Investigation of a Comprehensive Truck Weight Data Collection Plan Using Low Cost Permanent and Portable Weigh-in-Motion Equipment

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ABSTRACT

The Washington State Department of Transportation (WSDOT) and the Washington State Transportation Center (TRAC) are currently investigating existing weigh-in-motion (WIM) technologies for use in a comprehensive, low cost truck weight data collection program. TRAC and WSDOT are examining the feasibility of using low cost, piezo-electric cables as permanent and semi-permanent WIM stations, and using medium cost bridge WIM equipment for providing portable, short duration WIM stations. The piezo-electric stations will provide estimates of seasonal and temporal variations in truck weights at a variety of locations throughout the state and will tie into the existing telemetry system. This information can then be used for seasonally adjusting truck weight data collected over short time periods as well as providing extensive truck information for selected roads. Use of bridge WIM will allow the state to inexpensively collect truck weight information at particular sites, as required by a statistical sampling plan or as needed for particular projects. Sites that are unfit for bridge WIM (due to a lack of bridges or bridges unsuited to the system) can still be examined by cutting the pavement and installing piezo-electric cables at an intended cost of roughly $5,000 per lane.

INTRODUCTION

Truck weight data is collected for a wide variety of purposes by almost all highway authorities. Unfortunately, the data collected is almost always far less than optimal in quantity and quality due to the costs involved in collecting that information. However, technological advances being made in the electronics industry are showing promise of providing the required information at more reasonable costs.

Because cost constraints in weight data collection have existed for so long, little has been written about the appropriate level of truck data that should be collected if given either unlimited resources or new technology which could collect that information within available resources. This paper proposes such an "ideal" truck weight monitoring plan, based on the needs of pavement designers and the potential capabilities of the emerging truck weigh-in-motion (WIM) technologies.

BACKGROUND

WSDOT currently collects truck weight data for non-enforcement purposes in a manner similar to that followed by many other U.S. state agencies, that is,

- using portable scales,
- once a year (or once every other year in some states),
- at a limited number of locations, and
- for a limited number of hours at each location.

With the exceptions of a gradual upgrading in the equipment used and periodic changes in the dates and locations where weighings occur, the collection of truck weight information in Washington has changed very little since the implementation of the U.S. biennial truck weight survey.

The collection of data is performed by WSDOT crews using highly visible, slow speed WIM scales. The system functions well in terms of crew safety and accuracy of the truck weight data collected, but the data collection suffers because overweight

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trucks often by-pass the scales, and because the manned operation causes the Department to avoid weighing trucks in many locations and at some hours at other locations because of cost and safety concerns. The result is that the data collected is not always representative of trucks in the state and usually under-represents the number of overweight vehicles on the highway system.

WIM SYSTEMS

With the appearance of the first generation of WIM equipment (Streeter-AMET, Radian, IRD, etc.), many states (although not Washington) have had their first opportunity to install scale systems that automatically collected truck weight information throughout the year. These systems

- have allowed screening operations at enforcement scales,
- have provided the opportunity to collect dynamic loading information, and
- have permitted the inconspicuous weighing of vehicles at highway speeds.

