AN EVALUATION OF MONTANA'S STATE TRUCK ACTIVITIES REPORTING SYSTEM

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EXECUTIVE SUMMARY

Based on the results of this study, the Montana Department of Transportation's (MDT's) recently developed *State Truck Activities Reporting System (STARS)* has met three of its primary objectives, namely,

(1) improving the efficiency and effectiveness of truck weight enforcement activities performed by the Motor Carrier Services (MCS) Division of MDT,

(2) providing MDT access to improved truck-related data for use in pavement design and

(3) providing various divisions within MDT access to improved truck-related data for use in engineering and planning applications.

STARS consists of an array of weigh-in-motion/automatic vehicle classification (WIM) sensors deployed across the Montana highway system that feed data to customized software programs. At each *STARS* location, WIM hardware installed directly in the traveling lanes of the roadway unobtrusively and automatically collects information on the weight and configuration of the vehicles traveling on that roadway. This data is subsequently processed to characterize commercial vehicle operations at the site by vehicle classification and weight. Information of this type is essential to several MDT activities, from vehicle weight enforcement, to roadway design, to transportation planning. The quantity and quality of information provided by *STARS* for these various tasks is a notable improvement over existing data sources. In this evaluation, the impact of *STARS* and the information it provides was assessed relative to weight enforcement, pavement design and general data enhancements for other MDT activities.

In the area of vehicle weight enforcement, the MCS Division of MDT conducted a pilot project to investigate the use of *STARS* data in scheduling mobile weight enforcement activities. While WIM data may seem like an obvious source of information on overweight vehicle operations, it was discovered that little work has been done nationwide on its use in this application. Therefore, MCS designed their own methodology to incorporate this information into enforcement, and then engaged in a two year pilot program to determine its effectiveness. One of the primary objectives of the weight enforcement efforts of the MCS Division is to protect the highway infrastructure from damage caused by overweight vehicles. In support of this objective, the weight enforcement methodology used in the pilot program was designed with the objective of reducing the excess pavement damage caused by overweight vehicles.

While there is an attraction to using *STARS* data in real-time to dispatch enforcement personnel to individual overweight incidents, the decision was made in the pilot program to address long-term patterns of overweight behavior on a coordinated state wide basis. The methodology followed by MCS in the pilot project began with using *STARS* data to identify those locations around the state that historically experienced the worst pavement damage from overweight vehicles. Instrumental in identifying these locations, which were then the object of focused enforcement, was the *Measurement of Enforcement Activity Reporting System (MEARS). MEARS* is a software program that processes the *STARS* data specifically to obtain information on commercial vehicle and overweight vehicle activity. Using information in the *MEARS* reports and engineering analyses, those locations historically experiencing the greatest pavement damage were identified over a baseline year (2000 to 2001). Enforcement resources were then directed to these sites in the following year (2001 to 2002) at the times when the greatest overweight vehicle activity was observed in the previous year.

During the year of focused enforcement, a statistically significant reduction was seen in the percent of overweight vehicles in the traffic stream. Statewide, throughout the extensive network of highways covered by *STARS*, the percent of overweight vehicles in the traffic stream dropped by 22 percent (from being 8.8 percent of the commercial vehicles in the traffic stream in the baseline year to 6.9 percent in the enforcement year). The average amount of overweight on each vehicle also decreased by 16 percent in the enforcement year. The overall reduction in pavement damage attributable to the *STARS* program statewide over the year was on the order of magnitude of 6 million ESAL-miles of travel. The cost savings associated with this change in pavement damage was estimated to be approximately $700,000.

STARS will continue to have a role in future MCS weight enforcement activities. The specific manner in which it will be used in this regard, however, is still evolving. While the approach used in the pilot project was effective in reducing overweight vehicle impacts, issues do exist relative to its continued effectiveness into the future. This evaluation has shown that *STARS* provides the data necessary to assess the effectiveness of an enforcement activity from a performance perspective. That is, *STARS* data can be used to directly quantify changes in various aspects of overweight vehicle operations that enforcement is attempting to control (e.g., proportion of overweight vehicles in the traffic stream, average amount overweight, pavement damage from overweight vehicles).

In the area of pavement design, *STARS* was found to offer better information on the traffic related fatigue demands used in design, relative to the existing information that is collected for this purpose at permanent weigh stations. From a geographic perspective, *STARS* collects information at more locations around the state than is available at the existing weigh stations. From a temporal perspective, *STARS* collects data continuously at these sites, while weight data for pavement design purposes is only collected at the weigh stations at a few selected times during the year. Commercial vehicle operations on the State's highways generally vary significantly by geographic location and time of year. Thus, it is questionable whether the current vehicle weight sample being collected by weigh stations is able to accurately represent actual fatigue demands around the state and throughout the year. Evidence was further discovered that the weigh station sample is biased toward fully-loaded vehicles. These biases arise from basic problems associated with attempting to collect traffic data at facilities designed for other purposes. The *STARS* WIM installations unobtrusively collect information on every commercial vehicle in the traffic stream directly in the traveling lanes of the roadway at highway speeds.

In light of the above observations, MDT has started to use WIM data in the pavement design process, rather than weight data collected at weigh stations. In this regard, a comparison was made between the fatigue demands for design purposes that would be calculated from WIM versus weigh station data. Based on two years of data (2000 and 2001), fatigue demands calculated from the WIM data were 11 and 26 percent lower than those calculated from the weigh station data for the Interstate and non-Interstate NHS/primary systems, respectively. Note that part of this reduction is due to using data from different sources in the analysis process, and part of this difference is due to *STARS* focused enforcement. A projected cost impact of using *STARS* data in the pavement design process (rather than weigh station data) was determined from the changes in fatigue demands reported above. These changes in fatigue demands were found to result in changes in the facilities designed to carry them, which subsequently translated into changes in the costs of the constructed facilities. The relationship between changes in fatigue demand and changes in subsequent project construction costs was determined by redesigning typical projects at various levels of fatigue demand. The resulting relationship was used at a network level to project annual changes in construction costs if WIM-based fatigue demands were to be used in the design process.

Following the methodology above, pavement costs were projected to decrease approximately \$0.7 million and \$3.5 million per year on the Interstate and non-Interstate NHS/Prirmary systems, respectively, if WIM-based fatigue demands were used in the design process. The change (decrease) in fatigue demands and attendant pavement costs determined in this evaluation indicate that existing highways were designed for greater fatigue demands than they actually will experience. While this situation might suggest that the service life of existing highways will be extended (in that they were over-built with respect to fatigue capacity), it is important to note that fatigue is only one of several mechanisms that initiates failures in highways, and often it may not be the controlling mechanism. Nonetheless, use of the fatigue demands from the improved WIM data should lead to pavement designs that are better optimized for the demands that they will actually experience in-service.

The final issue considered in this evaluation was the possible benefits *STARS* offers to traffic data users throughout MDT. A survey across the major divisions at MDT found that *STARS* data will primarily benefit planning, engineering, and commercial vehicle enforcement efforts.

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1 INTRODUCTION

With the advent of weigh-in-motion (WIM) and automatic vehicle classification (AVC) technologies, the ability to monitor commercial vehicle traffic has been greatly enhanced. Nationally, the information available from WIM systems has commonly been used: (1) to prescreen overweight commercial vehicles to improve static weigh station efficiency, (2) to support the calculation of traffic loading demands for roadway design and (3) to generally support traffic data driven activities within departments of transportation.

With these applications in mind, the Montana Department of Transportation (MDT) recently developed and deployed the *State Truck Activities Reporting System* or *STARS*. *STARS* consists of an extensive system of WIM hardware installed across the Montana highway system that feed data to customized software programs. The software can subsequently be used to characterize commercial vehicle operations by classification and weight and to further perform varied analyses specifically addressing overweight commercial vehicle operations. In this last regard, MDT believed that the data made available from *STARS* could potentially and significantly benefit its vehicle weight enforcement program. While the potential usefulness of WIM data in weight enforcement efforts may appear obvious, little work of this kind has been done around the country. Thus, a pilot program was developed and executed cooperatively by MDT and Montana State University with the objective of minimizing pavement damage attributable to overweight vehicles through WIM-directed (*STARS*-directed) weight enforcement activities. This same system of WIM hardware and software was utilized in this pilot program to evaluate the effectiveness of *STARS*-directed enforcement.

1.1 Objectives

The purpose of this study was to determine if *STARS* achieved its fundamental objectives as conceived by MDT. The first of these objectives was to improve the efficiency of MDT's commercial vehicle enforcement program and to document this improvement through a demonstrable reduction in the number of overweight trucks in the traffic stream and a reduction in their negative impacts on the highway system. The second objective was to improve the quality and quantity of truck weight and classification data available for use by MDT for pavement design. Note that these first two objectives could provide direct monetary benefits to highway users by potentially reducing pavement damage from overweight vehicles and by allowing for optimized pavement designs (rather than less efficient over-designed or under-designed structures). The third objective of *STARS* was to improve the quality and quantity of truck weight and classification data available for use agency-wide by MDT to enhance general system performance. The monetary benefit of this third objective may be substantial, but it is also difficult to quantify.

Although not formally addressed as part of this evaluation, secondary objectives of *STARS* include: (1) supporting Montana's long-term Commercial Vehicle Operations (CVO) goals of automating the state's priority weigh stations, (2) supporting the objectives of both the national *Long Term Pavement Performance (LTPP)* project of the *Strategic Highway Research Program (SHRP)* and the *Commercial Vehicle Information Systems and Networks (CVISN)* initiative, and (3) furnishing better data to the Federal Highway Administration for their national Truck Weight Study/Heavy Vehicle Information Systems (TWS/HVTIS) database and for their annual highway statistics publication.

Finally, this study provides FHWA with both the documentation and the opportunity to consider *STARS* as one tool for evaluating the effectiveness of weight enforcement activities. Information available from *STARS* on the characteristics of the overweight vehicles in the traffic stream and on their impact on the highway infrastructure before and during an enforcement activity can be used to assess the effectiveness of that activity. A desirable feature of this approach to measuring enforcement effectiveness is that it directly addresses the objectives of weight enforcement of reducing the number of overweight vehicles on the highways and reducing the excess damage that they cause to the infrastructure.

1.2 Scope

In this investigation, the effectiveness of *STARS* in achieving the above objectives was evaluated by comparing conditions before and after *STARS* WIM data became available to support commercial vehicle weight enforcement, pavement design and agency-wide activities. In this regard, the focused enforcement aspect of this evaluation incorporated two full years of data collection. One year of historical data (May 2000 through April 2001) was used to establish a baseline of overweight commercial vehicle activity at each of 16 *STARS* sites located across the state. In the following year (May 2001 through April 2002), mobile enforcement efforts across the state were dispatched using the WIM data collected from the *STARS* sites the previous year. Commercial vehicle activity and effects during the baseline year were then compared to those during the year of focused enforcement. Furthermore, costs were assessed against changes in the pavement damage attributable to overweight vehicles between the two years. While it would have been preferable to have more than a single year of historical data to characterize overweight vehicle activity prior to implementing *STARS*, there was considerable interest in taking advantage of the WIM data as soon as possible after its deployment (which was substantially completed by May 2000) for MDT's planning, pavement design and other activities.

To investigate the potential impact of improved commercial vehicle data from *STARS* on new pavement designs, changes were calculated in the design fatigue demands as derived from *STARS* compared to those derived using data from traditional sources (weigh stations). These changes in design demands were translated into changes in projected annual pavement costs for constructed projects, comparing WIM data based designs and weigh station data based designs.

Agency-wide benefits attributable to overall enhanced commercial vehicle data were obtained through a non-scientific, qualitative survey distributed to each of the divisions within MDT. This survey also helped to establish how MDT was utilizing existing commercial vehicle data available through static weigh stations and limited WIM sites, during the baseline year.

1.3 Report Purpose and Contents

The purpose of this report is to present the findings related to each of the three primary areas for evaluation: (1) focused enforcement impacts, (2) pavement design impacts and (3) impacts of agency-wide data enhancement. Research methodologies and findings are reported for each of these impact areas (Chapters 3 through 5). This material is prefaced by a general description of (1) the Montana state highway system, (2) the activities at MDT that might be impacted by *STARS* (i.e., weight enforcement, pavement design, and agency-wide data analysis) and (3) the *STARS* system, itself (Chapter 2). This report concludes with a summary of findings in each of the three investigation areas and makes recommendations as to the continued and/or expanded use of *STARS* (Chapter 6).

2 BACKGROUND

A thorough description of *STARS* is presented below, prefaced by a brief description of the state highway network in Montana and traditional activities related to commercial vehicle weight enforcement, pavement design and commercial vehicle data applications.

2.1 Montana State Highway System

In 2000, the Federal Aid Interstate and non-Interstate National Highway System (NHS) and the state Primary, Secondary and Urban systems totaled approximately 11,705 miles of highway in Montana (MDT 2001). A map of the system is shown in Figure 2-1. System mileage and use, measured in total and commercial vehicle miles of travel (VMT and CVMT, respectively), are summarized in Table 2-1. Referring to Table 2-1, 90 percent of the commercial vehicle traffic in the state is on the Interstate, non-Interstate NHS and Primary systems. Thus, the focus of both traditional enforcement (i.e., weigh stations) and *STARS* is on these routes.

