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16. ABSTRACT

This report documents Washington state's experiences with the FHWA's bridge weigh-in-motion system. The system was tested on four concrete bridges (one arched slab, one box girder and two pre-tensioned concrete girders) with moderate to heavy traffic volumes.

The system gave reasonable axle and gross vehicle weights under ideal conditions, but showed major limitations under high volumes. Over the life of the project, mean gross vehicle weight errors for individual trucks ranged between 11 and 18 percent with tandem and single axle weights having high mean errors. Errors for mean population gross vehicle weight estimates averaged two percent.

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TRUCK WEIGHT USING THE FHWA BRIDGE WEIGH-IN-MOTION (WIM) SYSTEM

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Final Report

FHWA Contract #DTFH61-85-C-00108
WSDOT Contract Y2811, Task 38

Prepared for

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and in cooperation with
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Federal Highway Administration

February 11, 1987

DISCLAIMER

ACKNOWLEDGMENTS

I would like to thank the many people involved in performing this project. Bill Barlow must top the list, as he helped run the system, troubleshoot the problems, maintain the equipment, and fix up the van. The project could never have succeeded without him. Don Kohse also played a crucial role in maintaining the equipment, drilling bridges, and working on the van. Cam Carlson managed the WSDOT staff and provided invaluable suggestions on a wide variety of tasks. Merl Vernia built the van's cabinets, and many others in the Transportation Data Office helped at times.

At TRAC, Amy O'Brien did her usual excellent job editing. Ron Porter did the word processing, and together they added a great deal to the layout, readability, and usability of the new Bridge WIM User's Manual. Chien Lin and David Chao helped collect and analyze the data, and Duane Wright made the graphics.

As a group, everyone's enthusiasm and innovative ideas added substantially to the quality of the project.

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CONCLUSIONS

Based on the data collected and the analyses performed, the project team reached the following conclusions:

- The FHWA bridge WIM system, when used on bridge types common in Washington, has significant limitations in accuracy when used on roads with moderate to high traffic volumes.
- Errors on individual truck gross vehicle weight estimates ranged between 11 and 18 percent for the test bridges.
- Errors on individual axles and tandems were larger than errors in estimating gross vehicle weight (21 to 35 percent for singles, 20 to 33 percent for tandems.)
- Mean population estimates were more accurate than individual truck estimates, averaging 2.0 percent for gross weights, 2.1 percent for single axles, and 3.1 percent for tandems.
- Use of the WIM axle weights for calculating EALs results in over-estimated EALs.
- The system is not sufficiently accurate for enforcement screening, except under very specific conditions.
- The most common cause of significant error was the presence of other vehicles on the bridge with a truck being weighed.

RECOMMENDATIONS

The project team makes the following recommendations based on the results of the research performed for this project:

- The Department should refrain from purchasing a WIM system until other alternative systems can be evaluated.
- If a WIM system is to be purchased, the Department will need to address the problem of dynamic versus static axle loadings (WIM weights will usually results in higher EAL estimates).
- If a bridge WIM system is purchased, it should only be used on low volume roads with relatively simple bridge spans.
- Slab and box girder bridges may be used in addition to concrete and steel girder bridges, although bridges of this type should be of short span length.

EXECUTIVE SUMMARY

This report documents the testing and research performed by the Washington State Transportation Center (TRAC) using the Federal Highway Administration's (FHWA) Bridge Weigh-In-Motion (WIM) system. The purpose of this project was to allow Washington State Department of Transportation personnel to gain experience using a bridge WIM system and to determine the accuracy of such a system on bridges common in the state of Washington.

BACKGROUND

The existing Washington (WSDOT and Washington State Patrol) weighing activities suffer from the following deficiencies, common to weighing activities in many states:

- overweight trucks avoid existing scales as a result of advanced notification of their presence via CB radio;
- the design of the equipment severely restricts the locations where weights can be safely collected; and
- the costs of data collection are relatively high, due to the labor intensive nature of the current equipment, restricting the amount of weight data that can be collected, given the available resources.

Both agencies are in need of an inexpensive, portable, accurate, inconspicuous truck scale to provide a better understanding of the number of overweight trucks operating on the state's highways.

Available literature shows very little data for the accuracy of bridge WIM systems on bridge types other than simply supported steel and concrete girder bridges. Washington's highway system utilizes many varieties of concrete bridges but very few steel girder structures. Therefore, the bridge WIM system was tested for accuracy on other bridge types common within the state.

OBJECTIVES

The main objective of this project was to provide additional information to both the state of Washington and to FHWA on the advisability of using the bridge WIM system to collect truck weight information for both planning and enforcement purposes.

INTRODUCTION TO WIM

Weighing of vehicles in motion has been a subject of research for several decades. The advantages of WIM in terms of time savings for both enforcement personnel and truckers have compelled researchers to continue to seek better and more accurate WIM equipment as the technological improvements in the electronics industry have made such advances possible.

The biggest difficulty in weighing a moving vehicle is that the motion of the vehicle causes both the load and the vehicle's suspension to move. Because of these movements the actual weights that any given wheel or axle might experience fluctuates. Therefore, taking a single weight reading of a moving axle and translating that reading into an accurate estimate of that axle's static weight (i.e., the weight experienced by that axle when the load is at rest) becomes difficult.

The bridge system tries to limit the effects of these fluctuations in two ways. The first is to weigh the vehicle at many points along a bridge span. In this manner, the system attempts to measure enough points that it can determine (by means of a curve fitting routine) what the mid-point of the oscillating weights is, and therefore, what the static weight is. The second advantage of the bridge system is that it does not actually measure the forces applied by the vehicle tires but the bridge span's reaction to those forces.

The disadvantage of the bridge system is that other forces also impact the movement of the bridge span. The most important of these is the presence of other vehicles, although weather conditions (particularly high, gusting winds) can also cause some bridge motion.

SITE SELECTION

Five bridges were selected for testing the bridge WIM system. The bridges used were called Pendleton, Nisqually, Nisqually Overflow, Martin Way and Snoqualmie. All but one of the bridges were located on Interstate 5, north of Olympia, Washington. The fifth bridge, Snoqualmie, was located roughly forty miles east of Seattle on Interstate 90. The bridges were all located within ten miles of a Washington State Patrol static scale. Each bridge had the following characteristics:

- its construction type (i.e., concrete box, concrete slab, concrete girder, etc.) was commonly found on the main lanes of travel on Washington State highways;
- the bridge experienced high degrees of truck travel; and
- the bridge offered a safe location in which to place the WIM van and equipment.

The Nisqually overflow bridge was used primarily for training and is not always included in the tabulated results.

STUDY RESULTS

The weight estimates examined in this report include gross vehicle weights, single axle weights, tandem axle weights, and equivalent axle loads. In addition, several other analyses are discussed in the main body of the report. For data collection for planning and design purposes, the most important analyses concern the mean vehicle (gross and axle) weights and the distribution of these weights for the population of trucks that are weighed. For enforcement needs, one-to-one comparison of dynamic and static weight estimates is most important.

Gross Vehicle Weights

The bridge WIM system produced reasonable estimates of the mean gross vehicle weight of trucks passing each of the weighing sites. Errors of the mean gross vehicle weight averaged 2.0 percent for the five locations. As can be seen in Exhibit E-1, some bridges provided considerably better mean weight estimates than other bridges, but all of the bridges gave reasonable averages. The range of the error in the mean gross vehicle weight was from 1.0 percent at the Martin Way bridge to 5.9 percent at the Nisqually bridge. The standard deviation of the weight estimates were much higher for the WIM scale than the static scale. Statistics showed that the WIM and static mean weights were not significantly different, with the exception of the Nisqually bridge.

Individual truck gross weight estimates were less accurate than the mean population estimates described above. The mean error for individual trucks ranged from 11 percent at Snoqualmie to 18 percent at Martin Way. These corresponded to errors of 5,800 to 8,700 pounds per vehicle, respectively. These errors were randomly distributed around the mean described in the preceding paragraph. Exhibit E-2 shows a tabular summary of the per vehicle accuracy of all of the four test bridges.

Essentially, the variation due to the dynamic motion of the trucks and the presence of other extraneous circumstances (e.g., other vehicles on the bridge) caused the in-motion weight for any one truck to fluctuate around the actual static weight. The WIM system's measurement of this fluctuation can most easily be visualized using an X/Y plot such as that in Exhibit E-3, which shows a plot of WIM gross vehicle weights versus static weights for the Snoqualmie bridge.

An analysis was also performed to determine whether the bridge system weighed heavier vehicles with more accuracy than lighter vehicles. Analysis showed that no

Exhibit E-1
Population Gross Vehicle Weight Statistics
WIM Versus Static

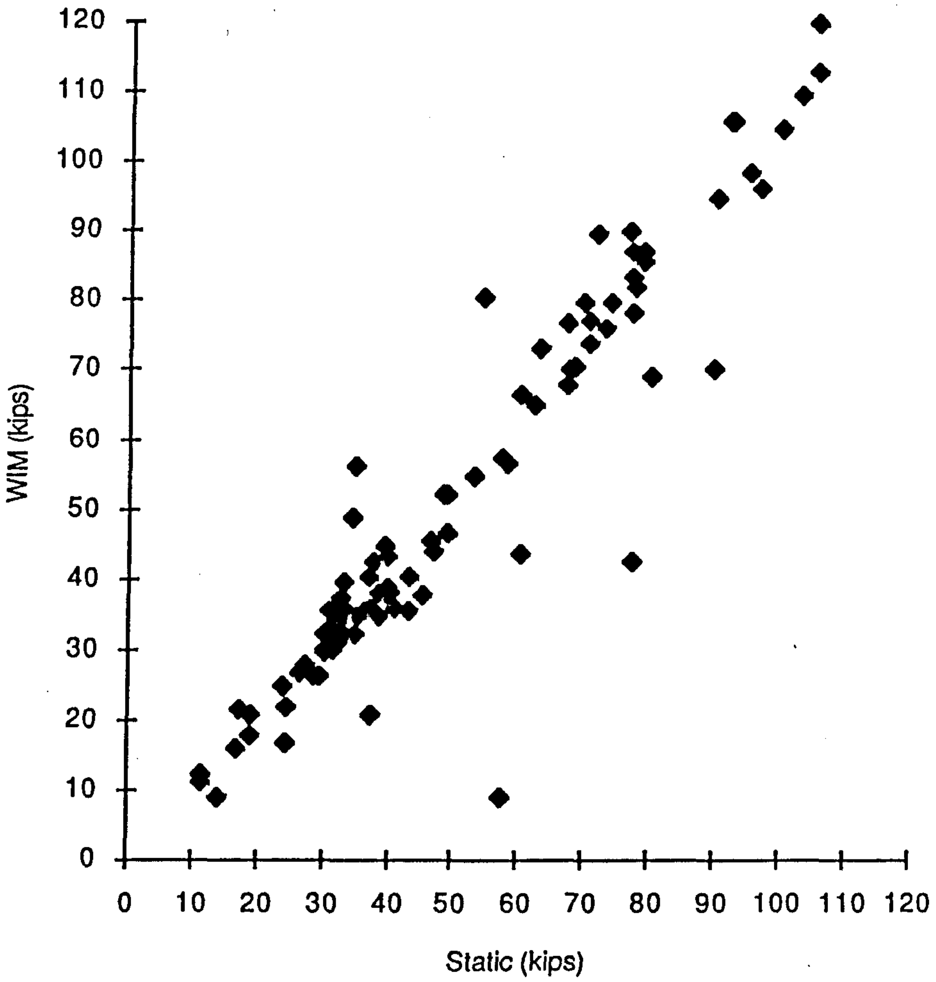
Bridge	Number of Trucks	Mean GVW			Standard Deviation	
		WIM	Static	%Difference	WIM	Static
Martin Way	96	52.92	53.44	-0.97	25.660	25.830
Pendleton	107	42.76	43.68	-2.11	22.849	21.778
Snoqualmie	93	52.25	51.70	1.06	27.566	24.480
Nisqually	101	49.45	52.55	-5.90	26.723	24.133
All Bridges combined	397	49.14	50.18	-2.06	25.911	24.275

Exhibit E-2
Individual Truck Comparisons of Gross Vehicle Weight

Bridge	All Vehicles		3S2 Type	
	≥10%	≥15%	≥10%	≥15%
Martin Way				
GVW	44.8%	29.2%	37.1%	22.6%
Single Axle	74.1%	59.4%	66.7%	47.0%
Tandem Axle	67.1%	55.5%	61.1%	47.6%
Pendleton				
GVW	38.3%	28.0%	35.8%	26.9%
Single Axle	60.3%	46.0%	55.6%	37.5%
Tandem Axle	47.1%	37.9%	48.5%	39.6%
Snoqualmie				
GVW	34.4%	17.2%	27.1%	12.5%
Single Axle	68.7%	60.8%	61.7%	56.7%
Tandem Axle	67.1%	50.3%	63.5%	43.3%
Nisqually				
GVW	41.6%	24.8%	34.4%	21.9%
Single Axle	80.8%	66.5%	84.0%	72.8%
Tandem Axle	76.6%	66.9%	75.8%	65.6%
Total				
GVW	39.8%	24.9%	34.0%	21.6%
Single Axle	70.8%	58.0%	67.7%	54.1%
Tandem Axle	64.5%	52.7%	62.0%	49.2%

Exhibit E-3

WIM vs. Static GVW (Snoqualmie)



statistical difference in the percentage of error in a gross weight estimate was apparent between heavy trucks and lighter trucks at Pendleton and Snoqualmie, but that heavier vehicles were weighed more accurately (in percentage terms) at Nisqually and Martin Way.

Axle weights

Single and tandem WIM axle weights were somewhat less accurate than the gross vehicle weights described above. These results were fairly consistent with the results published in the Wisconsin DOT study described in Chapter 2.

As with gross vehicle weights, the average error per axle or tandem was considerably higher than the error of the mean population estimate. While the single axle population mean was only off by 2.14 percent, the average single axle estimate was off by between 21 and 35 percent. The average front axle estimate was off by between 16 and 21 percent. Tandem axles were similar to single axles in accuracy, with errors of between 20 and 33 percent. The expected measurement errors on any one particular axle or tandem are shown in Exhibit E-4 for each of the four bridge sites.

The bridge system provided more accurate weights for heavy tandem axles than it did for light tandem axles. Surprisingly, however, it weighed lighter single axles better than heavier single axles at two of the bridge sites. (The other two sites showed no statistical difference between single axle weight estimates.)