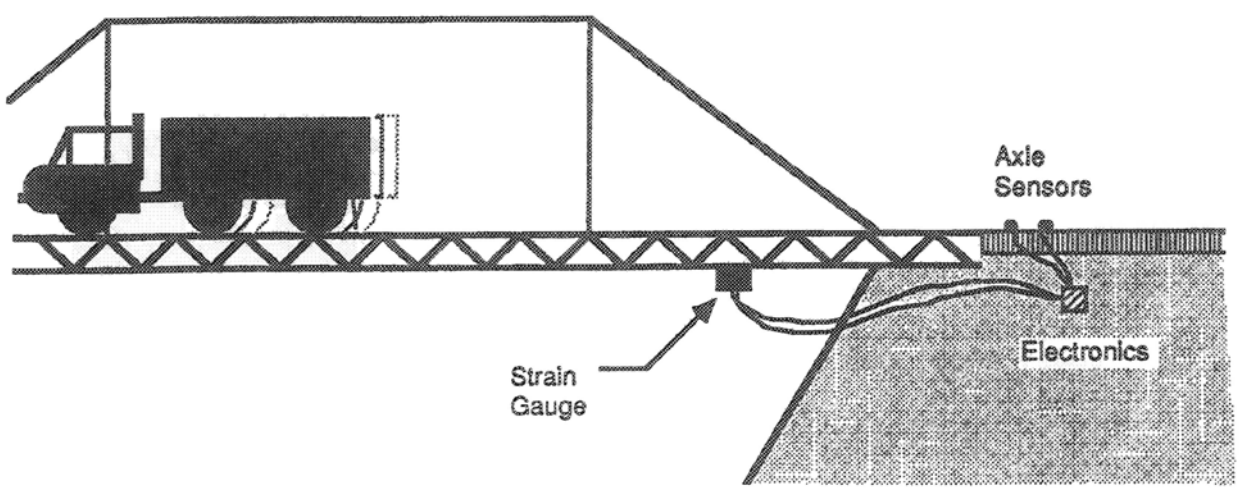
The primary drawback to these systems has been their cost. Most of these systems have cost well over $100,000 for equipment and software and have required considerable additional expenditures for placement in the pavement. The result is that although these scales can provide excellent data, they have been too expensive to install throughout the state.

As might be expected, the advantages of WIM systems and the limitations in this first generation of equipment have caused a considerable interest in producing more accurate, lower cost high speed truck scales. The next generation of WIM equipment is just coming of age. This equipment currently runs in the moderate cost spectrum ($30,000 to $100,000 for equipment with little or no installation cost), with development efforts under way to bring costs down even further. Several scale systems under development may provide accurate axle weights for as little as $5,000 per location. This figure represents the cost desired for scales to be used in such projects as the Crescent Program and Strategic Highway Research Program (SHRP).

The three most promising new technologies in this moderate to low cost spectrum include

- bridge systems,
- piezo-electric systems, and
- capacitor pad systems.

Figures 1, 2 and 3 illustrate WIM sites using these technologies. Of these technologies, only the bridge system is currently used in the United States as part of the routine vehicle weight data collection effort of state highway agencies. The states of Oregon, Ohio, Utah, Idaho and Maryland have used or are using bridge WIM. The states of Washington, Iowa and Minnesota are currently testing piezo-electric systems. Arizona recently



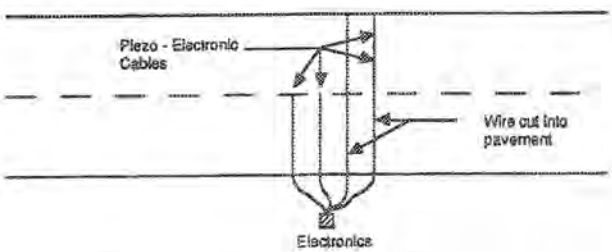
Bridge WIM location

FIGURE 1

completed development of a capacitor pad system, which is currently being marketed.

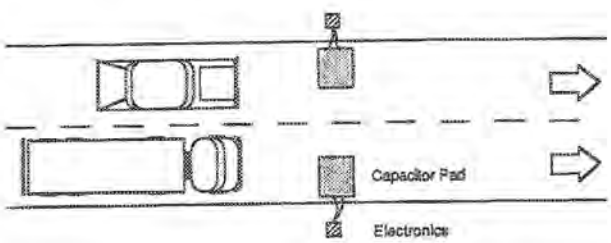
The bridge and capacitor systems are both essentially portable systems, not designed for permanent placement in the roadway, although some work is under way to examine their potential as permanent stations. The piezo-electric system is viewed as a semi-permanent system. Piezo cables (or other piezo-electric sensors) are installed in the roadway, requiring a crew to cut pavement and install the cable, but electronics are attached or detached at the state's convenience (in much the same way as the 55 mph speed studies, currently mandated by U.S. federal law, are conducted). The current life span of installed cables is under examination, although weather, truck volume and maintenance operations appear to be the primary causes of cable failure.