2.2 Commercial Vehicle Weight Enforcement in Montana

The Motor Carrier Services (MCS) Division of MDT is the lead agency for truck size and weight enforcement in Montana. MCS currently operates a network of permanently- and intermittently-staffed weigh stations equipped with static scales, and a statewide mobile enforcement program

Table 2-1. Highway System Length and Traffic Volume (MDT 2001)

Highway System[a]	Centerline Miles	Daily VMT	
		All Vehicles	Commercial Vehicles[b]
Interstate	1,191	6,675,168	1,348,384
Non Interstate NHS	2,683	6,668,228	780,183
Primary	2,815	3,326,906	306,075
Secondary	4,698	1,977,647	185,899
Urban	382	2,287,417	98,359
State Highways	1,180		

[a] Local municipal and county roads not included

[b] Proportion of commercial vehicles estimated from Stephens and Menuez (2000)

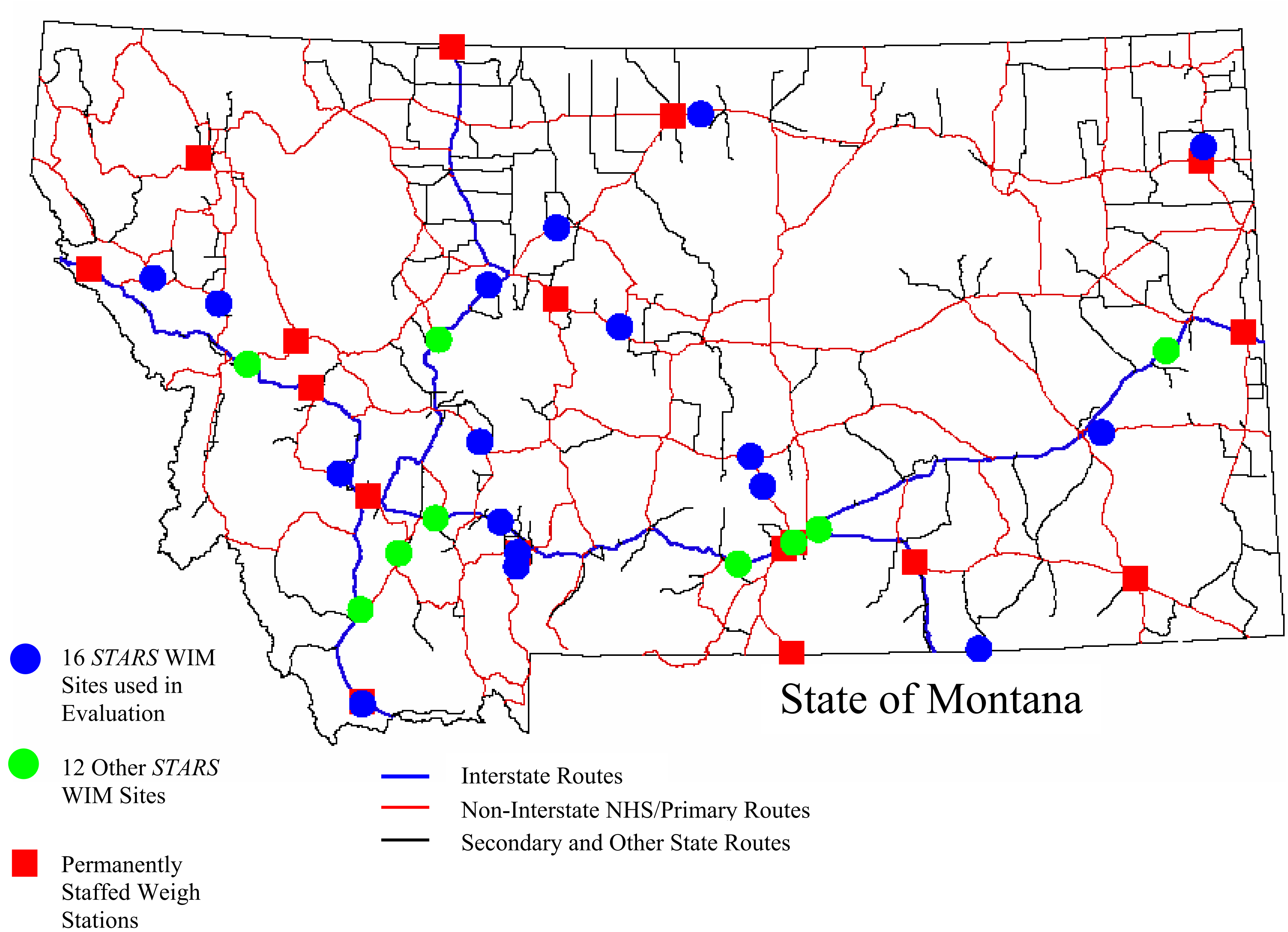


Figure 2-1. Montana State Highway System, Weigh Stations and *STARS* Sites (Little 2003)

comprised of individual officers who work out of their vehicles using portable weighing equipment. Montana's weigh stations provide an effective size, weight, safety, and fuel tax evasion deterrent during the hours they are open and specific to the highways they service. Overall weigh station enforcement effectiveness is subject to staffing availability. Permanently-staffed Montana weigh stations service both Interstate and strategic non-Interstate highways (see Figure 2-1).

Weigh station enforcement in Montana is strategically supplemented by mobile enforcement. Montana has had a weigh station bypass mitigation plan in effect since the mid-1990s, prior to *STARS*, and MCS mobile patrol officers have traditionally devoted up to 70 percent of their time to the random enforcement of local roads and highways that were not serviced by weigh stations (Livesay and Hult 2003). Each patrol officer, within his or her assigned geographic area, exercised considerable discretion when deciding which roads to patrol and how to be most productive. Hence, an officer's effectiveness was collectively based on a combination of the individual officer's experience, knowledge of truck traffic patterns and enforcement intuition. Consequently, new officers and staffing changes sometimes caused temporary enforcement and performance inefficiencies. A new patrol officer experiences a significant learning curve while developing his or her skills, and patrol officers may inadvertently devote considerable time and energy to non-productive activities before being identified as such and corrected by MCS managers. *STARS* provides MCS managers with the ability to focus mobile enforcement resources of experienced and non-experienced officers alike on those sections of highway where overweight activity is known to have occurred, at the most appropriate time of the day or night.

2.2.1 Enforcement Effectiveness

Currently, FHWA judges the effectiveness of Montana's truck weight enforcement program annually through the *Truck Size and Weight Enforcement Plan (PLAN) and the Federal Certification of Accomplishment (CERT)* process, in compliance with the *Code of Federal Regulations (CFR) 23, Part 657*. The *PLAN* establishes Montana's commercial vehicle enforcement goals and the *CERT* documents Montana's achievements as compared with the *PLAN*. All states are required to participate in this same annual process. Although the *PLAN/CERT* process has proven merits, the metrics used to gage performance (e.g., citations) may not directly address the ultimate objective of weight enforcement (e.g., pavement preservation). *STARS* provides the data necessary to evaluate the effectiveness of mobile weight enforcement using performance-based metrics more directly related to some of the objectives of weight enforcement.

2.3 Traditional Pavement Design

MDT uses the American Association of State Highway and Transportation Officials (AASHTO) equivalent single axle load (ESAL) approach (AASHTO 1993) to design for the fatigue demands that vehicles place on pavements. This approach is based on the results of the *AASHO Road Test* (Highway Research Board 1962), in which a variety of pavement sections were subjected to repeated axle loads while their associated deterioration was recorded. This information was used to develop a design relationship between: (1) the number, magnitude and type of axle loads a pavement experiences, (2) the structure of the pavement (types of layers and their strength) and (3) its deterioration. This design relationship was generalized to accommodate the fatigue demands of any traffic stream by expressing the number, magnitude and type of axle loads that all the vehicles in the traffic stream will place upon a pavement throughout its lifetime in terms of ESALs. Notably, while the fatigue demand that an axle or axle group places on a pavement is proportional to the weight it carries, the nature of the relationship between weight and fatigue demand varies by type of axle (i.e., single, tandem, tridem, etc.). Thus, to sum up the fatigue demands that all the different axle and axle group loads in the traffic stream are expected to place on a roadway during its lifetime, these axle and axle group loads must be converted to a common reference, generally, the ESAL. Simply stated, the ESAL indicates the number of 18,000-pound axle loads required to generate the same fatigue demand on a pavement as the single passage of the axle in question. Equations/tables that relate axle and axle group loads to ESALs are available for most axle configurations (AASHTO 1993).

The number of ESALs to be used in the design of any given project is directly related to the historical level of ESAL demands at the project site. This demand is calculated from data collected at or near the site on vehicle use by type, which is subsequently transformed into fatigue demand using ESAL factors. That is, total fatigue demand expected on the pavement is calculated by multiplying the number of vehicles of each type at the site by the average fatigue demand by vehicle type (ESAL factor). The results are accumulated across all vehicle types and across the expected service life of the facility, with due consideration of traffic growth. A typical design ESAL calculation is shown in Table 2-2.

The expected total ESALs of demand at a given location are substituted in design equations developed by AASHTO to determine the required pavement thickness based on fatigue. These equations relate pavement thickness to, among other things, the strength of the materials involved, the selected initial and terminal conditions of the pavement and the total ESALs of demand expected throughout its lifetime.

Table 2-2. Typical Fatigue Demand Calculation in ESALs at a Specific Project Site

FHWA Vehicle Class[a]		Vehicles per Day (projected annual average over 20 yr design life)	ESAL Factor	Fatigue Demand (ESALs/day)
1, 2	motorcycle, passenger car	2,288	0.001	2
3	2 axle, 4 tire single unit	2,165	0.007	15
4	Buses	15	0.257	4
5	2 axle, 6 tire single unit	94	0.391	37
6	3 axle single unit	49	0.609	30
7	4 axle or more single unit	0	1.433	0
8	4 or fewer axle, single trailer trucks	20	0.378	7
9	5 axle, single trailer trucks	148	1.462	216
10	6 or more axle, single trailer trucks	39	1.419	56
11	5 or fewer axle, multi trailer trucks	5	1.301	6
12	6 axle, multi trailer trucks	5	1.271	6
13	7 or more axle multi trailer trucks	104	1.746	181
	Total ESALs/Day			561
	Total ESALs over 20 yrs			4,096,814

[a] See Appendix A for vehicle descriptions by class

2.3.1 ESAL Factors

A critical element in the design process described above is the ESAL factors that are used to determine expected fatigue demands on the pavement. These ESAL factors are currently calculated on an annual basis from a sample of vehicles weighed on the static scales at weigh stations around the state. The sampling program used in this process is loosely designed to collect a representative sample of the traffic operating each year on the state's highways. To collect the sample, all commercial vehicles passing selected weigh stations are stopped and weighed at certain times during the year. Specifically, data is collected for at least one eight-hour period each month, with the day of week and the week of the month varying between successive months. Nonetheless, the sample is only collected at a few locations around the state (e.g., in 2001, data was collected for this purpose at five weigh stations on the non-Interstate NHS and Primary systems, and at eight weigh stations on the Interstate system) and for a few days throughout the year (a minimum of 12). The ability of this sample to reasonably characterize highway use is a concern, if such use varies significantly at different locations around the state and at different times of the year. An additional concern with this sample is that overweight commercial vehicles may not be well-represented, due their potential avoidance/bypass of weigh station facilities.

In any event, after the individual vehicle weights are collected for the sample, the ESALs associated with the axle and axle group weights in each vehicle are calculated. These values are averaged across the entire sample by vehicle class to obtain an ESAL factor for each vehicle class. Recognizing that vehicle loading and use patterns may be different on the Interstate versus the non-Interstate NHS and Primary routes, ESAL factors are developed separately for these systems. Also, recognizing that vehicle operations may vary somewhat from year to year, the ESAL factors used in design are further averaged across a moving ten-year window. Typical results for these calculations are presented in Tables 2-3 and 2-4 for Interstate and Primary/Non-Interstate NHS systems (Bisom 2002). Note that the data used in determining these ESAL factors (which are applied statewide) were collected from only 15 weigh stations around the state. Table 2-5 lists the specific weigh stations used for the 2000 and 2001 calculations.