EAL Estimates

The conversion of axle weight estimates into EALs has a significant effect on the quality of the weight estimate, and consequently on future pavement designs. This is a direct result of the random dynamics of the axles being measured and the limitations experienced by the WIM system when it is collecting data and calculating axle weights.

The errors in the mean EAL estimate per single or tandem axle were considerably larger than the corresponding errors for mean single and tandem axle weights (see

Exhibit E-4
Individual Comparisons of WIM and Static Axle Measurements (in kips)

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Single Axles					
Mean Absolute Error	3.04	2.06	3.05	2.88	2.74
Percentage Error	35%	21%	32%	29%	29%
Standard Deviation of Absolute Error	3.601	2.611	3.398	2.862	3.14
Front Axles					
Mean Absolute Error	1.95	1.39	1.93	2.46	1.92
Percentage Error	21%	16%	21%	26%	21%
Standard Deviation of Absolute Error	2.17	1.135	1.885	2.039	1.871
Tandem Axles					
Mean Absolute Error	5.58	3.45	3.05	2.88	5.00
Percentage Error	26%	20%	32%	29%	25%
Standard Deviation of Absolute Error	5.803	4.753	3.398	2.862	5.691

Exhibit E-5). In addition, the EAL estimates for the population tended to significantly overestimate the average EAL per axle or tandem. With the exception of tandem EALs at Martin Way, the error in the EAL estimate was between 18 and 50 percent per axle or tandem. Only at Martin Way was the EAL per axle lower from the WIM estimate than from the static estimate.

The errors in EAL estimates occurred because of the presence of a few very heavy axles in the WIM weight estimates. The nature of the weight to EAL conversion is such that errors in weight estimates are magnified on the order of the fourth exponential. Because of this fourth order effect,.a few extra very heavy axles caused a significant increase in the EAL mean estimate.

CONCLUSIONS

On the whole, the bridge system did not function as well as desired during the research tests. Both gross vehicle weights and axle weights were not as accurate as they should be for use by the Department. In particular, the system collected too many extreme pieces of data (i.e., negative axle weights and gross weights). While the negative weights were relatively easy to remove from the collected data, the presence of a few, high, single and tandem axle weights, which are not easily removed, skewed the calculation of EALs based on WIM information. Such a skew would have significantly altered pavement design estimates. These errors will have to be addressed before the system is considered for purchase and use by the Department.

To be fair to the bridge system, much of the testing performed as part of this research could be termed "worse case" scenarios. The test sites tended to have very high volumes of trucks and automobiles (except for Snoqualmie), which created a situation in which other vehicles were continually on the bridge at the same time as the truck being weighed. The one structure where this was not the case was a long box girder with both

Exhibit E-5
Mean EAL Per Axle
Static Versus WIM

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Single Axles					
WIM Mean EAL/Axle	0.30	0.22	0.35	0.21	0.27
Static Mean EAL/Axle	0.12	0.16	0.20	0.14	0.16
Mean of Absolute Error	0.28	0.17	0.27	0.19	0.23
Standard Deviation of Absolute Error	0.832	0.777	0.821	0.418	0.728
Tandem Axles					
WIM - Mean EAL/Axle	0.57	0.37	0.45	0.65	0.49
Static - Mean EAL/Axle	0.53	0.28	0.31	0.48	0.40
Mean of Absolute Error	0.34	0.15	0.26	0.55	0.32
Standard Deviation of Absolute Error	0.422	0.263	0.563	1.222	0.731

curvature and camber attributes which undoubtedly affected the accuracy of the system and particularly the axle weight estimates.

Department Usage

The author believes that the bridge system can fulfill a significant part of the weight data collection tasks of the Department within necessary accuracy limits, despite the less than sterling results described in this report. However, before a bridge system is purchased, the Department should thoroughly examine other alternative WIM systems, as other systems may provide means of obtaining data that are just as accurate and more flexible. If the bridge system is purchased, the system's use should be confined to sites where its limitations would be minimized. This means that the bridges chosen should have the following attributes:

- a limited number of times during which multiple vehicles are on the bridge at the same time (this can be the result of low traffic volumes, or relatively small bridges (i.e., two lanes maximum with short spans), or a combination of both),
- small skew angles, and
- no curve or camber in the bridge.

In practice, this means that the system would be best utilized on moderate to low volume rural roads that are either two-lane or four-lane divided highways.

The research conducted can not draw definitive conclusions about the use of box girder and slab bridges, but the results indicate that these bridges can be used in place of standard steel or concrete girder structures. The shorter the structure, and the closer to being simply supported it is, the more likely the axle and gross weights will be accurate. Improvements needed by the system are addressed in Chapter 6 of the main report.

Enforcement Usage

The bridge system would be less successful as an enforcement tool than it would as a data collection tool for the Department. If it were used at sites similar to those included in this research, the very large fluctuations in individual axle and gross weights would make its use for writing citations or even as a screening tool suspect. However, if its use were restricted to those locations described above, it could serve as a reasonable screening device.

CHAPTER 1
INTRODUCTION

This report documents the testing and research performed by the Washington State Transportation Center (TRAC) using the Federal Highway Administration's (FHWA) Bridge Weigh-In-Motion (WIM) system. The research effort included

- reviewing previous WIM research,
- training WSDOT staff on the FHWA system,
- providing a van to house the FHWA system,
- selecting candidate Washington highway bridges,
- collecting WIM weights, static weights, and other data,
- analyzing the collected data, and
- reporting on the findings of the project.

The main objectives of this project were to allow WSDOT personnel to gain experience using a bridge WIM system and to determine the accuracy of such a system on bridges common in the state of Washington.

BACKGROUND

Washington's current weighing activities fall under two basic categories, weighing by the Washington State Patrol (WSP) for enforcement of weight regulations and weighing by the Department of Transportation (WSDOT) for planning and design purposes.

The WSP operates 64 permanent weigh stations throughout the state. Four of these are ports of entry and are operated 24 hours per day. Other stations are operated as determined by traffic volume and available personnel. In addition, WSP has 75 sets of portable scales, used in problem areas and on those state highways not covered by permanent scales. Washington state's enforcement plan is certified by FHWA, and its overall goal is to impose those measures necessary to curtail the illegal movement of overweight vehicles upon all Washington highways, using available personnel and facilities.

Truck weight planning information is currently collected as part of the long term pavement monitoring project in which the Department is participating for FHWA. Weight and vehicle classification information are collected at ten locations throughout the state. Truck weighing is performed using Siemans (PAT) low speed WIM equipment. This weighing is performed in rest areas, on highway shoulders, and occasionally in the right-hand lane of traffic when this lane can be safely marked off.

The existing Washington weighing activities suffer from several deficiencies common to weighing activities in many states, primarily the following:

- overweight trucks may avoid existing scales after being notified of their presence via CB radio;
- the design of the equipment severely restricts the locations where weights can be safely collected; and
- the costs of data collection are relatively high, due to the labor intensive nature of the current equipment, restricting the amount of weight data that can be collected given the available resources.

Both agencies are in need of an inexpensive, portable, accurate, inconspicuous truck scale to provide a better understanding of the number of overweight trucks operating on the state's highways.

Several states are currently using bridge WIM technology to perform these functions; among them are Oregon, Idaho, Ohio and Maine. As demonstrated by these states, the bridge system offers several advantages over other existing technologies. The primary advantages are that the system

- can be used at many locations throughout the state,
- is readily portable,
- is inconspicuous, and
- is reasonably accurate for the bridges and bridge types used.

Available literature contains little data on the accuracy of WIM systems used on bridge types other than simply supported steel and concrete girder bridges. Since Washington's highway system utilizes many concrete bridges but very few steel girder structures, this study tested the accuracy of the bridge WIM system on other bridge types common within the state. Using the results of these tests and other ongoing WSDOT research efforts, the state will be in a position to determine which WIM system(s) is best for use by the state.

OBJECTIVES

The main objective of this project was to provide additional information to both the state of Washington and to FHWA on the advisability of using the bridge WIM system to collect truck weight information for both planning and enforcement purposes. Specifically, this research effort provides the state with the following:

- an evaluation of the capabilities and limitations of the bridge WIM system currently used by FHWA in its research,
- the approximate cost of maintaining and operating the system,
- the accuracy of the system, not only in absolute terms but in relation to other available WIM systems,
- additional information as to the accuracy of the system for different bridge and truck configurations,
- a demonstration of a state's ability to set up, calibrate and use a bridge WIM system based on information provided to it by FHWA, and

- estimates of the potential for using a bridge device for enforcing weight laws, both in place of static scales and as a method for determining the avoidance of existing static and portable scales.

In addition, the project resulted in

- the acquisition of a fully equipped van for demonstrating the system at sites of FHWA's choosing,
- suggestions concerning the content, design and usability of FHWA's training and instruction for the bridge system,
- estimations of the system's potential for freeing enforcement officers' time so that they can more fully concentrate on examining trucks for safety violations, and
- conclusions about the advisability of purchasing a bridge WIM system for either planning information collection or weight enforcement.

CONTENT

This report is broken into six chapters, a conclusions and recommendations section, an executive summary, and various appendices. The six chapters include

- Introduction,
- Review of Previous Research,
- Bridge Selection and Description,
- Study Results,
- Cost of Operating the System, and
- Recommended Equipment and/or Software Changes,

Appendix A describes the van which houses the WIM equipment and was provided to FHWA as part of the contract. Appendix B provides a series of tables and graphs giving additional detail on the study results for individual bridges.

The introduction provides background information on the bridge system in general. It states the goals and objectives of the project and describes the structure of the report.

The literature review summarizes published research on the bridge system. This chapter also briefly describes alternative WIM systems that might be used in place of the bridge WIM system being tested.

The bridge selection and description chapter provides detailed descriptions of the bridges tested in the research effort. Five different spans were instrumented at some point in the research effort. Four of these spans are included in the detailed analyses presented in this report. The fifth was used simply for instructional purposes. Also included in this chapter is a complete description of the data collection process at each of these spans. This description includes an analysis of the difficulties encountered at each of the locations.

Chapter 4, Study Results, describes the major findings of the research effort. The purpose of this chapter is to describe the accuracy and limitations of the bridge system in comparisons to the estimates obtained from static scales. Some of the detailed results described in this chapter are summarized in additional graphs and tables in Appendix B. Also included in this chapter are descriptions of the data manipulation steps that were necessary to make comparisons of WIM and static weight measurements.

Given the capabilities and limitations detailed in Chapter 4, the next chapter describes the effort and expense requirements for operating the bridge system as it is currently configured. The final chapter recommends how the current system's configuration should be changed to allow for less expensive operation and better interfacing with other ongoing WSDOT data collection efforts. This includes necessary changes that should be made to the system before the state purchases a similar system.

CHAPTER 2
REVIEW OF PREVIOUS RESEARCH

This chapter provides an overview of weigh-in-motion technology. It describes the cause of differences between static and dynamic vehicle weights and summarizes the results of previously published research on the accuracy and limitations of bridge weigh-in-motion and other portable WIM technologies.

INTRODUCTION TO WIM

Weighing of vehicles in motion has been a subject of research for several decades. The advantages of WIM in terms of time savings for both enforcement personnel and truckers have compelled researchers to continue to seek better and more accurate WIM equipment as the technological improvements in the electronics industry have made such advances possible.

The biggest problem in weighing a moving vehicle is that the motion of the vehicle causes the load to move. This is particularly true for vehicles carrying liquid cargoes (such as gasoline or milk). The movement of the cargo causes the actual weights that any given wheel or axle might experience to fluctuate. Therefore, taking a single weight reading and translating that reading into an accurate estimate of that axle's static weight (i.e., the weight experienced by that axle when the load is at rest) becomes difficult.

In addition to the shifting of the cargo, the motion characteristics of the truck itself cause fluctuations in the load applied at any point in time to a particular axle. This motion is caused by the interaction between the vehicle's suspension system and the profile of the road. Essentially, the uneven road surface causes the vehicle to bounce. If an axle is weighed while it is moving in an upward direction, its weight will be underestimated. If that same axle is weighed as it reaches the bottom of its oscillation, the static weight will be overestimated.

The bridge system tries to limit the effects of these fluctuations in two ways. The first is to weigh the vehicle at many points along a bridge span. In this manner, the system attempts to measure enough points that it can determine (by means of a curve fitting routine) what the mid-point of the oscillating weights is, and therefore, what the static weight is.

The second advantage of the bridge system is that it does not actually measure the forces applied by the vehicle tires but the bridge span's reaction to those forces. The inertia of the span dampens the oscillations in the axle measurements made by the bridge system.

The disadvantage of the bridge system is that other forces also impact the movement of the bridge span. The most important of these is the presence of other vehicles, although weather conditions (particularly high, gusting winds) can also cause some bridge motion.

PREVIOUS BRIDGE WIM EXPERIENCES

Three major reports have been published that directly discuss the use of the FHWA bridge WIM system. These were written by Fred Moses at Case Western Reserve University,[1] the Wisconsin Department of Transportation,[2] and Richard Snyder, et al., in a project for the Turner-Fairbank Highway Research Center.[3] While all of these reports

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[1] Fred Moses, et al., Weigh-in-Motion Using Instrumented Highway Bridges, Case Western Reserve University for the Federal Highway Administration, December 1981, Report No. FHWA/OH-81/008.

[2] Wisconsin Department of Transportation, Evaluation of the Bridge Weigh-in-Motion System, March 1985.

[3] R.E. Snyder et al., Loading Spectrum Experienced by Bridge Structures in the United States, for the Federal Highway Administration, February 1985, Report No. FHWA/RD-85/012.

are useful, the Wisconsin DOT report must be considered the most objective, as the researchers involved in the study were not trying to describe the merits of a system they played a role in developing.

Case Western

The Case Western report documents the initial testing of the bridge system by the team of engineers that designed it. This report documents the weighing of 1,706 trucks and discusses two types of accuracy tests. The first is a repeatability test, in which a test vehicle is repeatedly weighed with the bridge system and the variation in those weight estimates was used to determine accuracy. The second test is a comparison of bridge WIM weight estimates with those of static and conventional portable scales.

The report concludes that the bridge system should be able to estimate gross vehicle weights with a coefficient of variation of three to five percent. For axle weights, the coefficient of variation should increase to just under 10 percent. The majority of bridges tested as part of the Case Western project fell within these guidelines, although some of the bridges did produce slightly poorer results.