Bridge systems could also become semi-permanent weigh stations if the industry were able to develop an axle sensor that was inexpensive, accurate, and sufficiently durable to allow continuous monitoring without human intervention over the course of a year. Piezo-electric cable is one possible solution to this need.



Piezo-electric cable – WIM installation

FIGURE 2



Capacitor pad – WIM installation

FIGURE 3

ACCURACY OF NEW WIM SYSTEMS

It is hard to quantify the true magnitude of the "normal" errors associated with using these new technologies to estimate static axle weights on moving vehicles. For the most part, studies have indicated that these new systems tend to be slightly less accurate (when trying to estimate static weights) on a truck by truck basis than their more expensive, first generation counterparts. This increase in error seems more related to road condition and speed of vehicles than a result of limitations in the technology. Because these systems are designed to be easily placed on most roadways without extensive road reconstruction, the sensors are susceptible to a greater amount of dynamic load movement than many of the original WIM scales. It is this increase in dynamics that have caused the majority of observed increases in error.

Despite the increased error associated with the new systems, they do represent a large reduction in cost for the amount of data they can provide, and because the dynamic errors that are present tend to be randomly distributed, the newer systems provide estimates of average weight/truck that are similar to both static and first generation dynamic weights.

USES OF DATA

The system presented in this paper was developed to directly meet the truck data needs identified in a previous series of WSDOT research efforts and shown in Table 1. Each need controls how much information is collected and how accurate that information should be, given the financial impact of that need on WSDOT. For example, if truck weights are under-estimated for a pavement overlay project, the pavement placed at that location will deteriorate before its design life is reached, causing WSDOT to expend funds for repair that could otherwise have been used elsewhere. On the other hand, if weights are over-estimated, WSDOT must pay for placing more pavement than is required, thus expending funds that could be better utilized elsewhere. The more accurate the data used in the design, the more likely the design will optimize WSDOT's costs.

The uses for truck weight information can normally be broken into two basic, functional categories. These include weight information for use in

- taxation and weight enforcement, and
- engineering design and planning.

The uses within each of these areas are discussed below.

TAXATION AND ENFORCEMENT

Washington State taxes trucks based on their designated gross vehicle weights. The state does not use a weight/distance tax. Consequently, Washington State's major need for weight data in this area is for use in enforcement of the weight laws.

Because of the dynamic effects of moving trucks, WIM is not sufficiently accurate to use as a basis for writing citations for overloaded axles, gross weights or bridge formula violations without stopping vehicles to allow for static weighings. It is possible that WIM data (particularly low cost WIM data, for which pavement smoothness improvements can not be made) will never be sufficiently accurate to allow these weighings. Accuracies may become good enough, however, that such systems can be used to monitor overload usage of roads when enforcement officers are not present (thus better determining the extent of overload problems and the need for greater enforcement actions on particular roads) and to identify potentially overweight vehicles for static weighing several miles down the highway (essentially a high speed sorting scale). In the latter case, enforcement officers would require portable Loadometer scales and a real-time link to the data being collected by the low cost WIM station.

Since WIM data does not provide information that can be used directly in the enforcement of weight laws, the placement and number of WIM stations in this sample design is, for the most part, independent of the enforcement needs of the state. However, the use of portable WIM equipment by the enforcement branch to assist the state in determining the extent of its overload problem is part of the program design.

ENGINEERING DESIGN AND PLANNING

The dynamic effects mentioned above are not a significant issue for the collection of planning information. This is because planning and design information is based on the mean condition rather than the extreme conditions (overloads) that need to be monitored by enforcement agencies. Because the dynamic effects are random, the mean values from the WIM equipment are reasonable representations of the static loadings, and are therefore of value for design and planning. To a certain extent, knowledge of the in-motion characteristics of vehicle weights is actually more appropriate for pavement design than the static weights, as these are the actual loadings being experienced by the pavement.

