Map showing California Truck Scale Bypass Route

The data analysis also addressed Excess ESAL observation patterns by time-of-day and day-of-week. Table 2 on page 5 lists Excess ESAL violations on the bypass route by day-of-week and hour-of-day. Comparison of these data with hours of operation for the Santa Nella main-line weigh scale indicated that 70 percent of the Excess ESAL violations occurred during hours of main line scale operation, thus confirming the presence of scale diversion behavior. The observed average Excess ESAL level during hours of main line scale operation was 1.55, by comparison with 2.01 Excess ESALs when the scales were closed. However, this observed level of Excess ESAL violation between periods of scale operation and closure is not significantly different.

Table 1. Summary of Portable WIM Data on California Diversion Route

	Type 9	Type 11
Sample Size	236	484
Average Gross Weight	55,854	51,849
Average Axle 1 Weight	9,405	8,598
Average Axle 2 Weight	12,933	14,128
Average Axle 3 Weight	12,087	10,235
Average Axle 4 Weight	11,295	9,787
Average Axle 5 Weight	11,140	10,034
Proportion Overweight Trucks	.05	.05
Axle 1 Proportion Overweight	.09	.03
Axle 2 Proportion Overweight	.09	.22
Axle 3 Proportion Overweight	.04	.05
Axle 4 Proportion Overweight	.04	.02
Axle 5 Proportion Overweight	.05	.02
Average ESALs	1.4	1.3
Average Excess ESALs	1.9	1.6
Proportion Exceeding ESALs	.07	.08
Bridge Formula Violation Rate	.025	.004

The majority of overweight violations occurred during the early morning hours, i.e., between 3 a.m. and 8 a.m., with the highest single-hour violation occurrence between 6 a.m. and 7 a.m. Unlike the violation trend observed at the Florida bypass, there was no clear

Date	Day	Hour	Excess ESALs
10/2/95	Monday	18	1.8
10/3/95	Tuesday	1	2.2
10/3/95		2	2.4
10/3/95		3	0.5
10/3/95		4	0.4
10/3/95		4	3.7
10/3/95		5	1.3
10/3/95		5	1.5
10/3/95		5	4.1
10/3/95		6	0.3
10/3/95		6	0.8
10/3/95		6	0.9
10/3/95		6	1.3
10/3/95		8	6.4
10/3/95		9	1.9
10/3/95		10	0.4
10/3/95		10	0.6
10/3/95		18	1.8
10/3/95		18	2.0
10/3/95		18	2.9
10/4/95	Wednesday	15	1.0
10/4/95		21	5.5
10/4/95		23	3.3
10/5/95	Thursday	0	1.8
10/5/95		1	1.1
10/5/95		1	5.3
10/5/95		5	0.9
10/5/95		5	1.2
10/5/95		5	4.7
10/5/95		6	2.9
10/5/95		7	0.2
10/5/95		8	2.1
10/5/95		8	3.4
10/5/95		8	2.0
10/5/95		8	0.1
10/6/95	Friday	3	2.9
10/6/95		8	2.0
10/6/95		9	2.1
10/6/95		10	2.8
10/6/95		10	0.9
10/6/95		11	0.8
10/6/95		21	0.1
10/6/95		23	0.9
10/10/95	Tuesday	0	0.1
10/10/95		0	1.0
10/10/95		6	1.1
10/10/95		7	0.5

Excess ESAL Violations on California By-pass Route
Type 9 and 11 Trucks

Table 2. Excess ESAL Violations on California Bypass Route

majority of violations occurring during daylight hours. An analysis of Excess ESAL violations by severity revealed no additional hour-of-day or day-of-week trends, other than being more likely to occur during hours of main line weigh scale operation.

Florida The selected permanent weigh scale is located in northern Florida on U.S. Route 1, approximately 1.7 miles south of the Georgia State line. The diversion route circumventing the weigh station is indicated on the map (See Figure 2) shown on the following page.

Data were collected using portable IRD WIM equipment by a field team from Texas A&M University. The intended data collection plan involved concurrent data collection (using separate WIM units) over a week-long period. Unfortunately, problems with the WIM devices precluded concurrent data collection activity; so the overall data collection was extended to somewhat compensate for this problem.

Data were collected on the scale bypass route from 5 p.m., July 14, 1995 to 11 a.m., July 19, allowing for 5 1/2 consecutive days of observations. Five consecutive business days of data were collected on the main line between 5:00 p.m., July 8 and 5:00 p.m., July 12, 1995. During this period data were gathered on 1,789 main line trucks, while the bypass route truck volume was extremely sparse, i.e., 63 trucks.

Table 2 summarizes output generated from WIM output and subsequent analysis. Due to the fact that the vast majority of observed trucks were Type 9, tractor with semi-trailer, the table output is restricted to Type 9 trucks. The table indicates truck sample sizes, average truck weights, and average axle-weights. The proportion of overweight trucks and overweight weight axles are then listed by truck type. The "Average ESALs" row lists average of total truck-specific ESALs (summed over all axles). "Excess ESALs" are then computed as the excess over the legal limit for each truck type. The table concludes with average observed Excess ESALs for violators, the proportion of violators for trucks exhibiting Excess ESALs and Bridge Formula violations.

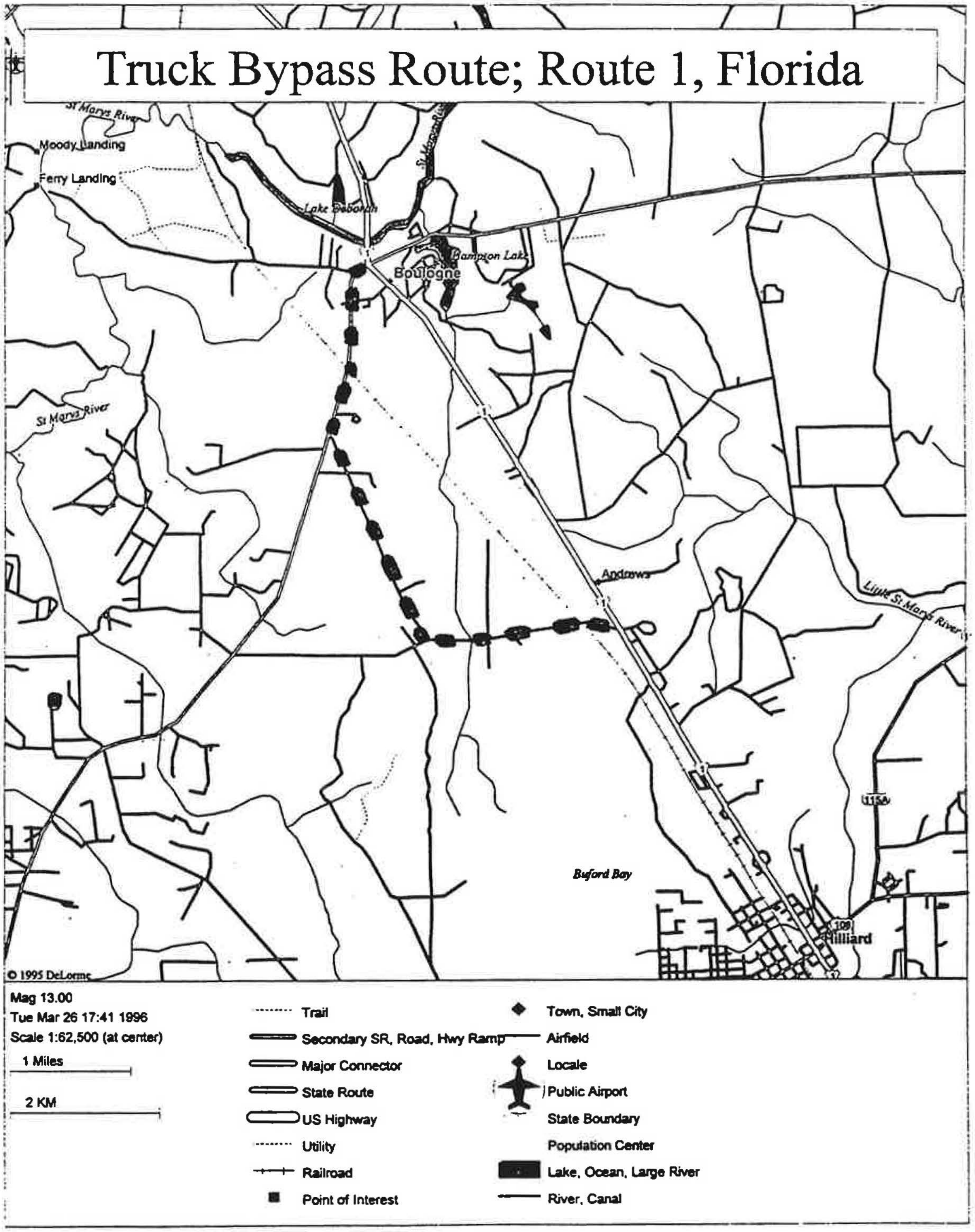

Figure 2. Map Showing Florida Truck Scale Bypass Route

Table 3. Summary of Portable WIM Data on Florida Main Line and Diversion Routes

	Main Line	Bypass
Sample Size	1,161	63
Average Gross Weight	61,933	63,691
Average Axle 1 Weight	9,546	9,297
Average Axle 2 Weight	14, 080	13,690
Average Axle 3 Weight	13,785	12,723
Average Axle 4 Weight	12,062	12, 938
Average Axle 5 Weight	12,400	13,377
Proportion Overweight Trucks	.15	.26
Axle 1 Proportion Overweight	.09	.13
Axle 2 Proportion Overweight	.18	.21
Axle 3 Proportion Overweight	.17	.19
Axle 4 Proportion Overweight	.09	.22
Axle 5 Proportion Overweight	.14	.32
Average ESALs	2.89	11.8
Average Excess ESALs	2.78	12.5
Proportion Exceeding ESALs	.19	.73
Bridge Formula Violation Rate	.045	.048

The reader may conclude, based on a close examination of the above table, that truck weights on both the main line and bypass routes seem a little heavier than expected. While the WIM devices were calibrated by the Texas A&M data collection team at the Florida site, a question does remain regarding the precision of the observed weights. We would note, however, that this problem is inconsequential for the purpose of the ensuing analysis in that the M.O.E. applicability evaluation is based on between-location differences. Therefore, any calibration-error effect would be offset, due to the fact that the same WIM device was used at both the main line and bypass locations.

Trucks traveling the bypass route were only slightly heavier on average, i.e., 63,691 pounds versus 61,933 pounds, than those on the main line. However, a statistically significant increase, i.e., 25.8 versus 15.1 percent[1], was observed in the proportion of gross-weight

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[1] This higher-than-expected range is likely due to the calibration of the TTI WIM equipment.

overload violations on the diversion route. The distribution of axle-specific bypass-route overload violations revealed that overweight violations occurred on the trailer axles.

While fewer trucks were observed to violate the gross weight limit on the main line route, those trucks which violated this limit tended to do so by a greater margin; e.g., the average violation severity being 7,739 pounds versus 4,056 pounds on the bypass route. This observed effect is likely due to the larger main line truck volume. Heaviest main line axle-specific violations were on the lead drive axle.

The most significant difference between truck samples observed on the main line and bypass routes was the high level of exhibited ESALs. Average ESALs were 11.8 for trucks on the bypass route, by comparison with 2.9 ESALs on the main line route. Accordingly, the level of excess ESALs was higher, i.e., 12.5 versus 2.8, for trucks on the bypass route.

Relatively few trucks were observed to violate Bridge Formula criteria on either the main line or bypass routes. While 73 of 1,661 trucks were observed to violate the Bridge Formula on the main line, only one Bridge Formula violation was observed on the bypass route. Due to this small sample, the observed difference is not statistically significant.

A primary objective of the Truck Diversion study was to examine truck violation patterns by time-of-day and day-of-week. Table 4 on the next page lists Excess ESAL violations on the bypass route by day-of-week and hour-of-day. The clear majority of the violations occurred on weekdays. The majority (approximately 60 percent) of the violations was generally seen to occur during daylight hours, e.g., between 7 a.m. and 5 p.m. Approximately 40 percent of the violations were observed between 11 p.m. and 6 a.m. No excess ESAL violations were observed between the hours of 6 p.m. and 11 p.m. The heaviest violations were generally seen to occur during the early morning hours, e.g., 6 a.m. to 9 a.m.

Date	Day	Hour	Excess ESALs
7/14/95	Friday	17	8.8
7/14/95	Friday	21	1.3
7/14/95	Friday	22	2.4
7/15/95	Saturday	1	15.2
7/15/95	Saturday	5	0.5
7/15/95	Saturday	7	2.7
7/15/95	Saturday	9	24.2
7/15/95	Saturday	22	0.2
7/16/95	Sunday	23	16.4
7/17/95	Monday	1	23.9
7/17/95	Monday	8	15.2
7/17/95	Monday	12	15.3
7/17/95	Monday	15	17.4
7/17/95	Monday	15	4.3
7/17/95	Monday	16	16.9
7/17/95	Monday	17	13.4
7/17/95	Monday	17	9.1
7/17/95	Monday	17	14.6
7/17/95	Monday	23	12.5
7/18/95	Tuesday	3	16.1
7/18/95	Tuesday	3	2.7
7/18/95	Tuesday	6	17.2
7/18/95	Tuesday	7	18.9
7/18/95	Tuesday	9	17.6
7/18/95	Tuesday	13	8.9
7/18/95	Tuesday	16	2.4
7/18/95	Tuesday	16	14.1
7/18/95	Tuesday	16	6.4
7/18/95	Tuesday	17	6.5
7/18/95	Tuesday	17	9.2
7/18/95	Tuesday	21	4.0
7/18/95	Tuesday	23	0.5
7/19/95	Wednesday	1	6.7
7/19/95	Wednesday	3	22.8
7/19/95	Wednesday	4	15.4
7/19/95	Wednesday	6	21.4
7/19/95	Wednesday	7	18.6
7/19/95	Wednesday	7	17.7
7/19/95	Wednesday	7	23.1
7/19/95	Wednesday	7	26.4
7/19/95	Wednesday	11	5.3
7/19/95	Wednesday	11	6.4

Excess ESAL Violations on Florida By-pass Route

Table 4. Excess ESAL Violations on Florida Truck Scale Bypass Route

Truck Diversion Study Summary

This study examined truck-weight and travel trends on potential bypass routes that circumvented permanent weigh scales. WIM data were collected on both the main line and truck bypass routes in California and Florida. Similar truck overweight trends were observed in both states. Customary truck weight distributions, determined by average gross and axle weights, did not statistically differ between bypass and main line routes. However, trucks samples observed to use bypass routes were consistently more likely to exhibit higher average ESALs and Excess ESALs. Similar travel time trends were observed between the two states; despite differing hours of main-line permanent scale operation. In Florida, in the presence of 24-hour and 7-day per week scale operation, the majority of overweight diversion activity occurred during the early morning hours, e.g., 6 a.m. to 9 a.m. In California, while time-of-day diversion travel was affected by permanent scale operation, a tendency was observed for early morning scale diversion, e.g., 3 a.m. to 8 a.m.

IMPLICATIONS FOR PERMIT-ISSUED OVERWEIGHT TRUCKS

The obviously inherent confounding factor in a WIM-based truck-weight-enforcement surveillance procedure is the absence of an accounting for permitted overweight trucks. The general practice with regard to permitted overloads is to issue permits for the transport of nondivisible loads that exceed allowable weight limits. Single-trip permits cover either a one-way or round trip and may be valid for periods of two to 30 days. Some states issue multiple-trip permits covering periods of a few weeks up to three years. The permit issuance process ensures that routes used for these movements can accommodate them. Additionally, in some instances, states exercise grandfather legislative authority to issue divisible load permits for Interstate highway operation. This concession accommodates industry deemed critical to the state's economy, such as agriculture and forestry activity.

This problem was investigated from two perspectives during the course of the current project. First, interviews were conducted with a number of state highway agencies to investigate the feasibility of integrating state-of-the-art automated Overweight Vehicle

Permit Record System data into an automated truck weight records database to correct for the presence of permitted vehicles. The second step, a literature review attempt to investigate possible weight-distribution effects of permitted vehicles, was initiated as the result of state agency interview findings.

State Highway Agency Permits Record Systems

Truck overweight permit record-keeping practices were addressed with state highway agency officials in Ohio and Texas, in addition to officials of participating field study states. With a single exception, record-keeping systems for interviewed states did not provide adequate specificity to allow matching of permit-issuance data with WIM records.

The Texas Department of Transportation (TxDOT) operates a sophisticated, automated permitted load record-keeping system. Permit applicants call a toll-free number to operators equipped with highway network mapping workstations. The operator maps out the authorized route and travel dates that are automatically input to the automated record system. Thus, the permitted truck's authorized load and route are computerized prior to initiation of the trip.

With the TxDOT system, virtually every permitted load is tracked over 77,000 miles of automated routing with sufficient precision to determine the presence of overweight vehicles on specific routes within a 24- to 48-hour time window depending upon the length of trip. That is, truckers complete travel within a 24-hour time window for short trips. For trips across the state, a 3-day operation period is allowed; however, given the length of this trip, a trucker's presence can be estimated within a 48-hour time window. Automated truck route and weight data are uploaded to enforcement agency computers on a daily basis.

During the course of this project, the Principal Investigator met with the Director of the TxDOT Central Permits Office[2] confirming the TxDOT system's applicability in the evaluation of truck weight enforcement activities. Although the TxDOT system is unique, Mr. Lundell did offer to supply interested state agencies with the TxDOT software in order to allow their tracking of permitted overweight vehicles.

Possible WIM Data Confounding Due to Permit-Issued Overloads

A literature survey was attempted to gather insight regarding the possible weight-data confounding effect associated with permitted overweight truck presence in a traffic stream. A number of relevant literature items were cited. Two mathematical modeling efforts were cited which predicted truck weight distributions as a function of a variety of influencing factors (Fekpe and Clayton, 1995; and Clayton and Thom, 1991). These research projects confirmed the obvious. Permitted overloads do confound truck weight distributions by violating weight limit applied compliance constraints in the modeling processes.

However, a field study (Middleton et al., 1988), addressing overload permit issuance versus actual traffic stream observation did provide significant insight regarding the extent of this confounding effect. The study compared traffic flow observations with permit oversize/overweight records. Table 5 on the next page indicates that actual permitted loads in the traffic stream did not account for a significant proportion (between 42 and 57 percent) of illegal truck operations. The direct inference of this finding is that field observation techniques, in the absence of permitted overload records, provide a valid indication of violation occurrence.

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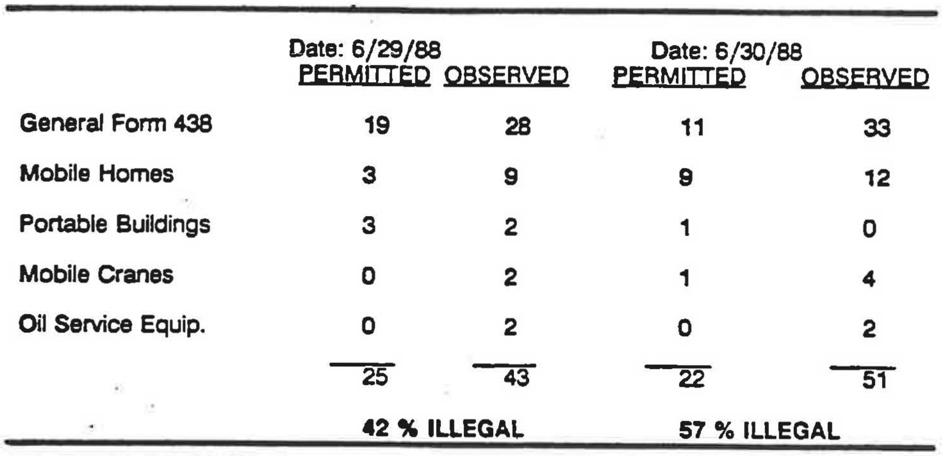
[2] Mr. Bert Ludell, Director, Central Permits Office, Texas Department of Transportation, 125 E. 11th Street, Austin, TX 78701-2483; Phone 512-465-3570

Table 5. Observed Truck Types Which Warrant Permits



	Date: 6/29/88		Date: 6/30/88	
	PERMITTED	OBSERVED	PERMITTED	OBSERVED
General Form 438	19	28	11	33
Mobile Homes	3	9	9	12
Portable Buildings	3	2	1	0
Mobile Cranes	0	2	1	4
Oil Service Equip.	0	2	0	2
	25	43	22	51
	42 % ILLEGAL		57 % ILLEGAL	

Source Middleton, et al. (1988):

Conclusions Regarding Permit-Issued Truck Presence

While the presence of permitted overweight trucks in the traffic stream can not be detected by WIM systems, the distinct possibility exists for its confounding the recorded traffic stream compliance with legal weight limits. However, the literature has demonstrated that traffic observations provide a valid indication of violations in the absence of permitted truck flow data. A further consideration is that enforcement effectiveness studies, whereby "before" and "after" periods are taken in close time proximity (so as to avoid seasonal influences), may logically be void of confounding permitted vehicle influences. These effects may tend to be "washed out" by the similar presence of permitted trucks in the "before" and "after" study conditions.