Table 2-3. Typical Weigh Station ESAL Factors, Interstate System (Bisom 2002)

FHWA Vehicle Class[a]	2000		2001		Ten Year Average (1992 – 2001)	
	No. of Vehicles in Sample	ESAL Factor	No. of Vehicles in Sample	ESAL Factor	No. of Vehicles in Sample	ESAL Factor
5	219	0.370	289	0.540	6563	0.366
6	195	0.482	294	0.537	3694	0.500
7	14	2.000	21	0.905	332	1.443
8	106	0.472	142	0.648	3112	0.564
9	4109	1.348	6216	1.353	91524	1.421
10	321	1.259	606	1.469	5354	1.348
11	39	1.615	107	1.505	2860	2.015
12	40	1.300	92	0.815	1470	1.284
13	360	1.917	441	1.810	9080	1.877

[a] See Appendix A for vehicle descriptions by Class

Table 2-4. Typical Weigh Station ESAL Factors, Non-Interstate NHS/Primary Systems (Bisom 2002)

FHWA Vehicle Class[a]	2000		2001		Ten Year Average (1992 – 2001)	
	No. of Vehicles in Sample	ESAL Factor	No. of Vehicles in Sample	ESAL Factor	No. of Vehicles in Sample	ESAL Factor
5	165	0.509	291	0.478	7627	0.409
6	89	0.596	151	0.483	3593	0.570
7	18	1.333	34	1.000	518	1.413
8	48	0.583	63	0.381	2258	0.372
9	1263	1.505	1960	1.819	26242	1.452
10	158	1.354	204	1.319	2708	1.340
11	1	3.000	0	0.000	173	1.324
12	8	1.250	5	0.600	257	1.198
13	121	1.736	194	2.113	4027	1.771

[a] See Appendix A for vehicle descriptions by Class

Table 2-5. Weigh Stations Included in ESAL Factor Calculations for Pavement Design, 2000 and 2001 (Bisom 2003)

Weigh Station			
2000		2001	
Interstate	Non Interstate NHS And Primary	Interstate	Non Interstate NHS and Primary
Crow Agency	Culbertson	Crow Agency	Culbertson
Butte	Broadus	Billings	Broadus
Wibaux	Bozeman	Lavina	Bozeman
Coutts		Drummond	Clearwater
Lima		Butte	Kalispell
Forsyth		Haugen	
		Wibaux	
		Coutts	

2.3.2 Other Design Factors

Fatigue demand is only one factor that influences pavement design. On low-traffic roads, environmental demands (e.g., thermal expansion and contraction) and/or maximum demands from a single load event could control the design. The minimum structure required to meet these demands may offer substantially more fatigue resistance than is necessary for the ESALs the pavement is expected to experience. Pavement designs are further affected by some construction-related issues/constraints. Notably, there is a minimum thickness of surfacing material that can be reasonably placed in a single lift. Thus, for example, in an overlay situation, this minimum construction thickness could substantially exceed the thickness required simply based on fatigue demands.

2.4 Traditional Commercial Vehicle Data Collection and Use

Historically, MDT's Motor Carrier Services Division utilized commercial vehicle weight data from static weigh station facilities and a limited number of permanent and portable WIM systems to demonstrate the effectiveness of Montana's truck weight enforcement program under FHWA's *PLAN/CERT* process. The data available from the static weigh station facilities was also used to support ESAL calculations for pavement preservation and construction projects.

MDT's Data and Statistics Bureau collected and processed truck weight and classification data from 11 WIM sites across the state. This information was used in responding to various traffic data reporting requirements of the federal government, and to a lesser extent, to support engineering decisions at the project level for long range planning.

2.5 State Truck Activities Reporting System (*STARS*)

STARS consists of a network of 28 permanent WIM sites supplemented by 62 sites that are to be operated intermittently on a three-year cycle using fully portable WIM equipment. Included in these sites are four automated weigh stations that utilize WIM and Automatic Vehicle Identification (AVI) equipment to allow legal bypass of weigh station facilities by credentialed weight-compliant commercial vehicles. Data collected from these automated weigh stations is treated just like the data collected at the *STARS* WIM sites.

The permanent WIM sites, shown in Figure 2-1 and described in Table 2-6, are placed around the state on major routes that carry significant truck traffic. Locations were generally selected based on the volume of commercial vehicle traffic carried on the various routes and systems (i.e., Interstate, non-Interstate NHS, primary, secondary, urban) and the location of existing weigh station facilities, with due consideration of the recommendations of FHWA's *Traffic Monitoring Guide* (FHWA 2001). Since weigh station coverage is greatest on the Interstate system, the *STARS* sites are focused on the non-Interstate NHS and Primary routes around the state. The portable sites additionally cover less-traveled routes known to continuously or seasonally experience significant truck traffic. This evaluation focused on the 28 permanent *STARS* sites. The precise location of each WIM installation along a particular route was determined based on siting requirements of the WIM system, itself (e.g., roadway grade and alignment criteria, etc.). In light of *STARS* potential role in weight enforcement, consideration was also given in the siting process to the location of places in the vicinity of each site at which vehicles could be safely pulled off the highway during an enforcement activity.

Table 2-6. WIM System Location and Equipment (Bisom 2003)

Site	Highway System	Route	Technology
Townsend	Primary and Non Interstate NHS	U.S. Highway 287	Piezoelectric
Decker	Secondary	Highway 314	Piezoelectric
Bad Route	Interstate	Interstate 94	Piezoelectric
Manhattan	Interstate	Interstate 90	Piezoelectric
Arlee	Primary and Non Interstate NHS	US Highway 93	Piezoelectric
Four Corners	Primary and Non Interstate NHS	US Highway 191	Piezoelectric
Gallatin	Primary and Non Interstate NHS	US Highway 191	Piezoelectric
Big Timber[c]	Interstate	Interstate 90	Piezoelectric
Galen	Secondary	Highway 273	Piezoelectric
Broadview	Primary and Non Interstate NHS	State Route 3	Piezoelectric
Miles City East	Primary and Non Interstate NHS	US Highway 12	Piezoelectric
Ulm	Interstate	Interstate 15	Piezoelectric
Ryegate	Primary and Non Interstate NHS	US Highway 12	Piezoelectric
Stanford	Primary and Non Interstate NHS	US Highway 87	Piezoelectric
Fort Benton	Primary and Non Interstate NHS	US Highway 87	Piezoelectric
Havre East	Primary and Non Interstate NHS	US Highway 2	Piezoelectric
Twin Bridges[b]	Primary and Non Interstate NHS	State Route 41	Piezoelectric
Paradise	Primary and Non Interstate NHS	State Route 200	Piezoelectric
Mossmain[a]	Interstate	Interstate 90 W	Piezoelectric Bending plate
		Interstate 90 E	Bending plate
Culbertson[a]	Primary and Non Interstate NHS	State Route 16	Bending plate
Lima[a]	Interstate	Interstate 15	Bending plate
Rocker[b]	Interstate	Interstate 90	Piezoelectric
Armington[a]	Primary and Non Interstate NHS	US Highway 87 W	Piezoelectric
		US Highway 87 E	Piezoelectric
Columbus	Interstate	Interstate 90	Piezoelectric
Bonner	Interstate	Interstate 90	Piezoelectric
Dillon	Interstate	Interstate 90	Piezoelectric
Pryor Creek	Interstate	Interstate 90	Piezoelectric
Wolf Creek	Interstate	Interstate 15	Piezoelectric

[a] PrePass Site (one direction only, unless indicated otherwise)
[b] to be constructed
[c] removed

2.5.1 Hardware Components

The specific hardware installed at each of the 28 permanent sites is listed in Table 2-6. Of the three types of WIM sensors commonly used - piezoelectric, bending plate and load cell - the majority of the installations are piezoelectric (25 out of 28); the remainder are bending plate (3 out of 28). The piezoelectric systems were manufactured by Electronic Control Measurement (ECM), while the bending plate systems were manufactured by PAT America. The relative accuracy and cost of these WIM systems continues to be a subject of debate among the public agencies that use them. The piezoelectric sensors are expected to provide adequate accuracy for MDT's intended use at the most attractive life cycle cost (Livesay and Hult 2002), based on MDT's experience to-date with these technologies and preliminary results from active research projects investigating their performance (Bylsma and Carson 2002, Carson and Stephens, 2003).

MDT calibrates the permanent WIM sites twice each year according to standard procedures using a 5-axle tractor, semi-trailer of known weight. MDT also performs standard quality control checks on the raw and processed data.

2.5.2 Software Components

The data collected at the various WIM sites is automatically analyzed using the *Measurement of Enforcement Activities Reporting System (MEARS)* computer software program specifically developed for MDT. *MEARS* generates reports on the commercial vehicle activity by site and month and for the entire year. Reports are also generated on the general performance of the WIM hardware. The full suite of reports available from *MEARS* is summarized in Table 2-7. Typical reports for the Townsend *STARS* site for the month of October 2001 are provided in Figures 2-2 and 2-3. Figure 2-2 graphically shows the number of overweight commercial vehicles by time of day for a Class 9-1 truck (5 axle tractor, semi-trailer). Figure 2-2 provides information on the number of total and overweight commercial vehicles in the traffic stream, the percent of overweight vehicles, the average amount of the legal weight exceedance, the direction of travel, etc. for individual vehicle configurations.

Table 2-7. *MEARS* Reports (Bisom 2003) by Month and By Site (unless otherwise indicated)

25: Overweight Vehicle Report by Class[a]
Number of commercial vehicles
Percent of overweight commercial vehicles
Average amount of legal weight exceedance

30: Overweight Violations by Time Period and Class
Day of week and 4-hour segment of day
Direction of travel

35: Weight Information by Class
Number of commercial vehicles
Percent of overweight commercial vehicles
Average operating weight
Average amount of legal weight exceedance

40: Scatter Graphs by Class[b]
Scatter graph of overweight commercial vehicle events as a function of day of week and time of day

45: Calibration Tracking
Weight frequency plots of vehicles in the traffic stream used for auto-calibration

70: Summary of Records Violating Rules
Total number of records that violate rules validating reasonableness of recorded vehicle characteristics

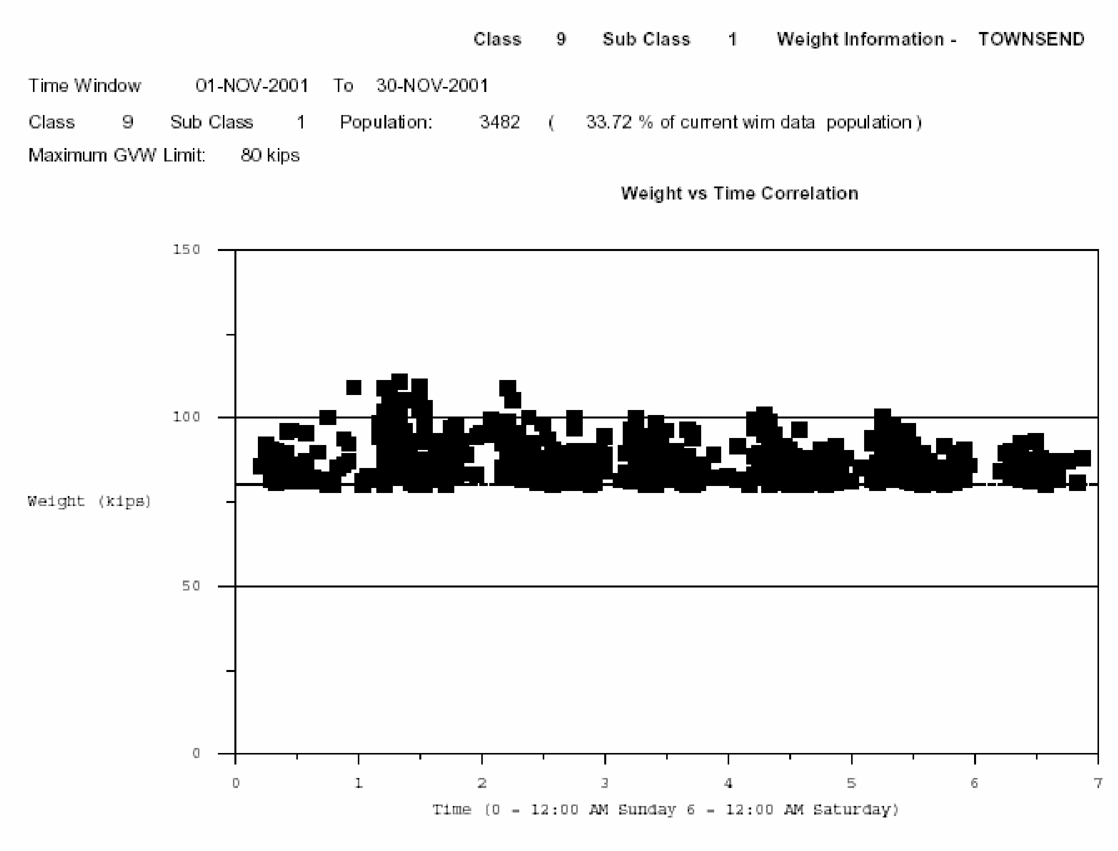
90: Truck Weight Upload Process Summary Report
Total number of records screened
Total number of bad records

105: Site Activities Roll-up
Total number of vehicles
Total number of commercial vehicles
Percent of overweight commercial vehicles
Average amount of legal weight exceedance
Change in overweight commercial vehicle percent
Change in average legal weight exceedance amount

205: ESAL Report
Excess ESALs attributable to overweight vehicles by duration of reporting period