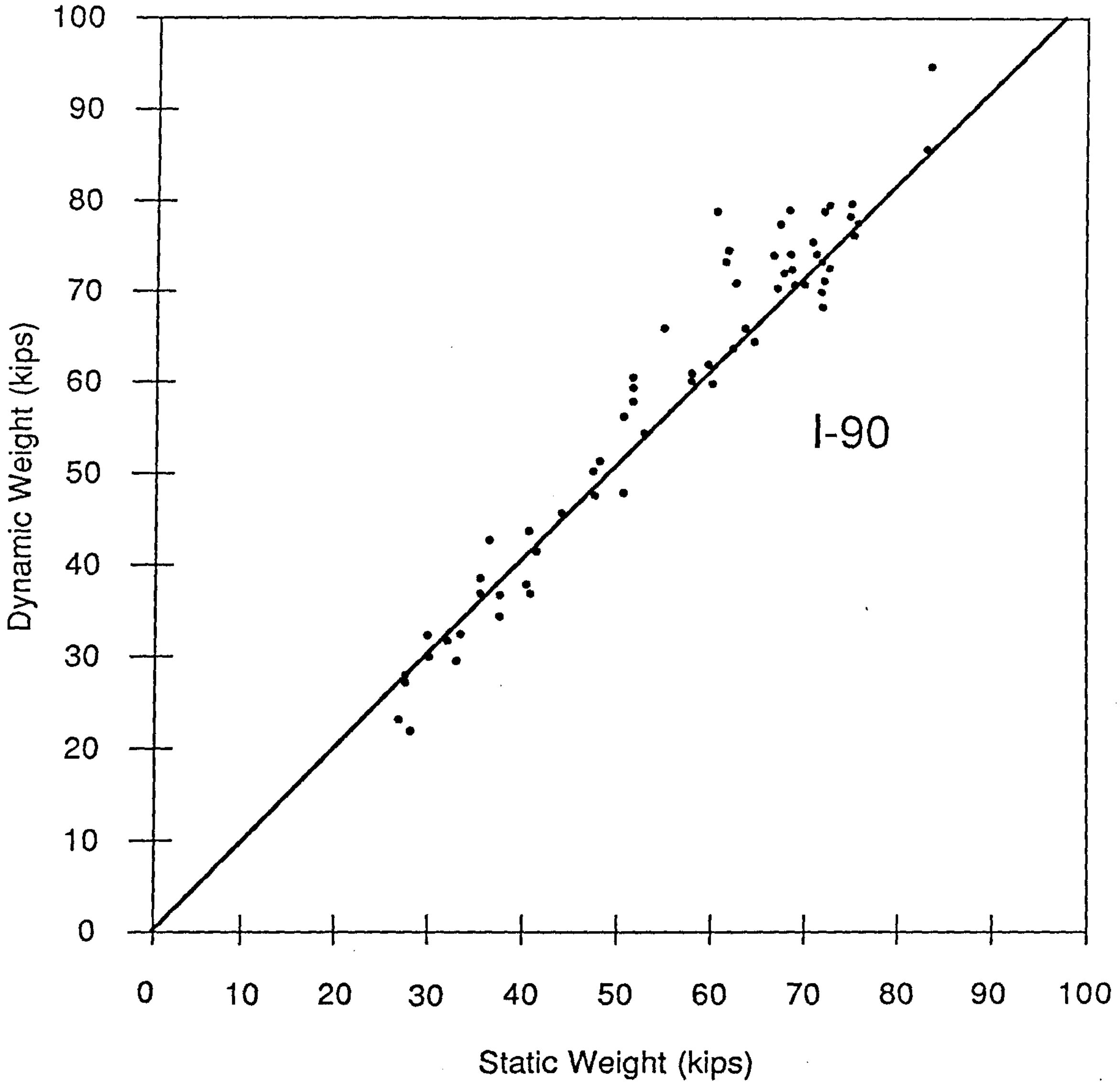
Very little information was printed in the report on the direct comparisons between static and WIM estimates. One exhibit from the report is reproduced in this chapter as Exhibit 2-1. From one table in the report comparing WIM to conventional portable weights, the following information was obtained:

- the mean absolute difference between WIM and static gross vehicle weights was 5,000 pounds;
- this mean absolute difference was 10 percent of total gross vehicle weight;
- the co-efficient of variation for the absolute error was roughly 1.0;
- the mean error for the weighings was 300 pounds; and
- the standard deviation of the mean error was 8,100 pounds.

Exhibit 2-1

Comparison of Weigh in Motion Results with Static Scale (Case Western Results).

(Dynamic Weight - Weigh in Motion Prediction)
(Static Weight - Loadometer Station)



These results indicate that the estimates obtained with the WIM system were randomly oriented around the static estimate, but that the average errors were slightly larger than the repeatability tests indicated.

Wisconsin

For the most part, the Wisconsin DOT report is more critical of the merits of the bridge system than the other two reports. Wisconsin summarizes its report by saying that up to a 25 percent error could be expected on any given axle or tandem weight. Gross vehicle weights were determined to be more accurate. These errors were concluded to fall in the range of 1000 pounds on the average.

This report also indicates that the bridge WIM system was more accurate for heavier vehicles (greater than 40,000 pounds) than it was for lighter vehicles. Exhibit 2-2 shows the errors that Wisconsin DOT determined from comparing static and dynamic weights for 313 trucks operating under normal highway conditions. As can be seen from this table, the system more accurately estimated drive and trailer axles than it did steering axles. Not shown in this table is the fact that the system tended to underestimate the weight of drive axles and overestimate weights of trailer axles.

The Wisconsin report also notes the following aspects of the bridge WIM system:

- the slower the speed of the vehicle, the more accurate the WIM weight estimate;
- 95 percent of recorded vehicles were correctly classified;
- speed calculations were "reasonably accurate"; and,
- the presence of a DOT person monitoring traffic caused a slight decrease in the the mean vehicle speed passing the bridge site.

The conclusions of the report are generally in favor of using the system for planning data collection but not for enforcement. Wisconsin DOT concludes that the system lacked sufficient accuracy to give enforcement officers sufficient "probable

Exhibit 2-2
Wisconsin DOT Bridge WIM Tests

	Range of Error				
	< ± 5%	< ± 5-10%	< ± 10-15%	< ± 15-20%	< 20%
Steering Axle					
Under 40,000 lbs	16.7	11.1	19.1	14.8	38.3
Over 40,000 lbs	22.5	27.2	13.9	13.2	23.2
Total Vehicles	19.5	18.8	16.6	14.1	31.1
Drive Axles					
Under 40,000 lbs	24.5	24.5	15.1	13.7	30.9
Over 40,000 lbs	42.8	29.7	15.9	10.3	5.5
Total Vehicles	30.7	24.6	14.1	11.5	19.1
Trailer Axles					
Under 40,000 lbs	30.7	35.1	21.1	7.0	14.9
Over 40,000 lbs	39.9	34.3	9.8	8.4	11.2
Total Vehicles	37.7	36.5	15.6	8.2	13.5
Gross Weight					
Under 40,000 lbs	62.3	36.2	13.0	4.3	0.7
Over 40,00 lbs	72.4	19.3	8.3	6.2	4.1
Total Vehicles	70.5	28.8	8.9	4.4	3.0

cause" for stopping vehicles that the bridge system indicated were only slightly overweight. This limited the use its enforcement branch could make of the system.

Turner-Fairbank

This report contains information on the weighing of over 27,000 trucks. However, only a limited number of comparison weighings were made between static scales and the bridge system. Of those statistics that are included in the report, the difference between dynamic gross vehicle weights and static scale weights appears to have had a coefficient of variation of roughly seven percent. This report also points out that even static scale weights were subject to some variation, as repeated static weighings of the test vehicle showed variation in the calculated weight of the test vehicle.

This report also provides some interesting comments on the functioning of the system. This report indicates that

- gross vehicle weights were reliable for all bridges tested;
- axle weights were more reliable on those bridges with short span lengths and low truck volumes; and
- bridges with large skew angles (greater than 45 degrees) did not provide good axle weight measurements.

The conclusions of the report are very much in favor of making more use of the system.

Utah

The Utah Department of Transportation published their review of the Bridge WIM system in August 1986.[4] Their results showed an average error in the gross vehicle

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[4] Bridge Weigh-In-Motion Demonstration Project, RTAP Final Report. HPR-IR-RTAP-49-001, Utah Department of Transportation, Materials and Research Section, August 1986.

weight estimate of 4.9 percent. Errors in the single and tandem axle weight estimates were on the order of 14 to 16 percent with a standard deviation of that error in the range of 11 to 14 percent. Some shifting of weight to the drive axles was noted during the weight comparisons.

Concern was also expressed in the report about the durability and reliability of the computer used by the system. The Bridge WIM system suffered several hardware failures during the Utah project. The report also noted that Utah had only a limited number of bridge structures that met the criteria for being candidate weighing platforms for Bridge WIM.

The report concluded that the advantages of the system in terms of portability, ease of setup and use, and unobtrusive weighing operations did outweigh its accuracy limitations for non-enforcement data collection on many highways in the state. However, the report recommended that improvements be made to the system and that it be used for tasks within its recognized limitations.

OTHER PORTABLE SYSTEMS

Several other moderately priced WIM systems are currently on the market. Three types have undergone a significant amount of testing, and the results of which have been been published. These types are the capacitor pad, the culvert weighing system, and the piezo-electric cable system.

Capacitor Pad

The capacitor pad is made by Golden River corporation. This system was developed in conjunction with the Arizona Department of Transportation (ADOT), and its testing is described in the report, "WIM-RTAP Final Report," Arizona Department of Transportation, December 1985.

This report does not describe large scale comparison tests between static and WIM measurements for vehicles traveling on the state's highways. It does provide the results of the initial testing of the system, which included driving a few vehicles of known weight repeatedly across the WIM sensor.

The conclusions of this report are that the system could weigh individual axles within ±15 percent, 90 percent of the time. However, closer analysis of the tables included in the report lead to some concern over the accuracy of those estimates. A detailed examination indicates that the system tends to suffer from significant biases in calculating its weight estimates. These biases appeared to be as high as 10 percent of the gross weight. These biases are in addition to any fluctuation in the weights caused by the dynamic motion of the vehicle. Only the dynamic effects appear to have been used in determining the accuracy of the system.

Culvert Systems

The CULWAY WIM system is a direct parallel to the bridge system. It uses the same basic technology as the bridge system but instruments culverts instead of bridges. The use of culverts has two major advantages over the use of bridges as a weighing platform. A culvert is by definition a short span. This decreases the likelihood of there being two vehicles on the structure simultaneously and therefore increases the accuracy of the system. The second advantage is that most culverts are covered by a significant amount of earth. The added material between the sensors and road surface helps dampen the fluctuation of the vehicle weights due to their dynamic motion.

While only initial test results are currently available on the CULWAY system its accuracy appears to be similar to the bridge system's accuracy in measuring gross and axle weights. Reliability tests similar to those done by Moses and Snyder show that the CULWAY system can achieve the following coefficients of variation:

■	gross vehicle weights	3.6 percent
■	steering axle	3.4 percent
■	drive tandem	4.1 percent

These indicate a slightly better estimate of axle weights than those provided by the bridge system but a slightly poor estimate of gross vehicle weight.

Piezo-electric Cable

Piezo-electric cable WIM systems are being developed and marketed by several different sources. The research and marketing of such systems are currently being led by

- the states of Iowa and Minnesota,
- the French national laboratory, Laboratoire Central Des Ponts Et Chausses (LCPC), and
- the British firm, Weighwrite.

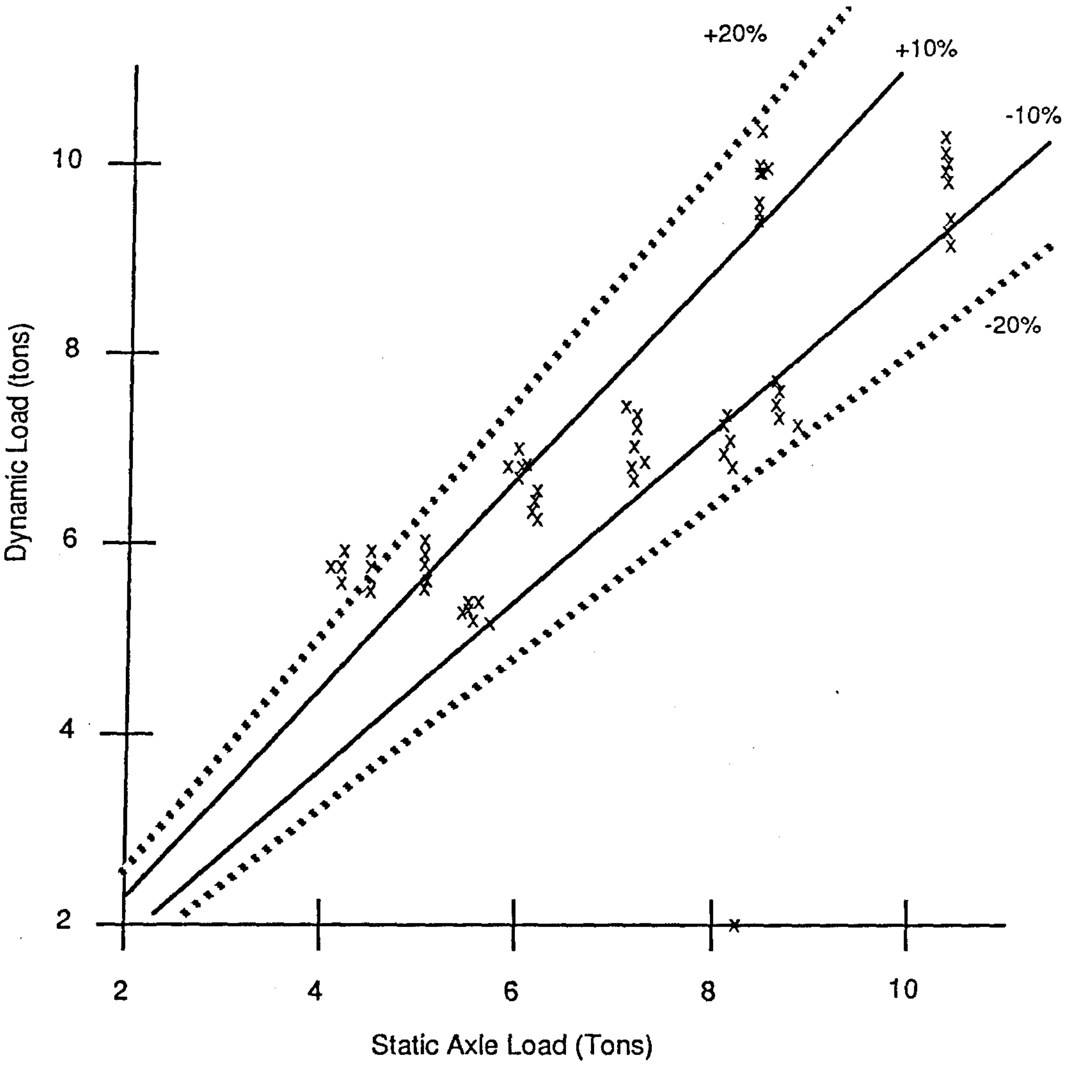
Iowa and Minnesota are currently attempting to develop a low cost piezo system. The work for this project is being done by a consultant, Castle Rock Consultants. The system is in the early development stages. Results should be available by the end of 1987.