A state-of-the-art solution does exist to integrate automated permitted overweight vehicle data into WIM databases applied to evaluate truck weight enforcement. The automated system applied by TxDOT is available to interested state agencies as the result of the TxDOT offer to share its software. However, due to the expense of associated hardware and operational costs, this solution is not currently applicable to WIM-based truck weight surveillance for enforcement purposes.

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APPENDIX **E**

EFFECTS OF AXLE WEIGHT ENFORCEMENT ON PAVEMENT LIFE[1]

1.0 INTRODUCTION

One of the basic premises of truck weight enforcement is that there will be a net increase in pavement life (reduction in the rate of pavement deterioration). The following discussion summarizes two methods of determining the increase in pavement life one could expect from reduced axle loadings accrued through enforcement activities. The methods makes use of an AASHTO design procedure (1) providing for the traffic input to design to be in terms of accumulated (or projected) 18,000 lb. equivalent single axle loads (ESALs).

In their approach, AASHTO uses the definition: "Load equivalency factors represent the ratio of the number of repetitions of any axle load and axle configuration (single, tandem, tridem) necessary to cause the same reduction in Present Serviceability Index (PSI) as one application of an 18-kip single axle load."(1). Thus, an axle load with an 18-kip equivalency of 2.5 could be considered to be 2.5 times more damaging than the 18-kip loading.

The general approach, applied to both methods, is to determine the cumulative ESALs a given pavement is capable of sustaining before it's serviceability is reduced to an unacceptable level, ie, the design load capacity. Then, the traffic stream using that pavement is analyzed both before and after enforcement efforts are implemented to determine the effects of that enforcement on daily ESALs generated by the stream. Finally, the daily ESALs before and after enforcement are used to determine the estimated times (before and after enforcement) required to consume the load capacity.

The first method discussed, an approximation method, probably is the most appropriate for the present NCHRP project as it is much easier to program and use and is in the spirit of the study where the goal, rather than focusing on the pavement design process, is to quantify what is accomplished by weight enforcement efforts. The method has a disadvantage in that it is unable to recognize the fact that most traffic streams have an inherent growth rate. Not dealing with that growth rate may result in significant errors with some traffic streams.

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[1] The contribution of Pavement Design Consultant, Ken McGhee, for this appendix is gratefully acknowledged.

The second method, covered in Section 5 of this appendix, is theoretically more precise, but is much more difficult to apply as one needs a reasonably good grasp of the AASHTO pavement design process. The second method does deal with the expected growth rate of the traffic steam in question.

2.0 AN APPROXIMATION METHOD FOR DETERMINING THE EFFECTS OF AXLE WEIGHT ENFORCEMENT ON PAVEMENT LIFE

2.1 Introduction

The method described here is designated as an approximation because it makes use of a means of approximating axle equivalencies.

2.2 Assumptions

A. The analysis will be applied to a generic pavement that is defined as either a flexible pavement or a rigid pavement. The user will have to specify which. It should be noted that, as shown below, for this approximation method the pavement thickness or structural number is not a factor.

B. The fourth power rule will be used to calculate axle equivalency factors. (The rule states that the load equivalency factor increases approximately as a function of the ratio of any given axle load to the standard 18-kip single axle load raised to the fourth power.)(1)

C. The approximation will be reasonably accurate, but may be in error up to about 10% in estimated changes in pavement life expectancy as compared to the more precise method given in Section 5 of this appendix. One of the reasons the approximation method is likely to be somewhat in error is the inability of the method to account for growth in traffic volume throughout the life of the pavement.

2.3 Procedure

A. Estimate daily ESALs from axle weights measured or assumed prior to enforcement and after enforcement for the traffic stream in question. To do this, use the fourth power rule to calculate equivalencies. Then follow the procedure outlined in Section 4 of this appendix to calculate ESALs. This procedure will need to be gone through twice, once to determine the daily ESALs before enforcement ($ESAL_b$) and once for afterward ($ESAL_a$). Examples of using the fourth power rule and of calculating daily ESALs for both rigid and flexible pavements are given in Sections 3 and 4, respectively.

B. Estimate the effects on pavement life brought about by weight enforcement. A given pavement will have a design load capacity of W_{18} ESALs and many designers use a 30 year design life. However, real ESALs typically far exceed those used in the design. So, the concept, assuming a zero annual growth rate in traffic, is:

1. Calculate the life expectancy before enforcement (L_b) from:

$$L_b = W_{18}/(ESAL_b*365), \text{.........Equation (1)}$$

2. Calculate the life expectancy after enforcement (L_a) from:

$$L_a = W_{18}/(ESAL_a*365), \text{.........Equation (2)}$$

3. Calculate the percentage increase in life (L_i) from:

$$L_i = 100*(L_a - L_b)/L_b. \text{........Equation (3)}$$

Note, however, that W_{18} cancels out of Equation (3) so that the percentage increase in pavement life is also the percentage decrease in daily ESALs brought about by enforcement and can be expressed as

$$L_i = 100*(ESAL_b - ESAL_a)/ESAL_b.$$

Because the design w_{18} does cancel out of the equations to estimate the benefit of enforcement the only real chore when using the approximation method is in calculating the 18-kip equivalencies and the average daily ESALs. It is important to recognize, however, that only relative increases in pavement life can be determined using the approximation method. Absolute values of pavement life and changes therein can be determined only through using the method outlined in Section 5 of this appendix..

3.0 FOURTH POWER RULE OF CALCULATING AXLE EQUIVALENCIES

The formidable equations and calculations (Section 5 of this appendix) used to develop theoretically correct 18 Kip axle equivalency factors have led to much interest in handy methods of estimating those factors given a minimum of information. Fortunately, there is a generally applicable rule of thumb: "The load equivalency factor increases approximately as a function of the ratio of any given axle load to the standard 18-kip single axle load raised to the fourth power."(1). For example, calculations and AASHTO tabulations show that a 28 kip single axle load on a flexible pavement has 18 kip equivalency factors ranging from 3.93 to 7.54 depending upon the structural number and terminal serviceability of the pavement being analyzed. On the other hand, the estimated factor from the 4th power rule, independent of pavement structure and terminal serviceability, would be

$$e_{28} = e_{18}*(28/18)^4 = 1*5.86 = 5.86$$

where e_{28} is the 18-kip equivalency for a 28-kip single axle load on a flexible pavement, and

e_{18} is the 18-kip equivalency for an 18-kip single axle load on a flexible pavement, i.e. $e_{18} = 1.0$.

In order to make full use of the fourth power rule in calculating equivalencies it is necessary to establish some bases for those calculations for tandem and tridem loads and to reflect differences in 18-kip equivalencies relating to pavement type (rigid or flexible). Table E1 below has been determined from AASHTO calculations and tabulations (1) to provide reasonable starting points for each axle configuration and pavement type.

TABLE E - 1
BASES FOR ESTIMATION OF 18-kip EQUIVALENCY FACTORS

Axle Configuration	Basic Load (kips)	Flexible Equivalency Factor	Rigid Equiv. Factor
Single	18	1.00	1.00
Tandem	34	1.09	1.95
Tridem	48	1.03	2.55

Using Table E1 the 18-kip equivalency for any axle loading can be estimated through use of the fourth power rule. For example, a 50 kip tandem axle on a flexible pavement would have an estimated 18-kip equivalency of

$$e_{50} = e_{34}*(50/34)^4 = 1.09*4.68 = 5.10.$$

AASHTO tabulations show a 50 kip tandem axle load on a flexible pavement to have equivalencies ranging from 3.74 to 6.15.

While most designers will use the tabulated 18-kip equivalencies for pavement designs, it is well recognized that the fourth power rule may be close enough for many practical purposes given the uncertainties in estimating traffic characteristics including axle loads.

Even when using the fourth power rule, however, pavement type (rigid or flexible) is important. Again, as an example a 50 kip tandem axle on a rigid pavement would have an equivalency much higher than above for a flexible pavement of approximately

$$e_{50} = e_{34}*(50/34)^\wedge 4 = 1.95*4.68 = 9.13.$$

AASHTO tabulations show that the actual equivalency for a 50 kip tandem on a rigid pavement ranges from 7.17 to 10.73 depending upon pavement thickness and terminal serviceability. Estimated equivalencies for other single, tandem, or tridem loads on both rigid and flexible pavements would be determined similarly using the factors given in Table E1 as the bases for those estimates.

4.0 APPLICATION OF THE FOURTH POWER RULE TO DETERMINATION OF DAILY 18-KIP EQUIVALENCIES (ESALs) FOR A TYPICAL TRAFFIC STREAM

Table E-2 provides an example of determining the average daily ESALs for a typical traffic stream both before and after weight enforcement. In the procedure, single and tandem (tridem if present) axle load ranges for all axles in the traffic stream are provided. The fourth power rule is used to calculate the 18-kip equivalency for the mid-point of each axle load range. For example, the 12,000 - 15,999 range has a mid-point at 14-kips so the 18-kip equivalency of the 14-kip load is needed. As given in Section 3 of this appendix, the equivalency is calculated

$$e_{14} = e_{18}(14/18)^4 = 1*.366 = 0.366.$$

All other equivalencies in Table E-2 are calculated using the procedures given in Section 2 which follows and using the base values given in Table E-1.

To calculate the daily ESAL contribution of each load class the number of axles in each class is multiplied by the 18-kip equivalency for that class. The sum of the contributions of all classes is the average daily ESALs for the traffic stream. Note in the example, that the daily ESALs before enforcement ($ESAL_b$) was 917 while after enforcement ($ESAL_a$) the total was 653.

Table E -2

FLEXIBLE PAVEMENT, 4th Power Rule
ESAL ESTIMATES FOR TYPICAL TRAFFIC STREAM

		BEFORE ENFORCEMENT			AFTER ENFORCEMENT	
	Axle Load Ranges	Eqivalency Factor	No. Axles	Daily ESALs	No. Axles	Daily ESALs
Single	3000 - 6999	0.006	18	0.108	18	0.108
Axles	7000 - 7999	0.03	12	0.36	10	0.3
	8000 - 11999	0.095	370	35.15	260	24.7
	12,000 - 15,999	0.366	40	14.64	30	10.98
	16,000 - 19,999	1	300	300	320	320
	20,000 - 23,999	2.23	42	93.66	6	13.38
				0		0
Tandem	6000 - 11,999	0.005	18	0.09	16	0.08
Axles	12,000 - 17,999	0.042	24	1.008	23	0.966
	18,000 - 23,999	0.16	50	8	40	6.4
	30,000 - 31,999	0.76	48	36.48	36	27.36
	32,000 - 33,999	0.976	25	24.4	123	120.048
	34,000 - 37,999	1.38	43	59.34	52	71.76
	38,000 - 41,999	2.11	163	343.93	27	56.97
			Total	917.166		653.052

As shown earlier, the percentage increase in pavement life is estimated to be

$L_i = 100*(ESAL_b - ESAL_a)/ESAL_b = 28.8\%$.

Table E-3 is an example of the ESAL calculations for a rigid pavement assumed to be in the same traffic stream as above. Note the substantially higher values for both before and after enforcement ESALs as compared to the flexible case. The estimated increase in pavement life due to enforcement is not greatly different for the two pavement types as the rigid L_i is

$L_i = 100*(1283-872)/1283 = 32.0\%$.

5.0 MORE PRECISE METHOD OF CALCULATING INCREASED PAVEMENT LIFE DUE TO WEIGHT ENFORCEMENT

AASHTO design procedures provide for the traffic input to design to be in terms of accumulated (or projected) 18,000 lb. equivalent single axle loads (ESALs). In their approach, AASHTO uses the definition: "Load equivalency factors represent the ratio of the number of repetitions of any axle load and axle configuration (single, tandem, tridem) necessary to cause the same reduction in Present Serviceability Index (PSI) as one application of an 18-kip single axle load."(1). Because of that definition, many designers view the equivalency factor of a given axle load to be a relative measure of pavement damage inflicted by that load.

The serviceability index (PSI or p) is a subjective measure of pavement condition on a 0 to 5 scale with 0 defined as unusable and 5 defined as perfect. While there are many variations, a typical new road will have an initial serviceability (p_0 or PSI at time 0) of about 4.4 while the terminal or no longer acceptable serviceability (p_t) generally ranges from 2.0 to 3.0.

Unfortunately, the analysis of traffic data from a pavement design standpoint is greatly complicated by the fact that the relationship between axle loads and ESALs (equivalency factor) is geometric rather than linear and the relationship is a function of pavement structural capacity as well the level-of-service at which the pavement is considered to have failed (the terminal PSI). Further, the relationships differ for flexible and rigid pavements. ESAL equations for both types of pavements and for single and tandem axle loads were derived from the AASHO Road Test (2). Relationships for tridem axles have been developed through other research to extend the Road Test results (3).

Table E - 3

RIGID PAVEMENT, 4th Power Rule
ESAL ESTIMATES FOR TYPICAL TRAFFIC STREAM

		BEFORE ENFORCEMENT			AFTER ENFORCEMENT	
	Axle Load Ranges	Eqivalency Factor	No. Axles	Daily ESALs	No. Axles	Daily ESALs
Single	3000 - 6999	0.006	18	0.108	18	0.108
Axles	7000 - 7999	0.03	12	0.36	10	0.3
	8000 - 11999	0.095	370	35.15	260	24.7
	12,000 - 15,999	0.366	40	14.64	30	10.98
	16,000 - 19,999	1	300	300	320	320
	20,000 - 23,999	2.23	42	93.66	6	13.38
				0		0
Tandem	6000 - 11,999	0.01	18	0.18	16	0.16
Axles	12,000 - 17,999	0.074	24	1.776	23	1.702
	18,000 - 23,999	0.284	50	14.2	40	11.36
	30,000 - 31,999	1.35	48	64.8	36	48.6
	32,000 - 33,999	1.73	25	43.25	123	212.79
	34,000 - 37,999	2.45	43	105.35	52	127.4
	38,000 - 41,999	3.74	163	609.62	27	100.98
			Total	1283.094		872.46

The ESAL equivalency factor equations for flexible pavements are:

$$\log_{10}(w_x/w_{18}) = 4.79*\log_{10}(18+1)-4.79*\log_{10}(L_x+L_2) + 4.33*\log_{10}L_2 + G_t/b_x - G_t/b_{18}$$

.............Equation (4)

$$G_t = \log_{10}[(4.2 - p_t)/2.7]$$

..........................Equation (5)

$$b_x = 0.40 + [0.081*(L_x + L^2)\text{^}3.23]/[(SN + 1)\text{^}5.19*L_2\text{^}3.23]$$

.........Equation (6)

where

w_x = number of loads of magnitude L_x required to reduce the PSI to p_t,

w_{18}= number of 18 kip loads required to reduce the PSI to p_t,

L_x = load on one single axle or one tandem axle set (kips),

L_2 = axle code (1 for single axle and 2 for tandem axle),

SN = pavement structural number (see Section 6 for examples of SN determination),

p_t = terminal serviceability (on a 0 to 5 scale typical p_t values are 2.0, 2.5, and 3.0), and

b_{18}= value of b_x when $L_x = 18$ and $L_2 = 1$.

For rigid pavements, the equations are:

$$\log_{10}(w_x/w_{18}) = 4.62*\log_{10}(18+1)-4.62*\log_{10}(L_x+L_2) + 3.28*\log_{10}L_2 + G_t/b_x - G_t/b_{18}$$

.......................Equation (7)

$$G_t = \log_{10}[(4.5 - p_t)/3.0]$$

.......................Equation (8)

$b_x = 1.00 + [3.63*(L_x + L^2)^\wedge 5.20]/[(D + 1)^\wedge 8.46*L_2^\wedge 3.52]$

..................Equation (9)

where D is the slab thickness in inches.

5.1 Flexible Pavement Examples

Equations 6 and 7 above solve for the $\log_{10}$ of the inverse of the equivalency factors. For the flexible pavement example used in the 1993 AASHTO Design Guide (1) the SN = 5, and $p_t = 2.5$. Assuming that on that pavement we want to determine the 18 kip equivalency for a 22 kip single axle load $L_x = 22$ kips, $L_2 = 1$, and Equation 1 reduces to

$\log_{10}(w_{22}/w_{18}) = -0.34$

$w_{22}/w_{18} = 0.457$ and the equivalency factor $e_{22} = 1/(0.457) = 2.18$.

Similar calculations produce the tabulation of flexible pavement single axle load equivalency factors for $p_t = 2.5$ and structural numbers 1 through 6 given in Table E-4.

Again, for the flexible pavement example one can calculate equivalency factors for tandem axle loads by assigning $L_2 = 2$ in Equations 4 and 5. Then, using a 34 kip tandem axle load Equation 4 reduces to

$\log_{10}(w_x/w_{18}) = -0.037$

$w_x/w_{18} = 0.918$ and the equivalency factor $e_{34} = 1/(0.918) = 1.09$.

The last calculation shows that for a flexible pavement a 34 kip tandem load is approximately equivalent to an 18 kip single axle load. Similar calculations produce the tabulation of flexible pavement tandem axle load equivalency factors for $p_t = 2.5$ and structural numbers 1 through 6 given in Table D.5 of the 1986 AASHTO *Guide for the Design of Pavement Structures.*

Studies by Treybig, et.al.(3) have extended the AASHO Road Test results to tridem axles. While the analysis of tridem axle equivalencies is well beyond the scope of the present study, Table D.6 of the 1986 AASHTO *Guide for the Design of Pavement Structures* is a tabulation of flexible pavement tridem equivalency factors for structural numbers 1 through 6 and $p_t = 2.5$. It should be noted in that Table that a 48 kip tridem load has an 18 kip equivalency of approximately one.

5.2 Rigid Pavement Examples

For the rigid pavement example used in the 1993 AASHTO Design Guide (1) the slab thickness D = 10, and $p_t = 2.5$. Assuming that on that pavement we want to determine the 18 kip equivalency for a 22 kip single axle load $L_x = 22$ kips, $L_2 = 1$, and Equation 7 reduces to

$\log_{10}(w_{22}/w_{18}) = -0.376$

$w_{22}/w_{18} = 0.421$ and the equivalency factor $e_{22} = 1/(0.421) = 2.38$.

Similar calculations produce the tabulation of rigid pavement single axle load equivalency factors for $p_t = 2.5$ and slab thicknesses of 6 through 14 given in Table D.13 of the 1986 AASHTO *Guide for the Design of Pavement Structures*.