[a] Example report presented in Figure 2-3

[b] Example report presented in Figure 2-2

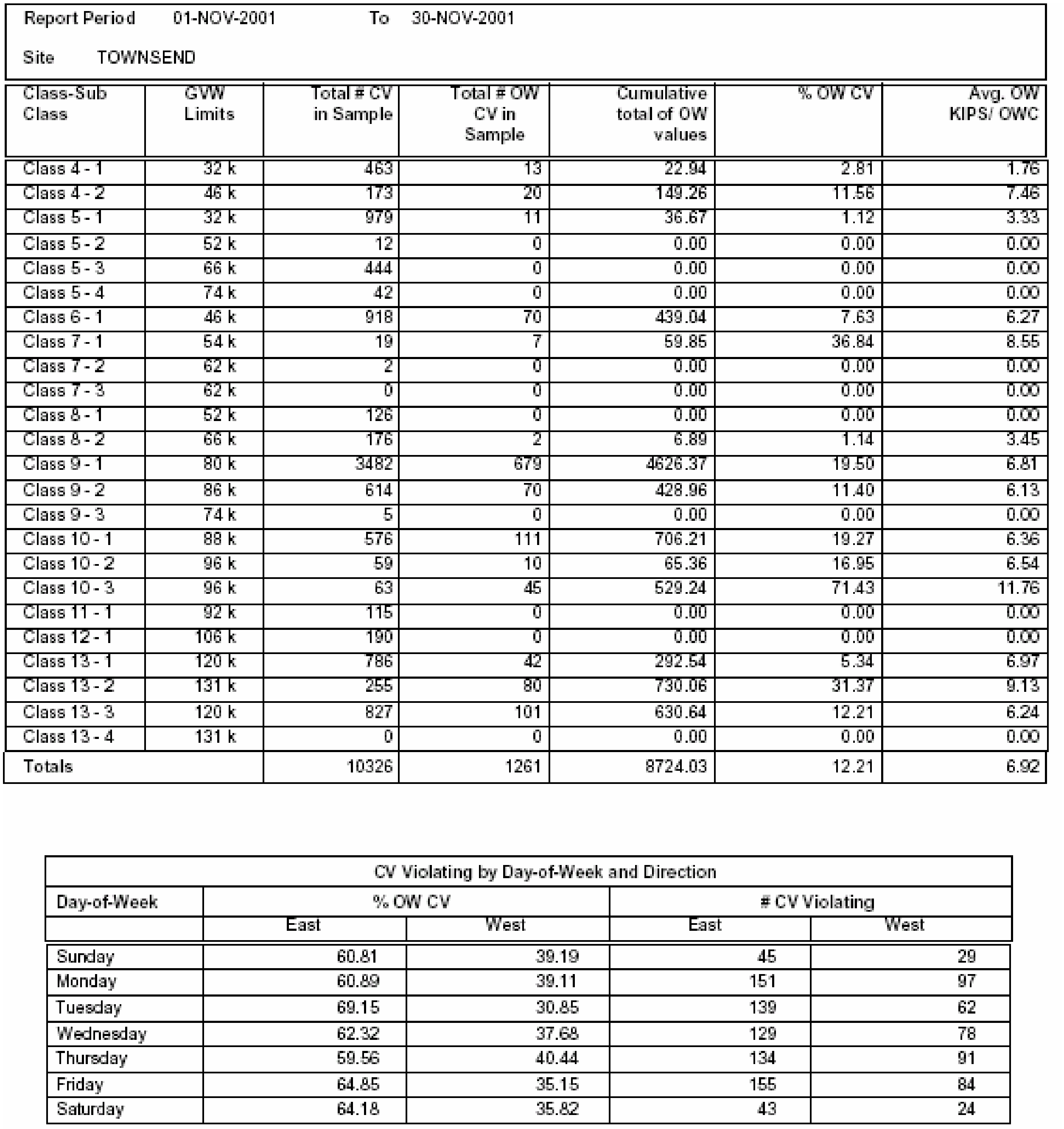


Class 9 Sub Class 1 Weight Information - TOWNSEND

Time Window 01-NOV-2001 To 30-NOV-2001
Class 9 Sub Class 1 Population: 3482 (33.72 % of current wim data population)
Maximum GVW Limit: 80 kips

Weight vs Time Correlation

Figure 2-2. Typical *MEARS* Report: Scatter Graph of Overweight Vehicle Activity



Report Period 01-NOV-2001 To 30-NOV-2001

Site TOWNSEND

Class-Sub Class	GVW Limits	Total # CV in Sample	Total # OW CV in Sample	Cumulative total of OW values	% OW CV	Avg. OW KIPS/ OWC
Class 4 - 1	32 k	463	13	22.94	2.81	1.76
Class 4 - 2	46 k	173	20	149.26	11.56	7.46
Class 5 - 1	32 k	979	11	36.67	1.12	3.33
Class 5 - 2	52 k	12	0	0.00	0.00	0.00
Class 5 - 3	66 k	444	0	0.00	0.00	0.00
Class 5 - 4	74 k	42	0	0.00	0.00	0.00
Class 6 - 1	46 k	918	70	439.04	7.63	6.27
Class 7 - 1	54 k	19	7	59.85	36.84	8.55
Class 7 - 2	62 k	2	0	0.00	0.00	0.00
Class 7 - 3	62 k	0	0	0.00	0.00	0.00
Class 8 - 1	52 k	126	0	0.00	0.00	0.00
Class 8 - 2	66 k	176	2	6.89	1.14	3.45
Class 9 - 1	80 k	3482	679	4626.37	19.50	6.81
Class 9 - 2	86 k	614	70	428.96	11.40	6.13
Class 9 - 3	74 k	5	0	0.00	0.00	0.00
Class 10 - 1	88 k	576	111	706.21	19.27	6.36
Class 10 - 2	96 k	59	10	65.36	16.95	6.54
Class 10 - 3	96 k	63	45	529.24	71.43	11.76
Class 11 - 1	92 k	115	0	0.00	0.00	0.00
Class 12 - 1	106 k	190	0	0.00	0.00	0.00
Class 13 - 1	120 k	786	42	292.54	5.34	6.97
Class 13 - 2	131 k	255	80	730.06	31.37	9.13
Class 13 - 3	120 k	827	101	630.64	12.21	6.24
Class 13 - 4	131 k	0	0	0.00	0.00	0.00
Totals		10326	1261	8724.03	12.21	6.92

CV Violating by Day-of-Week and Direction

Day-of-Week	% OW CV		# CV Violating	
	East	West	East	West
Sunday	60.81	39.19	45	29
Monday	60.89	39.11	151	97
Tuesday	69.15	30.85	139	62
Wednesday	62.32	37.68	129	78
Thursday	59.56	40.44	134	91
Friday	64.85	35.15	155	84
Saturday	64.18	35.82	43	24

Figure 2-3. Typical *MEARS* Report: Overweight Vehicle Report (see Appendix A for vehicle descriptions by Class)

One limitation of *MEARS* (and *STARS*) is its inability to identify permitted vehicles that operate in excess of standard legal weights (such vehicles are simply classified as overweight). This limitation should not be significant for many applications of *MEARS* data (including this evaluation). As a result of this limitation, the proportion and absolute number of overweight vehicles in the traffic stream as determined from *MEARS* data will be overstated. Changes in these parameters, however, as a function of enforcement activity over some time period will be unaffected by this situation, as such changes are calculated as the difference in the absolute magnitudes of two parameters, both of which include permitted overweight vehicles. A similar circumstance exists regarding infrastructure impacts from overweight vehicles. Absolute impacts will be overstated, while changes in impacts resulting from enforcement activities (calculated as a difference between absolute quantities) will be accurate. Nonetheless, efforts are underway to determine how the presence of weight permitted vehicles in the traffic stream can be accommodated in *MEARS*.

3 FOCUSED ENFORCEMENT EFFORT AND IMPACTS

The fundamental idea behind using *STARS* in weight enforcement is that a state's limited mobile enforcement resources are more effective if those resources can be focused at the appropriate time of day or night at those locations where the greatest overweight problems are known to exist. While WIM data would appear to be an obvious means of determining where and when overweight activity occurs, only limited information was found on the use of WIM data in weight enforcement efforts. MDT therefore made the decision to: (1) install WIM systems at various locations across the state, (2) implement a calibration program to insure these systems are collecting accurate information, (3) develop specialized processing and reporting software to extract information on overweight vehicle operations at these locations (i.e., *MEARS*) and finally, (4) initiate a two-year pilot program to investigate the operational issues and resulting effects of using this hardware/software for "real world" enforcement activities. In planning the pilot program, MCS reviewed existing weight enforcement objectives to confirm that *STARS* would complement these objectives. MDT also developed temporary operating policies and procedures for both the enforcement and the data processing/reporting aspects of the *STARS* project. The pilot project included collection of "baseline" overweight commercial vehicle data for one year, followed by a second year of focused and controlled enforcement action based on the data collected during the baseline year. Following the year of focused enforcement activity, and in compliance with Federal funding requirements, *STARS* performance was then evaluated formally in a written report.

More specifically, the effectiveness of the *STARS* enforcement effort during the two-year trial period was evaluated by comparing the activity and infrastructure impacts of overweight commercial vehicles during the enforcement year to their activity and infrastructure impacts during the previous year (i.e., baseline year). Overweight commercial vehicle activity during both the baseline and enforcement years was characterized using data from *STARS* WIM systems. This data, processed by *MEARS*, was used to determine changes in the percent of overweight vehicles in the traffic stream and changes in the average amount of excess weight carried by these vehicles in the baseline and enforcement years. Using engineering principles, this data was further used to estimate the change in pavement damage that resulted from the change in overweight commercial vehicle activity between the two years and the attendant costs associated with this damage.

3.1 Montana's Strategy for *STARS*-directed Weight Enforcement

General objectives of the MCS weight enforcement program include improving the safety and longevity of the highway system by controlling the number of overweight commercial vehicles in the traffic stream and the amount by which they are overweight. The information available from *STARS* most directly supports the second objective of the program, namely, improving the longevity of the highway system. Notably, the service life of a pavement is closely related to the axle weights of the vehicles that travel upon it, while safe vehicle operation is affected by several parameters in addition to vehicle weight (e.g., roadway geometry, road surface condition, driver experience, etc.). Therefore, the decision was made to pursue the use of *STARS* in directing enforcement efforts to minimize pavement damage caused by overweight vehicles. It has long been established that the relationship between pavement damage and axle weight is non-linear. Thus, under normal circumstances, less pavement damage is incurred if freight is carried on more vehicles operating legally, rather than a fewer number of vehicles operating overweight.

3.1.1 Review of Previous WIM System Applications in Weight Enforcement

In developing a strategy for the most effective use of *STARS* data in vehicle weight enforcement, methodologies employed by other agencies to utilize WIM data in this regard were reviewed. Few previous investigations have attempted to dispatch enforcement resources in response to WIM-generated information on overweight vehicle movements. With respect to enforcement, WIM systems have been and are increasingly being used to sort non-compliant vehicles from the truck traffic stream and direct these vehicles to a weight enforcement station, thereby improving the efficiency of existing enforcement facilities (Bergan, et al. 1998; Chou and Tsai 1999). WIM systems have also been used to investigate avoidance of weight enforcement activities (Jessup and Casavant 1996; Cunagin, et al. 1997; Walton 2002). Use of WIM data to evaluate the effectiveness of weight enforcement efforts (but not to direct them) has been extensively researched by Hanscom (1998). Some of the metrics reported by *MEARS* are similar to the "measures of effectiveness" recommended by Hanscom for evaluating enforcement outcomes.

Ruback and Middleton (1999) demonstrated an approach for using WIM data to direct commercial vehicle enforcement in real-time. In this study, an enforcement officer was equipped with a computer that received WIM data directly via an Internet connection. An officer in the vicinity of an overweight truck having just passed over a WIM site would be notified immediately. Hence, a greater portion of an enforcement officer's time could be spent capturing overweight trucks rather than searching for violators based on experience and intuition. This mobile enforcement system can be implemented using relatively inexpensive equipment, but requires fast and reliable hardware and software to accommodate the required rapid information exchange between the WIM system and mobile computer. The State of New York is reportedly using a similar approach to that investigated by Ruback and Middleton for WIM-based weight enforcement (2002). State troopers can identify overweight vehicles in real-time using laptop computers connected to WIM systems. Indiana has also experimented with detecting vehicles operating overweight in real-time using portable computers connected to WIM sensors (Nichols 2002). The Maine State Police (MSP) are identifying chronic overweight vehicle situations by graphically analyzing WIM data (American Image, Inc. 2002). Some of the overweight vehicle reports they are generating are similar to those produced by *MEARS*. MSP are still investigating methods to incorporate this information in their weight enforcement efforts.

Consideration has also been given to automatically issuing overweight citations based on WIM-captured vehicle weights (similar in concept to systems that automatically issue traffic citations for running red lights, etc.). While such a system may be employed in the future, current WIM hardware apparently does not offer the necessary reliability and accuracy to be used in such an application (McCall and Kroeger 2002).

3.1.2 Implementation of STARS-directed Weight Enforcement

While there is an attraction to using *STARS* in real-time to dispatch enforcement personnel to individual overweight incidents, the decision was made in the pilot program to address long-term patterns of overweight vehicle activity on a coordinated statewide basis. These patterns were identified using historical information on overweight commercial vehicle activities reported in *MEARS*. One year of historical data (May 2000 through April 2001) was used to establish a baseline of overweight vehicle activity at each *STARS* site. In the following year (May 2001 through April 2002), mobile weight enforcement efforts across the state were dispatched based on the WIM data collected the previous year. It would have been preferable to have more than a single year of historical WIM data to more reliably characterize overweight vehicle activity prior to implementing the *STARS*-directed enforcement, but there was considerable interest in taking advantage of *STARS* data in MDT's planning and design activities as soon as possible after its deployment.