Table 1 — Uses of truck weight information

Function	Type of project	Type of data required
Engineering	Structural design	Total EAL for design period
Engineering economy	Benefits of truck climbing lane	Loaded vs unloaded percentage
Finance	Weight distance taxes	Mean weight per vehicle
Legislation	Permit policy for oversize vehicle	Mean weight per vehicle and per vehicle type
Planning	Resurfacing forecasts	Mean EAL per vehicle and/or per vehicle type
Research	Pavement and structural design	Gross and Axle EALS per vehicle and/or mean EAL per vehicle
Safety	Posting of bridges for load limits	Gross and axle weights per vehicle
Statistics	Ton-miles of travel	Mean weight per vehicle or per vehicle type
Private sector	Trends in freight movement	Mean weight per vehicle or per vehicle type

Of the data needs shown in Figure 4, the pavement design needs are the most important engineering and planning requirements because of their financial impact on the expenditure of WSDOT funds. Consequently, the design of the data collection process is structured to meet these needs as well as possible.

All pavement design procedures are based on estimates of the loadings a pavement will receive during its expected life span. In most cases this is expressed in equivalent axle loads (EALs) or equivalent wheel loads (EWLs). These estimates are usually developed based on volume counts, vehicle classification counts (or estimates) and estimates of EAL per vehicle.

Total EALs are normally calculated as follows:

- take a short duration volume count;
- factor it to represent average annual daily traffic (AADT);
- apply vehicle classification factors (percent trucks by truck type);
- multiply the number of trucks (by type) by the average EAL per truck of that type; and
- sum the EALs for each truck type.

To provide volume data, a state will usually make a special effort to collect a short count, unless an existing count has been recently taken at that location. Vehicle classification data is sometimes collected for specific projects but often is taken from historical files. In either case, it is rarely adjusted for seasonality and often has not been collected for a full 24 hours.

Truck weight data is almost never collected on a project basis and almost never factored for seasonality, time of day, or day of week. To the author's knowledge, almost all states rely on the data collected as part of their annual (or biennial) weighing program to provide EAL estimates for all pavement designs in the state. This means that weight data collected at a small number of locations, over a small number of hours (when considering 365 days of 24 hours per year), are extrapolated to represent an entire state. Given the nature of most of the states' weighing programs, the data that are collected are heavily skewed towards vehicles traveling in the daytime, during months with good weather, and towards trucks which have no desire to avoid being weighed. Consequently, the weight estimates used or pavement design tend to under-estimate the true vehicle weights on the roads included in the sample, while ignoring many overweight trucks (which are not weighed at all).

If volume data were collected in a similar fashion, the engineers on a project requesting those data would be outraged. Since limited truck weight data have been traditionally all the weight data that were available, few engineers have complained about their accuracy, despite the importance of the information. As a result, few (if any) efforts are now made to collect truck weight information in a way that might produce results better than these "crude" estimates.

PROPOSED SYSTEM DESIGN

The proposed weighing scheme attempts to provide the information needed for all statewide uses, but concentrates on the needs of pavement design. The system's basis is the standard volume counting efforts followed by most transportation authorities. In summary, the proposed weighing plan includes

- 365 days a year (permanent) weigh stations at a limited number of locations,
- portable weighing systems for site specific data collection,
- site specific weight data collection for all major pavement design projects (particularly overlay designs), and
- seasonal correction of site specific data.

PERMANENT STATIONS

The permanent stations will serve the same function for truck weighing that permanent volume recorder stations perform for traffic counting. That is, they will provide the basic information needed for determining annual trends and for calculating seasonal factors for expanding short duration counts to annual averages. Only through the use of stations that operate year around can an agency truly determine what types of fluctuations occur over the year in truck travel and then apply that information in a manner that improves the quality of traffic inputs for road design.