Again, for the rigid pavement example one can calculate equivalency factors for tandem axle loads by assigning $L_2 = 2$ in Equations 7 and 9. Then, using a 34 kip tandem axle load Equation 7 reduces to

$\log_{10}(w_{34}/w_{18}) = -0.289$

$w_{34}/w_{18} = 0.514$ and the equivalency factor $e_{34} = 1/(0.514) = 1.95$.

The last calculation shows that for a rigid pavement a 34 kip tandem load has an equivalency nearly double that for an 18 kip single axle load. Similar calculations produce the tabulation of rigid pavement tandem axle load equivalency factors for $p_t = 2.5$ and slab thicknesses of 6 through 14 inches given in Table D.14 in the 1986 AASHTO *Guide for the Design of Pavement Structures.*.

Again, while the analysis of tridem axle equivalencies is well beyond the scope of the present study, Table D.15 in the 1986 AASHTO *Guide for the Design of Pavement Structures* is a tabulation of rigid pavement tridem equivalency factors for slab thicknesses of 6 through 14 inches and $p_t = 2.5$.

5.3 Calculating ESAL Applications for Mixed Traffic

Table E-4 is an example of total daily ESAL calculation for trucks (in most such analyses buses are included with trucks while passenger cars and pickup trucks are ignored as the ESAL contributions of those classes are insignificant) in a traffic stream for a flexible pavement where SN = 5 and $p_t = 2.5$. Note that the table summarizes single and tandem axles separately as the equivalency factors are quite different.

Table E - 4

FLEXIBLE PAVEMENT SN =5, psubt = 2.5
ESAL ESTIMATES FOR TYPICAL TRAFFIC STREAM

		BEFORE ENFORCEMENT			AFTER ENFORCEMENT	
	Axle Load Ranges	Eqivalency Factor	No. Axles	Daily ESALs	No. Axles	Daily ESALs
Single Axles	3000 - 6999	0.005	18	0.09	18	0.09
	7000 - 7999	0.032	12	0.384	10	0.32
	8000 - 11999	0.088	370	32.56	260	22.88
	12,000 - 15,999	0.36	40	14.4	30	10.8
	16,000 - 19,999	1	300	300	320	320
	20,000 - 23,999	2.18	42	91.56	6	13.08
				0		0
Tandem Axles	6000 - 11,999	0.005	18	0.09	16	0.08
	12,000 - 17,999	0.037	24	0.888	23	0.851
	18,000 - 23,999	0.151	50	7.55	40	6.04
	30,000 - 31,999	0.758	48	36.384	36	27.288
	32,000 - 33,999	0.974	25	24.35	123	119.802
	34,000 - 37,999	1.38	43	59.34	52	71.76
	38,000 - 41,999	2.08	163	339.04	27	56.16
			Total	906.636		649.151

In the tabulation, axle loadings are grouped as convenient. Then, the equivalency factors are determined from Equations 4 through 9. Alternatively, the equivalencies could be interpolated from the appropriate tables (Tables D.4 , D.5, D.6, D.13, D.14, or D.15 of the 1986 AASHTO *Guide for the Design of Pavement Structures* as appropriate) in order to estimate the ESAL contribution from each axle grouping. For example, note that the heaviest single axle class in the stream is 26,000 - 29,999. The equivalency factor applied to that group is 5.39 as given in Table D.4 of the 1986 AASHTO *Guide for the Design of Pavement Structures* for a 28 kip single axle load. There was only one axle in that group so the total ESAL contribution from the group is 1*5.39 = 5.39 ESALs. Similarly, the total ESAL contribution from all groups is the estimated ESALs for the traffic stream. For the example, daily ESALs are determined for both the before and after enforcement conditions. The total daily ESALs before enforcement ($ESAL_b$) is 907 while the total after enforcement ($ESAL_a$) is 649.

The estimated increase in pavement life is then

$L_i = 100*(ESAL_b - ESAL_a)/ESAL_b = 100*(907 - 649)/907 = 28.4\%$.

Note that this value is very close to that determined in Section 4 through the fourth power rule for the same traffic stream on a generic flexible pavement.

A similar analysis has been applied to the above traffic stream assuming the pavement in question is rigid with a slab thickness (D) of 10 in. and a terminal serviceability index (p_t) of 2.5. This analysis is summarized in Table E-5 where it may be noted that the major difference is in the equivalency factors for tandem axles which are much higher than for the flexible pavement case. For the rigid case, the total daily ESALs before enforcement ($ESAL_b$) is 1303 while the total after enforcement ($ESAL_a$) is 871.

The estimated increase in pavement life for this case is then

$L_i = 100*(1301-871)/1301 = 33.1\%$.

Again, the estimated increase in pavement life for this method is very close to that determined in Section 4 through the fourth power rule for the same traffic stream on a generic rigid pavement.

If, instead of estimating the increase in pavement life, it is desired to determine an estimate of absolute pavement life before and after enforcement activities it is necessary to apply the AASHTO design equations as given in Section 6 of this appendix.

Table E - 5

RIGID PAVEMENT, D = 10, psubt = 2.5
ESAL ESTIMATES FOR TYPICAL TRAFFIC STREAM

		BEFORE ENFORCEMENT			AFTER ENFORCEMENT	
	Axle Load Ranges	Eqivalency Factor	No. Axles	Daily ESALs	No. Axles	Daily ESALs
Single Axles	3000 - 6999	0.006	18	0.108	18	0.108
	7000 - 7999	0.03	12	0.36	10	0.3
	8000 - 11999	0.081	370	29.97	260	21.06
	12,000 - 15,999	0.338	40	13.52	30	10.14
	16,000 - 19,999	1	300	300	320	320
	20,000 - 23,999	2.38	42	99.96	6	14.28
				0		0
Tandem Axles	6000 - 11,999	0.085	18	1.53	16	1.36
	12,000 - 17,999	0.064	24	1.536	23	1.472
	18,000 - 23,999	0.254	50	12.7	40	10.16
	30,000 - 31,999	1.32	48	63.36	36	47.52
	32,000 - 33,999	1.72	25	43	123	211.56
	34,000 - 37,999	2.48	43	106.64	52	128.96
	38,000 - 41,999	3.87	163	630.81	27	104.49
			Total	1303.494		871.41

6.0 DETERMINATION OF FLEXIBLE PAVEMENT STRUCTURAL NUMBER AND ESTIMATED PAVEMENT LIFE FROM AASHTO EQUATIONS

6.1 DETERMINATION OF FLEXIBLE PAVEMENT STRUCTURAL NUMBER

The structural number (SN) is a measure of relative pavement strength and is defined as:

$SN = a_1h_1 + a_2h_2 + - - - - + a_ih_i$........Equation (10)

where:

from the top down, h_1 is the thickness of layer one which has a layer coefficient of a_1, h_2 is the thickness of layer two which has a layer coefficient of a_2, etc. Table E-6 is a tabulation of layer coefficients for materials typically used in flexible pavement construction.

As an example of SN determination, if a pavement is comprised of 6-in. of crushed stone base ($a_2 = 0.14$) and 4-in. of asphalt concrete ($a_1 = 0.44$) the pavement has a $SN = 0.44*4 + 0.14*6 = 2.6$.

6.2 DETERMINATION OF ESTIMATED PAVEMENT LIFE FROM AASHTO EQUATIONS

6.21 FLEXIBLE PAVEMENTS

6.211 AASHTO Design Equation

The AASHTO Design equation for flexible pavements is:

$$\log_{10}W_{18} = Z_R*S_o + 9.36*\log_{10}(SN + 1) - 0.20$$

$$+ (\log_{10}(DPSI/2.7))/(0.40 + 1094/(SN+1)^{5.19})$$

$$+ 2.32*\log_{10}M_R - 8.07 \qquad \text{Equation......(11)}$$

where:

W_{18} = The predicted accumulated traffic on the design lane during the design period (typically 30 years) in equivalent ESALs,

Z_R = the standard normal deviate corresponding to the desired design reliability (for 50% reliability $Z_R = 0$ and 1/2 of the pavement will fail before the end of the design period, etc.) (a typical reliability for major highways is 95% with $Z_R = -1.64$),

S_o = the overall standard deviation associated with pavement performance prediction (a typical value for flexible pavements is 0.35),

SN = the pavement structural number defined earlier,

DPSI= the change in pavement serviceability during the design period (a typical value is 1.9), and

M_R = the effective roadbed soil resilient modulus (AASHTO T 274) in psi.

6.212 Example of Design Equation Use

For purposes of demonstrating the effects of changes in cumulative ESALs it may be best to simplify Equation 11 above by using typical values for all variables except ESALs and SN. The 1993 AASHTO Design Guide (1) offers a convenient example where the following values are assigned:

$Z_R = -1.64$ (reliability = 95%)
$S_0 = 0.35$
DPSI = 1.9
$M_R = 5000$ psi.

Then, the AASHTO flexible design equation reduces to:

$$\log_{10}W_{18} = -0.26 + 9.36*\log_{10}(SN + 1)$$

$$- 0.153/(0.40 + 1094/(SN+1)^{5.19}) \quad \text{Equation......(12)}$$

It should be emphasized that Equation 12 is a gross simplification of the AASHTO flexible pavement design equation and should never be used for the design of specific pavements. The sole purpose of the simplified equation is to permit analysis of the ESAL vs. thickness relationship as a part of the study to assess the effects of weight enforcement on pavement performance.

To examine the effects of various cumulative ESALs on pavement life it is convenient to assume a known existing pavement of say SN = 5. Equation 12 then solves

TABLE E - 6

PAVING MATERIALS USED IN AASHTO DESIGNS

RIGID PAVEMENTS

Material	Typical Thickness (in.) (4 characters)	Modulus of Rupture (psi) (3 characters)	Modulus of Subgrade Reaction (pci) (3 characters)
PCC (portland cement concrete)	6 - 15 in.	Default = 650	Default = 200

FLEXIBLE PAVEMENTS

	Material	Typical Thickness (h) (in.) (4 characters)	Strength* Coefficient (a) (4 characters)
Surface:	high stab. asphalt concrete	1 - 4 in.	Default = 0.44
	low stability asphalt concrete	1 - 4 in.	Default = 0.20
Base:	high stab. asphalt concrete	2 - 16 in.	Default = 0.40 (1)
	crushed stone	2 - 12 in.	Default = 0.14
	sandy gravel	2 - 12 in.	Default = 0.07
	cement treated stone	4 - 8 in.	Default = 0.20
	asphalt treated stone	4 - 8 in.	Default = 0.34
	lime treatment	4 - 8 in.	Default = 0.22
Subbase:	sandy gravel	2 - 18 in.	Default = 0.11
	sand or sandy clay	2 - 18 in.	Default = 0.08

* Except as noted, default values are from the 1972 AASHTO Interim Guide for Design of Pavement Structures.

(1) Recommendation of the Project 20-34 research team.

$\log_{10}W_{18} = 6.72$ and $W_{18} = 5.2 \times 10^6$.

If the traffic stream analyzed above for a flexible pavement with SN = 5 and $p_t = 2.5$ is used the before ($ESAL_b$) and after ($ESAL_a$) enforcement daily ESALs are 907 and 649, respectively.

It can be shown that a pavement undergoing an annual growth rate in traffic volume will accumulate the design W_{18} according to the equation

$n = [\log_{10}*(1 + r*W_{18}/365*ESAL)]/\log_{10}(1 + r)$....Equation (13)

where n = the estimated pavement life in years,
r = the annual growth rate expressed as a decimal,
ESAL = the average daily ESALs at the beginning of the analysis period.

Assuming a 5% annual rate of growth in traffic for the above example the pavement would have been predicted to last

$n_b = [\log_{10}*(1 + 0.05*5.2 \times 10^6/365*907]/\log_{10}(1.05) = 12.0$ yrs.

With the same growth rate after enforcement the pavement would be predicted to last

$n_a = [\log_{10}*(1 + 0.05*5.2 \times 10^6/365*649]/\log_{10}(1.05) = 15.3$ yrs.

Then, the increase in expected pavement life due to enforcement is 15.3 - 12.0 = 3.3 years or 27.5%. Note that the percentage increase in pavement life compares well with that determined from the approximation method used earlier.

6.22 RIGID PAVEMENTS

6.221 AASHTO Design Equation

The AASHTO Design equation for rigid pavements is:

$$\log_{10}W_{18} = Z_R*S_o + 7.35*\log_{10}(D + 1) - 0.06 + [\log_{10}(DPSI/3.0)]/[1 + (1.624*10^7)/(D+1)^{8.46}] + (4.22 - 0.32p_t)*\log_{10}\{[s'*c_d(D^{0.75} - 1.132)]/[215.63*J(D^{0.75} - 18.42/(E_c/k)^{0.25}]\}$$ ....Equation (14)

where, in addition to that defined above:

D = the slab thickness (in.)

s' = estimated mean PCC modulus of rupture (AASHTO T97) in psi,

J = a factor used to account for the ability of rigid slab to transfer loads across discontinuities such as cracks and joints (typical values range from 2.5 to 4.0, see AASHTO),

E_c = PCC elastic modulus in psi (typically 4 to 5 * 10^6), and

k = the modulus of subgrade reaction, the load in pounds per square inch on a loaded area of the roadbed soil or subbase divided by the deflection in inches of the soil or subbase (psi/in), (typical values are 50 to 300).

In addition, for rigid pavements the initial serviceability (PSI_0 or PSI at time 0) is about 4.2 while the terminal or no longer acceptable serviceability (PSI_t) is about 2.5. Therefore, a typical DPSI is about 1.7.

Now, it is possible to solve Equation 14 for local conditions and, and making the appropriate substitutions in Equation13, go through the analysis of before and after enforcement traffic streams to assess the impact of that enforcement on pavement life.

7.0 CONCLUSION

The foregoing discussion of pavement design principles has addressed the major issues underlying methods of determining the increase in pavement life one could expect from reduced axle loadings accrued through enforcement activities. The application of these principles is seen in the software product of NCHRP 20-34, the Truck Weight Enforcement Evaluation Tool.

8.0 REFERENCES

1. American Association of State Highway and Transportation Officials, "AASHTO Guide for Design of Pavement Structures", Washington, DC, 1993.

2. American Association of State Highway and Transportation Officials, "AASHTO Interim Guide for Design of Pavement Structures 1972", (Chapter III Revised, 1981), Washington, DC, 1972, 1981.

3. Treybig, H. J. and H. L. Von Quintus, "Equivalency Factor Analysis and Prediction for Triple Axles", Report No. BR-2/1, Austin Research Engineers for Texas Research and Development Foundation, Austin, TX, 1976.

APPENDIX **F**

M.O.E SAMPLING PLAN DEVELOPMENT[1]

INTRODUCTION

An essential step in the conduct of NCHRP Project 20-34 was the development of an aid to state highway and enforcement agencies in their determination of how many data-collection sites are required to detect **regional** M.O.E. differences which may result from a truck weight enforcement effort. The applied approach to this process is that the user agency would specify what level of M.O.E. difference (e.g., 5-, 10- , 20-percent) is to be detected. The user would then apply results of this sampling guide, based on a statistical analysis of nation-wide M.O.E. data, to determine how many study sites are required.

M.O.E sampling requirements were developed on the basis of M.O.E. distributional data gathered at a sample of LTPP sites. Each site provided 24-hour continuous WIM monitoring and afforded observations of both weekday and weekend traffic.

The site utilization strategy for this Sampling Plan development process designated high, intermediate, and low truck volume sites, representative of the following three functional classes: Interstate, Primary Arterial, and Minor Arterial routes. A minimum of three sites was chosen from each of the above functional classification groups. The selection process avoided sites with very low average ESAL values, as M.O.E.s do need to address violation occurrences.

Table 1 on the next page lists locations of the sites for which data were collected in the development of this Sampling Plan.

The selection process designated the 22 sites noted above, resulting in a highway functional class distribution as follows: 6 Rural Interstates, 6 Rural Principal Arterials, 3 Rural Minor Arterials, 4 Urban Interstates, and 3 Urban Primary Arterials . The resulting distribution by region is as follows: 8 Central, 5 West, 4 Atlantic, 5 South. Thus, data were collected for the LTPP sites to fill the functional class/truck volume matrix of Table 2 on the next page. Site designations noted in the cells consist of state name abbreviations followed by LTPP site number.

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[1] The substantive contributions to this appendix of Statisticians, Dr. Olga Pendleton of Pen-Hock Statistical Consultants, and Ms. Cindy Cornell, of Chaparral Systems Corporation, are gratefully acknowledged.

Table 1. Applied LTPP Sites in Sampling Plan Development

STATE/PROVINCE	LOCATION
Arkansas	State Highway 1
Arkansas	I U 540, North of State Highway 253
Florida	U.S. 1, South of State Route 442
Florida	U.S. 92, East of U.S. 17
Indiana	State Route 37, North of State Route 469
Kansas	State Route 68
Kansas	U.S. 50
Kansas	U.S. 166
Kentucky	I - 65, North of Lebanon Junction
Michigan	U.S. 23, Dundee
Missouri	I - 44, West of Route H
Missouri	I - 435, South of Route 291
Nova Scotia	Route 201, Kelly Lake
Rhode Island	State Route 146, Massachusetts State Line
Tennessee	I -75, North of State Route 61
Virginia	Route 8, Floyd County
Virginia	I - 95, Sussex County
Washington	State Route 5, South of State Route 104
Washington	State Route 14, East of State Route 105
Washington	State Route 167, South of State Route 405
Washington	State Route 82, West of State Route 22

Table 2. Sites selected for sampling plan development

Functional Class	% truck volume		
	Low	Medium	High
Rural Interstates	WA7409 NS6802	VA1023 TN1023	KY3016 MO1010
Rural Principal Arterials	FL4109 FL4138	RI7401 KS1006	MI9030 AR3011
Rural Minor Arterials	VA1002 IN2009 KS1005	None	None
Urban Interstates	WA3812	MO4036 AR3059 WA3019	None
Urban Primary Arterials	WA3813 WA6049	KS4067	None

Sites were not available for some cells, probably due to the fact that such sites are not plentiful in reality. For example, rural minor arterials tend to have low truck volumes and urban highways do not typically support high truck volume as these are not the roads of choice for truckers. At least two sites were needed per cell to provide an estimate of within cell variability needed for developing sample size. In the case of urban interstates with low truck volumes and urban primary arterials with medium truck volume, only one site was available for those cells so cell sample size could not be developed. However, these sites were used in combining urban interstates and primary arterials.

Documented truck weight sampling literature[2] has applied criteria for establishing low, medium, and high truck presence on the traffic stream. Low truck volume sites were considered to contain less than 8 percent trucks as a proportion of the total traffic volume. Medium truck presence was considered to be in the range of 8-16 percent trucks, and high truck presence was taken to be greater than 16 percent. Given the documented significance of considering low-, medium, and high truck presence, candidate M.O.E. distribution site were accordingly stratified. The noted truck proportion criterion was applied as a guideline; however, due to site availability and observed nationwide traffic-mix trends (i.e., low rural volumes, producing large truck proportions) the applied percent varied slightly from the Texas study. Table 3 presents the truck volume percentages for utilized sites in the Sampling Plan development.

Table 3. Percent truck volume for sampling plan development

Functional Class	% truck volume		
	Low	Medium	High
Rural Interstates	7.9, 10.5	21.8, 30.2	61.4, 42.5
Rural Principal Arterials	3.1, 3.6	11.4, 9.1	41.3, 38.5
Rural Minor Arterials	4.9, 6.8, 10.4	None	None
Urban Interstates	4.0	15.3, 13, 28.3	None
Urban Primary Arterials	7.3, 8.9	23.9	None

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[2] Maxwell, D. A. et al , *Evaluation of the Texas Truck Weighing Program*, Research Report 424-1F, Texas Transportation Institute, College Station, TX , 1986

The Sampling Plan development process first applied a detailed examination of site number requirements on the basis of two M.O.E.s, ESALs and Excess ESALs. Statistical distributions for these two M.O.E.s were examined for Vehicle Classifications shown in Table 4 below. Given the results of this analysis, a more limited approach was applied with regard to site number requirements on the basis of remaining M.O.E.s.