Sixteen *STARS* sites were used in the evaluation of the focused enforcement effort. At the beginning of this project, 19 of the permanent WIM systems had been installed across the state. Of these 19 sites, 3 had various problems with the WIM equipment or the pavement in which it was installed, resulting in significant losses in useable data. Thus, these sites were generally dropped from consideration. Table 3-1 indicates those sites included in the *STARS* evaluation. Note that many of these sites did experience occasional equipment problems. Questionable WIM data was identified using performance logs prepared by MDT, as well as visual observation of gross vehicle weight distributions generated monthly from the recorded data. When such data is presented in this report, it is clearly designated as questionable. Furthermore, in several cases, such data simply was excluded from the analyses. In one instance, the WIM data from two *STARS* sites were collectively evaluated as a single site. The Four Corners and Gallatin sites were considered singularly to account for months where there were problems with data at either site. This combination was thought feasible due to the close proximity of and limited junction access between the two sites.

3.1.3 Site Selection

A step-by-step procedure was developed to identify and prioritize the locations within the state that would benefit most from focused enforcement (i.e., the locations within the state experiencing the greatest pavement damage from overweight commercial vehicle activity). First, the amount of pavement damage attributable to overweight vehicle operations at each *STARS* site was calculated for each month during the baseline year. The results of these calculations were expressed in "excess ESALs", which has become an accepted manner to quantify that fraction of the damage sustained by pavements that is specifically due to the weight carried by vehicles in

Table 3-1. *STARS* Focused Enforcement Sites and Activity

	2001[c]								2002[c]			
Site	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**[b]	**Apr**[b]
Townsend	X	X	X	X	X	X	X	X			X	X
Decker					X	X				X		
Bad Route[a]	X		X	X								
Manhattan						X			X			
Arlee			X						X			
Four Corners/Gallatin	X	X X	X	X	X	X	X	X X	X	X	X	X
Big Timber[a]	X	X										
Galen												
Broadview												
Miles City East				X								
Ulm							X	X	X	X		
Ryegate					X		X	X	X	X	X	X
Stanford	X	X	X	X	X	X	X			X	X	X
Fort Benton												
Havre East												
Paradise												
Culbertson												
Lima												

[a] Removed from analysis due to WIM equipment/pavement problems
[b] Focused enforcement occurred at only four sites due to patrol officer staffing constraints
[c] X indicates site was selected for enforcement during the indicated month of the enforcement year
XX indicates site was selected for intensive enforcement (twice the regular schedule) during the indicated month of the enforcement year

excess of the legal limit. These calculations were done using information available from *MEARS* on the number of overweight vehicles operating at each site (by class), and the average amount of overweight per vehicle. The number of overweight vehicles reported in each class was multiplied by an excess ESAL factor for the overweight vehicles in that class. These excess ESAL factors were determined by vehicle class simply as the difference between the ESAL factor for a vehicle operating at the average overweight for the class and the ESAL factor for the same vehicle operating at its maximum legal weight. These excess ESALs were accumulated across all commercial vehicle classes at each site.

Results of the pavement damage calculations described above were depicted graphically to more easily identify and prioritize focused enforcement sites each month. Figure 3-1 provides an example for the baseline month of October 2000. Each month, the five sites with the greatest amount of pavement damage resulting from overweight commercial vehicle activity were selected as candidates for focused enforcement. The number of sites to be enforced was governed primarily by the size of the MCS patrol staff. Manhattan, Townsend, Four Corners, Stanford and Decker were selected for focused enforcement during the evaluation month of October 2001 based upon the amount of pavement damage observed the previous year. Note that Ryegate and Miles City East experienced higher levels of pavement damage than Decker in the baseline year, but were not selected for focused enforcement. The vehicles contributing to the pavement damage at these sites were technically over legal weight limits but below the limit at which penalties are imposed by state statute (this determination was made using information available from the *MEARS* reports).

Table 3-1 presents a summary of *STARS* enforcement activity. For the five sites selected for focused enforcement each month, *MEARS* reports were subsequently used to determine the vehicle configuration(s) responsible for the greatest amount of pavement damage and their respective time(s) and direction(s) of operation. Prior to each month of focused enforcement, a proposed enforcement schedule, similar to the one provided in Table 3-2, was sent to MDT's MCS Division. This schedule, derived from historical WIM information, was then used to guide the dispatching and scheduling of mobile enforcement officers for the same month, one year

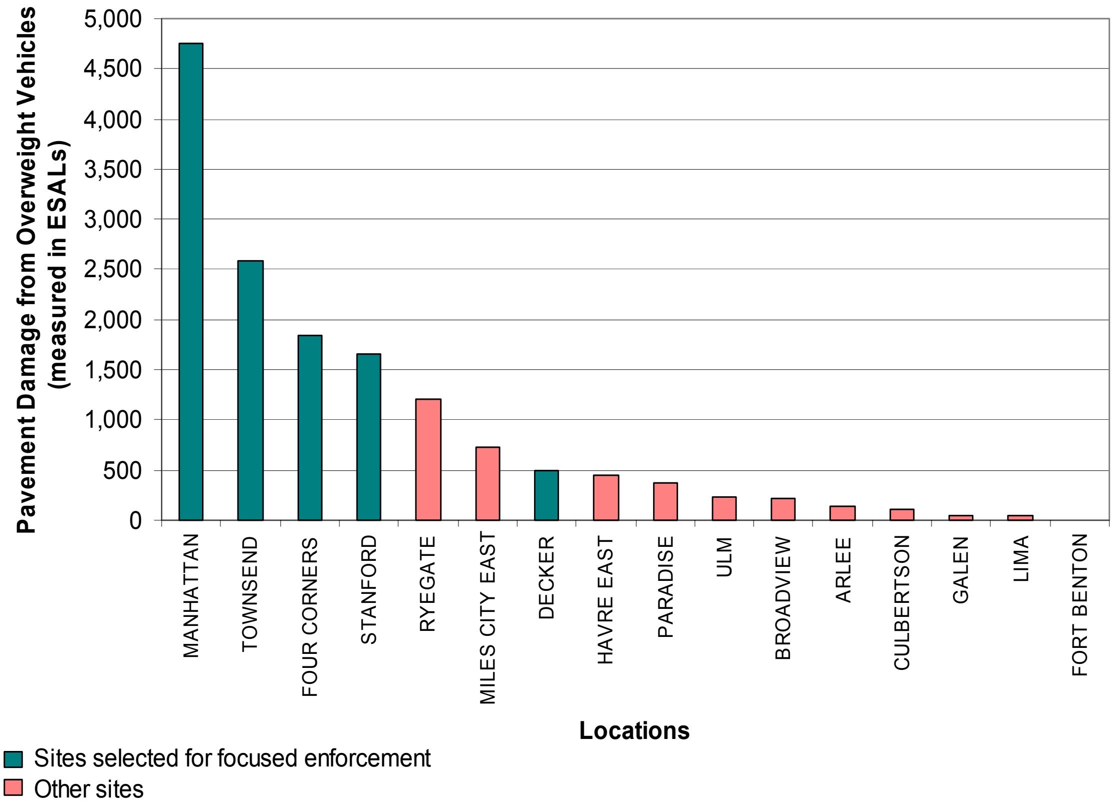


Figure 3-1. Typical Pavement Damage (measured in ESALs) for each *STARS* Site for October 2000 (Baseline Year).

later in 2001-2002. Patrol officers were only available to focus on weight enforcement at each of the five sites for three days per week and for eight hours per day, in light of their other duties. This level of effort was generally consistent with that devoted to this activity in the previous year. Within these constraints, enforcement hours were selected based on the relative amount of overweight vehicle traffic at various times throughout each week. Note that during the last two months of the enforcement year, only four sites were selected for *STARS*-directed enforcement. Patrol-based enforcement efforts had to be curtailed during these months due to unanticipated staffing shortages.

During the *STARS*-designated enforcement times at each site, MCS patrol officers concentrated their efforts on those vehicles listed in the enforcement schedule. For some of the enforcement

Table 3-2. Typical Monthly Focused Enforcement Schedule Generated from WIM System Data

Site	Day of Week	Critical Time of Day	Direction of Travel and Vehicle Configuration(s)
Townsend	Monday	8:00 am to 4:00 pm	9, 10 East or West; 13 West
	Tuesday	8:00 am to 4:00 pm	9 East or West; 10 East, 13 West
	Wednesday	8:00 am to 4:00 pm	9, 10 East or West; 13 West
Decker	Monday	8:00 am to 8:00 pm	13, 10 North; 9 North or South; 6 North
	Wednesday	8:00 am to 8:00 pm	13, 10 North; 9 North or South
	Friday	8:00 am to 8:00 pm	13, 10 North; 9 North or South
Gallatin	Monday	noon to midnight 4:00 am to noon	9, 6 North or 9, 13 South
	Tuesday	noon to midnight	9, 6 North
	Friday	noon to midnight	9, 6 North
Manhattan	Monday	8:00 am to 8:00 pm	10, 9 West; 6 East
	Wednesday	8:00 am to 8:00 pm	10, 9 West; 6 East
	Thursday	8:00 am to 8:00 pm	10, 9 West; 6 East
Stanford	Monday	Noon to midnight	9, 10 East or West
	Tuesday	Noon to midnight	9, 10 West
	Friday	Noon to midnight	9, 10 West

activities, the patrol officers were provided with one or two alternatives with respect to the time of day and the vehicles of interest for their enforcement effort. Such alternatives were used when, upon reviewing the *MEARS* data, several overweight activities appeared to be simultaneously habitual and excessive in nature. In all cases, the patrol officers measured axle weights during their enforcement activities using portable scales. Also, during focused enforcement periods, any passing vehicles that were operating in an unsafe manner and/or operating obviously over legal weight limits took precedence relative to the *STARS* enforcement activity.

With respect to vehicle type, Class 6, 9, 10, and 13 vehicles (see Appendix A for vehicle descriptions by Class) were consistently found to be responsible for the most pavement damage attributable to overweight operation; therefore, these vehicle classes were the subject of focused enforcement activity at various sites and various times during the enforcement year. With the exception of light 2-axle commercial vehicles, these vehicles are the predominant commercial vehicle configurations operating on the state's highways. The greatest source of excess ESALs in almost every case was Class 9 vehicles. While the average amount of weight exceedance was often not as extreme for Class 9 vehicles as for some of the other vehicle classes, they made up a significantly greater proportion of the total traffic stream, and thus were responsible for the greatest cumulative pavement damage effects. Of the four vehicle classes listed above, Class 6 vehicles were the most infrequent subject of focused enforcement.

3.1.4 Affected Mileage

Though focused at sixteen spot-location sites in the state, enforcement activities at any given *STARS* site were presumed to influence commercial vehicle activities over an extended but finite length of roadway upstream and downstream of the site. This presumption, related to the amount of mileage affected by *STARS*-directed enforcement activities, was required to determine changes in pavement damage and attendant cost savings. The extent of affected mileage was determined using the roadway distance to an adjacent junction with a highway, Interstate or state line upstream and downstream of the *STARS* site. At these locations, truck traffic volumes may significantly change and confound the *STARS* program effects. In some instances, the affected mileage was extended in either direction beyond the junctions; if truck traffic remained constant through the nearest junction, the affected mileage was extended to a subsequent junction. A summary of affected mileage for each *STARS* site is included in Table 3-3. Instances where the affected mileage was adjusted based on constant truck volumes are noted as "Comments."

An attempt was made to further trace the route of the vehicles that passed through each *STARS* site beyond the end points enumerated in Table 3-3 below. Until a vehicle reached its destination or crossed the state line, the effect of *STARS* on that vehicle's operations would continue to extend across additional mileage of the state highway system. Initially, it was thought possible to better estimate: (1) the percentage of truck traffic at an end junction that could reasonably be presumed to continue on past that junction and (2) the routes and distances these continuing vehicles might travel. Specifically, if the nature of the trip could be discerned based on an assumption of the commodity carried, such estimations could be made. It was eventually decided, however, that in the absence of quality commodity flow information, extension of the analysis beyond the segments defined in Table 3-3 was too uncertain.