LCPC is marketing a system they developed that is currently used by the French government. The LCPC claims in submitted bid documents that their system can weigh 90 percent of all axles within 15 percent of their static weight on a smooth highway surface. Specific research data to verify this information was not available at this time.

Weighwrite is marketing their system in the United States through the firm of CMI-Dynamics, Inc. CMI has distributed a technical bulletin describing Transportation Road Research Laboratory (England) tests indicating that this system provides a individual gross vehicle weights within 15 percent of static vehicle weights 68 percent of the time. Exhibit 2-3 presents a reprint of some of the test data used to determine this figure.

Exhibit 2-3

CMI Test Track Results



38.3% Less Than 10% error

56.7% Less Than 15% error

75.6% Less Than 20% error

CHAPTER 3
BRIDGE SELECTION AND DESCRIPTION

Five bridges were selected for testing the bridge WIM system. All but one of the bridges were located on Interstate 5, north of Olympia, Washington. The fifth bridge, Snoqualmie, was located roughly forty miles east of Seattle on Interstate 90. The bridges were all located within ten miles of a Washington State Patrol static scale. Each bridge had the following characteristics:

- its construction type (i.e., concrete box, concrete slab, steel girder, etc.) was commonly found on the main lanes of travel on Washington State highways;
- the bridge experienced high degrees of truck travel; and
- the bridge offered a safe location in which to place the WIM van and equipment.

The five bridges used are referred to as

- Nisqually,
- Pendleton,
- Martin Way,
- Snoqualmie, and
- Nisqually Overflow.

Each of these five bridges is described in detail below.

NISQUALLY

This bridge was a simply supported, pre-tensioned concrete girder bridge. The "bridge" instrumented was actually a lead span to a much larger steel truss bridge which spanned the Nisqually River at milepost 114.86 on Interstate 5. The concrete lead span was 60 feet long (59 feet from centerline to centerline). The bridge carried three lanes of traffic. It was located on a slight uphill grade and had no skew. The road surface of the bridge and for the 30 feet immediately preceding the bridge was concrete. More than 30 feet in front of the bridge, the roadway was asphalt. The road was in good condition.

Only one lane of traffic was instrumented during data collection at this location. Four strain gages were used on the bridge, although eight girders were available. The girders chosen were the second through the fifth from the right side of the bridge. These corresponded to the girders most influenced by traffic traveling in the monitored lane of traffic.

Conventional road tubes and "D" shaped road tubes were used at this location as axle sensors. Both types of road tubes gave poor axle readings. As a result of these poor readings, additional help was sought for describing some of the inputs to the computer program which runs during the data collection effort. Some of these inputs were not discussed at all in the FHWA documentation. Revisions to some of these inputs (primarily the "NN" input during revision of permissible vehicle lengths) seem to have improved the accuracy of the tube based axle counts.

For the most part, the axle count errors at Nisqually were caused by the WIM consistently missing the second axle of a tandem. The project team was able to identify these errors manually and therefore still make comparisons between static tandem weights and WIM weights, although the WIM calculation algorithm was actually for measuring single axles. These difficulties partially explain the poor axle weight estimates that resulted at the Nisqually bridge site.

The WIM van was placed beneath the bridge while data collection was occurring for this location. Access to this location was obtained by using a dirt road used primarily by fishermen.

An observer was placed beside the main roadway with a low power FM radio. He/she would transmit a description of the truck approaching the bridge. This description would then be passed on to observers at the static scales, along with the WIM ID number of that vehicle. The static scale would then weigh that vehicle and record the appropriate weights and identifying information.

The Nisqually bridge was the first bridge used for collecting corresponding WIM weights and static weights. Consequently, the project team learned many lessons at this site. The primary lesson learned was that operating the van's CB-radio microphone while collecting or processing strain gage information severely impacted the values recorded by the computer. The magnetic forces produced by the microphone overwhelmed the electronic signals coming from the signal conditioner. As a result, care was taken to reduce the amount of radio transmission during data collection, and specifically, an effort was made to avoid transmitting whenever a vehicle was on or approaching the bridge.

PENDLETON

Pendleton was a 39-foot, slightly arched concrete slab bridge. It was six lanes wide, carrying both north- and south-bound traffic. The bridge was skewed (6 degrees) slightly, and spanned a small, two-lane road leading into the Fort Lewis Army Base. The road surface was asphalt at this point on Interstate 5 and was in good repair.

Three strain gages were attached semi-permanently to the underside of the bridge. To do this, a cherry-picker truck was borrowed from the local Department maintenance section, and holes were drilled into the bottom of the bridge. Bolts were then anchored into the bridge, and the strain gages were then attached to these bolts. To protect the stain gages from weather, the wires were placed inside a metal container attached to the side of the bridge. The container was accessible from the bridge without the need for the cherry picker. Permission and directions for drilling into the bridge were obtained from the Department's Bridge Division and from the Ft. Lewis base engineer before this operation took place. Two flagmen were necessary on Pendleton Avenue to direct traffic when drilling the Pendleton bridge.

Only one lane of traffic could be monitored at this location. The lack of a median prevented placing tape switches on the inside lane of travel. Tape switches were placed on the roadway as axle sensors.

This bridge caused two interesting problems. The first was that it was nearly impossible to determine from either the bridge plans or by sight observation where the bridge actually began. The study team eventually determined that a cracking in the pavement that paralleled the road being crossed indicated the likely bearing of the bridge.

The second problem was the failure of one of the three strain gages before the data collection started. Because a cherry picker truck was needed to access the strain gages, and it was not possible to readily replace the failed gage, the data were collected using the two remaining gages. The cause of the gage failure was not known. The most likely choices were

- intrusion of water into the gage wiring,
- metal fatigue in the gage,
- improper bolting of the gage to the bridge, and
- shifting in the bridge due to weather conditions (expansion and contraction) that adversely impacted the gage.

When finally removed from the bridge, the strain gage operated sporadically. At this time, the gage has not been completely examined to determine the cause of the failure.

MARTIN WAY

The third bridge instrumented was Martin Way. This bridge was a pre-tensioned concrete girder bridge. It carried two lanes of traffic in the northbound direction. The bridge was located at milepost 109.1 on Interstate 5. The bridge was 281 feet long, had a skew of 51 degrees, and consisted of three simply supported spans. The first span, which was 75 feet long, was instrumented.

Both lanes of the bridge were instrumented. The outside lane used tape switches placed directly on the roadway. The inside lane used tape switches placed inside rubber "boots" which were nailed to the roadway. Four strain gages were attached to the bridge's six girders. The two outside girders did not have gages attached.

The WIM van was parked in the median of the interstate, immediately preceding the bridge. The approach to the bridge was concrete, and the roadway approached the bridge using a lefthand curve. The bridge and preceding road surface were in good condition and were level.

Because of the large skew, data from this bridge were used to examine the potential for weighting the influence of particular girders in the processing routine to dampen the effects of other traffic on the bridge at the same time as the truck being weighed. By heavily weighting the strain information from the two girders immediately beneath a lane of traffic, a slight improvement in the accuracy of gross vehicle and axle weights was achieved. In most cases, this improvement was not statistically significant.

SNOQUALMIE

The Snoqualmie bridge was a 486-foot, four span, steel reinforced, concrete box girder bridge located at approximately milepost 37.02 on Interstate 90. The bridge spanned the Snoqualmie River near the town of North Bend, Washington. The bridge had no skew angle, but did start to curve midway through the second span. In addition, the bridge had a slight camber. (The left lane was higher than the right since the roadway turned to the right during the second through fourth spans.) The bridge was not on a grade.

While the Snoqualmie bridge was a three lane structure like most of the I-5 bridges (eastbound lanes were separated from westbound lanes), the level of traffic was considerably smaller than that on I-5. Consequently, only one lane was instrumented, and the majority of trucks passed over the tape switches.

The bridge was accessed via a road on top of the river dike. The van was parked beside the bridge, out of sight of traffic on the bridge, but in a position where the system operators could observe traffic.

Like the Pendleton bridge, the research team had to drill into the Snoqualmie structure in order to place the strain gages. Because the bridge spanned a river, no traffic control was necessary to perform this function. The generator on the WIM van was used to power the drill, whereas at Pendleton, the cherry-picker truck supplied the necessary power.

Four strain gages were placed on the bridge. Each gage was placed in the center of one of the concrete webs in the box structure. Special care was taken to avoid hitting the reinforcing steel when drilling the structure. As with Pendleton, permission was obtained to drill the bridge from the Bridge Division of WSDOT before work on the bridge began.

NISQUALLY OVERFLOW

The Nisqually Overflow bridge was used as the training bridge for University, WSDOT and WSP personnel. At this location, milepost 114.54 of Interstate 5, two separate structures (one in each direction) spanned the southern overflow channel of the Nisqually river. Each bridge was a two span, pre-tensioned concrete girder bridge. Each span was 100 feet long. The structure for northbound traffic was continuous across the mid-span pier. The southbound structure was simply supported.

On most occasions, the project team used the northbound structure for training. Access to this structure was excellent. Strain gages could be placed while standing on solid ground, and parking existed for the WIM van, support vehicles and visiting personnel next to the freeway, immediately outside of the right-of-way.

The northbound structure carried three lanes of traffic. Two of these lanes (the extreme inside and outside) were normally instrumented for weighing trucks. In addition, a merge lane from an offramp immediately upstream of the bridge further widened the bridge and increased the width of the outside roadway lane. The bridge was located at the base of two hills, with the structure itself being on a slight upgrade. As a result of the incline, WIM weights were expected to be slightly lower for steering axles when compared to static weights, and slightly higher than static weights for rear axles because of shifting loads. The road surface of the bridge was concrete.

The bridge consisted of eight concrete girders. The two girders farthest to the right angled slightly inward on the first span of the northbound structure, as the merge lane crossed the bridge. Four or six strain gages were placed on this bridge, depending on the availability of functioning signal conditioning modules. When six gages could be placed, the middle six girders were instrumented. When four gages were placed, girders 2 through 5 (counting from the right) were instrumented. The outside girders on the bridge were ignored primarily because they carried little of the traffic loading occurring in the structure.

For the Nisqually Overflow bridge, conventional road tubes were used as axle sensors for the WIM equipment. This was necessary because of the extreme width of the outside lane of travel due to the upstream merge. Use of the available tape switches would either have meant exposing cable to vehicles using the on-ramp or missing the vast majority of traffic by being too far from the wheel path of the majority of vehicles.

A second difficulty at this bridge, and the main reason why it was not used extensively for collecting vehicle weights, was that communications between this location and the WSP static scale were poor. While the bridge was only 3 miles from the static scale, the intervening hill had a high iron content, and communication between the two points was very poor. As a result, only a modest number of weight comparisons were made at this location. These comparisons are included in the appendix of this report but are not as comprehensive as those available for the remaining four bridges.

CHAPTER 4
STUDY RESULTS

This section details the results of the testing performed with the bridge system. The testing centered on determining the accuracy of the weight estimates produced by the system. In addition, some less rigorous tests were performed to examine the accuracy of the system in terms of vehicle speeds and classifications.

The weight estimates examined included gross vehicle weights, single axle weights, tandem axle weights, and equivalent axle loads. Several analyses were performed for each of these measurements. The analyses are presented below and include the following:

- estimates of mean population weight and the standard deviation of those estimates are compared between WIM and static equipment;
- the mean error between WIM and static scale estimates for individual axles and vehicles are examined;
- a comparison is made between estimates for 3S2 trucks and other styles of vehicles to see if the bridge system was particularly sensitive to or especially accurate for the most common truck type; and
- other conclusions and observations pertaining to the manipulation and analysis of the data are provided.

Finally, some conclusions about the accuracy and limitations of the system are presented.

For data collection for planning and design purposes, the most important analyses concerned the mean vehicle (gross and axle) weights and the distribution of these weights for the population of trucks that are weighed. For enforcement needs, the one-to-one comparison of weight estimates was most important.

GROSS VEHICLE WEIGHTS

The bridge WIM system produced reasonable estimates of the mean gross vehicle weight of trucks passing each of the weighing sites. Errors of the mean gross vehicle weight averaged 2.0 percent for the five locations. As can be seen in Exhibit 4-1, some bridges provided considerably better mean weight estimates than other bridges, but all of the bridges gave reasonable averages. Exhibit 4-1 also shows that the range of the error in the mean gross vehicle weight was from 1.0 percent at the Martin Way bridge to 5.9 percent at the Nisqually bridge. Statistics showed that the WIM and static mean weights were not significantly different, with the exception of the Nisqually bridge.

Individual truck gross weight estimates were less accurate than the mean population estimates described above. The mean error for individual trucks ranged from 11 percent at Snoqualmie to 18 percent at Martin Way. These corresponded to errors of 5,800 to 8,700 pounds per vehicle respectively. These errors were randomly distributed around the mean described in the preceding paragraph.

Essentially, the variation due to the dynamic motion of the trucks and the presence of other extraneous circumstances (e.g., other vehicles on the bridge) caused the in-motion weight for any one truck to fluctuate around the actual static weight. The WIM system's measurement of this fluctuation can most easily be visualized using an X/Y plot such as that in Exhibit 4-2, which shows a plot of WIM gross vehicle weights versus static weights for the Snoqualmie bridge. Similar plots for the Nisqually, Martin Way and Pendleton bridges are included in Appendix B.