Table 4. Description of Vehicle Classifications

VEHICLE CLASSIFICATION	TRUCK CONFIGURATION
VC 5	Two-axle Single Unit
VC 6	Three-axle Single Unit
VC 7	Four or More Axle Single Unit
VC 8	Four or Less Axle Single Trailer
VC 9	Five-axle Single Trailer
VC 10	Six or More Axle Single Trailer
VC 11	Five or Less Axle Multi-Trailer
VC 12	Six-Axle Multi-Trailer
VC 13	Seven to More Axle Multi-Trailer

SITE NUMBER REQUIREMENTS FOR ESALs AND EXCESS ESALs

Sample size estimates are determined herein for a wide range of precision levels for two M.O.E.'s - percent Excess ESALs and average ESALs. The main purpose in providing estimates over a range of precisions is to give the user some idea of the maximum and minimum sample size requirements that exist based on these data. The final sample size determination will depend on the factors which are most important in evaluating enforcement and the feasible and practical expectations for implementation. Some states may have more resources and want to aim at higher precision levels than others. Also, the amount of roadway mileage for a particular functional class may be greater in some states than others so they may opt to focus on maximizing the precision for that functional class. For example, if a state like Texas believes that enforcement is a bigger problem on rural interstates and there are a lot of miles of rural interstates in Texas, the state may opt to aim for selecting a 20 percent reduction in Excess ESALs after enforcement as opposed to 30 percent, i.e. they want to be able detect a smaller change in violations for this functional class.

The precision levels in the sample size computations were based on Minnesota data where truck weights were measured when weight scales were and were not opened. The change in percent Excess ESALs when stations were and were not opened ranged from 2 percent to 30 percent. Hence, the selected range for Excess ESALs in the sampling plan was from 5 to 20 percent. The average ESALs in these data had relative changes of between 10 to 55 percent of the average when scales were opened to when they were closed

. Truck weight enforcement effects comparing baseline and enforcement conditions in Idaho were also examined in the development of the Sampling Plan. The Idaho results confirmed application of the 5 to 20 percent range for Excess ESALs and 10 to 50 percent for average ESALs.

Sample size tables for each cell of Table 2, i.e., functional class for low-, medium-, and high- truck percentage, are indicated in the discussion which follows. A brief explanation of the interpretation of these tables follow the first cell analysis. Graphs of these changes are also provided.

Rural Interstates with Low % Truck Volumes (WA7409,NS6802)

All sample sizes are based on the five- percent significance level with 80% power of detecting the corresponding precisions. Table 5 lists summary statistics, table 6 lists sample sizes for the M.O.E. percent Excess ESALs and table 7 lists these for the M.O.E. average ESALs.

Table 5. Summary Statistics for Rural Interstates with Low % Truck Traffic

	WA7409			NS6802		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	46618	0.356	0.1762	64830	2.314	0.1464
6	14243	0.828	0.3941	27458	20.355	0.9085
7	1862	0	0.9517	144	21.528	1.4411
8	20413	0.652	0.6872	42410	0.424	0.1051
9	150197	1.399	1.1763	109908	8.060	1.1277
10	8429	0.546	1.164	24272	27.076	3.2464
11	7712	2.036	1.332	26344	6.111	0.966
12	8139	0.762	1.1781	5813	26.922	3.732
13	25400	0.169	1.7485	5431	1.639	0.8917
All	283013	1.376	0.9908	306610	8.478	0.9538

Table 6. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be detected			
Vehicle Class	5	10	15	20
5	31	8	3	2
6	248	62	28	16
7	32	8	4	2
8	10	3	1	1
9	85	21	9	5
10	337	84	38	21
11	103	26	12	7
12	217	54	24	14
13	9	2	1	1
Total	98	24	11	6

Table 7. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	2	1	1	1	1
6	33	16	11	8	7
7	9	4	3	2	1
8	113	57	38	28	23
9	1	1	1	1	1
10	47	23	16	12	9
11	5	3	2	1	1
12	57	28	19	14	11
13	22	11	7	6	4
All	68	34	23	17	14

Table 6 is to be interpreted as follows: If we want to be able to say that a 10 percent decrease in the percentage of trucks with Excess ESALs after enforcement is a statistically significant reduction in violations (at the 5 % level with 80% power), and if we are most interested in detecting this for vehicle class 9, we will need 21 sites. If we are willing to lower our precision requirement to detecting a 20 percent reduction in Excess ESALs, we can do this with only 5 sites. If we want to do this for all vehicle classes, we will need 6 sites.

Table 7 focuses on the M.O.E. of average ESALs. For vehicle class 7 to declare a 30 percent reduction in average ESALs as a statistically significant reduction due to enforcement, three sites are needed. To detect this for vehicle class 8, 38 sites are needed. Thus, it is important to know which vehicle class is most important and this may well be determined by the percentage of vehicles in this class typically travel rural interstates or by the class with the highest percentage frequency of Excess ESALs. Figure 1 provides the total vehicle frequency distribution and figure 2 the frequency distribution of vehicles with Excess ESALs (violators) by vehicle class. Figures 3 and 4 show sample size requirements for each vehicle class (corresponding to tables 6 and 7).

Since vehicle class 9 was dominant in both frequency on rural interstates with low truck volume and frequency of violations (percent Excess ESALs), we might focus on this vehicle class in determining sample size. In this case, 5 sites would be sufficient to detect a 20 percent change in Excess ESALs and a 10 percent change in average ESALs on rural interstates with-truck volumes of 7-10 percent.

Rural Interstates with Medium % Truck Volumes (VA1023,TN1023)

Table 8 lists summary statistics, table 9 lists sample sizes for the M.O.E. percent Excess ESALs and Table 10 lists these for the M.O.E. average ESALs.

Table 8. Summary Statistics for Rural Interstates with Medium % Truck Traffic

	VA1023			TN1023		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	162802	2.114	0.1188	113763	13.908	0.9241
6	15928	5.198	0.4137	13879	14.338	1.1493
7	413	26.877	2.2417	920	57.609	5.7411
8	91545	1.784	0.2861	37618	13.563	1.2974
9	785951	9.861	1.4935	448886	27.038	2.8013
10	4951	3.016	0.9927	3417	20.076	2.8910
11	43397	10.174	1.7424	30237	39.257	4.2635
12	3786	0.924	0.7539	5295	7.970	2.0508
13	349	6.304	1.4010	3525	38.922	6.1977
All	1109112	7.947	1.1818	657540	24.206	2.4250

Table 9. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be detected			
Vehicle Class	5	10	15	20
5	136	34	15	8
6	180	45	20	11
7	524	131	58	33
8	104	26	11	6
9	284	71	32	18
10	188	47	21	12
11	362	90	40	23
12	100	25	11	6
13	484	121	54	30
Total	252	63	28	16

Table 10. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	125	63	42	31	25
6	70	35	23	18	14
7	65	33	22	16	13
8	95	47	32	24	19
9	45	23	15	11	9
10	73	36	24	18	15
11	62	31	21	16	12
12	68	34	23	17	14
13	94	47	31	23	19
All	91	45	30	23	18

Since vehicle class 9 was dominant in both frequency on rural interstates with medium truck volume and frequency of violations (percent Excess ESALs), we again focus on this vehicle class in determining sample size. In this case, 18 sites are needed to detect a 20 percent change in Excess ESALs and a 20-30 percent change in average ESALs have to occur to conclude that enforcement was successful on rural interstates with truck volumes of 20-30 percent.

Rural Interstates with High % Truck Volumes (KY3016,MO1010)

Table 11 lists summary statistics, table 12 lists sample sizes for the M.O.E. percent Excess ESALs and Table 13 lists these for the M.O.E. average ESALs.

Table 11. Summary Statistics for Rural Interstates with Low % Truck Traffic

	KY3016			MO1010		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	111747	3.929	0.2442	291531	0.763	0.0479
6	33041	15.242	1.4038	15282	27.164	2.151
7	2547	61.798	5.9905	904	43.142	4.380
8	79092	7.393	0.7362	74754	3.203	0.368
9	969868	18.239	1.8413	471435	12.590	2.109
10	3922	14.329	5.3457	2207	5.437	1.232
11	55438	18.767	2.6332	74022	14.974	2.592
12	7145	3.639	2.4896	5442	5.7332	1.178
13	1888	14.672	36.611	92	0.000	0.2427
All	1264688	16.229	1.7292	935672	8.557	

Table 12. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be Detected			
Vehicle Class	5	10	15	20
5	34	8	4	2
6	324	81	36	20
7	516	129	57	32
8	107	26	12	7
9	288	72	32	18
10	208	52	23	13
11	291	73	32	18
12	91	23	10	6
13	253	63	28	16
Total	273	59	26	15

Table 13. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	95	47	32	24	19
6	9	5	3	2	2
7	5	3	2	1	1
8	23	12	8	6	5
9	1	1	1	1	1
10	82	41	27	21	16
11	1	1	1	1	1
12	27	13	9	7	5
13	205	102	68	51	41
All	460	230	153	115	92

Since vehicle class 9 was dominant in both frequency on rural interstates with high truck volume and frequency of violations (percent Excess ESALs), we again focus on this vehicle class in determining sample size. In this case, 7 sites are needed to detect a 20 percent change in Excess ESALs and this will be sufficient to detect as little as a 10 percent change in mean ESALs on rural interstates with truck volumes of 40-60 percent.

Rural Primary Arterials with Low % Truck Volumes (FL 4138, FL 4138)

Table 14 lists summary statistics, table 15lists sample sizes for the M.O.E. percent Excess ESALs and Table 16 lists these for the M.O.E. average ESALs.

Table 14. Summary Statistics for Rural Primary Arterials with Low % Truck Traffic

	FL 4109			FL 4138		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	9914	0.1111	0.0073	4492	1.135	0.0540
6	181	36.464	4.531	437	33.638	3.471
7	7	28.571	7.224	4	100.00	13.524
8	301	12.957	1.5670	303	23.762	2.930
9	257	10.506	1.523	152	15.789	1.700
10	1	0.000	0.958	8	25.000	2.2400
11	14		1.8300	3	0.000	0.352
12	3	0.0000		0		
13	0					
All	10678	1.376	.0172	5400	5.574	0.5524

Table 15. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be detected			
Vehicle Class	5	10	15	20
5	9	2	1	1
6	475	118	53	30
7	521	130	58	33
8	315	79	35	20
9	230	57	26	14
10	363	91	40	23
11	218	55	24	14
ll	57	14	6	4

Table 16. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	122	61	41	30	24
6	4	2	1	1	1
7	19	10	6	5	4
8	19	10	6	5	4
9	1	1	1	1	1
10	34	17	11	8	7
11	96	48	32	24	19
All	151	76	50	38	30

Vehicle class 5 was dominant in total frequency on rural primary arterials with low truck volume and vehicle class 6 was the class with the highest frequency of violations (percent Excess ESALs). There is a wide variability in the sample size requirements for these two vehicle classes for the two M.O.E.'s. However, it would appear that a sample size of 30 sites are needed to detect a 20 percent change in Excess ESALs and a 40 percent change in average ESALs have to occur to conclude that enforcement was successful on rural primary arterials with truck volumes of 3 to 4 percent. This probably suggests that it is not practically feasible to attempt to evaluate M.O.E.'s on primary rural arterials at these low truck volumes.

Rural Principal Arterials with Medium % Truck Volumes

Table 17 lists summary statistics, table 18 lists sample sizes for the M.O.E. percent Excess ESALs and Table 19 lists these for the M.O.E. average ESALs.

Table 17. Summary Statistics for Principal Arterials with Medium % Truck Traffic

	RI 7401			KS 1006		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	86928	7.228	0.388	6450	3.008	0.164
6	18605	23.101	3.571	822	3.041	0.465
7	1058	84.405	20.203	14	14.286	1.547
8	60449	14.394	1.460	1160	0.603	0.229
9	173950	26.668	6.226	3666	4.255	0.827
10	1934	32.989	5.835	40	2.500	0.968
11	981	15.494	2.187	67	1.493	0.486
12	49	32.653	4.915	29	0	0.204
13	22	50.000	10.631	22	0	0.849
All	343976	21.106	3.800	12270	3.146	0.396

Table 18. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs

	Percent Change to be detected			
Vehicle Class	5	10	15	20
5	136	34	15	8
6	364	91	40	23
7	290	73	32	18
8	255	64	28	16
9	434	109	48	27
10	460	115	51	29
11	264	66	29	17
12	343	86	38	21
13	394	99	44	25
All	342	86	38	21

Table 19. Number of Sites Required to Detect 10-50 percent Change in Average ESALs

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	35	17	12	9	7
6	125	63	42	31	25
7	155	77	52	39	31
8	112	56	37	28	22
9	123	62	41	31	25
10	108	54	36	27	22
11	85	43	28	21	17
12	178	89	59	45	36
13	153	76	51	38	31
All	233	117	78	58	47

Sample size requirements are high for this category because of the large differences in % Excess ESALs and average ESALs between these two sites. For example, for vehicle class 7 (see table 17) RI 7401 had 84% Excess ESALs whereas KS 1006 had only 14%. For this same vehicle class, average ESALs were 20.2 for RI and 1.5 for KS. Similarly, for vehicle class 13 RI had 50% Excess ESALs and KS had none. These data should be reexamined to determine if these discrepancies are indeed correct. Perhaps some vehicle classes should be omitted if they are providing less reliable data.

Since vehicle class 9 was dominant in both total frequency on rural primary arterials with medium truck volume and frequency of violations (percent Excess ESALs), we again focus on this vehicle class in determining sample size. In this case, 27 sites would be required to detect a 20 percent change in Excess ESALs and a 50 percent change would be required to declare a significant reduction in average ESALs due to enforcement for rural primary arterials with 9-11 % truck volume.

Rural Principal Arterials with high %Truck Volumes (AR3011, MI9030)

Table 20 lists summary statistics, table 21 lists sample sizes for the M.O.E. percent Excess ESALs and Table 21 lists these for the M.O.E. average ESALs.

Table 20. Summary Statistics for Rural Principal Arterials with High % Truck Traffic

	AR3011			MI9030		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	1408	1.207	0.1667	50278	6.317	0.8971
6	460	5.217	0.4463	12433	7.36	0.5745
7	45	44.44	2.6913	693	13.997	1.356
8	1428	5.742	0.6385	22178	2.511	0.5247
9	12287	6.885	1.249	331716	7.089	1.1588
10	154	12.338	2.336	14133	6.439	1.7154
11	1159	1.898	1.082	16821	2.931	1.480
12	84	11.905	1.885	6193	6.346	1.946
13	6	0.000	0.360	10212	5.631	2.121
All	17031	6.107	1.092	464657	6.597	1.142

Table 21. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be detected			
Vehicle Class	5	10	15	20
5	122	30	14	8
6	146	36	16	9
7	280	70	31	18
8	55	14	6	4
9	138	35	15	9
10	128	32	14	8
11	58	15	7	4
12	126	32	14	8
13	112	28	12	7
Total	129	32	14	8

Table 22. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	99	50	33	25	20
6	3	2	1	1	1
7	23	11	8	6	5
8	2	1	1	1	1
9	1	1	1	1	1
10	5	2	2	1	1
11	5	2	2	1	1
12	1	1	1	1	1
13	105	53	35	26	21
All	36	18	12	9	7

Since vehicle class 9 was dominant in both total frequency on rural primary arterials with high truck volume and frequency of violations (percent Excess ESALs), we again focus on this vehicle class in determining sample size. In this case, 9 sites would be sufficient to detect a 20 percent change in Excess ESALs and a 10 percent change in average ESALs would be declared a statistically significant reduction due to enforcement for rural primary arterials with about 40 percent truck volumes.

Rural Minor Arterials with Low % Truck Volumes

Table 23 lists summary statistics, table 24 lists sample sizes for the M.O.E. percent Excess ESALs and Table 25 lists these for the M.O.E. average ESALs.

Table 22. Summary Statistics for Rural Minor Arterials with Low % Truck Traffic

	KS 1005			IN 2009			VA 1002		
VC	Total	% Excess	Average ESALs	Total	% Excess	Average ESALs	Total	% Excess	Avg ESAL
5	7169	4.87	0.214	56009	3.86	0.184	15588	17.46	1.250
6	776	17.4	0.974	14528	6.07	0.588	8047	28.17	2.290
7	13	23.1	2.224	3455	70.2	4.381	1616	75.93	6.844
8	1175	1.96	0.374	9962	3.98	0.563	5583	15.73	1.646
9	1386	5.84	0.863	47245	5.05	1.027	8217	14.90	1.840
10	67	2.98	0.867	841	4.4	0.963	112	16.07	1.921
11	64	1.56	0.176	950	20.2	2.226	414	16.18	2.694
12	2	0	0.116	45	4.44	1.329	6	0	1.209
13	1	0	1.060	25	0	2.056	3	0	0.160
All	10653	5.58	0.378	133060	6.37	0.705	39586	21.23	1.885

Table 24. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent change to be detected			
Vehicle Class	5	10	15	20
5	87	22	10	5
6	169	42	19	11
7	283	71	31	18
8	100	25	11	6
9	85	21	9	5
10	74	18	8	5
11	64	16	7	4
12	51	13	6	3
13	0	0	0	0
All	121	30	13	8

Table 25. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be detected				
Vehicle Class	10	20	30	40	50
5	128	64	43	32	26
6	53	27	18	13	11
7	28	14	9	7	6
8	67	33	22	17	13
9	19	9	6	5	4
10	23	11	8	6	5
11	65	33	22	16	13
12	60	30	20	15	12
13	85	42	28	21	17
All	100	50	33	25	20

Sample size requirements are high for vehicle class 7 on percent Excess ESALs primarily due to IN 2009 that had 70% of the vehicle in this class as overweight. These data again should be checked for realistic accuracy and perhaps some vehicle classes should be omitted if they are providing less reliable data.

Vehicle class 5 was the most dominant in total frequency for rural minor arterials with low truck volumes. At least 26 sites would be required to declare even a 50 percent reduction in average ESALs as statistically significant. For the M.O.E. Excess ESALs, 5 sites would be sufficient to declare a 20 percent reduction as significant for rural minor arterials with 5-10 percent truck volumes.

Urban Roadways

The LTPP database only had the minimum number of sites needed to develop sample size (two or more) for urban interstates with medium truck volumes (13-28 % trucks) and urban primary arterials with low percent truck volume (7-9 % trucks). Thus, in addition to developing sampling requirements for these two cells, all urban roads (interstate and primary arterials) were combined to provide sampling requirements for low and medium percent truck volume (see table 1). There were no sites available for urban high truck volumes for either interstates or primary arterials, probably because these roads do not, in practice, experience high truck volumes.

Urban Interstates with Medium % Truck Volumes (MO 4036, AR 3059, and WA 3019)

Table 26 lists summary statistics, table 27 lists sample sizes for the M.O.E. percent Excess ESALs and Table 27 lists these for the M.O.E. average ESALs.