Such changes are particularly important in those portions of a state where truck travel varies considerably over the year. Such changes can occur both in truck volume and in commodity type. Both types of change would be noted by the WIM installation. For example, in Eastern Washington, a considerable amount of grain is hauled by truck. While grain moves through the state throughout the year due to movements from various storage locations to rail and barge shipping points, a large fluctuation in the amount of grain hauling occurs during harvest time. In addition, the WSDOT suspects that a significant number of the peak season vehicles are overweight. Because this seasonal movement occurs at a slightly different time each year, it is extremely difficult for the state to arrange for weighing crews to be in the correct place at the correct time to measure the number and weight of vehicles in this movement. Some kind of permanently mounted, continually functioning, automated scale is needed to collect this type of data so that the data could be collected regardless of when these movements occur. Only after such information is collected can design inputs accurately reflect such vehicle movements.

SHORT DURATION COUNTS

Unfortunately, permanent counters are not the only type of equipment needed to provide good pavement loading data for pavement design. As with volume counts, basic seasonal trends can be identified with permanent counters, but site specific information is needed for pavement design.

Two factors control the depth of pavement designed for any particular roadway: the number of trucks or various kinds, and the weights of those trucks. It is highly likely that vehicle weights (by truck type) vary from location to location. This is particularly true in states where the basic axle configuration (e.g., 3S2 or three axle tractor with a two axle semi-trailer) does not indicate the type of commodity being carried (e.g., logs or electronic components). Such commodity differences can have significant effects on the average weight of a particular vehicle type. One example of this would be a road which led past a cement plant, which might show an unusually high average weight per 3-axle, single unit truck.

Consequently, every road over which significant amounts of pavement are to be placed should have a vehicle classification study done on it (to determine the number of trucks using that road and the types of those trucks), and ideally, the weights of those specific trucks should be collected. Given the costs of placing pavement on a stretch of highway (few pavement projects are completed for less than $1,000,000), the cost of either collecting data with systems such as bridge WIM or of buying a low cost WIM system and installing it temporarily at a site ($5,000 to $10,000 as currently envisioned) is minimal. Given the importance of the data that such a system could collect, and the direct bearing that such data would have on the design of that pavement, such data collection is certainly warranted.

At the present time, both the bridge system and the capacitor pad provide the capability of performing site specific weighings for many sections of highway. Both types of systems are readily portable and their costs are reasonable. Unfortunately, neither system is capable of weighing vehicles that are not traveling in a lane bordering a shoulder. Thus these systems can be avoided by trucks (accidentally or intentionally) on multi-lane roads. These limitations point out the need for continued development of WIM systems.

SEASONAL FACTORS

Like short duration volume counts, short duration truck weighings (i.e., less than a year) can suffer from skewed data if used directly to represent annual conditions. Furthermore, the collection of yearly data in the first portion of this idealized program allows the development of seasonal factors for truck weights. Seasonal factors will be applied to short counts to better estimate true "annual" conditions, as required by the pavement design process. Without a seasonal factor, weights collected in July may under or over represent truck travel for an "annual" condition. Little information currently exists in most states to indicate how large these seasonal changes might be. However, given the importance of truck weights and numbers of trucks to the design process, it is imperative that such data be collected and utilized.

NUMBER AND LOCATION OF COUNTERS

Due to a lack of data to verify statistical tests that would help select appropriate sample sizes, the system design described below is a first cut, and will undoubtedly be revised based on data that are collected by this initial program. In addition, the

costs involved with setting up these locations (even the "low cost" equipment) are sufficiently high to require caution in the initial expenditure of funds for the system. This initial design places relatively few permanent stations until the technology proves reliable and sufficient information is available to make an informed choice about how and where to expand the number of stations. Essentially, it is better to initially under-estimate the data collection needs and purchase more equipment later, than to purchase more equipment at the beginning of the project and ultimately decide that the amount of information is unnecessary.