Exhibit 4-3 shows a tabular summary of the per vehicle accuracy of all of the four test bridges. As can be seen in this exhibit and Exhibit 4-2, 64.9 percent of the WIM gross vehicle weights fell within 10 percent of the actual static weight for the Snoqualmie bridge. Eighty-three percent were within 15 percent of the

Exhibit 4-1
Population Gross Vehicle Weight Statistics
WIM Versus Static

Bridge	Number of Trucks	Mean GVW			Standard Deviation	
		WIM	Static	%Difference	WIM	Static
Martin Way	96	52.92	53.44	-0.97	25.660	25.830
Pendleton	107	42.76	43.68	-2.11	22.849	21.778
Snoqualmie	93	52.25	51.70	1.06	27.566	24.480
Nisqually	101	49.45	52.55	-5.90	26.723	24.133
All Bridges combined	397	49.14	50.18	-2.06	25.911	24.275

Exhibit 4-2

WIM vs. Static GVW (Snoqualmie)

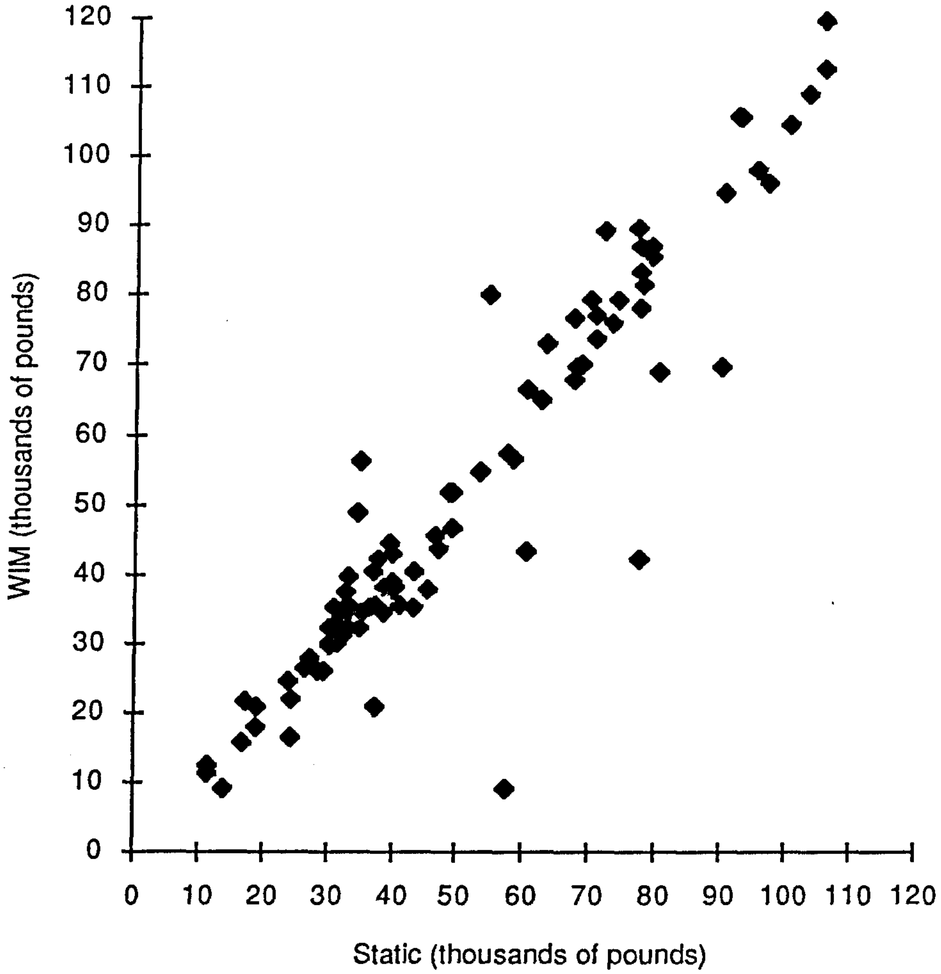


Exhibit 4-3
Individual Truck Comparisons of Gross Vehicle Weight

	All Vehicles		3S2 Type	
Bridge	≥10%	≥15%	≥10%	≥15%
Martin Way				
GVW	44.8%	29.2%	37.1%	22.6%
Single Axle	74.1%	59.4%	66.7%	47.0%
Tandem Axle	67.1%	55.5%	61.1%	47.6%
Pendleton				
GVW	38.3%	28.0%	35.8%	26.9%
Single Axle	60.3%	46.0%	55.6%	37.5%
Tandem Axle	47.1%	37.9%	48.5%	39.6%
Snoqualmie				
GVW	34.4%	17.2%	27.1%	12.5%
Single Axle	68.7%	60.8%	61.7%	56.7%
Tandem Axle	67.1%	50.3%	63.5%	43.3%
Nisqually				
GVW	41.6%	24.8%	34.4%	21.9%
Single Axle	80.8%	66.5%	84.0%	72.8%
Tandem Axle	76.6%	66.9%	75.8%	65.6%
Total				
GVW	39.8%	24.9%	34.0%	21.6%
Single Axle	70.8%	58.0%	67.7%	54.1%
Tandem Axle	64.5%	52.7%	62.0%	49.2%

static weight. For all bridges combined, 60.2 percent of the WIM gross vehicle weights were within 10 percent and 75.1 percent were within 15 percent.

These results are generally poorer than those achieved by Wisconsin in its testing of the bridge system. Furthermore, the best results were apparent at the box girder bridge (Snoqualmie), which was rather unexpected. Further analysis led to the conclusion that the reason for the good results at Snoqualmie and the poorer results at the other three bridges was the presence of other vehicles on the bridge when vehicles were being weighed. This was continually the case on the three I-5 bridges, which showed the poorer results.

An analysis was also performed to determine whether the bridge system weighed heavier vehicles with more accuracy than lighter vehicles. The split of 40,000 pounds was chosen to duplicate the results of Wisconsin. Our analysis showed that no statistical difference in the percentage of error in a gross weight estimate was apparent between heavy trucks and lighter trucks at Pendleton and Snoqualmie, but that heavier vehicles were weighed more accurately (in percentage terms) at Nisqually and Martin Way. Exhibit 4-4 shows this analysis.

3S2 Versus Other Truck Types

Because the 3S2 truck type makes up such a large percentage of the truck mix, these trucks were analyzed separately from all other truck types. Accuracy of gross vehicle weights for 3S2 trucks was roughly equal to that of non-3S2 vehicles. Exhibit 4-5 shows this comparison of 3S2 trucks to non-3S2 trucks for gross vehicle weights.

From this exhibit it can be seen that three of the four bridges had smaller absolute errors (i.e., individual truck weights were better) for non-3S2 vehicles than for 3S2. However, in no case was the percentage error per vehicle smaller for non-3S2 vehicles. This indicates that the non-3S2 vehicles tended to be lighter than the 3S2s, and

Exhibit 4-4
Comparison of WIM Estimates For Heavy Versus Light Trucks (GVW)

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
GVW<=40					
Number of Vehicles	37	60	42	39	178
Mean of GVW Percent Error	25.34%	12.47%	11.26%	23.36%	17.25%
Standard Deviation of Percent Error	30.53%	13.19%	12.97%	39.57%	25.70%
GVW>40					
Number of Vehicles	59	47	51	62	219
Mean of GVW Percent Error	11.47%	15.97%	11.53%	12.49%	12.74%
Standard Deviation of Percent Error	14.98%	19.71%	14.20%	11.57%	16.10%
Difference	13.87%	-3.50%	-0.27%	10.87%	4.51%
Pooled S.D.	22.26%	16.37%	13.66%	27.39%	21.17%
F value	8.83	1.20	0.01	3.77	4.549
t-value	2.58	-1.05	-0.09	1.64	2.13
Significantly different	yes	no	no	yes	yes

Exhibit 4-5
3S2 WIM Gross Vehicle Weights Versus Other Types of Vehicles

	3S2	Other Vehicles
Martin Way		
Mean Absolute Error Static-WIM	7.40 kips	7.19 kips
Absolute Error (Percentage of Static)	13%	24%
Population Mean Estimate Error (Static-WIM)	-1.87	1.93
Pendleton		
Mean Absolute Error Static-WIM	6.80 kips	4.89 kips
Absolute Error (Percentage of Static)	14%	14%
Population Mean Estimate Error (Static-WIM)	-0.34	-1.91
Snoqualmie		
Mean Absolute Errorr Static-WIM	5.11 kips	6.51 kips
Absolute Error (Percentage of Static)	9%	14%
Population Mean Estimate Error (Static-WIM)	1.37	-0.33
Nisqually		
Mean Absolute Errorr Static-WIM	8.56 kips	6.11 kips
Absolute Error (Percentage of Static)	16%	18%
Population Mean Estimate Error (Static-WIM)	-3.27	-2.79
Total		
Mean Absolute Error Static-WIM	7.08 kips	6.15 kips
Absolute Error (Percentage of Static)	13%	17%
Population Mean Estimate Error (Static-WIM)	-1.17	-0.82

further reinforces the conclusion that little inherent difference in the accuracy of the calculation exists because of the 3S2's standard configuration.

AXLE WEIGHTS

Single and tandem WIM axle weights were somewhat less accurate than the gross vehicle weights described above. These results were fairly consistent with the results published in the Wisconsin DOT study described in Chapter 2, although again, the results achieved in these tests were less accurate than those achieved by Wisconsin. The dynamic effects that hindered the accuracy of the gross vehicle weight calculations seem to have had a similar and slightly greater effect on axle weight estimates.

Exhibit 4-6 shows the comparison of mean single and tandem axle weights collected by the WIM system versus those collected at the static scale for each of the four bridges. For the group as a whole, the mean population error for single axles ranged from 2.85 to 8.35 percent. For tandems the mean population error ranged from 2.85 to 6.51 percent. Front singles were more accurate than all single axles combined, with a mean population error of between 1.35 and 6.67 percent.

As with gross vehicle weights, the average error per axle or tandem was considerably higher than the error of the mean population estimate. The expected measurement errors on any one particular axle or tandem are shown in Exhibit 4-7 for each of the four bridge sites. While the single axle population mean was only off by 2.14 percent, the average single axle estimate was off by between 21 and 35 percent. The average front axle estimate was off by between 16 and 21 percent. Tandem axles were similar to single axles in accuracy, with errors of between 20 and 33 percent.

The data in Exhibit 4-7 show that the Pendleton bridge provided the best axle weight estimates. They were even better estimates than those from the Snoqualmie bridge, which had a lower error for calculating gross vehicle weights. The WIM device

Exhibit 4-6
Population Axle Weight Statistics
WIM Versus Static (in kips)

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Mean Single Axle Weight					
WIM	10.38	9.03	9.52	9.55	9.59
Static	9.58	9.76	10.00	9.83	9.80
Difference	0.80	-0.73	-0.48	-0.28	-0.21
Percentage	8.35%	7.48%	4.8%	2.85%	2.14%
Number of Axles	143	174	166	167	650
Mean Front (Steering) Axle Weight					
WIM	9.74	8.67	9.62	9.93	9.47
Static	9.61	9.29	9.37	9.63	9.47
Difference	0.13	-0.62	0.25	0.30	0.00
Percentage	1.35%	6.67%	2.67%	3.12%	0.00
Number of Axles	96	107	93	101	397
Mean Tandem Axle Weight					
WIM	22.68	19.54	9.52	9.55	21.64
Static	24.26	19.44	10.00	9.83	21.28
Difference	-1.58	0.10	-0.48	-0.28	0.66
Percentage	6.51%	0.51%	4.80%	2.85%	3.10%
Number of Tandems	155	153	166	167	611

Exhibit 4-7
Individual Comparisons of WIM and Static Axle Measurements (in kips)

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Single Axles					
Mean Absolute Error	3.04	2.06	3.05	2.88	2.74
Percentage Error	35%	21%	32%	29%	29%
Standard Deviation of Absolute Error	3.601	2.611	3.398	2.862	3.14
Front Axles					
Mean Absolute Error	1.95	1.39	1.93	2.46	1.92
Percentage Error	21%	16%	21%	26%	21%
Standard Deviation of Absolute Error	2.17	1.135	1.885	2.039	1.871
Tandem Axles					
Mean Absolute Error	5.58	3.45	3.05	2.88	5.00
Percentage Error	26%	20%	32%	29%	25%
Standard Deviation of Absolute Error	5.803	4.753	3.398	2.862	5.691

at Snoqualmie bridge did a poor job generally at estimating axle weights, despite the bridge's better gross weights and lower traffic volume.

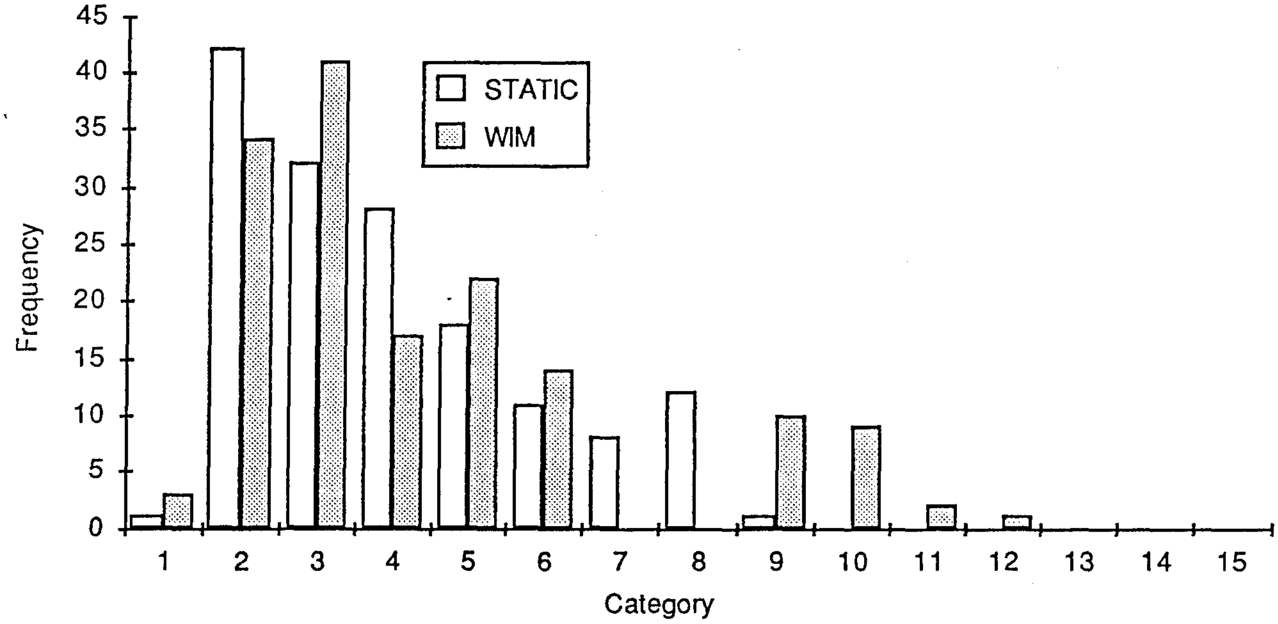
The accuracy at the Pendleton bridge was most likely due to its shorter span length, as this has been cited in several of the previous studies as an important criterion in selecting a good bridge site. In addition, one box girder bridge used in a previous study also failed to provide good axle estimates. How much of the Snoqualmie error can be attributed to the bridge type, and how much should be attributed to the length, camber and slight curve of the bridge is not known at this time.