Table 26. Summary Statistics for Urban Interstates with Medium % Truck Traffic

	MO 4036			AR 3059			WA 3019		
VC	Total	% Excess	Average ESALs	Total	% Excess	Average ESALs	Total	% Excess	Avg ESAL
5	14828	8.329	0.544	6506	3.228	0.1919	15394	2.111	0.164
6	12238	26.30	2.850	1741	12.06	0.822	4207	2.139	0.275
7	897	84.39	13.49	253	61.66	4.503	3662	42.76	2.233
8	22088	5.781	0.680	1960	2.857	0.344	5647	1.045	0.333
9	211942	13.24	1.708	6261	14.98	2.464	136118	6.407	1.259
10	1750	16.17	3.026	165	9.091	2.338	16202	1.531	0.795
11	27809	12.17	1.901	121	0.826	0.455	9579	4.186	1.012
12	3437	10.30	2.055	23	0	0.663	8099	1.358	0.824
13	900	7.778	2.204	9	0	0.574	13883	1.116	1.281
All	295889	13.06	1.656	133060	9.308	1.196	212791	5.487	1.091

Table 27. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be Detected			
Vehicle Class	5	10	15	20
5	64	16	7	4
6	218	55	24	14
7	350	88	39	22
8	63	16	7	4
9	133	33	15	8
10	41	10	5	3
11	127	32	14	8
12	56	14	6	4
13	21	5	2	1
All	124	31	14	8

Table 28. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be Detected				
Vehicle Class	10	20	30	40	50
5	74	37	25	19	15
6	108	54	36	27	22
7	93	46	31	23	19
8	46	23	15	11	9
9	35	18	12	9	7
10	59	29	20	15	12
11	68	34	23	17	14
12	68	34	23	17	14
13	63	32	21	16	13
All	149	74	50	37	30

Sample size requirements are high for vehicle classes 6 and 7 on percent Excess ESALs primarily due to MO 4036 which had 26% and 84% of the vehicles in this class as overweight when the other sites had far less. These data again should be checked for realistic accuracy and perhaps some vehicle classes should be omitted if they are providing less reliable data.

Since vehicle class 9 was dominant in both total frequency and frequency of violations (percent Excess ESALs) on urban interstates with medium truck volume, this will be our focal point in sample size determination. In this case, 15 sites would allow a declaration of a 15 % reduction in Excess ESALs and a 30 percent reduction in average ESALs to be a statistically significant indicator of an effective enforcement program for urban interstates with 13-28 percent truck volume.

Urban Interstates and Primary Arterials with Medium % Truck Volumes (MO4036, AR3059, WA3019, and KS4067)

Table 29 lists summary statistics for urban primary arterials (KS 4067 - urban interstate summary statistics were listed in table 26), table 30lists sample sizes for the M.O.E. percent Excess ESALs and table 31 lists these for the M.O.E. average ESALs.

Table 29. Summary Statistics for Primary Arterial with Medium % Truck Traffic (KS4067).

	KS4067		
Vehicle Class	Total	% Excess	Average ESALs
5	20152	2.233	0.184
6	5730	11.187	0.795
7	112	12.5	1.732
8	7483	6.027	0.565
9	109456	6.837	1.322
10	1963	2.598	1.188
11	11551	4.969	1.439
12	746	1.877	0.660
13	1661	1.505	1.332
Total	158854	6.108	1.127

Table 30. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be Detected			
Vehicle Class	5	10	15	20
5	53	13	6	3
6	201	50	22	13
7	350	88	39	22
8	66	17	7	4
9	123	31	14	8
10	40	10	5	3
11	114	28	13	7
12	52	13	6	3
13	21	5	2	1
All	115	29	13	7

Table 30. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be Detected				
Vehicle Class	10	20	30	40	50
5	48	24	16	12	10
6	97	48	32	24	19
7	104	52	35	26	21
8	13	7	4	3	3
9	11	6	4	3	2
10	33	16	11	8	7
11	28	14	9	7	6
12	43	22	14	11	9
13	26	13	9	6	5
All	204	102	68	51	41

Since vehicle class 9 was dominant in both total frequency on urban interstates and frequency of violations (percent Excess ESALs), this will be our focal point in sample size determination. In this case, 15 sites would allow a declaration of a 15 % reduction in Excess ESALs and a 10 percent reduction in average ESALs to be a statistically significant indicator of an effective enforcement program for urban interstates and primary arterials with 13-28 percent truck volume.

Urban Primary Arterials with Low % Truck Volumes (WA 3813, WA 6049)

Table 32 lists summary statistics, table 33 lists sample sizes for the M.O.E. percent Excess ESALs and Table 34lists these for the M.O.E. average ESALs.

Table 32. Summary Statistics for Urban Primary Arterials with Low % Truck Traffic

	WA 3813			WA 6049		
Vehicle Class	Total Vehicles	% Excess ESALs	Average ESALs	Total Vehicles	% Excess ESALs	Average ESALs
5	41473	3.947	0.2890	420144	2.927	0.1712
6	23898	7.5911	0.6638	151406	3.453	0.3194
7	311	10.006	1.6908	6833	6.586	0.9614
8	12707	2.849	0.3850	168363	2.233	0.3743
9	46167	11.287	1.4753	492414	3.827	0.6937
10	17730	4.585	0.8768	78564	1.148	0.6166
11	3153	12.908	1.6904	44956	5.085	0.9464
12	3980	5.276	1.3103	36356	2.580	0.7667
13	16097	5.237	1.8900	66500	1.290	1.4790
All	165516	6.859	0.9540	1465536	3.109	0.5109

Table 33. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be Detected			
Vehicle Class	5	10	15	20
5	62	15	7	4
6	81	20	9	5
7	138	35	15	9
8	47	12	5	3
9	90	22	10	6
10	37	9	4	3
11	91	23	10	6
12	58	13	6	3
13	53	13	6	3
All	71	18	8	4

Table 34. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be Detected				
Vehicle Class	10	20	30	40	50
5	38	19	13	10	8
6	52	26	17	13	10
7	41	21	14	10	8
8	2	1	1	1	1
9	54	27	18	15	11
10	26	13	9	6	5
11	42	21	14	10	8
12	40	19	13	10	8
13	18	9	6	5	4
All	62	31	21	16	12

The most prominent vehicle classes in both total frequency and frequency of violations (percent Excess ESALs) on urban primary arterials with low truck volume were vehicle class 9 and 5, respectively. Examining the sample size requirements for these classes, 15 sites would allow a declaration of a 15 % reduction in Excess ESALs and a 40 percent reduction in average ESALs to be a statistically significant indicator of an effective enforcement program. If we were only interested in the M.O.E. of Excess ESALs, only 7 sites would be necessary to detect a significant difference for urban primary arterials with 7-9 percent truck volume.

Urban Interstates and Primary Arterials with Low % Truck Volumes (WA 3813, WA 6049, WA3812)

Table 35 lists summary statistics for urban interstates with low truck volume (table 33 lists these for primary arterials), table 35 lists sample sizes for the M.O.E. percent Excess ESALs and Table 37 lists these for the M.O.E. average ESALs.

Table 35. Summary Statistics for Urban Interstates (WA 3812) with Low % Truck Traffic

	WA 3812		
VC	Total	% Excess	Average ESALs
5	264994	0.702	0.077
6	32771	3.405	0.439
7	3157	5.195	0.804
8	57515	0.847	0.412
9	221963	1.029	0.749
10	30794	0.786	0.848
11	13081	0.742	0.871
12	10535	1.187	0.815
13	32901	0.602	1.366
All	667711	0.984	0.476

Table 36. Number of Sites Required to Detect 5-20 percent change in % Excess ESALs.

	Percent Change to be Detected			
Vehicle Class	5	10	15	20
5	30	7	3	2
6	53	13	6	3
7	85	21	9	5
8	27	7	3	2
9	47	12	5	3
10	21	5	2	1
11	61	15	7	4
12	34	9	4	2
13	23	6	3	1
All	38	9	4	2

Table 37. Number of Sites Required to Detect 10-50 percent Change in Average ESALs.

	Percent Change to be Detected				
Vehicle Class	10	20	30	40	50
5	37	19	12	9	7
6	14	7	5	4	3
7	18	9	6	4	4
8	1	1	1	1	1
9	21	11	7	5	4
10	4	2	1	1	1
11	16	8	5	4	3
12	10	5	3	3	2
13	3	2	1	1	1
All	36	18	12	9	7

The most prominent vehicle classes in both total frequency and frequency of violations (percent Excess ESALs) on urban interstates and urban primary arterials with low truck volume were vehicle classes 9 and 5, respectively. Examining the sample size requirements for these classes, 9 sites would allow a declaration of a 10-15 % reduction in Excess ESALs and a 40 percent reduction in average ESALs to be a statistically significant indicator of an effective enforcement program. If we were only interested in the M.O.E. of Excess ESALs, only 5 sites would be necessary to detect a significant difference for urban interstates and primary arterials with 4-9 percent truck volume.

ESALs and Excess ESALs Sampling Requirements Conclusion

Depending on the M.O.E. of interest, the required sample sizes differ. Detecting changes in percent Excess ESALs generally requires more samples than detecting a percentage change in Excess ESALs. That is, if we are most interested in declaring a 15 percent reduction in the percent of Vehicle Class 9 trucks with Excess ESALs after enforcement, this requires more sites than if we want to be able to say that the reduction in average ESALs was 15% less than the average ESALs before enforcement. Table 38 shows the number of sites for detecting a 15 percent change in excess ESAL change and table 39 shows the number of sites required to detect a 30 percent change in average ESALs (detecting a 15 percent change in average ESALs is probably an unrealistic). Alternative site number requirements to these can be constructed from preceding tables in this report in order to assess the significance of other observed ESAL changes.

Table 38. Number of sites required to detect a 15% change in Excess ESALs.

	% truck volume		
Functional Class	Low	Medium	High
Rural Interstates	9	32	32
Rural Principal Arterials	2	15	15
Rural Minor Arterials	9	-	-
Urban Interstates	-	15	-
Urban Principal Arterials	10	-	-
Urban Interstates and Principal Arterials Combined	10	14	-
Total	30	51	47

Table 39. Number of sites required to detect a 30% change in average ESALs.

	% truck volume		
Functional Class	Low	Medium	High
Rural Interstates	2	15	2
Rural Principal Arterials	2	41	2
Rural Minor Arterials	6	-	-
Urban Interstates	-	12	-
Urban Principal Arterials	18	-	-
Urban Interstates and Principla Arterials Combined	5	4	-
Total	15	60	4

SITE NUMBER REQUIREMENTS FOR OVERWEIGHT VIOLATIONS

Given the foregoing detailed development of ESAL and Excess ESAL sampling requirements, a more streamlined approach was applied with regard to the remaining M.O.E.s, i.e., Proportion of trucks with Gross Weight Violations, Proportion with Tandem Violations, and Proportion with Single Axle Violations. On the basis of field observations and preliminary Sampling Plan developmental effort, it was evident that M.O.E. development needed to concentrate on the Vehicle Class 9 truck type as these were the predominate truck type and the predominate violators. Therefore, development of sampling requirements for these measures addressed M.O.E. distributions exhibited by Type 9 trucks at the 22 LTPP sites.

As in the process which established ESAL and Excess ESAL sampling requirements, actual truck weight enforcement effects were examined for existing project databases, e.g., California, Georgia, Idaho, and Minnesota. On the basis the data examination, sampling requirements were developed to accommodate the detection of 10-, 20-, 30-, 40- and 50-percent changes in the M.O.E.s.

Proportion of Gross Truck Weight Violations

Table 40 below indicates the required site numbers to detect changes in the proportion of trucks exceeding the legal gross weight limit, given the specified detection level thresholds.

Table 40. Site Number Requirements for Gross Truck Weight Violations

	PERCENT CHANGE TO BE DETECTED				
FUNCTIONAL CLASS	**10**	**20**	**30**	**40**	**50**
Rural Interstate					
< 15 % Trucks	40	10	4	3	2
15 to 30 % Trucks	97	24	11	6	4
> 30% Trucks	48	12	5	3	2
Rural Primary Arterial					
< 9 % Trucks	40	10	4	3	2
9 to 30 % Trucks	105	26	12	7	4
> 30% Trucks	20	5	2	1	1
Rural Minor Arterial	44	11	5	3	2
Urban Interstate					
< 9% Trucks	5	1	1	1	1
≥ 9% Trucks	25	6	3	2	1
Urban Primary Arterial					
< 9% Trucks	32	8	4	2	1
≥ 9% Trucks	49	12	5	3	2

The shaded cell above indicates the most likely expected percent change and site requirements to be associated with truck weight enforcement activity on the basis of field observations conducted in the current study.

Proportion of Trucks with Overweight Tandem Violations

Table 41 on the next page indicates the required site numbers to detect changes in the proportion of trucks exhibiting at least one tandem axle pair that exceeds the legal weight limit, given the specified detection level thresholds.

Table 41. Site Number Requirements for Tandem Weight Violations

	PERCENT CHANGE TO BE DETECTED				
FUNCTIONAL CLASS	**10**	**20**	**30**	**40**	**50**
Rural Interstate					
< 15 % Trucks	54	13	4	3	2
15 to 30 % Trucks	97	24	11	6	4
> 30% Trucks	48	12	5	3	2
Rural Primary Arterial					
< 9 % Trucks	40	10	4	3	2
9 to 30 % Trucks	105	26	12	7	4
> 30% Trucks	20	5	2	1	1
Rural Minor Arterial	44	11	5	3	2
Urban Interstate					
< 9% Trucks	5	3	1	1	1
≥ 9% Trucks	25	6	3	2	2
Urban Primary Arterial					
< 9% Trucks	32	8	4	2	1
≥ 9% Trucks	49	12	5	3	2

The shaded cell above indicates the most likely expected percent change and site requirements to be associated with truck weight enforcement activity on the basis of field observations conducted in the current study.

Proportion of Trucks with Single Axle Weight Violations

Table 42 on the next page indicates the required site numbers to detect changes in the proportion of trucks exhibiting at least one overweight axle which exceeds the legal weight limit, given the specified detection level thresholds.

Table 42. Site Number Requirements for Single-Axle Violations

	PERCENT CHANGE TO BE DETECTED				
FUNCTIONAL CLASS	**10**	**20**	**30**	**40**	**50**
Rural Interstate					
< 15 % Trucks	33	8	4	3	2
15 to 30 % Trucks	84	21	9	5	3
> 30% Trucks	50	13	6	3	2
Rural Primary Arterial					
< 9 % Trucks	45	11	5	3	2
9 to 30 % Trucks	98	24	11	6	4
> 30% Trucks	20	5	2	1	1
Rural Minor Arterial	36	9	4	2	1
Urban Interstate					
< 9% Trucks	7	2	1	1	1
≥ 9% Trucks	24	6	3	1	1
Urban Primary Arterial					
< 9% Trucks	28	7	3	2	1
≥ 9% Trucks	31	8	3	2	1

Appendix G

USER GUIDE SOFTWARE HELP SCREENS

This appendix documents the applied Help Screens included in the TWEET software, in order to assist NCHRP Project 20-34 panel members with their understanding of the developed User Guideline documentation. While much of the text shown here is similar to that in the Chapter 3 User Guide, it is more detailed in certain areas, e.g., the Pavement Analysis explanation, due to the fact that software users may not necessarily have access to the project documentation.

Truck Weight Enforcement Effectiveness Tool 1.2

Contents

Welcome to the Truck Weight Enforcement Effectiveness Tool, or TWEET, Version 1.2. The following help topics are available. Click on Overview for a general explanation of this software; this is a good starting point for the new user. Otherwise, please select one of the following topics.

General Topics

Overview
General explanation of the TWEET software and how to use it to determine the effectiveness of a weight enforcement program

Input Overview
A step by step explanation of the process of entering the program's input

Output Overview
A step by step explanation of the program's output, including how to interpret the data tables, print them, etc.

Specific Topics

In addition to the general topics above, some more specific topics are provided to aid the user at each step of the program. The program uses a series of dialogs; each of the topics below corresponds to one of these dialogs. (Please note that each of these topics can also be accessed by pressing the Help button in its respective dialog; e.g., the Select Units Dialog topic can be viewed which running the TWEET software by pressing the Help button in the Units dialog itself.)

Select Units Dialog
Legal Weight Limits Dialog
Data File Format Dialog
Enforcement Condition Dialog
Number of Data Files Dialog
Select Data File Dialog
Pavement Analysis Dialog
Percentage of Overweight Trucks Dialog
Truck Classification Data Dialog
Breakdown of Violations Dialogs
Severity of Violations Dialog

ESAL Data Dialog
Data File Conversion Dialog
Comparison of Enforcement Condition Dialog
Sampling Guide Dialog
Pavement Effects Analysis Dialog

Overview

To dive right into the exciting world of truck weight enforcement, click on Quick Start

TWEET is a software application designed to aid users in determining the effectiveness of user-specified truck weight enforcement policies. It works by reading WIM data which has been collected under different enforcement conditions, and allowing the user to compare the data from each condition to determine the most effective method of enforcement.

This software presents the user with a variety of "dialog boxes" , i.e., pop-up screens which enable the user to provide required input to run the software. The software is designed to be user friendly, e.g., in most cases the user will simply press the "Next" button to continue operation.

To start a truck weight enforcement analysis, press the start analysis button in the program's main window. There are three discrete steps to the analysis process:

User Input
This phase of the programs requires the user to enter such information as the type of units the program is to use (English or Metric), the format of the data files used, etc. See Input Overview for more information.

Calculation
In this phase of operation, the program performs the necessary calculations on the data, including percentage of violations, Bridge Formula calculations, etc. This is done entirely automatically by the program, and the user need not be concerned with this part of the program.
During calculations a graphical percentage meter is displayed.

Output
In this phase of the program, the calculated data is displayed to the user. The data is displayed on-screen in a series of dialog boxes, each of which can be printed by the user. The program will automatically display the calculated values after finishing the calculations. Once the program has performed the calculations, the output can be viewed again by pressing the View Results button on the main window. See Output Overview for more information.

Input Overview

The first main phase of the program's operation is to accept input which defines how the calculations are to be performed. The input phase consists of a series of dialog boxes which ask you to enter certain values. Below is a short list of each input dialog in the order you will encounter them. Please select one of the following topics:

Select Units Dialog
Legal Weight Limits Dialog
Data File Format Dialog
Enforcement Condition Dialog

Number of Data Files Dialog
Select Data File Dialog
Pavement Analysis Dialog
Data File Conversion Dialog

Output Overview

After the program has completed its calculations, which are done without any action on the user's part immediately following the input phase, it displays the output. Each output dialog displays its data, and has four buttons at the bottom of the window. These buttons are:

"NEXT" Closes the current output dialog and displays the next output dialog.
Cancel Closes the current output dialog and returns the user to the main window immediately.
Print Prints the information in the dialog on the user's printer.
Help Takes the user to the appropriate page in this help system. For example, if you were using the ESAL Data dialog and you pressed its Help button, the ESAL Data Dialog help topic would be displayed.

Below is a list of the output dialog help topics. Select the one which corresponds to the dialog with which you need help.

Percentage of Overweight Trucks Dialog
Truck Classification Data Dialog
Breakdown of Violations Dialogs
Severity of Violations Dialog
ESAL Data Dialog
Data File Conversion Dialog
Comparison of Enforcement Condition Dialog
Sampling Guide Dialog
Pavement Effects Analysis Dialog

Select Units Dialog

This dialog asks you to select the system of units of measure to be used by the program. The choices are the English (feet, pounds) or Metric (meters, kilograms) units. Simply click on the radio button which denotes the choice you would like to use, and press "Next".

Number of Data Files Dialog

This dialog asks you to enter the number of data files you wish to combine for studying a particular condition. For example, if you collected three data files for the condition which is under study, type a "3" in this dialog.

Enforcement Condition Dialog

This dialog allows you to enter the information about both of the enforcement conditions. For each condition, you will be asked to enter the following information:

Name You may give the condition any name you want. Names do not have to be unique (you can name all the conditions "condition" if you like) although it is advisable that they are unique.

Location This field allows you to enter a location from which the data was collected. This field may be optionally left blank.

Start Date This field asks you to enter the starting date of the study; it too may be left blank.

End Date This field asks you to enter the ending date of the study; it too may be left blank.

Legal Weight Limits Dialog

The Set Legal Weight Limits dialog asks you to enter the maximum allowable weights as defined by your local laws. There are three fields presented: Gross Weight, Single Axle Weight and Tandem Axle Weight. The Gross Weight is the total weight of the entire vehicle; the Single Axle Weight is the weight of one axle of the vehicle; the Tandem Axle Weight is the combined weight of a set of axles that are within a certain distance of each other. The defaults in this dialog should be adequate for almost all users. Modification of these defaults may be necessary depending upon prevailing legal regulations.