Table 3-3. Affected Mileage for each *STARS* Site

WIM Site	Route	System[1]	From:		To:		Mileage[2]
Townsend	US 287	NHS Non-Interstate	I-15	Helena	I-90	W. of Three Forks	62
Comments[3]: Truck volumes stay consistent through intersection with US 12 in Townsend							
Decker	Hwy 314	Secondary	US 212	W. of Busby	MT/WY Border		44
Manhattan	I-90	NHS Interstate	US 287	W. of Three Forks	SR 85/US 191	Belgrade	23
Arlee	US 93	NHS Non-Interstate	I-90	W. of Missoula	SR 200	Ravalli	27
Four Corners/ Gallatin	US 191	NHS Non-Interstate	I-90	Belgrade	MT/ID Border		98
Comments[3]: Truck volumes stay consistent through intersection with US 287 and US 20 (West Yellowstone).							
Galen	Hwy 273	Secondary	I-90	S. of Deer Lodge	SR 1	E. of Anaconda	11
Broadview	SR 3	NHS Non-Interstate	US 12	N. of Lavina	I-90	Billings	47
Miles City East	US 12	Primary	I-94	E. of Miles City	SR 7	Baker	77
Ulm	I-15	NHS Interstate	US 87/SR 3	Great Falls	US 12	Helena	86
Comments[3]: Low truck volumes on US 287 (S. of Craig).							
Ryegate	US 12	NHS Non-Interstate	US 191	Harlowton	SR 3	Lavina	45
Stanford	US 87	NHS Non-Interstate	I-15	Great Falls	US 191	W. of Moore	88
Comments[3]: Low truck volumes on US 89 (E. of Belt) and SR 80 (Stanford).							
Fort Benton	US 87	NHS Non-Interstate	I-15	Great Falls	US 2	Havre	112
Comments[3]: Low truck volumes on SR 80 (Fort Benton).							
Havre East	US 2	NHS Non-Interstate	US 87	Havre	SR 24	Glasgow	158
Comments[3]: Low truck volumes on SR 66 (Fort Belknap) and US 191 (Malta).							
Paradise	SR 200	Primary	SR 135	S. of Paradise	SR 28	Plains	7
Culbertson	SR 16	NHS Non-Interstate	SR 200	Sidney	SR 5	Plentywood	82
Comments[3]: Truck volumes stay consistent through intersection with US 2 (Culbertson).							
Lima	I-15	NHS Interstate	SR 41	Dillon	MT/ID Border		64

[1] System names determined from MDT Montana Highway System Map.

[2] Mileage determined from Montana 1998-99 Official State Highway Map and 1997 MDT Road Log.

[3] Truck volumes determined from MDT 1999 Montana Rural Traffic Flow Map.

Therefore, the decision was made to attribute the influence of *STARS* simply to the road segments identified in Table 3-3, with the expectation that the impacts determined in this analysis would be a lower bound on the actual impacts.

3.2 Evaluation Methodology for *STARS*-directed Weight Enforcement Effort

Following the one-year trial period of focused enforcement (May 2001 to April 2002), any changes in overweight vehicle operations and impacts attributable to *STARS* were determined by comparing the WIM data from the baseline year to the WIM data from the enforcement year. Traditionally-applied measures of truck weight enforcement such as the number of trucks weighed and citations issued, were believed to be inadequate for measuring the effectiveness of the *STARS* program enforcement objectives - deterring overweight behavior and minimizing pavement damage. Hanscom and Goelzer (1998) developed and subsequently validated alternate measures of effectiveness (MOEs) in a comprehensive four-state field evaluation. Matched WIM data sets, collected under controlled baseline and enforcement conditions, were analyzed and the following MOEs were validated on the basis of their demonstrated sensitivity to truck weight enforcement objectives and the presence of enforcement activity: (1) severity of overweight violations, (2) proportion of overweight trucks, (3) average equivalent single-axle loads (ESALs), (4) excess ESALs and (5) bridge formula violations. These measures were proven sensitive to both legal weight limit compliance objectives of truck weight enforcement procedures and the potential for pavement deterioration.

Following the guidance of Hanscom and Goelzer (1998), the effectiveness of the *STARS* enforcement program was evaluated in terms of changes in: (1) the proportion of overweight trucks in the traffic stream and (2) pavement damage measured in ESALs and its associated cost. Changes in citation activity, a metric more aligned with traditional methods for gauging weight enforcement effectiveness, were also considered though the validity of this metric in evaluating *STARS* program effectiveness was suspect.

As mentioned earlier, the *STARS* hardware and *MEARS* software simply count legally permitted overweight vehicles as part of the general overweight vehicle population; there does not appear to be any practical manner for identifying these vehicles in the traffic stream using basic WIM technologies. While this situation is not ideal from an enforcement perspective relative to using *STARS* data to direct enforcement personnel to problem overweight locations, this treatment of permitted commercial vehicles likely had no impact on the *STARS* program evaluation outcome. The proportion of permitted commercial vehicles in the traffic stream and their amount of overweight was assumed to remain constant between the baseline year and the enforcement year, in the absence of any outside motivation to change their behavior. Thus, when changes due to enforcement are calculated as differences between these two samples, the effects of permitted vehicles will generally cancel out.

3.3 Changes in the Overweight Commercial Vehicle Population

The percentage of overweight commercial vehicles in the traffic stream decreased by 22 percent across all the *STARS* sites (enforced and un-enforced) during the year of focused enforcement. In the baseline year, 8.8 percent of commercial vehicles passing the *STARS* sites were overweight; in the enforcement year, 6.9 percent were overweight. Although the reduction in overweight vehicle operations varied from place-to-place, the greatest reductions occurred at the *STARS*-enforced sites. This correlation supports the conclusion that the use of WIM data to direct enforcement efforts under the *STARS* program was primarily responsible for this reduction in overweight commercial vehicle activity.

3.3.1 Proportion of Overweight Commercial Vehicles

The changes observed in the percentage of overweight commercial vehicles operating each month during the baseline versus the enforcement year are graphically presented for all sites in Appendix B; only a sample of the most illustrative sites is included below. In these figures, data points denoted with a triangle, Δ, represent the months that have potentially "questionable" or missing data. These points were considered in the data set for this aspect of the evaluation, but were scrutinized as to their appropriateness and eliminated from consideration as necessary in the analysis of the statistical significance of the observed changes in the percent of overweight vehicles and in the final pavement damage analysis. To facilitate examination of the focused enforcement effects, sites are grouped based on the frequency of *STARS*-directed enforcement at each site. More specifically, sites with more than six months, sites with one to six months and sites without any focused enforcement are described more fully below.

STARS Sites with More Than Six Months of Focused Enforcement. Four Corners/Gallatin, Ryegate, Stanford and Townsend are the *STARS* sites with seven to twelve months of focused enforcement. With few exceptions, the proportion of overweight commercial vehicles at these sites during the enforcement year is generally lower than that of the baseline year. Those months that are not consistent with this observation are typically the last two months of the enforcement year; a relaxed emphasis on enforcement nearing the end of the evaluation period may be the cause. One of the most notable reductions in overweight vehicle operations occurred at Ryegate during the months of October through May (see Figure 3-2). Following a peak during the non-enforced month of October, the percent of overweight vehicles in the traffic stream steadily decreased over several months of focused enforcement. A potential residual enforcement effect is observed in May 2002 following the enforcement year; the percent of overweight vehicles continued to decrease at this site, even though the focused enforcement concluded the previous month.

STARS Sites with One to Six Months of Focused Enforcement. *STARS* sites with one to six months of focused enforcement are Arlee, Decker, Manhattan, Miles City East and Ulm. The difference in the proportion of overweight commercial vehicles between the baseline and enforcement year is not as discernable as for those sites with more than six months of focused enforcement. In some instances, patterns of overweight activity can reasonably be explained based on months of focused enforcement activity, while in almost the same number of instances, explanations for observed behaviors are not so obvious.

The percent of overweight vehicles at Decker (see Figure 3-3) in the first focused enforcement month (September) clearly dropped relative to the previous month in the same year and the same month of the previous year (both of which were not targeted enforcement months). In October, this site was again selected for enforcement and the percentage of vehicles operating overweight remained well below that observed for same month the previous year, with residual effects

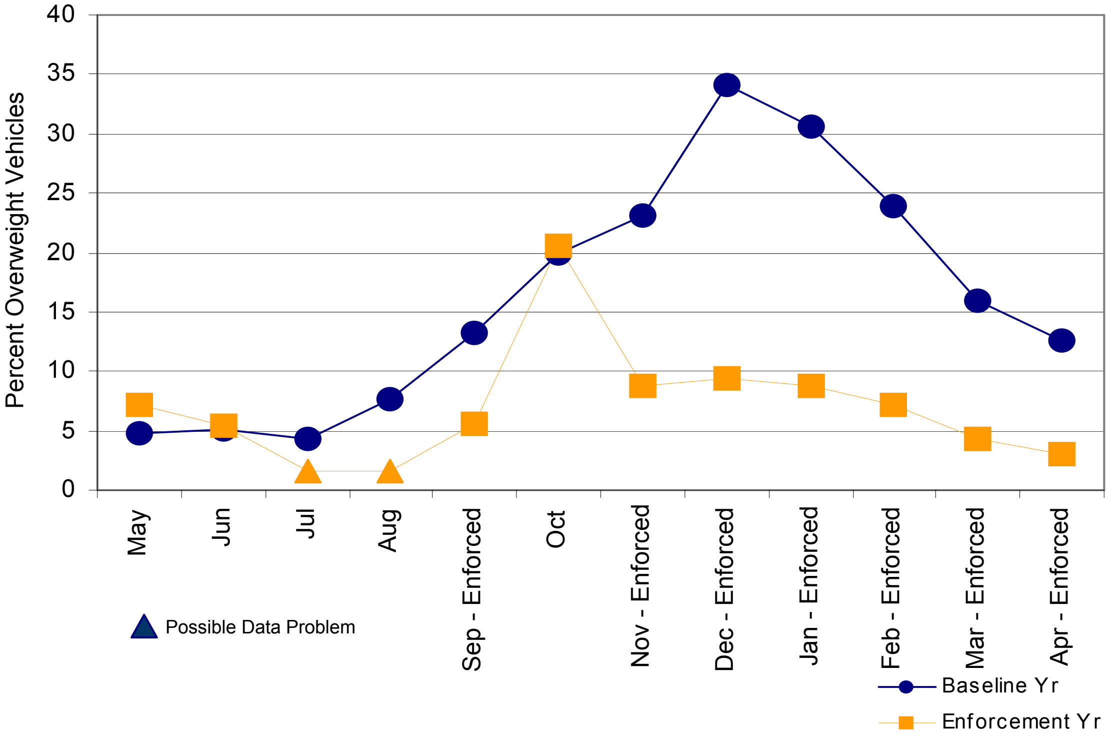


Figure 3-2. Percent Overweight Commercial Vehicles by Month at the **Ryegate** *STARS* Site, Baseline and Focused Enforcement Year

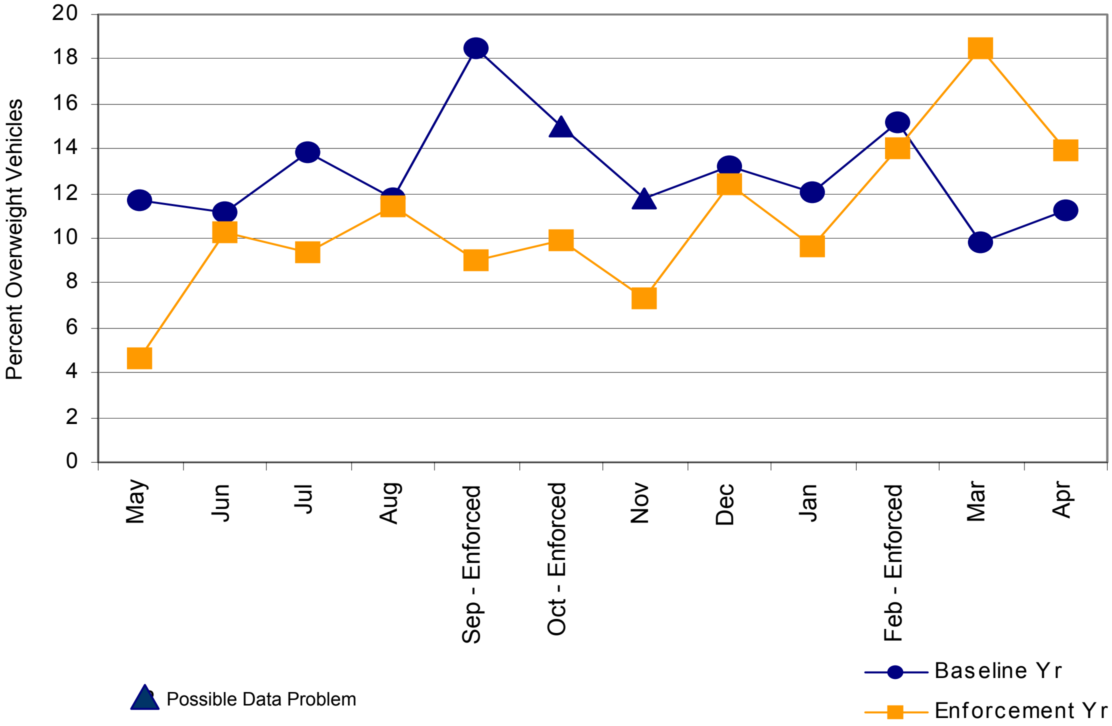


Figure 3-3. Percent Overweight Commercial Vehicles by Month at the **Decker** *STARS* Site, Baseline and Focused Enforcement Year

observed in November, which was not selected for targeted enforcement but none-the-less experienced a decline in overweight vehicle activity. The percentage of vehicles operating overweight in the traffic stream subsequently increased in December to the levels observed in previous years. It is possible therefore, that the enforcement effort had one month of residual effect on overweight vehicle operations at this site.

A similar effect can be seen at Arlee in the enforcement month of January (see Figure 3-4), where a decrease in the percent of overweight vehicles relative to the previous month and the same month the previous year is observed. Once again, a residual effect can be seen in the subsequent non-enforced month of February at this site with the percent of overweight vehicles increasing in March.