The high errors from the Nisqually and Martin Way sites were not surprising given the errors in gross vehicle weights at these sites. The errors seem to have been due to a combination of the volume of traffic at both sites, the skew of the Martin Way bridge, the axle sensor troubles encountered at the Nisqually bridge, and the relatively long spans used in both cases.

Another area of similarity between WIM axle and gross vehicle weights was in the increase in variation measured within the sample population. This increased variation had a more important role in axle weights than it did in gross vehicle weights. For axles, several axle weights were recorded as negative numbers. These axles were discarded from the analysis but still represented problems in the use of the system. In addition, the high WIM standard deviation resulted in several very heavy axles (see Exhibit 4-8), which caused significant errors in EAL calculations, as discussed in the next section in this chapter. Unlike the negative axle weights, no justification was apparent for allowing the project team to throw out the unusually heavy axle weights because without the static weights to compare against the WIM data, an engineer would not have known whether the weights observed were overloads or system errors. (In contrast, negative axles are automatically errors.)

Exhibit 4-8

Tandem Axle Weights – Pendleton



Category	Weight Range (pounds)
1	Under 6,000
2	6,000 - 11,999
3	12,000 - 17,999
4	18,000 - 23,999
5	24,000 - 29,000
6	30,000 - 32,000
7	32,001 - 32,500
8	32,501 - 33,999
9	34,000 - 35,999
10	36,000 - 37,999
11	38,000 - 39,999
12	40,000 - 41,999
13	42,000 - 43,999
14	44,000 - 45,999
15	46,000 - 49,999

The bridge system provided more accurate weights for heavy tandem axles than it did for light tandem axles. Surprisingly, however, it weighed lighter single axles better than heavier axles at two of the bridge sites. (The other two sites showed no statistical difference between single axle weight estimates.) These results are shown in Exhibit 4-9.

EAL ESTIMATES

The EAL estimate indirectly shows the effects the use of the WIM system will have on pavement design. EALs essentially drive the equation for estimating pavement thickness for overlay and new pavement design. As can be seen in Exhibit 4-10, the effect of converting the axle estimates into EALs has a significant effect on the quality of the weight estimate, and consequently on future pavement designs. This is a direct result of the random dynamics of the axles being measured and the limitations experienced by the WIM system when it is collecting data and calculating axle weights.

The errors in the mean EAL estimate per single or tandem axle were considerably larger than the corresponding errors for mean single and tandem axle weights (see Exhibit 4-10). In addition, the EAL estimates for the population tended to significantly overestimate the average EAL per axle or tandem. With the exception of tandem EALs at Martin Way, the error in the EAL estimate was between 18 and 50 percent per axle or tandem. Only at Martin Way was the EAL per axle lower from the WIM estimate than from the static estimate.

The errors in EAL estimates occurred because of the presence of a few very heavy axles in the WIM weight estimates (see Exhibit 4-11). The nature of the axle weight to EAL conversion is such that errors in weight estimates are magnified on the order of the fourth exponential. Because of this fourth order effect, a few extra, very heavy axles cause a significant increase in the mean EAL estimate.

As noted earlier, the unusually heavy and negative axles weights appeared to be directly related to the dynamic action of a truck's axles and to the presence of other

Exhibit 4-9
Comparison of WIM Estimates For Heavy Versus Light Trucks (Single & Tandem)

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Single <= 12 kips					
Number of Axles	131	146	133	140	550
Mean of Percent Error	35.20%	19.85%	29.69%	28.84%	28.17%
Standard Deviation of Percent Error	50.90%	20.88%	29.10%	25.55%	33.60%
Single > 12 kips					
Number of Vehicles	12	28	33	27	100
Mean of GVW Percent Error	31.06%	28.19%	39.94%	30.20%	32.95%
Standard Deviation of Percent Error	20.68%	26.96%	37.88%	24.23%	29.80%
Difference	4.14%	-8.34%	-10.25%	-1.36%	-4.78%
Pooled S.D.	49%	-155%	-145%	-26%	33%
F value	0.08	3.39	2.89	0.07	1.77
t-value	0.56	-1.55	-1.45	-0.26	-1.33
Significantly different	no	yes	yes	no	no
Tandem <= 24					
Number of Axles	68	103	91	67	329
Mean of Percent Error	33.60%	22.95%	27.34%	39.68%	29.78%
Standard Deviation of Percent Error	31.82%	30.17%	24.89%	66.29%	39.80%
Tandem > 24 kips					
Number of Vehicles	87	50	58	87	282
Mean of GVW Percent Error	19.19%	13.66%	18.71%	25.36%	20.02%
Standard Deviation of Percent Error	18.77%	18.72%	20.19%	19.64%	19.70%
Difference	14.41%	9.29%	8.63%	14.32%	9.76%
Pooled S.D.	25.32%	26.99%	23.18%	46.11%	32.50%
F value	12.36	3.99	4.91	3.65	14.03
t-value	3.31	2.34	2.32	1.71	3.75
Significantly different	yes	yes	yes	yes	yes

Exhibit 4-10
Mean EAL Per Axle
Static Versus WIM

	Martin Way	Pendleton	Snoqualmie	Nisqually	Total
Single Axles					
WIM Mean EAL/Axle	0.30	0.22	0.35	0.21	0.27
Static Mean EAL/Axle	0.12	0.16	0.20	0.14	0.16
Mean of Absolute Error	0.28	0.17	0.27	0.19	0.23
Standard Deviation of Absolute Error	0.832	0.777	0.821	0.418	0.728
Tandem Axles					
WIM - Mean EAL/Axle	0.57	0.37	0.45	0.65	0.49
Static - Mean EAL/Axle	0.53	0.28	0.31	0.48	0.40
Mean of Absolute Error	0.34	0.15	0.26	0.55	0.32
Standard Deviation of Absolute Error	0.422	0.263	0.563	1.222	0.731

EXHIBIT 4-11
STATIC VERSUS WIM AXLE WEIGHTS BY W4 TABLE CATEGORY

Single Axles Weight Range	Static	WIM
Under 3,000	5	43
3,000 - 6,999	105	114
7,000 - 7,999	35	48
8,000 - 11,999	410	305
12,000 - 15,999	65	102
16,000 - 18,000	20	23
18,001 - 18,500	5	0
18,501 - 20,000	10	16
20,001 - 21,999	7	7
22,000 - 23,999	5	8
24,000 - 25,999	5	4
26,000 - 29,000	5	6
30,000 or over	8	9
Total	685	685

Tandem Axles Number of Axles	Static	WIM
Under 6,000	4	27
6,000 - 11,999	130	99
12,000 - 17,999	115	133
18,000 - 23,999	70	90
24,000 - 29,999	84	77
30,000 - 32,000	56	56
32,001 - 32,500	23	0
32,501 - 33,999	73	3
34,000 - 35,999	30	26
36,000 - 37,999	5	32
38,000 - 39,999	1	22
40,000 - 41,999	3	13
42,000 - 43,999	0	3
44,000 - 45,999	0	9
46,000 - 49,999	0	4
50,000 or over	0	0
Total	594	594

vehicles on the bridge at the time of a vehicle weighing. To a greater or lesser extent, this same problem will occur for any dynamic scale, regardless of design. The negative axles can be easily discarded from subsequent processing and will not affect the subsequent EAL calculation. A method for disposing of the heavy axle weights would be to arbitrarily discard the highest "x" percent of axle weights from the EAL analysis. While this might result in the discarding of true heavy axle weights, the random effects of the dynamic axle movement should compensate for this potential problem. Exhibit 4-12 demonstrates a comparison of EAL estimates with and without the top two percent of WIM axle weights (i.e., x = 2).

Problems with Data Manipulation

The errors described above and summarized in the preceding exhibits were not the only errors in vehicle weights that occurred in the collection of vehicle weight data using the bridge WIM system. An extensive amount of data reduction was necessary to obtain the quoted WIM results, and a considerable amount of data was discarded during that process. Most of the estimates discarded were obviously bad (i.e., negative gross weights or gross weights exceeding 150,000 pounds). The study team discarded 107 vehicles out of 1,542 (6.9 percent) because of extremely high or negative weight estimates.

In all cases that the research team could trace, extreme weight estimates were due either to the presence of a second vehicle on the bridge, or to the use of the van's microphone during data collection. (Errors due to the microphone were eliminated after the microphone problems were discovered.) On three of the four bridge sites (those on Interstate 5), the presence of additional vehicles was a significant problem. Interstate 5 had very heavy truck traffic, with vehicles often traveling in groups. In addition, the presence of automobile traffic may have significantly affected axle load estimates and added to the variation present in both WIM gross vehicle weight and axle weight

Exhibit 4-12
EAL Estimates Discarding Heaviest* WIM Axles

	Bridge			
	Martin Way	Snoqualmie	Pendleton	Nisqually
EAL/Single Axle (WIM)	0.22	0.25	0.14	0.17
EAL/Single (Static)	0.12	0.20	0.16	0.14
Percent Difference	80%	25%	-13%	21%
Percent Difference with Heaviest Axles	150%	75%	38%	50%
EAL/Tandem Axle (WIM)	0.52	0.42	0.34	0.52
EAL/Tandem (Static)	0.53	0.32	0.28	0.48
Percent Difference	-2%	31%	21%	8%
Percent Difference with Heaviest Axles	8%	45%	32%	35%

---

*Heaviest = top 2 percent

estimates. The Snoqualmie bridge was the only bridge where this was not a problem. This is apparent in the lack of discarded vehicles for that bridge (see Exhibit 4-13).

If two trucks were very close together (positions shown as A and B in Exhibit 4-14), the bridge system would normally miss the trailing vehicle altogether, associating all of its weight with the first truck. The first vehicle's weight estimate would either be overestimated or become totally unreasonable, depending on the weights and positions of the two vehicles. Errors also occurred when trucks were in positions A and C, or A and D.

A second error, which was not as obvious as extreme gross weights, often occurred when vehicles reached the instrumented bridge in positions A and B, but with the following truck trailing the first vehicle by a distance of roughly two thirds of the bridge span's length. In this case, the bridge system would "see" only <u>part</u> of the second truck. That is, the computer would reactivate its observation of the axle sensors after the second truck's (truck B) initial axles had crossed the sensors, but before the trailing axles had crossed. For example, an eight axle double trailer (3S2-3) would appear as a five axle truck of unknown classification.

In these situations, the system would correctly weigh the first vehicle (or slightly overestimate its weight) but would undercount the number of axles on the second vehicle. As a result of undercounting the second vehicle's axles and missing that vehicle's first axles the system was unaware of the true axle configuration and the true position of the vehicle on the bridge. Consequently, estimates of the second vehicle's weights were usually unreasonable.

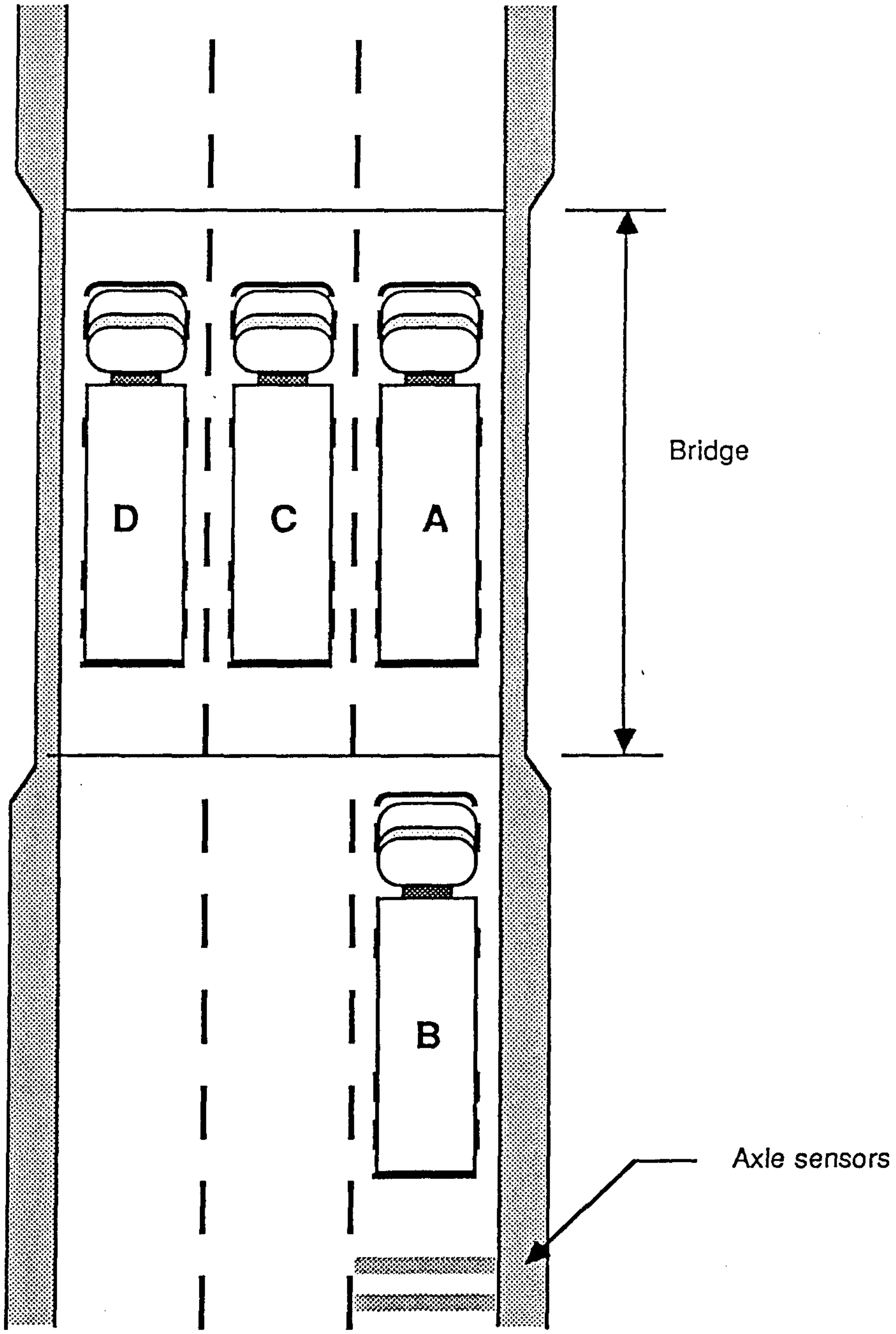
When processing the truck weights, the majority of the above situations could be readily identified and eliminated. The initial printout of vehicle weights was restricted to realistic weight ranges (zero to 150,000 pounds). This printout was then visually examined for unusual axle configurations or weights and further edited (usually by

Exhibit 4-13
Presence of Bad Axle Counts

	Number of Trucks Weighed	Number of Non-Negative GVW Weights	Number of "Valid" Trucks with at Least One Negative Axle Weight
Martin Way	400	(355)	29
Pendleton	544	(527)	11
Snoqualmie	210	(210)	8
Nisqually	370	(343)	68
Total	1542	(1435)	116

Exhibit 4-14

Position of Trucks on Bridges



simply eliminating vehicles). Comparisons were then made against static weights and configurations. This examination usually revealed several cases where the system had missed the initial portion of a truck. These trucks were then removed from the comparisons presented in this paper.