Pavement Analysis Dialog

INTRODUCTION

One of the basic premises of truck weight enforcement is that there will be a net increase in pavement life (reduction in the rate of pavement deterioration). The applied method makes use of an AASHTO design procedure providing for the traffic input to design to be in terms of accumulated (or projected) 18,000 lb. equivalent single axle loads (ESALs).

In their approach, AASHTO uses the definition: "Load equivalency factors represent the ratio of the number of repetitions of any axle load and axle configuration (single, tandem, tridem) necessary to cause the same reduction in Present Serviceability Index (PSI) as one application of an 18-kip single axle load." Thus, an axle load with an 18-kip equivalency of 2.5 could be considered to be 2.5 times more damaging than the 18-kip loading.

The general approach, is to determine the cumulative ESALs a given pavement is capable of sustaining before its serviceability is reduced to an unacceptable level, i.e., the design load capacity. Then, the traffic stream using that pavement is analyzed both before and after enforcement efforts are implemented to determine the effects of that enforcement on daily ESALs generated by the stream. Finally, the daily ESALs before and after enforcement are used to determine the estimated times (before and after enforcement) required to consume the load capacity.

DETERMINATION OF FLEXIBLE PAVEMENT STRUCTURAL NUMBER

The structural number (SN) is a measure of relative pavement strength and is defined as:

$$SN = a_1h_1 + a_2h_2 + - \ - \ - \ - + a_ih_i \text{........Equation D1}$$

where:

from the top down, h_1 is the thickness of layer one which has a layer coefficient of a_1, h_2 is the thickness of layer two which has a layer coefficient of a_2, etc. Table D1 is a tabulation of layer coefficients for materials typically used in flexible pavement construction.

As an example of SN determination, if a pavement is comprised of 6-in. of crushed stone base (a_2 = 0.14) and 4-in. of asphalt concrete (a_1 = 0.44), the pavement has a SN = 0.44*4 + 0.14*6 = 2.6.

DETERMINATION OF ESTIMATED PAVEMENT LIFE

Flexible Pavements

AASHTO Design Equation

The AASHTO Design equation for flexible pavements is:

$$\log_{10}W_{18} = Z_R{*}S_o + 9.36{*}\log_{10}(SN + 1) - 0.20$$

$$+ (\log_{10}(DPSI/2.7))/(0.40 + 1094/(SN+1)^{5.19})$$

$$+ 2.32{*}\log_{10}M_R - 8.07 \qquad \text{Equation......D1}$$

where:

W_{18} =	The predicted accumulated traffic on the design lane during the design period (typically 30 years) in equivalent ESALs,
Z_R =	the standard normal deviate corresponding to the desired design reliability (for 50% reliability Z_R = 0 and 1/2 of the pavement will fail before the end of the design period, etc.) (a typical reliability for major highways is 95% with Z_R = -1.64),
S_o =	the overall standard deviation associated with pavement performance prediction (a typical value for flexible pavements is 0.35),
SN =	the pavement structural number defined earlier,
DPSI=	the change in pavement serviceability during the design period (a typical value is 1.9), and
M_R =	the effective roadbed soil resilient modulus (AASHTO T 274) in psi.

Example of Design Equation Use For purposes of demonstrating the effects of changes in cumulative ESALs it may be best to simplify Equation D1 above by using typical values for all variables except ESALs and SN. The 1993 AASHTO Design Guide offers a convenient example where the following values are assigned:

$Z_R = -1.64$ (reliability = 95%)
$S_0 = 0.35$
DPSI = 1.9
$M_R = 5000$ psi.

Then, the AASHTO flexible design equation reduces to:

$$\log_{10}W_{18} = -0.26 + 9.36*\log_{10}(SN + 1)$$

$$- 0.153/(0.40 + 1094/(SN+1)^{5.19}) \quad \text{Equation......D2.}$$

It should be emphasized that Equation D2 is a gross simplification of the AASHTO flexible pavement design equation and should never be used for the design of specific pavements. The sole purpose of the simplified equation is to permit analysis of the ESAL vs. thickness relationship as a part of the study to assess the effects of weight enforcement on pavement performance.

To examine the effects of various cumulative ESALs on pavement life it is convenient to assume a known existing pavement of say SN = 5. Equation D2 then solves

$\log_{10}W_{18} = 6.72$ and $W_{18} = 5.2 \times 10^6$.

If the traffic stream analyzed above for a flexible pavement with SN = 5 and $p_t = 2.5$ is used the before ($ESAL_b$) and after ($ESAL_a$) enforcement daily ESALs are 907 and 649, respectively.

It can be shown that a pavement undergoing an annual growth rate in traffic volume will accumulate the design W_{18} according to the equation

$$n = [\log_{10}*(1 + r*W_{18}/365*ESAL)]/\log_{10}(1 + r) \text{....Equation D3}$$

where n = the estimated pavement life in years,
r = the annual growth rate expressed as a decimal,
ESAL = the average daily ESALs at the beginning of the analysis period.

Assuming a 5% annual rate of growth in traffic for the above example the pavement would have been predicted to last

$$n_b = [\log_{10}*(1 + 0.05*5.2 \times 10^6/365*907]/\log_{10}(1.05) = 12.0 \text{ yrs.}$$

With the same growth rate after enforcement the pavement would be predicted to last

$$n_a = [\log_{10}*(1 + 0.05*5.2 \times 10^6/365*649]/\log_{10}(1.05) = 15.3 \text{ yrs.}$$

Then, the increase in expected pavement life due to enforcement is 15.3 - 12.0 = 3.3 years or 27.5%.

Rigid Pavements

AASHTO Design Equation

The AASHTO Design equation for rigid pavements is:

$$\log_{10}W_{18} = Z_R{*}S_o + 7.35{*}\log_{10}(D + 1) - 0.06$$

$$+ [\log_{10}(DPSI/3.0)]/[1 + (1.624{*}10^7)/(D+1)^{8.46}]$$

$$+ (4.22 - 0.32p_t){*}\log_{10}\{[s'{*}c_d(D^{0.75} -$$

$$1.132)]/[215.63{*}J(D^{0.75} - 18.42/(E_c/k)^{0.25}]\}$$.........Equation D4

where, in addition to that defined above:

D = the slab thickness (in.)

s' = estimated mean PCC modulus of rupture (AASHTO T97) in psi,

J = a factor used to account for the ability of rigid slab to transfer loads across discontinuities such as cracks and joints (typical values range from 2.5 to 4.0, see AASHTO),

E_c = PCC elastic modulus in psi (typically 4 to 5 $*$ 10^6), and

k = the modulus of subgrade reaction, the load in pounds per square inch on a loaded area of the roadbed soil or subbase divided by the deflection in inches of the soil or subbase (psi/in), (typical values are 50 to 300).

In addition, for rigid pavements the initial serviceability (PSI_0 or PSI at time 0) is about 4.2 while the terminal or no longer acceptable serviceability (PSI_t) is about 2.5. Therefore, a typical DPSI is about 1.7.

Now, it is possible to solve Equation D4 for local conditions and, and making the appropriate substitutions in Equation D3, go through the analysis of before and after enforcement traffic streams to assess the impact of that enforcement on pavement life.

A more detailed discussion of the applied pavement-design analysis procedure by Consultant Ken McGhee is contained in the NCHRP Project 20-34 documentation.

Calculate SN

If the user knows the material composition of the pavement, TWEET can automatically calculate an SN value. In this case, the user clicks on 'Calculate SN', and the ***Automatic Calculation of SN*** screen allows the user to select the appropriate surface, base, and sub-base characteristics, i.e., pavement layer thickness (in inches), and strength coefficient. According to the specified material type, the program will suggest the most appropriate default Strength Coefficient. Pavement materials personnel who run this software have the option of overriding default values, depending upon their own knowledge of pavement materials and design procedures along with specific pavement characteristics associated with the enforcement location.

The structural number (SN) is a measure of relative pavement strength and is defined as:

$SN = a_1h_1 + a_2h_2 + - \ - \ - \ - + a_ih_i$........Equation D1

where:

from the top down, h_1 is the thickness of layer one which has a layer coefficient of a_1, h_2 is the thickness of layer two which has a layer coefficient of a_2, etc. Table D1 is a tabulation of layer coefficients for materials typically used in flexible pavement construction.

As an example of SN determination, if a pavement is comprised of 6-in. of crushed stone base ($a_2 = 0.14$) and 4-in. of asphalt concrete ($a_1 = 0.44$) the pavement has a $SN = 0.44*4 + 0.14*6 = 2.6$.

Select Truck Classification

This dialog allows you to select the type of truck classification system you wish to use. The choices are FHWA 13-Type or Custom. The 1995 FHWA *Traffic Monitoring Guide* 13-Type scheme is a standard 13-type vehicle classification system that should be adequate for most users. NOTE: At the time this software was developed, many states applied the FHWA Card-7format. ***If your data set is in the Card-7 format, go ahead and click on the default standard 13-type classification option.***

If you wish to use a custom classification scheme, click on the Custom check box and press Next. You will be prompted to enter the name for each of up to 15 different truck classifications in a series of dialog boxes. If using this feature be sure to read the notes in the help screen (press Help in the first Custom Classifications dialog).

File Conversion

This dialog box assists the user in converting data files to a an acceptable format. TWEET requires all data files to be in either the 1995 FHWA Truck Weight Record format of Card 7. If your data files are in one of these standard formats already, press Next to continue. If your data files are in another format, press the Convert button below to run TWEET's conversion utility which will convert your files to the proper format.

TWEET Data File Conversion Utility

There are an abundance of truck weight data file formats in existence today. The TWEET analysis tool supports the most common of these formats, the 1995 FHWA Truck Weight Record format. In an effort to assist users with data files formatted differently, TWEET incorporates a data file conversion utility which will convert most custom file formats into the standard FHWA 1995 Truck Weight Record format, the format required by TWEET to measure enforcement effectiveness. The conversion utility will also convert files of the popular Card 7 format into the 1995 FHWA Truck Weight Record Format.

Use of the conversion utility is fairly simple. For an overview of using the utility, click on Using the Conversion Utility

For information on custom file formats, and how to enter them into the utility, click on Using Custom File Formats

Using the Conversion Utility

The TWEET Data File Conversion Utility main window provides a fast, efficient way to convert data files from other formats to the 1995 FHWA Truck Weight Record format. Here is an overview of the features of the main windows:

Input File field: This field allows the entry of the name of an input file (in some foreign format) to be converted to the FHWA 1995 Truck Weight Record. If the name of the file is not known, the Browse button allows for a file to be selected from the available files on the system's hard disk or floppy disks.

Output File field: This field allows the entry of the name of the output file to be created which will contain the data in the input file, formatted in the FHWA 1995 Truck Weight Record format. If the name of an already existing file is entered in this field, that file will be permanently overwritten.

Input Format field: This field allows for the selection of an input file format. There are two choices of possible input file formats:

> *Card 7* - Files of this popular format cannot be automatically converted to FHWA 1995 Truck Weight Record format files.
>
> *Custom* - This option allows for the entry of a custom data file format, through the Custom Data Format dialog. For more information, see Using Custom File Formats.

Output Format field - This field, which is not changeable by the user, shows that all output files processed by the TWEET Data File Conversion Utility will be formatted as FHWA 1995 Truck Weight Record files.

Convert button - Once all of the four fields above have been set correctly (except for the Output Format field, which is set by the program itself) pressing this button will cause the file conversion to be performed.

Advanced button - This button allows for the use of a custom file filter in the case that the regular conversion program cannot handle a particular custom file format. A custom filter is a specific routine written by a user that would plug in to the TWEET Conversion Utility to convert its own unique, non-standard file format.

Help button - Brings up this help screen.

Exit button - Exits the TWEET Conversion Utility.

Using Custom File Formats

Pressing the Edit button in the main window or selecting custom from the Input Format field drop-down list box will bring up the utility's custom data file format entry dialog. Here is an overview of the options in this dialog:

Field Selection list box - The large list box at the left of the dialog allows for the selection of a particular field in the custom file format.

Columns Used For Highlighted Item fields - These fields correspond to the selected item in the Field Selection list box. The Start field is the position in the file (the first character is considered to be at position 1, the second at position 2, and so on) of the first character of the field; the End field is the position in the file of the last character of the field. For example, if "Year of Data" is selected in the list box, and the Start field reads "11" and the End field reads "14" it means that the 11th through the 14th characters in the custom formatted data file contain the year of the data. Checking the box labeled "Field not present in custom format" means that the selected field does not exist in the custom format, and it will thus be ignored. Some fields are required (e.g. axle weights, etc.) and in these cases the "Field not present in custom format" check box is disabled.

Units Used In Custom Format fields - These fields allow for the selection of the type of units used in the custom format. The Weight Units correspond to the type of units used in the gross vehicle weight and axle weights. The Length Units correspond to the type of units used in the axle spacings.

Select Data File Dialog

This dialog asks you to select a particular data file for the current condition. If you entered a "3" in the previous dialog, indicating you wish to combine three data files for the study of the current condition, you will be presented with this dialog three times. Each time, select one of the three data files you wish to use. For example, if the files were called DATA1.DAT, DATA2.DAT and DATA3.DAT, you would select DATA1.DAT the first time, DATA2.DAT the second time, and DATA3.DAT the third.

Percentage of Overweight Trucks Dialog

This dialog displays the calculated percentages of overweight trucks in the sample. It lists four calculations based on the data files:

Percentage of trucks over the legal gross weight limit This number is merely the percentage of all trucks whose gross weigh exceeded the legal limit as set by the user in the Legal Weight Limits dialog.

Percentage of trucks over the single axle weight limit This is the percentage of trucks exceeding the weight limit for a single axle.

Percentage of trucks over the tandem axle weight limit This is the percentage of trucks exceeding the weight limit for a set of tandem axles. Tandem axles are defined as a set axles which are within a certain distance of each other, usually 6ft (or metric equivalent). The sum of the weights of each axle which is within this distance from the other axles is called the tandem axle weight.

Percentage of trucks violating the Bridge Formula This is the percentage of all trucks in the sample which violated the Bridge Gross Weight Formula. The presence of a violation is determined by using an equation, the Bridge Formula, which relates the axle spacing and axle weights.

Breakdown of Violations Dialogs

This is a set of two dialogs. The first dialog displays the breakdown of violations by day of week and the second by the hour of the day.

Breakdown of Violations by Day-of-Week Dialog This dialog displays the percentage of violations occurring on each day of the week. The dialog simply lists each day of the week, and next to it lists the percentage of all violations which occurred on that day. Note that only gross, single-axle and tandem-axle violations are counted toward the percentages for each day (Bridge Formula Violations are not counted).

Breakdown of Violations by Day-of-Week Dialog This dialog displays the percentage of violations occurring at different hours of the day. Because it would be overly complex to display the percentage of violations occurring at each of the 24 hours of the day, the five hours with the most violations are list. If it is necessary to know what percentage of violations occurred at every hour of the day, the Print option will be of use. The printed copy of the data, unlike the on-screen display, does display the percentage of violations for each hour of the day. Like the Breakdown of Violations By Day of Week dialog, only gross, single-axle and tandem-axle violations are counted toward the percentages for each hour.

Severity of Violations Dialog

This dialog displays the information about how severe the recorded violations were. The first part of the dialog displays the absolute number of violations, once again divided into gross, single and tandem violations. The second dialog displays the average number of pounds (or Metric equivalent) overweight the trucks were. It too is divided into gross, single and tandem weights.

ESAL Data Dialog

This dialog displays the calculated average number of ESALs for each n-axled truck. ESALs are the units in which pavement consumption is measured. Because the "normal" range of values can vary depending on how many axles a truck has, a different average ESAL value is given depending on the number of axles on the truck.

Truck Classification Data Dialog

This dialog displays the violation information as broken down by truck classification. This information is useful in determining which types of trucks have the most (or least) violations, which types of trucks are the most (or least) common on the road, etc. The dialog consists of two parts:

Truck Classification List Box This list box lists all of the truck classifications which were input by the user during the beginning of the analysis, or if the default was selected, the FHWA 13-type classifications. Click on one of these classifications with the mouse or select it with the arrow keys on the keyboard. The data for the selected type of truck will appear at the right in the Violation Data section.

Violation Data This part of the dialog lists the violation data for the currently selected truck classification. The Total Number of Trucks field displays the number of trucks of the selected type which were in the sample (regardless of whether they were violators). The Number of Violators field lists the number of trucks of the selected type which violated the weight limits. The Percentage Violating field lists the percentage of trucks of the selected type which were violators (this is, of course, simply the Number of Violators divided by the Total Number of Trucks).

Comparison of Enforcement Conditions Dialog

This dialog box contains results of applied significance tests to the computed M.O.E.s and indicates to the user whether or not the observed differences are statistically significant. Separate tests of significance were applied to M.O.E.s depending upon whether the measure was calculated as a mean (i.e., average gross weight violation) or a proportion (i.e., proportion of gross weight violators). Significance tests were applied at the .05 level of confidence.

Sampling Guide

This dialog box is an aid to determine how many sites will need to be surveyed in order to detect **regional changes** for designated M.O.E.s given user-specified levels of certain statistical parameters (which will be explained later).

The user is presented with a table indicating the number of sites which are required for data collection if specified levels of M.O.E.s changes (i.e., 5, 10, 15 , or 20 percent) are to be detected. These numbers are based on an TWEET's analysis of the measured statistical characteristics (e.g., variance) of the observed M.O.E.s. The user will note that fewer sites are necessary for larger differences. This effect is due to the fact that smaller differences in real-world truck weight enforcement compliance are more subtle and therefore require more statistical rigor to detect.

Due to the fact that the number of required study site depends upon a variety of applied statistical criteria, the user is given the option of specifying two parameters related to the precision of the statistical estimate. These are the desired *Level of Significance_* and the *Power of Test.*

Level of Significance refers, in this case, to the probability which the user is willing to risk the error of rejecting a valid change in M.O.E. occurrence. In statistical jargon, the Level of Significance is the maximum probability with which we would be willing risk a *Type 1 error.* A Type 1 error occurs when a true hypothesis is rejected, i.e., that baseline versus enforcement M.O.E. variable sets are statistically different. In practice, a significance level of .05 or .01 is customary.

Power of Test refers to the likelihood of making a correct statistical assessment, i.e., that, statistically speaking, the proper hypothesis is accepted. The issue is to what extent is the user willing to risk accepting a invalid change in M.O.E. occurrence. In statistical jargon, the Power of a Test is the maximum probability with which we would be willing risk a *Type 2 error.* A Type 2 error occurs when a false hypothesis is accepted, i.e., that baseline versus enforcement M.O.E. variable sets are not statistically different.

Under the "Sampling Guide Options" box within this dialog, the user has the option of varying the Level of Significance and Power of Test. Required site sample numbers vary as function of these statistical parameters.

Pavement Effects Analysis

This dialog box indicates the theoretical pavement design-life effect associated with differential enforcement-related ESAL loading conditions. Had the user opted to include the pavement design-life effect computation, this screen would be displayed. Displayed information consists of the calculated pavement ESAL capacity, the estimated pavement life under both observed enforcement conditions, and estimated percentage pavement-life change due to the observed ESAL-loading difference associated with the enforcement activity. For information regarding computation of design pavement life, see the Pavement Analysis Dialog.

Quick Start

This Quick Start topic is a comprehensive tutorial which will walk you through the step by step process of conducting a sample truck weight enforcement analysis. If you have never used TWEET before, this is a good place to start. As this Help screen comprises a number of pages, we suggest that you make a printout for reference while running the program. Simply click on the "Print" option above.

Before performing this sample analysis, you may want to read the Overview topic to learn what TWEET is and what it does.

Starting the Analysis
Start the TWEET program. From the main window, press the button marked "Start Analysis." This will allow you to start a truck weight analysis and enforcement effects.