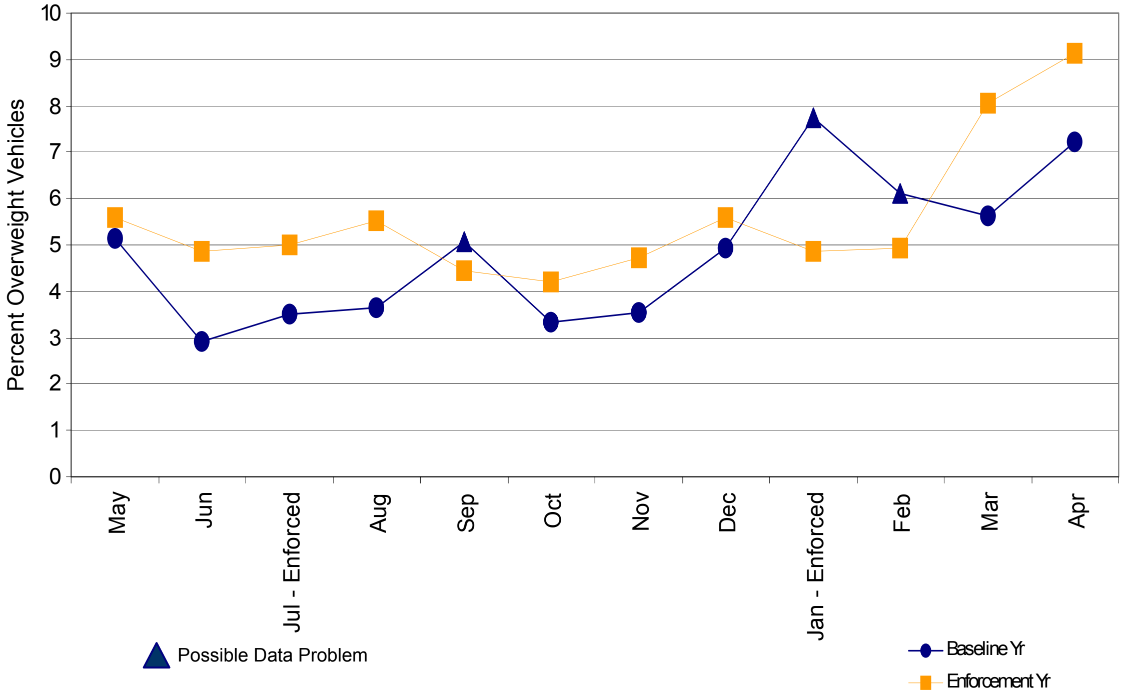


Figure 3-4. Percent Overweight Commercial Vehicles by Month at the **Arlee** *STARS* Site, Baseline and Focused Enforcement Year

The remaining changes in overweight vehicle operations from the baseline to the enforcement year at Decker and Arlee are not so easily correlated with *STARS* enforcement activities. Once again, referring to the Decker *STARS* site (Figure 3-3), focused enforcement efforts in February resulted in no apparent residual effect on the operation of overweight vehicles in the months following the enforcement activity. Further, the enforcement activity in February resulted in only a nominal reduction in overweight vehicles relative to the previous year, and in the month following the enforcement effort, the percent of overweight vehicles in the traffic stream actually increased (both with respect to the previous month and with respect to the same month the previous year). Referring to the Arlee *STARS* site (Figure 3-4), during the enforced month of July, overweight vehicle activity actually increased relative to the baseline year. As mentioned above, this pattern of behavior (no discernable correlation between enforcement effort and overweight vehicle activity) was also observed in several instances for the all the sites in this category (*STARS* sites with one to six months of focused enforcement).

STARS Sites Not Selected for Focused Enforcement. Broadview, Culbertson, Fort Benton, Galen, Havre East, Lima and Paradise are sites included in the *STARS* evaluation that did not warrant focused enforcement. As might be expected, it is difficult to discern any trends in overweight vehicle activity between the baseline and enforcement years at these sites. In some cases, the percent of overweight vehicles in the traffic stream during the enforcement year is higher than that of the baseline year (see Figure 3-5, Fort Benton), but in at least as many cases the opposite trend is true (see Figure 3-6, Havre East). *STARS* may have had a positive effect at some sites that were not the focus of enforcement due to residual geographic effects, particularly on commercial vehicle travel routes that encompass multiple *STARS* sites. Alternatively, *STARS* may have had a negative effect at some sites that were not the focus of enforcement, as enforcement resources previously used at these sites in the baseline year were shifted to the focused enforcement sites during the *STARS* pilot project. Finally, in certain circumstances, increased overweight vehicle activity at unenforced sites could be indicative of bypass activities, as overweight vehicles avoid those sites with focused enforcement. Note that bypass/avoidance issues are discussed in more detail later in this report (Section 3.5); only limited evidence of bypass activity was observed during the enforcement year.

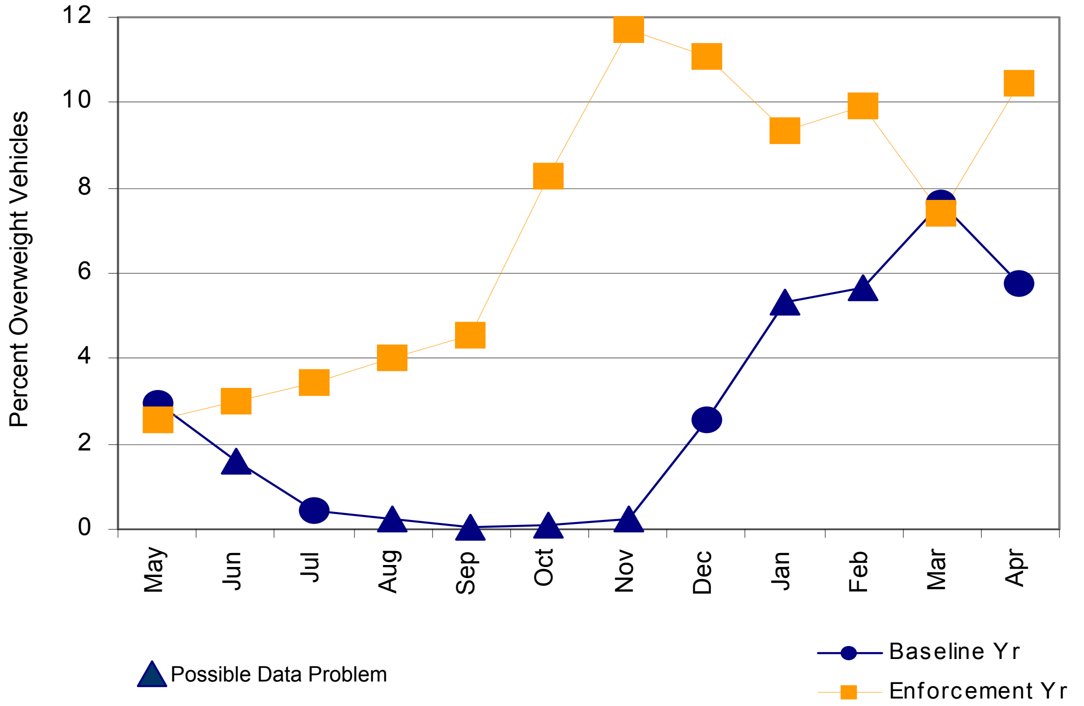


Figure 3-5. Percent Overweight Commercial Vehicles by Month at the **Fort Benton** *STARS* Site, Baseline and Focused Enforcement Year

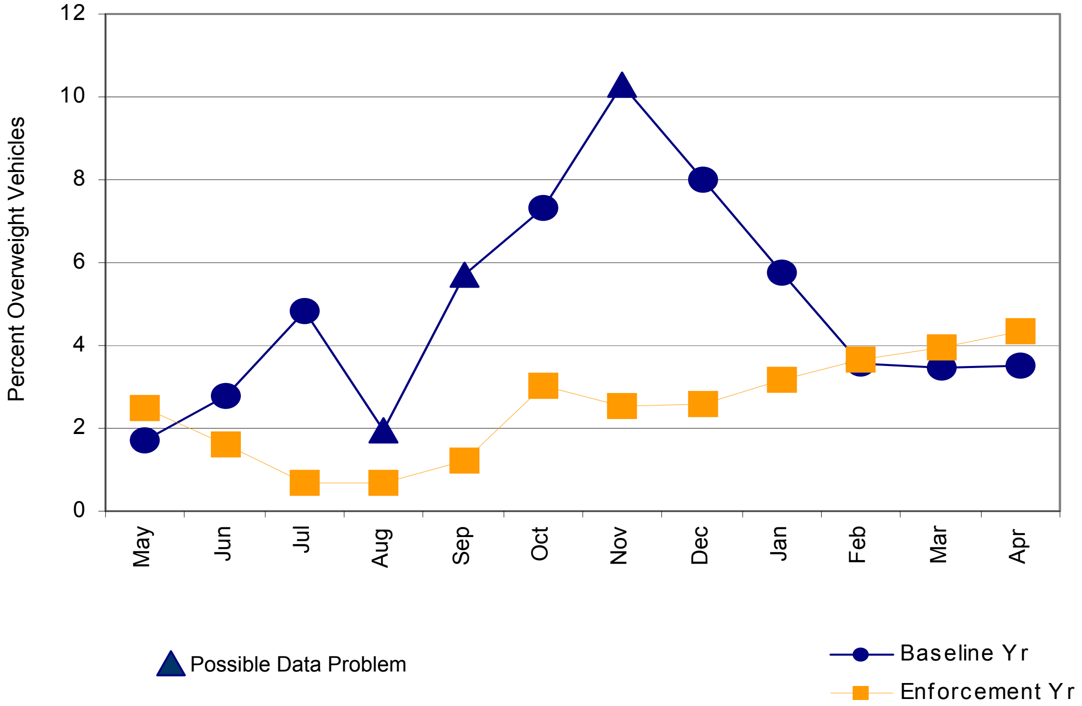


Figure 3-6. Percent Overweight Commercial Vehicles by Month at the **Havre East** *STARS* Site, Baseline and Focused Enforcement Year

3.3.2 Statistical Investigation of the Change in Overweight Commercial Vehicle Proportions

While the above observations are enlightening, they are qualitative in nature and represent observations made during a *single* baseline year and a *single* evaluation year. Hence, to explore the likelihood of observing repeated patterns of changed commercial vehicle loading behavior (or conversely, to explore the likelihood that either the baseline or enforcement year represents an anomaly in behavior), additional analyses were performed to determine if statistically significant differences existed in the overweight vehicle populations in the baseline and enforcement years. The primary question of interest was twofold:

1. For each site and for each month, did the proportion of overweight vehicles in the traffic stream significantly decrease from the baseline year to the enforcement year? The noted significance of reduced overweight commercial vehicle proportions can then be compared for *STARS* sites that experienced focused enforcement for any given month and those that did not.

2. Statewide, did the aggregate annual proportion of overweight commercial vehicles in the traffic stream significantly decrease between the baseline and enforcement year?

The statistical analyses in response to this twofold question considered only 146 of the possible 192 data points available to answer this question (16 sites multiplied by 12 months). During some months, various *STARS* sites experienced WIM equipment failure or malfunction. Less than 7 days of data per month were considered to be insufficient to characterize vehicle operations at a site; any such months were removed from further analysis. Sites that exhibited calibration problems (detected from *MEARS* calibration tracking graphs and frequency plots developed from load spectrum data) or at which data was collected only in a single direction of travel (identified using the *MEARS* overweight vehicle and calibration tracking reports) were also removed for the effected months.

Binomial Test for Equal Proportion. To investigate the site- and month-specific change in the percent of overweight vehicles from the baseline year to the enforcement year, a binomial test for equal proportions was conducted. For each site and for each month, this test confirms whether the percent of overweight vehicles in the traffic stream is equal in the baseline year and enforcement year or whether the *STARS*-directed enforcement efforts resulted in a significant decrease in the percent of overweight vehicles in the traffic stream during the enforcement year:

H_0: $p_b = p_e$

H_1: $p_b > p_e$

where p_b is the proportion of overweight commercial vehicles during the baseline year at site i during month j and p_e is the proportion of overweight commercial vehicles during the enforcement year at the same site and during the same month.

For this application, the population of commercial vehicles traveling Montana's highways is assumed to follow a binomial distribution with each vehicle identified as either overweight or within legal weight limits:

$$x \sim Bin\ (n, p)$$

where x is the number of overweight commercial vehicles at site i during month j, n is the total number of commercial vehicles at site i during month j and p is the proportion of overweight commercial vehicles at the same site and during the same month.

A Normal Distribution Approximation is often applied to this type of data, assuming that the observed sample proportion, $\hat{p}$, is normally distributed with mean p and variance $\hat{p}$:

$$\hat{p} \overset{\cdot}{\sim} N(p, \operatorname{var}(\hat{p}))$$

This approximation is only valid if both $n\hat{p}$ and $n(1-\hat{p})$ are > 5; values < 5 indicate a skewed binomial distribution that is not well-represented by the normal curve (Devore 1995). For this investigation, two site-specific months of data were found to violate these criteria: Culbertson in December and Lima in September. These data were omitted from this aspect of the evaluation.