The above error problems seemed to have little to do with the four bridge types examined. They all seemed to correspond directly to the amount and location of traffic using the bridge.

VEHICLE SPEED

The accuracy of measured vehicle speeds was tested informally at all of the locations. The tests were accomplished by driving the equipment van over the axle sensors at a known rate of speed and comparing that rate of speed with the estimate provided by the WIM system. In all cases, the WIM estimate was within acceptable levels of accuracy.

The only problems encountered with the speed estimation came from difficulties in placing the axle sensors on the roadway. Because three of the sites were on very high volume roads (Nisqually, Pendleton and Martin Way), the sensors had to be placed quickly. To ensure good speed readings, the axle sensors needed to be perpendicular to the road and parallel to each other. Both of these tasks were difficult on I-5 because of the speed necessary to place the sensors between small breaks in traffic. Consequently, the measured distance between the two sensors varied slightly along the length of the sensors. This variation probably introduced some error into the WIM system speed estimates, since differences in distance between sensors will result in slightly different estimates of speed. This will in turn lead to the input of slightly erroneous information on the actual location of the truck at any given point in the data collection process, generating some additional error.

One other problem that was encountered but quickly fixed occurred with the use of road tubes as axle sensors. The research team discovered that if tubes of different lengths were used, the difference in the time necessary for the air pulse to activate the switch varied significantly between the tubes. This caused significant errors in the speed estimates. While this was noticed immediately (and fixed), it raises the question of how much of a time lag the air switches introduced and whether that lag was significant (the speed differential indicated that this might be the case). The fact that the truck detected by the air switch might have been farther across the bridge than the computer estimated might explain some of the larger errors in the Nisqually axle estimates.

Project resources did not allow for further investigation of this problem.

AXLE COUNTS

With the exception of early attempts at the Nisqually bridge, the axle counts collected by the system were mostly reasonable. Problems encountered at Nisqually were related to an input into the data collection computer software that was not explained by the software manual. Once this needed entry was clarified, the axle counts improved in accuracy.

CONCLUSIONS

On the whole, the bridge system did not function as well as desired during the research tests. Both gross vehicle weights and axle weights were not as accurate as they should be for use by the Department. In particular, the few, high, single and tandem axle weights recorded by the WIM system but not recorded at the corresponding static weighing significantly skewed the calculation of EALs based on WIM information. Such a skew would have significantly altered pavement design estimates. These errors will have to be addressed before the system is considered for purchase and use by the Department.

To be fair to the bridge system, much of the testing performed as part of this research could be termed "worst case" scenarios. The test sites tended to have very high volumes of trucks and automobiles (except for Snoqualmie), which created a situation in which other vehicles were continually on the bridge at the same time as the truck being weighed. The one structure where this was not the case was a long box girder with both curvature and camber attributes which undoubtedly affected the accuracy of the system, and particularly the axle weight estimates.

One final system problem that probably affected the accuracy of the weight estimates was a result of the research team's use of a multimeter in place of an oscilloscope for checking strain gage output from the bridge (an oscilloscope was not available during the project). The multimeter was used to ensure that the strain gage output was amplified to the highest extent possible without exceeding the five volt limits set by the processing program. Unfortunately, the multimeter falsely indicated the strain levels obtained for the first three bridges tested. The meter reported overload conditions at high amplification settings, which caused the project team to reduce the amplification factor applied by the signal conditioner. Later the team determined that the strain levels were not overloaded (i.e., exceeding 5 volts), but that in fact the multimeter was simply changing to a different screen display factor as it approached three volts, and that the overload signal was simply a manifestation of this change. By the time the screen display was ready at the new level, the peak strain had passed, the higher display factor was no longer required, and the meter simply resumed operation at its normal level (i.e., the new display factor never appeared on the screen, only the overload indication was displayed).

The end result of this difficulty was that strain levels lower than what could have been measured were collected. According to earlier research, this lower strain output leads to lower accuracy in the system's weight estimates. Higher amplification of strain readings would most likely have produced better weight estimates. These problems were corrected at the Snoqualmie bridge and at subsequent bridge sites tested by the Department since the end of the basic research effort.

Given the nature of the bridge system, and the above circumstances, the results were not too surprising, despite being somewhat disheartening. However, these results are significant factors for consideration when the Department decides whether to purchase the system.

Department Usage

The author believes that the bridge system can fulfill a significant part of the weight data collection tasks of the Department within necessary accuracy limits, despite the less than sterling results described in this report. However, other WIM scales may provide means of obtaining data that are just as accurate and more flexible. The bridge system's use should be confined to sites where its limitations would be minimized. This means that the bridges chosen should have the following attributes:

- a limited number of times during which multiple vehicles are on the bridge at the same time (this can be the result of low traffic volumes, or relatively small bridges (i.e., two lanes maximum), or a combination of both),
- small skew angle, and
- no curve or camber in the bridge.

In practice, this means that the system would be best utilized on moderate to low volume rural roads that have either two lanes or are four-lane divided highways.

The research conducted can not draw definitive conclusions about the use of box girder and slab bridges, but the results indicate that these bridges can be used in place of standard steel or concrete girder structures. The shorter the structure, and the closer to being simply supported it is, the more likely the axle and gross weights will be accurate. However, further research should determine whether a computer program calculating different influence lines could be created that might improve the accuracy of weighings performed with this type of structure. In addition, further research needs to be conducted to determine the best manner to attach gages to such bridges to reduce the occurrence of gage failure.

Enforcement Usage

As an enforcement tool the bridge system would fare even less well than it would as a data collection tool for the Department. The very large fluctuations in individual axle and gross weights would make its use for writing citations or even as a screening tool suspect, if it were used at sites similar to those included in this research.

However, if its use were restricted to those locations described above, it could serve as a reasonable screening device.

CHAPTER 5
COST OF OPERATING THE SYSTEM

This chapter describes the operating costs of the bridge WIM system. It discusses the personnel requirements of the system, details the basic equipment needs of the system, and describes the primary issues regarding the personnel levels required to operate the system.

REQUIRED PERSONNEL LEVELS

Two people should be available to set up the bridge system. This task can be done by one person, but in many locations a single person might be exposed to hazardous situations. Once in operation, one person is necessary to "baby-sit" the computer, as it has a tendency to crash for no apparent reason. If a more reliable computer were obtained and if only one lane were to be monitored, the system could be left unattended provided the gasoline tank to the generator was sufficiently large. If two lanes are to be monitored, one person is needed to operate the keypad of the system. This person must have a good view of the bridge approach. If the WIM van can be placed in a position where the system operator can remain in the van and still see approaching traffic, one person can operate the system. If the approach can not be seen from the van, a second person is necessary to inform the system of approaching traffic in the second lane.

PERSONNEL ISSUES

The primary issues concerning staffing of the system are safety related. The principal issue revolves around the safety of leaving one person with the system, particularly during the late night and early morning hours. The researchers believe that, with the exception of those times when two individuals are required to operate the system (as described above), one person can safely operate the system. The current van setup allows the system operator to disconnect all cables from within the van. This allows a quick departure from a location if such a departure becomes necessary. The van should be equipped with a radio to allow for distress calls and other communications

EQUIPMENT NEEDS

The bridge system has few equipment needs. The major need is for a van similar to either of the vans used in this project. The initial van, a standard "maxi-van," cost less to operate, was easier to drive, and fit in more locations than the step van that will be turned over to FHWA. The step van could carry more equipment, and the additional interior room was more suited for teaching classes on the functioning of the system and for showing off the operating equipment to persons visiting the site. Either type of vehicle is suitable for future use as the primary WIM van.

The only other operating equipment needs of the system are replacement axle sensors, tape for the tape switches, and periodic computer maintenance. A more modern computer will be more reliable than the machine used by the FHWA system, but some costs (roughly $50 to $100 per month) should be set aside for routine maintenance. Tape switch axle sensors cost roughly $45 a piece for a 10-foot switch. Four switches were destroyed during the course of the project. Budgeting for 10 new switches per year would probably be sufficient to meet the state's needs.

Cloth tape seemed to work reasonably well for keeping the switch on the pavement. A case of inexpensive tape per year would only cost $100 or so. A more sturdy tape might cost $300 per year.

CHAPTER 6
RECOMMENDED EQUIPMENT AND/OR SOFTWARE CHANGES

This section describes equipment and software changes that should be made to the bridge WIM system before the state decides to purchase a similar system.

RECOMMENDED EQUIPMENT CHANGES

The primary difficulty the project team encountered with the bridge WIM equipment stemmed from the age and style of computer used to collect and process strain gage information. The bridge WIM system provided by FHWA operates off of a DEC MINC computer. This machine is out of date given the quickly advancing state of computer technology. In addition, its age was the probable cause of various hardware problems. Among the difficulties encountered with the machine were the following:

- the computer would not work in moderately cold surroundings (55 °F or less);
- the disk drives blew fuses twice during the project;
- the operating system is machine specific, and therefore must be learned by each system operator; this system is not used on other microcomputers at WSDOT; and
- the information stored on disk by the system can not be readily transferred to other computer systems for further analysis.

As a result of the above problems, the author recommends that a different computer be used to drive a similar system, if one is purchased by WSDOT. In particular, an IBM or IBM compatible microcomputer is recommended for use in place of the DEC system.

By using the IBM type of computer, the Department will gain the following benefits:

- disks used for storage could be directly transferred to other IBM machines for additional processing;
- data from those disks could be uploaded to the Department's mainframe as desired using existing WSDOT software and procedures;
- the Department already has equipment, experience and personnel capable of servicing and maintaining the equipment;
- in the event of major system failure near Olympia, a substitute machine could be found to replace the WIM machine;
- in the event of a failure on the road, the chance of finding service and parts for the machine would be significantly better with the IBM than for the older DEC model; and
- people already familiar with IBM micro-computers would be capable of performing routine system chores (formatting disks, checking for disk errors, copying programs and datasets, etc.) without the need for learning yet another operating system. Likewise, newly trained personnel would be able to transfer their new computer literacy skills back to their other jobs.

RECOMMENDED SOFTWARE CHANGES

In addition to the above equipment changes, several changes are recommended for the software that operates the equipment. These changes are listed and described below.

- The software should be capable of classifying and storing the number of vehicles that cross the bridge. This includes vehicles in at least two lanes. The system might need to accept an additional axle sensor as an input to perform this function.
- The system should readily acknowledge when more than one vehicle is on the bridge. It should then indicate this on the appropriate strain record.

- The software needs to be more "user friendly." That is, the information prompts on the existing system are cryptic. They should be improved to assist the operator in understanding what data are being requested. For example, the current system asks for Samples, # of Samples, and Sampling Rate. The first two of these refer to the same input, the number of data points to be eliminated from processing. The third indicates the number of data points that should be measured every second during data collection.
- Better error checking should be provided. A limited amount of error checking should be incorporated into the data input routines of the strain gage processing program. As it is now, the system accepts all information until it begins processing and then "bombs out" when it attempts to use bad data. Instead, the system should make an immediate review of the input data and ask for revisions of the input if it does not satisfy given criteria. This is particularly important for such inputs as dataset names and span lengths.
- Better error diagnostics. The current system essentially provides no error diagnostics. When processing errors occur, the system prints memory addresses or FORTRAN line numbers and quits. This leaves the user wondering what went wrong, with little or no information to assist him/her in debugging the problem.
- Additional options in the influence line diagram should be provided. For this research, the BILINE program for continuous girder bridges was used to estimate influence lines for box and slab bridges. The results were reasonable, but they might well be better if a program specifically designed to produce influence lines for those bridge types were available.

APPENDIX A
DESCRIPTION OF THE WIM VAN

APPENDIX A
DESCRIPTION OF THE WIM VAN

As a part of this research effort, the WSDOT is providing FHWA with a van to house the bridge Weigh-In-Motion equipment. The van provided is a 30-foot step van. Exhibit A-1 shows a plan view of the step van layout. Included in the working area of the van are two cabinets of drawers, a small desk, two file cabinets, storage areas for the bridge system equipment and additional table top working space.

Exhibit A-2 presents an elevated view of the left side of the van working area. This exhibit shows the location of the bridge WIM equipment (disk drives, monitor, CPU, signal conditioner, and printer) as it is viewed by someone sitting at the system operator's chair. In addition, a movable stool is included in the van for a second crew member or observer.

The generator for the WIM equipment is located in a compartment on the right outside rear of the van. Electrical cords are included in this compartment to run between the generator and two electrical outlets located on the left side of the van, which provide power to the computer equipment and air conditioning unit. A five gallon gasoline can is included in the generator compartment. This container allows the refilling of the generator gasoline tank without the need to leave the bridge site.

Air conditioning is provided by a unit located on top of the van. This unit also can provide warm air during winter months. The van's engine and heater can also be used to supplement this unit for heating the interior of the van. The air conditioner operates off of the same generator used to power the computer equipment.

Complete directions on the setup and use of the generator and other equipment in the van is included in the revised Bridge WIM Users Manual. This manual and the manual provided by FHWA are located in the van, either in the metal file cabinet closest to the computer equipment, or in the rear pocket of the operator's chair.