First you will encounter a dialog labeled ***Select Units***. Select the type of units you wish to use (English or Metric) and press "Next". See Select Units Dialog for more information.

Next, you will be asked to enter the weight limits you wish the program to use, via the ***Set Legal Weight Limits*** dialog box. Default values have been set to the most commonly used weight limits. If you need to modify these values, go ahead. Either way, press "Next" when you have finished. See Legal Weight Limits Dialog for more information on this dialog.

Now the user will see the ***Select Truck Classification*** dialog box. This dialog allows you to select the type of truck classification system you wish to use. The choices are FHWA 13-Type or Custom. The 1995 FHWA *Traffic Monitoring Guide* 13-Type scheme is a standard 13-type vehicle classification system that should be adequate for most users. NOTE: At the time this software was developed, many states applied the FHWA Card-7format. If your data is in the Card-7 format, go ahead and click on the default standard 13-type classification option.

If you wish to use a custom classification scheme, click on the Custom check box and press Next. You will be prompted to enter the name for each of up to 15 different truck classifications in a series of dialog boxes. If using this feature be sure to read the notes in the help screen (press Help in the first Custom Classifications dialog).

The ***File Conversion*** dialog box is designed to assist agencies whose data format does not conform to either the 1995 FHWA *Traffic Monitoring Guide* 13-Type scheme or Card-7 classification formats. If your data is not in either one of these formats, press the Convert button to run the conversion utility. For more information on using the Conversion Utility, see the TWEET Data File Conversion Help screen.

Now the program is asking you to enter information about the enforcement conditions you are going to study. Due to the fact that this exercise is just a demonstration of how to use the program, any name, location, and set of dates will suffice. See the Enforcement Condition Dialog for more information

The program is will now ask you about the data files you are going to use. These correspond to enforcement conditions to be observed in the field. The ***Enforcement Condition 1 of 2*** dialog box appears. As a suggestion, why not enter the name "Baseline" (as Enforcement Condition #1) presenting a non-enforcement condition. This tutorial will provide you with such a data set.. It is not necessary to enter a location and date to run the program. However, this information will be helpful in the evaluation of actual truck weight enforcement operations. In this demonstration, enter "Enforcement" as Condition #2.

For each designated enforcement condition, a ***Number of Files for Condition*** dialog box asks for the of WIM data files which pertain to each condition. For this exercise , designate one file for both conditions One and Two. See Number of Files for Condition Dialog for more information. Up to four files can be utilized for each condition.

The program will now ask you to select (or name) the data files pertaining to each condition. You will see a series of dialogs asking you to enter the path of each data file labeled "Select Data File x for Enforcement Condition y" where x is the replaced by the number of the data file for which you are currently selecting, and y is the number of the enforcement condition for which you are selecting data files. For the purpose of this tutorial, select the "BASELINE.PRN" file for the first enforcement condition and ENFORCE.PRN for the second condition. These files are located in the directory in which you installed TWEET. Please note that these are test data files representing an actual non-enforcement versus an enforcement comparison. See Select Data File Dialog for more information.

The ***Pavement Analysis*** dialog box now appears. Here, TWEET gives the user the option of conducting a pavement design-life enforcement-effects analysis. It will ask for specific (and detailed) pavement design data. Because of the complexity of the pavement design-life analysis, the user has the option of skipping the pavement analysis, i.e., simply click the 'skip pavement analysis' option. More information on this process is provided in the Pavement Analysis Help screen.

Assuming that you want the pavement design-life analysis, first select the applicable pavement material, either Flexible or Rigid. Note that depending on whether Flexible or Rigid pavement is selected there will be a different set of variables in the Pavement Characteristics box at the bottom of the dialog. This box will prompt the user for appropriate pavement design parameters.

Flexible pavement will be discussed first. Default values are shown on the screen for the following parameters.

SN	Pavement Structural Number. TWEET offers the option of computing this variable based on input values provided by the user.
p_o	Initial Serviceability Index
p_t	Terminal Serviceability Index
M_R	Default function of Serviceability Index
Z_R	Standard Normal Deviate corresponding to design reliability
S_O	Standard Deviation associated with pavement performance prediction

Because the pavement's Structural Number (SN) is so important, TWEET provides three ways for the user to enter this value. First, he may accept the commonly-applied default value show here. Second, he may apply his own value for SN, if it is known. Third, if the user knows the material composition of the pavement, TWEET can automatically calculate the SN value. In this case, the user clicks on 'Calculate SN', and the ***Automatic Calculation of SN*** dialog box allows the user to select the appropriate surface, base, and sub-base characteristics, i.e., pavement layer thickness (in inches), and strength coefficient. According to the specified material type, the program will suggest the most appropriate default Strength Coefficient. Pavement materials personnel who run this software have the option of overriding default values, depending upon their own knowledge of pavement materials and design procedures along with specific pavement characteristics associated with the enforcement location.

In the event the user selects Rigid Pavement, the following design values are considered.

k	Modulus of Subgrade Reaction
E	PCC Elastic Modulus
D	Slab Thickness (inches)
s_o	Standard deviation associated with pavement performance prediction
p_0	Initial Serviceability Index
p_t	Terminal Serviceability Index

As was the case with the Flexible Pavement Characteristics box, the most likely default values have been provided. The user has the option of manually entering values specific to the highway study site.

Viewing Results of Calculations

The program will now perform calculations. Unless your data files are extraordinarily large, these calculations should take no more than a few seconds. If the data files are very large, or you are using an older system, the calculations could take a while! A graphic will appear to advise of the program's progress on the computational process.

Once the calculations have finished, you will be presented with a series of "output" dialog boxes which displays calculated values based on your input data. Press "Next " button when you are ready to view the next calculation result.

You can press Help for more information about each dialog and its information, or click on one of the following links:

Percentage of Overweight Trucks Dialog
Truck Classification Data Dialog
Breakdown of Violations Dialogs
Severity of Violations Dialog
ESAL Data Dialog
Data File Conversion Dialog
Comparison of Enforcement Condition Dialog
Sampling Guide Dialog
Pavement Effects Analysis Dialog

The first M.O.E. dialog box, ***Severity of Violations,*** also reports summary information, i.e., enforcement condition, highway type, total vehicle, and truck sample. The violator numbers and average overweight values are indicated. Again, be reminded that displayed values, based on files BASELINE.PRN and ENFORCE.PRN, contain data generated by an over-calibrated Georgia LTPP system; and therefore the numbers are unrealistically large.

The ***Calculated Percentages of Overweight Trucks*** dialog box provides percentages of trucks in the sample which violate gross-, axle-, tandem-, tridem-, and Bridge Formula weight limits.

The ***Violation Data by Truck Classification*** dialog box indicates violators, by truck number and percentage, for each class of truck. Simply click on the truck classification list to the screen's left, and the statistics appear of the right side of the screen.

The ***Breakdown by Day-of-Week and Hour-of-Day*** dialog boxes provide violations by day and hour. However, day-of-week data were not coded for the sample data set and therefore results are not provided. Time-of-day violations are provided by indicating the five hours of the day (over the entire sampling period) when the most violations occurred. The level of those violations for each hour is shown. The sample data set contains only three hours of data.

The ***ESAL Data*** dialog box indicates average ESAL calculations using the FHWA *Traffic Monitoring Guide* procedure according to the number of axles. This dialog also indicates computed Excess ESAL violations by truck axle-count.

The next six dialog boxes contain the same M.O.E. calculations for Enforcement Condition #2.

Now, TWEET goes into its 'What does it all mean?' mode! The ***Comparison of Enforcement Conditions*** dialog box applies statistical significance tests to computed M.O.E.s and indicates to the user whether or not the observed differences are significant. For more information, see the Comparison of Enforcement Conditions Dialog Help screen..

The ***Sampling Guide*** dialog box is an aid to determine how many sites will needed to be surveyed in order to detect **regional changes** for designated M.O.E.s given specified levels of statistical confidence. The Sampling Guide Help screen will assist in your understanding what the statistical terms mean. It's not really that bad! This dialog box is based on an TWEET's analysis of the measured statistical characteristics of the observed M.O.E.s. The user is presented with a table indicating the number of sites which are required for data collection if specified levels of M.O.E.s changes are to be detected. The user will note that fewer sites are necessary for larger differences. This is due to the fact that smaller differences in real-world truck weight enforcement compliance are more subtle and therefore require more statistical rigor to detect.

The final dialog box presents results of the ***Pavement Effects Analysis***. This finding is based on a theoretical pavement design-life effect, associated with differential enforcement-related ESAL loading conditions. Had the user opted to include the pavement design-life effect computation, this screen would be displayed. Displayed information consists of the calculated pavement ESAL capacity, the estimated pavement life under both observed enforcement conditions, and estimated percentage pavement-life change due to the observed ESAL-loading difference associated with the enforcement activity.

Printing Out Results

Each out dialog box incorporates a Print button for the purpose of printing results shown. However, if you would like to print all of the results from your analysis rather than pressing the print button in every single output dialog box, press the Print Results button once the main window appears. This window (which incorporates the Start Analysis button for a new data computation) will appear following the output dialog boxes. The Print button in this dialog box will print all of the calculated results from the last analysis for both enforcement conditions

This concludes the Quick Start tutorial of the TWEET software. For more information, refer to any of the links in this topic, or read the printed documentation.

APPENDIX **H**

GLOSSARY OF TERMS

With Relevance to NCHRP Project 20-34

A

automatic vehicle identification (AVI) - AVI is one technology from the family of transportation technologies known as Intelligent Transportation Systems (ITS). AVI systems transmit data from a moving vehicle to data gathering centers via a communications device at the roadside. Agencies investing in AVI systems will use it to better monitor the types of trucks using a state's highways, whether specially permitted vehicles are traveling within permit bounds, and to ensure carriers are complying with all legal limits. AVI is also being used in some states along the I-75 corridor to allow legally registered and permitted carriers to bypass weigh stations between designated points on the highway.

axle - (1) the common axis of rotation of one or more wheels whether power-driven or freely rotating, and whether in one or more segments, and regardless of the number of wheels carried there-on; (2) a shaft on which or with which two or more wheels on a vehicle revolve; (3) the pin or shaft with which a wheel or pair of wheels revolves. Axles have federally designated weight limits, according the overall size and gross vehicle weight of the truck.

axle group - (1) an assemblage of two or more consecutive axles considered together in determining their combined load effect on a bridge or pavement structure; (2) two or more consecutive axles considered together in determining their combined load effect on a bridge or pavement structure.

axle load - the weight carried by one axle of a vehicle.

axle spacing - the distance between two consecutive axles of a truck or combination, usually measured from the point of ground contact of one tire to the same point on the other tire or from a point on an axle hub to the same point on the other axle hub.

axle weight - the weight transmitted to the surface by one axle or a combination of axles in a tandem assembly.

B

base course- the layer or layers of specified or selected material of designed thickness placed on a subbase or a subgrade to support a surface course.

bills of lading - Bills of lading, and other carrier documentation, specify the commodity, weight of the load, and provide other details about the transaction between shipper and receiver. Bills of lading and other documentation can be used by motor carrier enforcement officials to examine systematic violations of weight laws. (See Relevant Evidence)

bingo stamp - A bingo stamp is a stamp purchased by a carrier for all vehicles in its fleet that is expected to operate within a particular state jurisdiction within that year. These identification stamps are proof that the carrier has obtained the appropriate operating authority for that vehicle. These stamps must be affixed to a Form D or D-1 Cabcard and must be displayed in the cab of each vehicle. A stamp requires a fee that ranges from $1 to $11, depending on the state.

bridge formula - a standard to control the spacing of truck axles on vehicles that use highway bridges.

bridge formula limit - the Federal law states that any group of two or more consecutive axles may not exceed the weight as computed by the Bridge Formula even though the single axle, tandem axles, and gross weights are within legal requirements.

bypass - routes (usually state roads) which allow a truck to go around weigh stations, which are typically located on the interstate system, and to avoid safety and weight inspections.

bus - a motor vehicle designed primarily for the transportation of persons rather than property and having a passenger-carrying capacity of 10 or more persons, other than a taxicab constructed and designed for transporting persons for commercial purposes.

C

cargo - the items of freight to be moved; including items placed on or in a vehicle, towed by a vehicle, or a vehicle itself.

combination - (1) a truck or tractor coupled to one or more trailers (including semitrailers); (2) a power unit used in combination with trailers and semitrailers.

commercial vehicle - Any vehicle that has a GVW or GCW of 10,001 pounds or more; or, the vehicle is designed to transport more than 15 passengers including the driver; or, a vehicle used for transporting hazardous materials requiring placarding.

compliance reviews - Compliance reviews are conducted on carriers with unsatisfactory safety review ratings (see "Safety Reviews"). These reviews identify safety-related violations, levy fines, and require correction of all problems within 45 days. If a carrier has not qualified for a conditional or satisfactory safety review rating by the end of the 45 day period, the carrier is prohibited from transporting hazardous materials or passengers.

connecting mechanism - an arrangement of parts interconnecting two or more consecutive axles to the frame of a vehicle in such a manner as to equalize the load between axles.

cost-effectiveness - the situation that exists when the benefits exceed the costs for a given treatment, strategy, or improvement or when the benefit cost ratio is greater than one.

credentials - term used to describe all paperwork a truck driver is required to have processed and have copies available for inspection throughout the duration of a truck trip.

D

dynamic weight - the weight of a vehicle or an individual axle as measured while the vehicle is in motion.

E

ESAL - equivalent single axle load.

equivalent axle load (EAL) - the damage per pass to a pavement caused by a specific axle load relative to the damage per pass of a standard 18,000 point axle load moving on the same pavement.

equivalent single axle loads (ESALs) - the unit of measurement equating the amount of pavement consumption caused by an axle or group of axles, based on the loaded weight of the axle group, to the consumption of a single axle weighing 18,000 pounds. The summation ESALs is used to combine mixed traffic to design traffic for the design period.

Excess ESALs - excess ESALs equal the sum of the total ESALs attributable to the illegal portion of the individual single or tandem axle group.

F

fines - are payments levied to deter potential and repeat offenders from traveling illegally, and to recover administrative, court, and jail costs incurred in processing citations. Theoretically, the amounts of the fine levied are related to the amount of damage imposed on the road by an illegally overweight vehicle. Fine revenues are distributed differently in all states.

fixed weigh station - A weigh station is a facility, usually located on the interstate highway system, at which trucks can undergo weight and safety inspections. There are weigh scales and often (but not always) a scale house to house inspectors between trucks.

flexible pavement - a pavement structure which maintains intimate contact with and distributes loads to the subgrade and depends on aggregate interlock, particle friction, and cohesion for stability.

friction number (skid number) - the number that is used to report the results of pavement friction tests conducted in accordance with ASTM Standard E274.

fuel tax - All states have some form of tax on diesel fuel or a substitute fee or usage type of tax which replaces the revenues that the diesel fuel tax would otherwise generate. Motor fuel taxes are sometimes called "second structure" taxes, because they were the second major source of highway revenues to be introduced. In most states, they are the largest source of motor carrier-related state tax revenue. Intrastate vehicles, by the nature of their operations, pay their fuel taxes on fuel that is both purchased and consumed in the same state. However, large trucks can travel long distances without refueling, so it is easy for interstate operators to cross entire states without paying fuel taxes at the pump. Because of this, most states have instituted a procedure for motor carrier fuel use taxes in which a truck operator is responsible for reporting state mileage traveled, calculating fuel consumed within the states, and paying the taxes calculated as being due on the fuel consumed in that state.

Originally, each state had its own fuel tax reporting requirements. However, the International Fuel Tax Agreement (IFTA) and the Regional Fuel Tax (RFTA) were formed about 12 years ago to encourage uniform administration of the fuel tax laws, and to establish a base state arrangement for collecting and administering fuel taxes.

full trailer - a truck trailer with wheels on the front and rear (as opposed to a semitrailer in which the front rests on the rear of the tractor).

G

gross combined weight (GCW) - The weight of the power unit and trailer and the maximum payload.

gross vehicle weight (GVW) - The weight of the vehicle plus the weight of any load thereon.

gross weight - the weight of a vehicle and/or combination of vehicles plus the weight of any load thereon.

H

heavy truck - a term used to describe a truck weighing in excess of 80,000 pounds of gross vehicle weight.

Heavy Vehicle Use Tax (HVUT) - The Heavy Vehicle Use Tax is a federal tax levied on all common and contract carriers. It is an annual tax on carriers with registered gross vehicle weight, or gross combination weights, over 55,000 pounds. This tax is intended to cover pavement damage caused by heavy vehicles. Before a carrier can be registered, the owner must show that it has properly paid this federal tax.

height - the total vehicle dimension of a vehicle above the ground surface including any load and load-holding device thereon.

HELP - Heavy Vehicle Electronic License Plate Project--a project that (among other achievements) set early standards for weigh-in-motion equipment.

I

International Registration Plan (IRP) - an agreement between states for prorating fees between jurisdictions based on percentage of miles traveled by a fleet in each jurisdiction.

inspection levels - This refers to the five levels of inspection carried out as part of the Motor Carrier Safety Assistance Program (MCSAP). These levels are: Level 1, the North American Standard, is the most thorough inspection. Conducted at the roadside, it covers both the driver and the vehicle, and includes inspecting underneath the vehicle. Level 2 is the same as Level 1, except that it does not include inspecting underneath a vehicle, while Level 3 covers only the driver. Level 4 is a special inspection of a particular item generally done in support of a study or to check a suspected trend. Level 5 is the same as Level 1, except that it is conducted at the terminal and does not include inspection of the driver.

International Fuel Tax Agreement (IFTA) - This agreement was established about twelve years ago to encourage uniform administration of the motor fuel taxation laws, and to establish a base state arrangement for collecting and administering fuel taxes. Licensing with the base state satisfied a carrier's fuel tax licensing obligations to all members and the base state distributes payments and collects refunds for its carriers. The base state issues an external fuel tax decal for each fleet vehicle, and these decals are reissued annually. The base state may levy a fee for the decal on its own carriers, but may not collect fees imposed by other states. The IFTA covers the same class of vehicles as does IRP, but differs in that reporting is by fleet, rather than by individual vehicle. As is the case with IRP, a vehicle which needs to travel in a state for which its fleet is not apportioned under IFTA must obtain a temporary fuel tax permit for that state.

International Registration Plan (IRP) - This is the most widely used cooperative agreement for collecting and apportioning registration revenues from interstate motor carriers. All states were required to join the IRP system by September 30, 1996. It covers the United States and Canadian provinces. The distinguishing features of IRP are base state registration and auditing; a single license plate; and one cab card showing IRP registration. IRP is administered by the American Association of Motor Vehicle Administrators (AAMVA).

IRP provides for the payment of registration fees prorated according to fleet miles operated in various jurisdictions by vehicles over 26,000 pounds gross weight, or with at least three axles. When a motor carrier initially registers with IRP, it must select a "base jurisdiction" in which to file. For fleet registration purposes, the base jurisdiction is where the motor carrier has an established place of business, where mileage is accrued by the fleet, and where operational records of the fleet are maintained or can be made available for audits. The IRP application with the base states requires, at a minimum, the number of power units, trailers, semi-trailers, and auxiliary axles. The motor carrier must also include any additional information required by the particular base state in which it is filing, and any other state through which it will be traveling. Each apportioned carrier must file an annual report to its base state, reporting mileage and registered weight in each state for the preceding year as part of its renewal application for the coming year's IRP registration. Under IRP, each carrier makes a single payment to the base state. Most carriers rely on their base state to calculate their IRP fees and bill them for the appropriate amount. Or, a carrier makes a single payment to the base state. That state must calculate and remit the amount due to all other IRP member states based on the reported mileage for each jurisdiction. Carriers must maintain records of each vehicle's mileage by registered weight in every state for audit purposes.