The proposed data collection strategy is shown in Table 2, and includes 15 permanent (or "semi-permanent") WIM installations and one portable set of scales. The 15 permanent locations are split evenly between three types of roads. These roads include

- rural interstates,
- other rural roads, and
- urban roads (including interstates).

These categories are chosen for the following reasons:

- interstate highways fall under special federal funding provisions and require particularly good information;
- sufficient truck weight data are not available to accurately differentiate among the truck weight patterns of the functional classes of non-interstate, rural state highways;
- urban roads tend to carry different types of traffic from rural roads and consequently merit separate consideration; and
- the state maintains a relatively small number of non-interstate, urban highway miles.

On roads from each of the above three categories, five permanent WIM stations would be placed. At this time, WSDOT is hoping that a piezo-electric system will meet this need. These stations would be spread around the state to provide a range of geographic locations within each group. Five stations were chosen for each group because five is the smallest number that will give

- reasonable geographic coverage,
- sufficient data to provide statistically valid estimates of variation in truck weights by time of day, season of the year and location, and
- statistical reliability despite the loss of two stations in any one group due to malfunctioning equipment.

The short count program is directed around the need to provide short counts at specific project locations. The 15 permanent WIM stations should provide sufficient information to develop statewide

Table 2 — Proposed data collection program

	Permanent stations			
			Expected precision levels[1] for 3S2 trucks	
Strata	Number of stations	Number of days measured	Total mean EAL per truck	Seasonal correction factor[3]
Rural interstates	5	1,825	±5%[2]	±10%
Other rural roads	5	1,825	±5%[2]	±10%
Urban roads	5	1,825	±5%[2]	±10%

Portable stations: Sites chosen to correspond to pavement projects or other site specific agency needs.

1 Based on data from the Highway Performance Monitoring System Truck Weight Case Study, all estimates are expressed at a 95 percent level of confidence.

2 May vary depending on the variability of mean weights per truck type between locations.

3 Target estimates. Insufficient data are available to accurately estimate this vaule.

averages and seasonal correction factors. The portable scale system would be used to supplement that information at specific project locations (i.e., pavements to be reconstructed) and at locations where WSDOT or the state patrol were interested in inconspicuously studying vehicle weights, either for later enforcement actions or for other purposes. Such prospective needs of WSDOT include the submittal of vehicle weights from 10 sites included in the federally sponsored Long Term Pavement Monitoring Project. Such needs might also include special studies concerning the weights of logging or grain trucks on roads of particular interest to WSDOT.

WSDOT will review the data that are collected after the program has functioned for two or more years. Based on this information, the state may wish to restructure the three groups. For example, the available data might show that truck weights and variation patterns were significantly different between Eastern and Western Washington. In such a case, additional WIM equipment might be purchased (or existing equipment moved) to provide better information on these observed differences. At the same time, the statistical validity and completeness of the collected data would allow them to be used to more accurately measure the effects of variation in truck weights, and therefore size the program within specified limits. For example, at this point it would be possible to determine the benefits of collecting a lot of data at a few points (permanent stations) versus collecting some data at many locations (short counts).

The results from this review may indicate that mean EALs or vehicle weights for each vehicle type vary extensively from road to road across the state. If such is the case, a statistically valid sample of short duration counts (using portable WIM scales) could be added to the weighing program to increase the accuracy of estimates of statewide average vehicle weights. These short counts would be seasonally adjusted. They would provide a relatively inexpensive means for adding geographic diversity to the weighing program, which would provide a more accurate estimate of average statewide conditions. Such an estimate would be used for trend analysis and in those cases where site specific estimates could not be collected.

This type of program extension would bring the weighing program into a format almost identical to that of the volume counting now done in all U.S. states to estimate statewide vehicle miles of travel.

Whatever the necessary revisions, the end result of this type of program will be a statistically valid weight monitoring procedure that can account for the variation present in truck weights due to location, time of year, time of day or even day of week. All analyses using this information would subsequently improve in accuracy and reliability.