Exhibit A-1

Plan of WIM Van

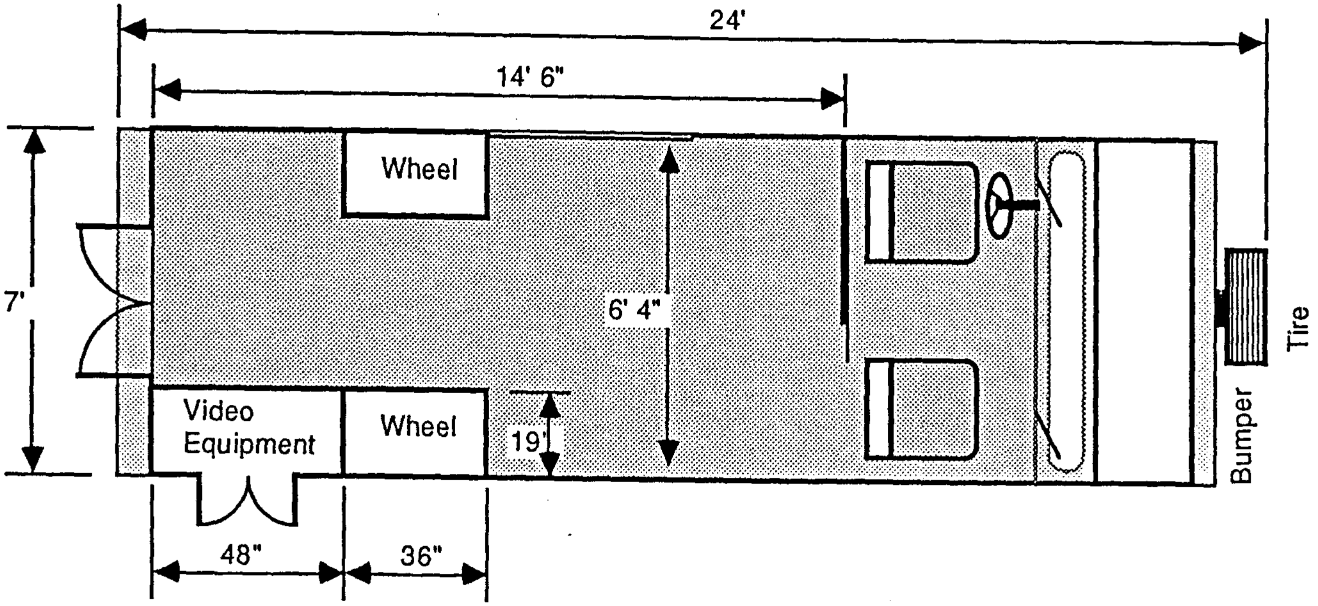
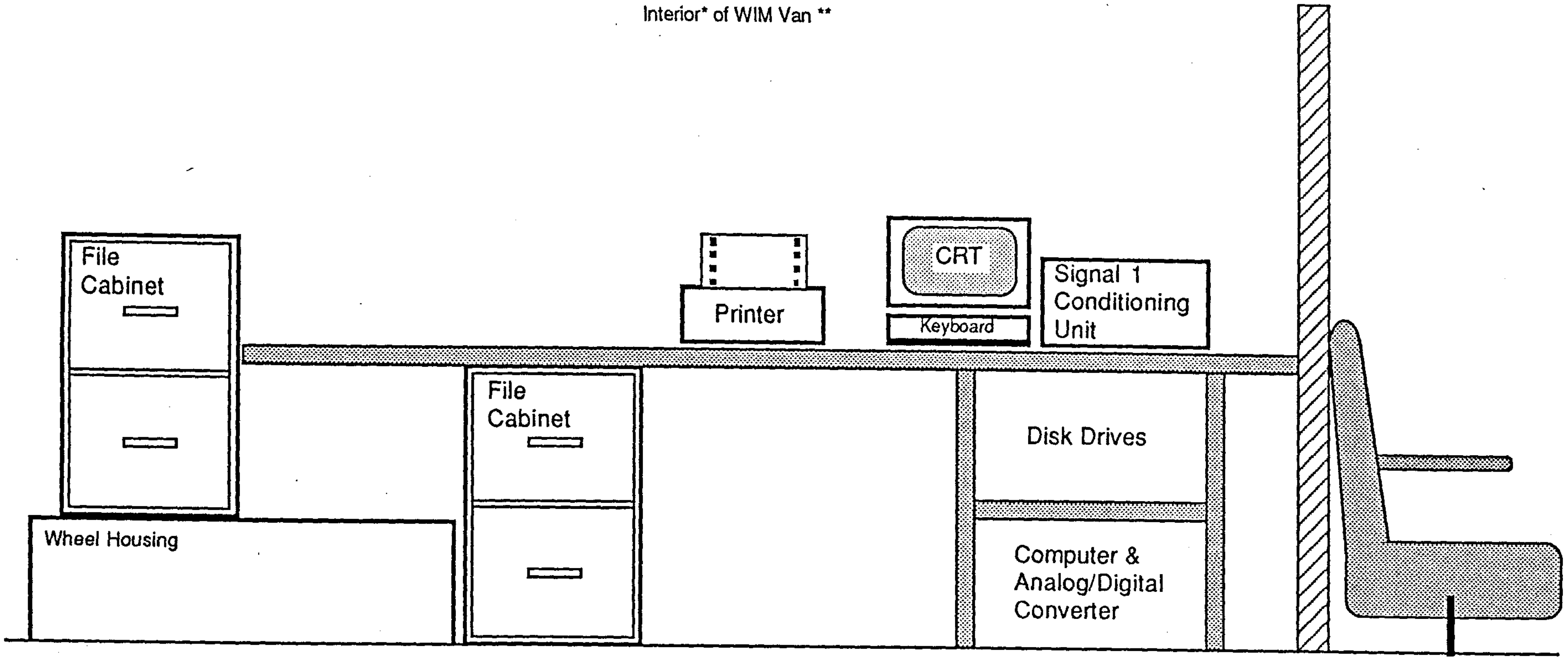


Exhibit A-2

Interior* of WIM Van **



* Viewed from side doors

** Two chairs are not shown in this figure

APPENDIX B
BRIDGE WIM VERSUS STATIC WEIGHT RESULTS

EXHIBIT B-1

WIM VS. STATIC GVW (MARTIN WAY)

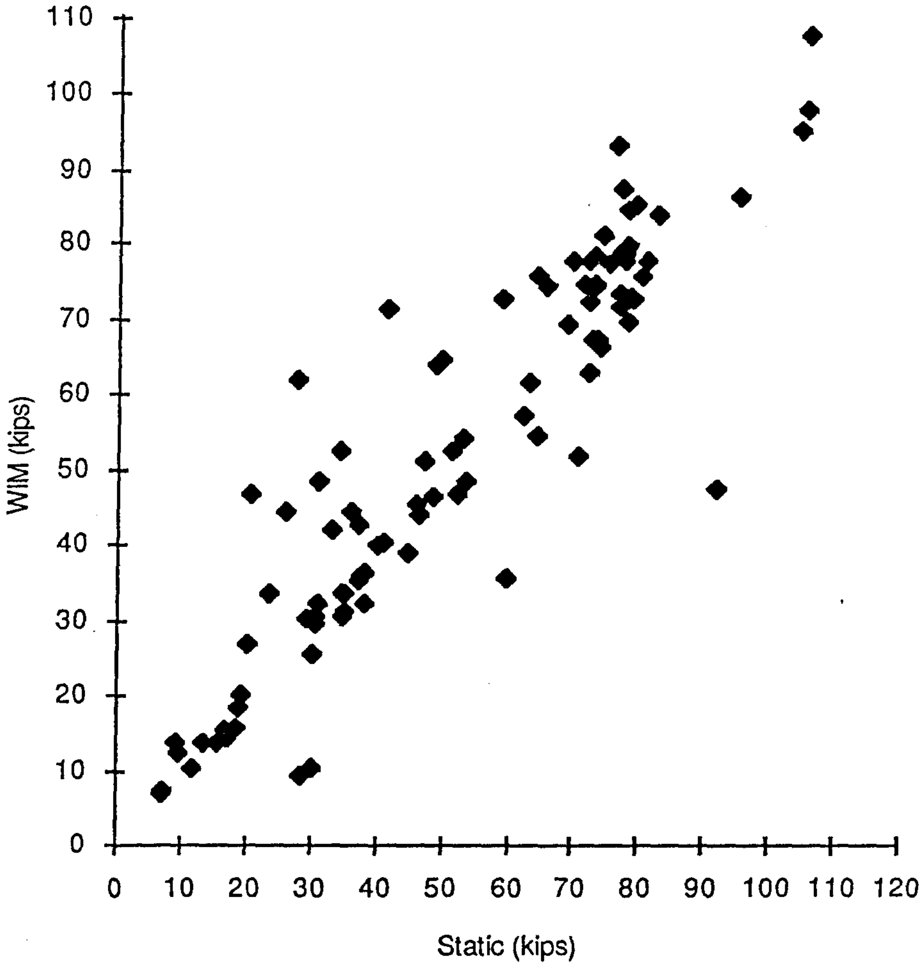


Exhibit B-2

WIM vs. Static GVW (Pendleton)

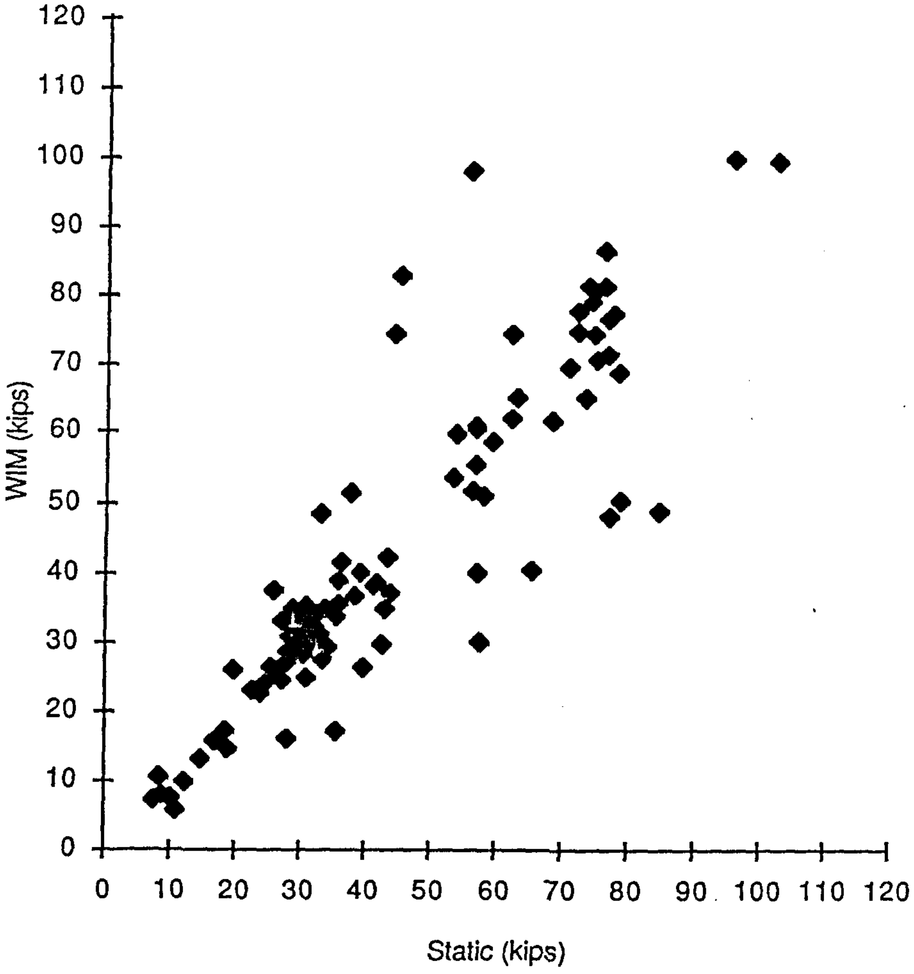


Exhibit B-3

WIM vs. Static GVW (Nisqually)

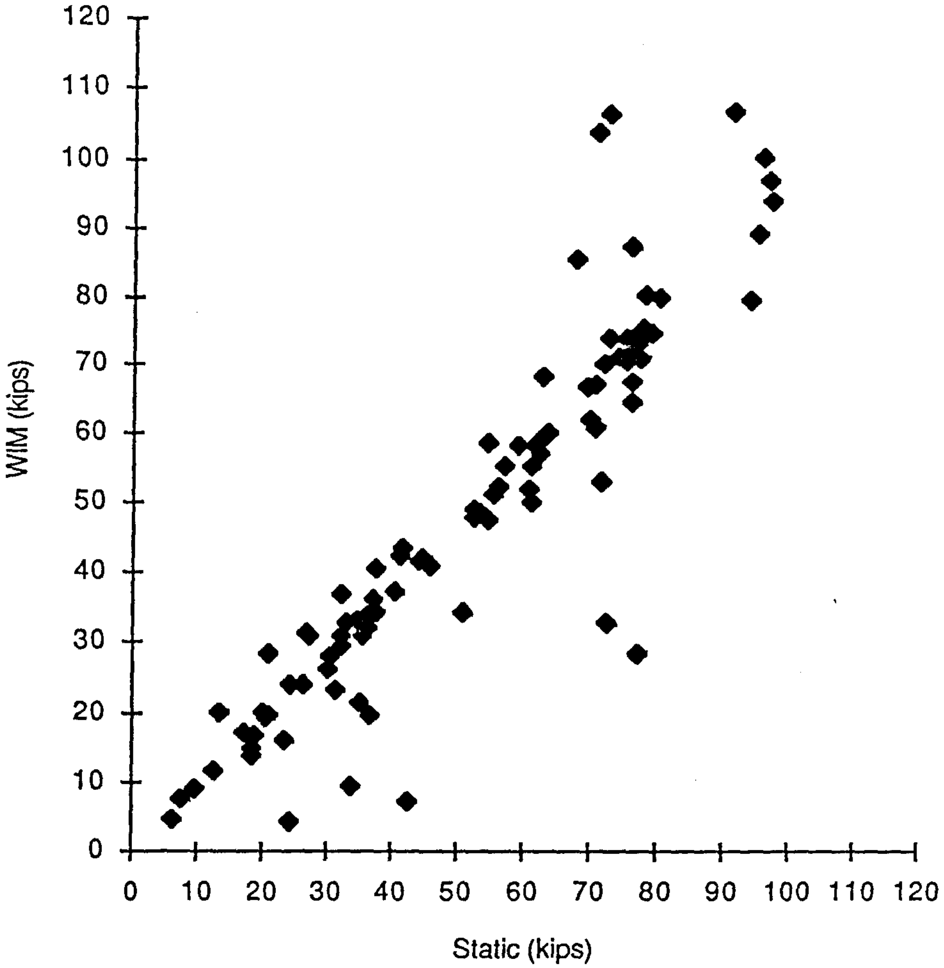


Exhibit B-4

WIM vs. Static GVW (Snoqualmie)