J

K

L

layer coefficient (a_1, a_2, a_3...)-The empirical relationship between structural number (SN) and layer thickness which expresses the relative ability of a material to function as a structural component of a pavement.

length - the total longitudinal dimension of a single vehicle, a trailer, or a semitrailer. Length of a trailer or semitrailer is measure from the front of the cargo-carrying unit to its rear, exclusive of all overhand, safety or energy efficiency devices, including air conditioning units, air compressors, flexible fender extensions, splash and spray suppressant devices, bolsters, mechanical fastening devices, and hydraulic lift gates.

level of statistical significance - the probability which the user is willing to risk the error of rejecting a valid change in M.O.E. occurrence.

life-cycle costing - an economic assessment of an item, area, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars.

load - a weight ot quantity of anything resting upon something else regarded as its support.

M

maintenance - the preservation of the entire roadway, including surface, shoulders, roadsides, structures, and such traffic control devices as are necessary for its safe and efficient utilization.

measures of effectiveness (M.O.E.s) - determinable quantities of what is achieved as the result of truck weight enforcement activity or program. Their application also quantifies the contribution that activity makes tower achievement of one ore more of the enforcement goals.

mobile patrols - Mobile patrols are weight or safety inspection teams which patrol portable scales or other portable inspection equipment. They are most frequently used in conjunction with fixed weight stations, although in some states can be the sole method of enforcement. There are two types of mobile enforcement: wing and portable. Wing patrols occur on bypass routes around fixed weigh stations and can be scheduled either as a special detail or as an ongoing operation. Portable enforcement occurs in areas where there are no weigh stations, and inspectors carry semi-portable ramp scales in their vehicles. Portable enforcement with semi-portable ramp scales is also often used in conjunction with wing patrols, depending on the configuration of road network, known truck travel patterns, and the availability of bypass routes.

modulus of subgrade reaction (k)-Westergaard's modulus of subgrade reaction for use in rigid pavement design (the load in pounds per square inch on a loaded area of the roadbed soil or subbase divided by the deflection in inches of the roadbed soil or subbase,(psi/in.).
monitoring data - those annual traffic loading estimates made from data collected specifically to meet the needs of the LTPP study. (see *historical estimates*.

Motor Carrier Management Information System (MCMIS) - MCMIS is the central federal repository of comprehensive safety data on more than 265,000 interstate motor carriers. Information is kept on a central mainframe computer and is exchanged electronically with computers in all federal field offices and MCSAP state offices using SAFETYNET software. The FHWA uses MCMIS data to set priorities and targets for conducting safety and compliance reviews, compile safety profiles of key data to support state and federal investigations, and make safety fitness ratings available in response to public and private inquiries. MCMIS also includes data on motor carrier accidents, safety and compliance reviews, and fitness ratings.

Motor Carrier Safety Assistance Program (MCSAP) - This program was established by Title IV of the Surface Transportation Assistance Act of 1982 to get potentially unsafe drivers and imminently hazardous vehicles off the road. This was done by substantially increasing the level of safety enforcement activity. MCSAP provides grants to states for the enforcement of federal (or compatible state) motor carrier safety regulations through roadside driver and vehicle inspections. MCSAP safety inspections are conducted under the auspices of the Commercial Vehicle Safety Alliance (CVSA).

motor vehicle - a vehicle which is self-propelled or propelled by electric power obtained from overhead trolley wires, but not operating upon rails.

N

national truck network - those interstate and other federal-aid primary highways on which commercial vehicles of the dimensions authorized by the STAA of 1982 are allowed to operate.

O

open/close strategy - This is a specific type of fixed weigh station operating strategy in which scales at weight stations are only open for two or three hours at any given time. After this time, a reduction in the number of overweight vehicles coming through the facility typical occurs. When this happens, the weight enforcement officials close the fixed scales and instead shift weight operations to bypass routes using portable scales stored in enforcement vehicles.

operating authority - The Interstate Commerce Commission (ICC) was granted authority to regulate the interstate motor carrier industry by the Motor Carrier Act of 1935. Eligible carriers are awarded operating rights, known as operating authority, by the I.C.C. The authority specifies the products the carrier may haul, and where it may haul them. In return for these operating rights, a carrier is obligated to provide reasonable service to the public and just, fair, and reasonable rates, classifications, and practices. Most states require that a copy of the ICC authority be filed with the state. In addition to the registration of operating authority, carriers generally also must identify the vehicles operating under those rights, present evidence of insurance and designate a resident process agent.

In addition to ICC operating authority, many states require carriers to obtain operating authority from the state as well. This may be issued by transportation commissions, public service commissions, utility commissions, state corporation commissions, or state departments of transportation. In some states, multiple agencies may grant operating authority, depending on whether the carrier is an intrastate carrier or an ICC regulated interstate carrier.

Most states require both intra- and interstate carriers to obtain operating authority. However, in a few states (Hawaii, Maryland, Nevada, New Jersey, and Pennsylvania), only intrastate carriers are required to file for operating authority; seven states (Alaska, Arizona, Delaware, Florida, Vermont, Wyoming, and the District of Columbia) have eliminated this regulation entirely.

out-of-service - If a violation found during the course of a weight or safety inspection is considered to pose an immediate danger to the public, the vehicle is pulled immediately out-of-service. A driver found to have an out-of-service violation during an inspection may not drive until the applicable violation has been corrected. Similarly, vehicles with an out-of-serve violation may not be operated until the violation has been fixed.

overweight - over the Federal or State legal restrictions for single axle weight, tandem axle weight or gross weight.

P

pavement condition - a quantitative representation of distress in pavement at a given point

pavement distress - the physical manifestations of defects in pavement at a given point.

pavement maintenance - all routine actions, both responsive and preventative, which are taken by the state or other parties to preserve the pavement structure, including joints, drainage, surface, and shoulders as necessary for its safe and efficient utilization.

pavement management system - a set of tools or methods that assist decision-makers in analyzing and designing cost-effective pavement construction, rehabilitation, and maintenance programs.

pavement performance - the trend of serviceability with load applications.

pavement structure - a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed.

pavement structure - the combination of subbase, base course, and surface course placed on an earth subgrade to support the traffic load and distribute it to the roadbed.

performance period - the period of time that an initially constructed or rehabilitated pavement structure will last (perform) before reaching its terminal serviceability; this is also referred to as the *design period*.

permit - in common usage, the written permission issued by a jurisdiction allowing specified operation. In IRP states a **Trip Permit** is a temporary permit issued by a jurisdiction to a motor carrier registered in another jurisdication in lieu of regular apportioned registration. Other temporary permits issued for varying lengths of time include **Oversize\Overweight Hauling Permits** and **Temporary Fuel Use Tax Permits**. The **Fuel Use Tax Permit** issued in Maryland for an entire year is called a decal or identification marker.

portable scale - a scale of such size and weight as to be readily transportable from station to station.

port-of-entry (POE) - A port-of-entry is a fixed weigh station located at the border between states. It serves as a gateway to a state's interstate and state highway system. States which use weigh stations as ports-of-entry have roadway configurations which have a limited number of access/egress points to that state so that carriers have few or no choices of routes which bypass the entry point.

power of statistical test - the likelihood of making a correct statistical assessment the proper hypothesis is accepted. The issue is to what extent is the user willing to risk accepting an invalid change in MOE occurrence.

pre-clearance - a pre-clearance system uses Intelligent Transportation System (ITS) technology to allow carriers traveling legally to bypass weigh stations. A truck carrying automatic vehicle identification (AVI) transponder tags approaches the first open weigh station after entering a highway corridor. A roadside reader system in advance of the weigh station will read the truck identification transponder. The AVI reader will pass the truck identification to the weigh station computer. The station computer checks for that truck, and finding no current data on axle weights or spacing information, directs the truck (with either a communication via the transponder or through the use of a variable message sign - VMS) to make a normal entry into the weigh station. Another AVI reader within the weigh station will again read the truck identification transponder as the truck passes and again will pass the identification to the weigh station computer. The computer will execute a processing sequence to automatically acquire axle and gross vehicle weights, verify legal weight in that jurisdiction, and check that the operating credentials are valid. If all conditions are proper, the truck is directed back to the mainline. A "trip data packet" is created containing the just-collected truck identification and weight data and will be transmitted to the next downstream weigh station. As the truck approaches the next weigh station, the AVI reader again automatically reads the truck identification on the transponder, and the weigh station computer checks for a matching trip data packet, indicating that the truck has been previously weighed upstream. If so, the trip packet with weight and axle spacing data will be on file, as well as all associated credential data. All credentials are checked at the current location to determine if the truck is legal and compliant. Since the processing time for weight and credentials compliance is virtually instantaneous, while the truck is on the mainline highway approximately one-half mile before the weigh station entry ramp, if all weights and credentials are legal, the truck driver is notified via an in-cab display that he or she is precleared and authorized to continue on the highway without entering the weigh station.

present serviceability index (PSI,p)-A number derived by formula for estimating the serviceability rating from measurements of certain physical features of the pavement.

Q

quality control - the process used to ensure that data submitted to LTPP meets expected levels of quality. QC is usually performed by comparing submitted data against an expected "norm."

R

reliability - is the degree of stability exhibited when a measurement is repeated under identical conditions. With regard to truck weight enforcement MOEs, the concept is of paramount importance in recommending weight-gathering procedures which are applied to obtain the measures.

regular operation - the movement over highways of vehicles, vehicle combinations, and loads thereon, subject to the recommended limitations contained in this guide governing maximum weights and dimensions for motor vehicles and loads thereon.

relevant evidence - relevant evidence is a type of illegal overweight truck enforcement which relies on the carriers' documentation to provide proof of an illegal trip. Documentation includes bills of lading, weight tickets, and other shipping documents which indicate the weight of a truck to be used. Relevant evidence laws allow a state to penalize truck drivers, truck owners, and shippers who operate a load or vehicle above the legal limits in that state. The advantage of this type of enforcement is that troopers or inspectors are not limited to identifying and citing illegal loads only while on the roadway. In addition, in states which have relevant evidence legislation, violations cited under these laws are brought to civil action instead of criminal action, which means that it is less likely that the case will be overturned (The standard of proof in civil cases is usually by a "preponderance of evidence" rather than proof beyond a reasonable doubt.). The disadvantage of relevant evidence is that it is only enforceable with gross weight limits, since shipping documents do not reflect axle weights, bridge formula weights, or tire width weights.

rigid pavement - a pavement structure which distributes loads to the subgrade, having as one course a portland cement concrete slab of relatively high-bending resistance.

S

SAFETYNET - This is a distributed system for managing safety data on both interstate and intrastate motor carriers and for federal and state offices to electronically exchange data on interstate carriers with MCMIS.

safety review - Safety reviews are conducted on-site at company office by federal field staff, or by state staff under the MCSAP program. It inspects compliance with critical driver and vehicle safety regulations. Passenger and hazardous materials carriers are given the highest priorities for review. Safety reviews involved examining company records to ensure that a carrier meets all safety-related regulations and has no unsafe operating practices. Each company receives a rating as satisfactory, conditional, or unsatisfactory, based on the outcome of the review. Carriers with less than satisfactory ratings are told how to become compliant, but there is no enforcement power associated with safety reviews. Companies receiving satisfactory ratings do not usually receive another safety review unless the company begins to fail MCSAP safety inspections, is involved in accidents, or is the subject of a complaint. (See Compliance Review)

scale tolerance - an allowable variation in the static weight of an axle load in accordance with, but not exceeding the precision of the scale involved.

semitrailer - every single vehicle without motive power designed for carrying property and so designed in conjunction and used with a motor vehicle that some part of its own weight and that of its own load rests or is carried by another vehicle and having one or more load-carrying axles.

sensitivity - the sensitivity of an MOE can establish that the applied measure produced a true indication of the sought attribute or condition. With regard to truck weight MOEs, we need experimental assurance that application of the MOE is a true indication of truck weight enforcement effects, i.e. the validity criterion is met.

serviceability - the ability at time of observation of a pavement to serve traffic (auto and trucks) which use the facility.

SHRP - Strategic Highway Research Program - a state sponsored research program designed to perform large-scale highway research on long-term pavement performance, asphalt, and portland cement concrete materials, and maintenance procedures.

single axle - (1) an assembly of two or more wheels whose centers are in one transverse vertical plan or may be included between two parallel transverse planes 40 inches apart extending across the full weight of the vehicle; (2) an axle on a vehicle that is separated from any pervious or succeeding axle by more than 2.44 meters (96 inches).

single axle load - the total load transmitted by all wheels whose centers may be included between two parallel transverse vertical planes 40 inches apart, extending across the full width of the vehicle.

single axle weight - the total weight transmitted by all wheels whose centers may be included between two parallel transverses vertical planes 1.02 meters (40 inches) apart, extending across the full width of the vehicle.

SN - (See structural number) - used to describe the strength of asphalt pavements.

special permit - a written authorization to move or operate on a highway a vehicle or vehicles with or without a load of size and/or weight exceeding the limits prescribed for vehicles in regular operation.

special permits - States issue permits for both regular and "special" (i.e. oversize and overweight) loads to travel off the interstate system on state roads. Special loads are indivisible, greater than 80,000 pounds gross vehicle weight, and exceed the axle weights and spacing specified by the federal bridge formula. Special permitting regulations vary widely, and sometimes conflict among states. In many cases, local geography, weather, population, or highway and bridge construction methods impose particular size and weight limits. In other cases, differences have developed over time in the absence of incentives to standardize these regulations.

States have varying fee structures for special permits based on incremental vehicle weights. Except in states with weight/distance taxes and a few other states, the fees for special permits in general are intended only to cover the administrative cost of issuing the permit, and are also grossly related to the amount of pavement damage caused by oversize or overweight vehicles on state roads. States must also verify that the vehicles Heavy Vehicle Use Tax (HVUT) has been paid before a special permit can be issued. Verification of special permits is done during a weight inspection if a truck weighs more than the allowable legal gross or axle weights.

special permit application - an individual, firm, partnership, corporation, or association making application for a special permit to transport a vehicle, vehicles, and/or load which is oversize or overweight and under whose authority and responsibility such vehicle or load is transported.

spread tandem - two axles that are articulated from a common attachment but are considered as two single axles rather than one tandem axle because they are separated by more than 2.44 meters (96 inches).

static scale - a scale that requires that a vehicle be stopped to be weighed.

steering axle - (1) the axle or axles of a motor vehicle or combination of vehicles by which the same is guided or steered; (2) the axle to which a vehicle's steering mechanism is affixed.

straight truck - a self-propelled vehicle designed and used for the transportation of property and not including tractors.

structural number (SN) - an index number derived from an analysis of traffic, roadbed soil conditions, and environment which may be converted to thickness of flexible pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer of the pavement structure.

subbase - the layer or layers of specified or selected material of designed thickness placed on a subgrade to support a base course (or in the case of rigid pavements, the portland cement concrete slab).

subgrade - the top surface of a roadbed upon which the pavement structure and shoulders are constructed.

surface course-One or more layers of a pavement structure designed to accommodate the traffic load, the top layer of which resists skidding, traffic abrasion, and the disintegrating effects of climate. The top layer of flexible pavements is sometimes called "wearing course."

T

traffic equivalence factor (e)-A numerical factor that expresses the relationship of a given axle load to another axle load in terms of their effect on the serviceability of a pavement structure. In the AASHTO Guide all axle loads are equated in terms of the equivalent number of repetitions of an 18-kip single axle.
tandem axle - any two axles whose centers are more than 1.02 meters (40 inches) but not more than 2.44 meters (96 inches) apart and are individually attached to or articulate from, or both, a common attachment to the vehicle including a connecting mechanism designed to equalize the load between axles.
tandem axle load - the total load transmitted to the road by two consecutive axles whose centers may be included between parallel vertical planes spaced more than 40 inches and not more than 96 inches apart, extending across the full width of the vehicle.

tandem axle weight - the total weight transmitted to the road by two or more consecutive axles whose centers may be included between parallel vertical plans spaced more than 1.02 meters (40 inches) and not more than 2.44 meters (96 inches) apart, extending across the full width of the vehicle.

TMG - Traffic Monitoring Guide (the handbook FHWA distributes that provides guidelines for collecting statewide traffic information for submittal to the federal government).

tractor - a vehicle designed and used primarily as the power unit for drawing a semitrailer or trailer.

trailer - every single vehicle without motive power designed for carrying property wholly on its own structure, drawn by a motor vehicle which carries no part of the weight and load of the trailer on its own wheels and having two or more load carrying axles.

traveled way - the portion of the roadway for the movement of vehicles, exclusive of shoulders and auxiliary lanes.

tridum axle - any three consecutive axles whose extreme centers are not more than 144 inches apart, and are individually attached to or articulated from, or both, a common attachment to the vehicle including a connecting mechanism designed to equalize the load between axles.

truck - a motor vehicle designed, used, or maintained primarily for the transportation of property.

truck tractor - a motor vehicle used primarily for drawing other vehicles and not so constructed as to carry a load other than a part of the weight of the vehicle and load so drawn.

U

V

validity - the validity of a measure refers to the degree to which it actually measures what it is designed to measure. For example, measurement of truck weight does not pose a threat to validity, i.e. cargo in a container displaces the container downward; and the gravitational pull on the truck and cargo can be reliably registered on a calibrated index, which reads "pounds" or "ESALs."

vehicle - a device in, upon, or by which any person or property may be transported or drawn upon a highway, except devices moved by human power or used exclusively upon stationary rails or tracks.

vehicle combination - an assembly of two or more vehicles coupled together for travel upon a highway.

vehicle registration - all trucks are required to register with a state before traveling through that state. "Trip permits" are issued for the trip for which the truck is traveling, or a truck may be registered under the International Registration Plan (IRP). Vehicle registration trip permits are a form of temporary vehicle registration for an out-of-state vehicle that does not have registration in the state through which they are traveling, or not apportioned under IRP.

All states collect fees for the registration of trucks traveling within their state. Registration fees, known as "first structure" taxes, are the oldest form of vehicle taxation, and have been in use for over 80 years. There are the second most important source of revenue (next to fuel taxes). Basically a form of capital equipment tax, these fees must be paid before a vehicle can be legally operated.

vehicle titling - A motor carrier operator must show proof of ownership by registering the title of the vehicle with the state in which it is stationed.

W

weight-in-motion - the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, and/or axle group, by measurement and analysis of dynamic forces applied by its tires to a measuring device.

Weigh-in-motion is one technology from the family of transportation technologies known as Intelligent Transportation Systems (ITS). A WIM system is a set of sensors and supporting instrumentation which measure the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time. The system estimates vehicle weights, speed, axle spacing, and vehicle class according to axle arrangements and other parameters concerning the vehicle, and processes, displays, and stores the information. WIM systems are installed in the pavement on highways or on bridges and determine the weight of vehicles passing over them by measuring the vertical component of dynamic force that is applied to the road surface by the wheels of the moving vehicle.

There are a number of vehicle factors which affect WIM accuracy, such as how the gross vehicle weight in distributed within the truck, vehicle movement affecting the suspension system, tire tread and inflation pressure, dynamic balance and wear, and vehicle aerodynamic characteristics. Roadway factors that affect accuracy include the vertical and horizontal alignment of the roadway, and the transverse slope of each lane. WIM accuracy also suffers in adverse weather conditions such as ice and snow at the sensor location and individual differences in the sensitivity of each

instrument. For these reasons, violations are not issued using WIM yet. It is almost exclusively used for either data collection, or to screen trucks on weigh station access lanes, rather than for direct enforcement activities.

weight-in-motion scale - a scale that allows vehicle weights to be electronically recorded as the vehicle passes over the scale without stopping.

weight station - a location equipped with weight scales at which the axle weights and gross weights of vehicles are determined.

weight violation - a single axle weight, axle group weight, or gross weight of a vehicle exceeding the maximum allowed weight for that vehicle.

wheelbase - the distance between the front and rear axles of a vehicle, or the center point of contact of the front and rear wheels with the ground.

width - the total transverse dimension of a vehicle including any load or load-holding devices thereon, but excluding approved safety devices and tire bulge due to load.

X

Y

Z