The test statistic, z, for the Normal Distribution Approximation is given as:

$$z = \frac{\hat{p}_b - \hat{p}_e}{s_p}$$

where $\hat{p}_b$ and $\hat{p}_e$ are the observed sample proportions of overweight commercial vehicles at site i during month j in the baseline and enforcement years, respectively and s_p is the pooled standard deviation:

$$s_p = \sqrt{\hat{p}(1-\hat{p})\left(\frac{1}{n_b}+\frac{1}{n_e}\right)}$$

where n_b and n_e are the total numbers of commercial vehicles observed at site i during month j in the baseline and enforcement years, respectively and $\hat{p}$ is the pooled sample proportion:

$$\hat{p} = \frac{x_b + x_e}{n_b + n_e}$$

where x_b and x_e are the numbers of overweight commercial vehicles observed at site i during month j in the baseline and enforcement years, respectively and other parameters are as previously defined.

This test statistic is used to determine the point value (p-value) defining the hypothesis acceptance and rejection regions. To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0:

- a p-value ≤ 0.05 (one-tailed) suggests rejecting H_0: $p_b = p_e$ and accepting H_1: $p_b > p_e$, the *STARS*-directed enforcement efforts resulted in a significant decrease in the proportion of overweight commercial vehicles in the traffic stream during the enforcement year
- a p-value > 0.05 suggests accepting H_0: $p_b = p_e$, the proportion of overweight commercial vehicles in the traffic stream is equal in the baseline year and enforcement year.

Table 3-4 summarizes the significance of site- and month-specific changes in the proportion of overweight commercial vehicles from the baseline year to the enforcement year. For 32 out of a total of 40 enforcement activities, a statistically significant reduction (p-value ≤ 0.05) was observed in the proportion of overweight commercial vehicles from the baseline to enforcement

Table 3-4. Significance of Site- and Month-Specific Changes in the Proportion of Overweight Commercial Vehicles, Baseline to Focused Enforcement Year

	May	June	July	August	September	October	November	December	January	February	March	April
Townsend[a]	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	▨	▨	▨	▨	░
Decker[a]	**X**		**X**		░ **X**	▨	▨		**X**	░		
Manhattan[a]			**X**	**X**	**X**	░ **X**	**X**	**X**	▨	▨	**X**	**X**
Arlee[a]			░		▨				▨	▨		
Gallatin[a]	▨	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	▨	▨	░	▨
Galen	▨		▨				**X**		▨	▨		**X**
Broadview												
Miles City East[a]			**X**	░ **X**	**X**	**X**			**X**	**X**	**X**	
Ulm[a]	▨	▨					░	░	▨	▨	▨	▨
Ryegate[a]			▨	▨	░ **X**		░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**
Stanford[a]	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	░ **X**	**X**	**X**	░ **X**	░	░
Fort Benton		▨		▨	▨	▨	▨		▨	▨		
Havre East		**X**		▨	▨	**X**	▨	**X**	**X**			
Paradise					**X**	**X**	▨	▨		▨	▨	
Culbertson					▨	**X**	▨	■			▨	
Lima			▨	▨	■	**X**	**X**	**X**		**X**	**X**	**X**
Total Sites Showing a Significant Decrease in Overweight Commercial Vehicle Proportions (p-value ≤ 0.05)	**3**	**4**	**6**	**5**	**9**	**9**	**7**	**6**	**5**	**4**	**4**	**4**

a	Sites with more than six months of focused enforcement
X	Significant decrease in the proportion of overweight commercial vehicles in the traffic stream during the enforcement year (p-value ≤ 0.05)
░	Enforced site and month
	Non-enforced site and month
▨	Missing data or data problems
■	Normal Distribution Approximation violation for Binomial Test for Equal Proportions

year. Of the 104 non-enforced months, 33 had statistically significant reductions between the baseline and enforcement year. In other words, 80 percent of the enforced months indicated a statistically significant decrease in the proportion of overweight vehicles, while only 32 percent of the non-enforced months experienced a statistically significant reduction in the overweight vehicle population, suggesting that *STARS*-directed enforcement efforts were effective in controlling the number of overweight commercial vehicles in the traffic stream.

Two-sample t-test. To investigate the aggregate impacts of the *STARS*-directed enforcement efforts, a two-sample t-test was conducted to statistically confirm whether or not the statewide annual percentage of overweight commercial vehicles in the traffic stream significantly decreased between the baseline and enforcement years:

H_0: $P_b = P_e$

H_1: $P_b > P_e$

where P_b is the mean percentage of overweight commercial vehicles statewide during the baseline year and P_e is the mean percentage of overweight commercial vehicles during the enforcement year. The two-sample t-test assumes that the data collected during the baseline year and data collected during the enforcement year are independent and that this data follows a normal distribution with mean P and variance $\hat{P}$:

$$\hat{P} = N(P, \mathrm{var}(\hat{P}))$$

Violation of the normal distribution assumption could lead to erroneous statistical inferences. As such, the Kolmogorov-Smirnov Test for Normality was conducted before proceeding with the two-sample t-test. For this application, the underlying hypothesis of the Kolmogorov-Smirnov Test is that the percentage of overweight commercial vehicles in the traffic stream, in either the baseline year or the enforcement year, follows a normal distribution or it does not:

H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$

H_1: $\hat{P} \neq N(P, \mathrm{var}(\hat{P}))$

To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0:

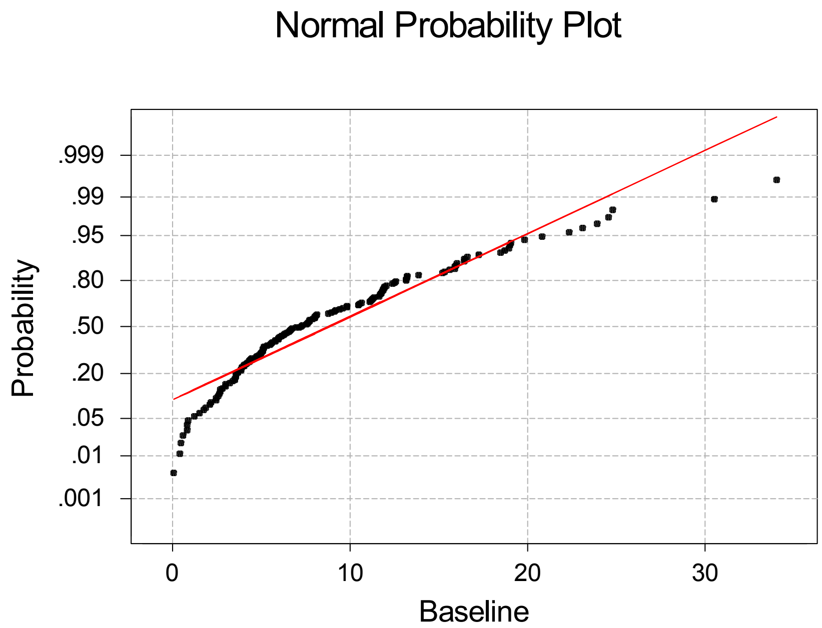
- a p-value ≤ 0.025 (two-tailed) suggests rejecting H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$ and accepting H_1: $\hat{P} \neq N(P, \mathrm{var}(\hat{P}))$, the percentage of overweight commercial vehicles in the traffic stream, in either the baseline year or the enforcement year, is <u>not</u> normally distributed

- a p-value > 0.025 suggests accepting H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$, the percentage of overweight commercial vehicles in the traffic stream, in either the baseline year or the enforcement year, is normally distributed.

A normal probability plot was generated and the Kolmogorov-Smirnov Test was performed for the percentage of overweight commercial vehicles in the baseline and enforcement years (see Figures 3-7 and 3-8). For the enforcement year sample, a p-value > 0.025 resulted confirming that the percentage of overweight commercial vehicles in the traffic stream is normally distributed (H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$ is accepted). However, for the baseline year sample, a p-value ≤ 0.025 resulted confirming that the percentage of overweight commercial vehicles in the traffic stream is <u>not</u> normally distributed (H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$ is rejected). Normally distributed samples cannot be confirmed.

To overcome violation of the normal distribution assumption, two common approaches are taken: (1) the data is mathematically transformed to achieve a normal distribution or (2) the two-sample t-test is abandoned in favor of a less-restrictive nonparametric test such as the Mann-Whitney Nonparametric Test. Both approaches were investigated in the continued analysis.

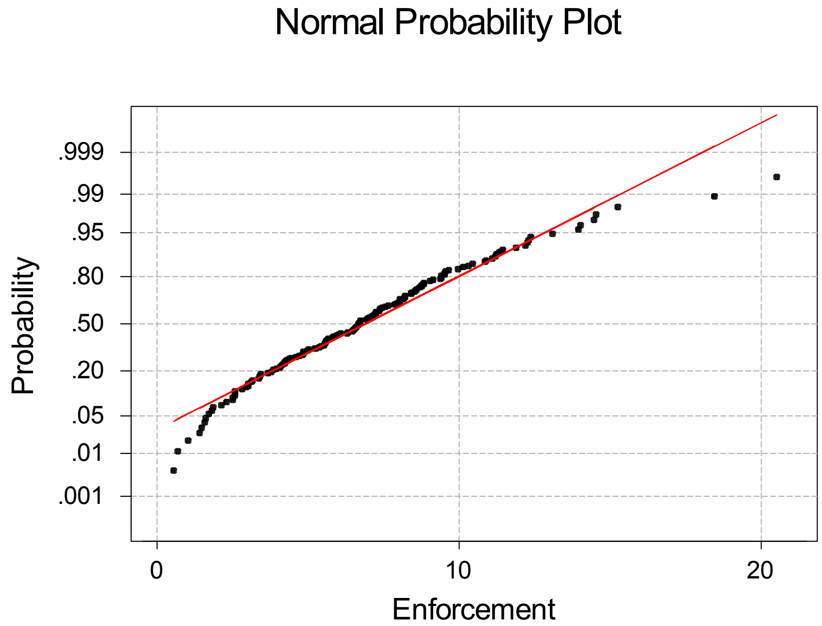
Data Transformation. Though several mathematical transformations of the data were explored, only the square root transformation of the baseline and enforcement percentage of overweight commercial vehicles achieved normally distributed data sets (see Figures 3-9 and 3-10). In each case, a p-value > 0.025 confirmed that the percentage of overweight commercial vehicles in the traffic stream, in both the baseline year and the enforcement year, is normally distributed (H_0: $\hat{P} = N(P, \mathrm{var}(\hat{P}))$ is accepted).



Average: 8.78692
StDev: 6.31845
N: 146

Kolmogorov-Smirnov Normality Test
D+: 0.130 D-: 0.086 D : 0.130
Approximate P-Value < 0.01

Figure 3-7. Percentage of Overweight Vehicles Normality Plot, Baseline Year



Average: 6.88904
StDev: 3.53450
N: 146

Kolmogorov-Smirnov Normality Test
D+: 0.063 D-: 0.040 D : 0.063
Approximate P-Value > 0.15

Figure 3-8. Percentage of Overweight Vehicles Normality Plot, Focused Enforcement Year

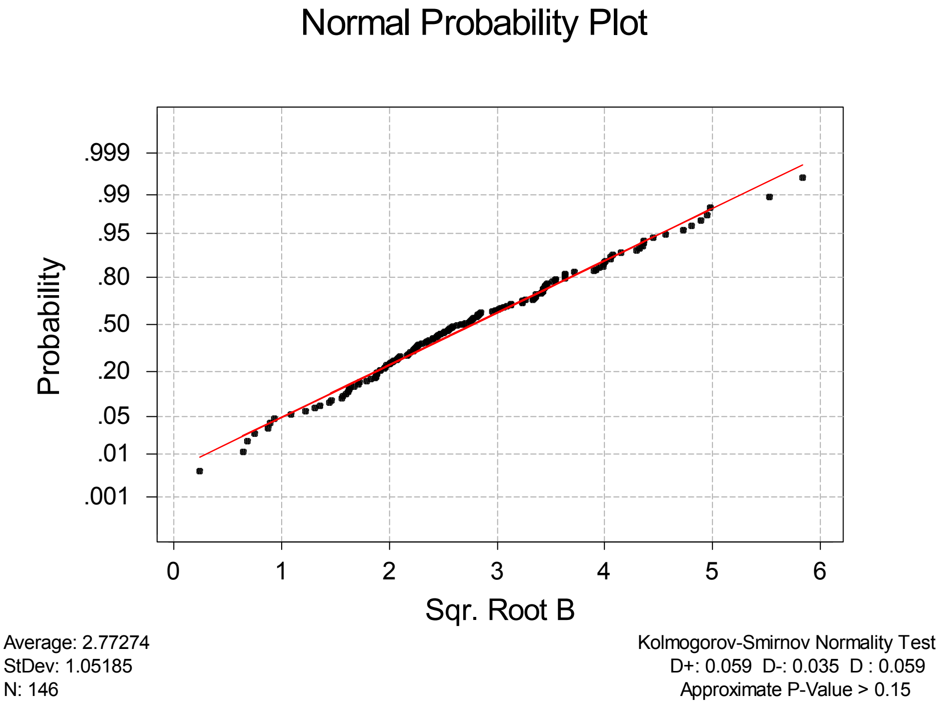


Figure 3-9. Square Root-transformed Percentage of Overweight Vehicles Normality Plot, Baseline Year

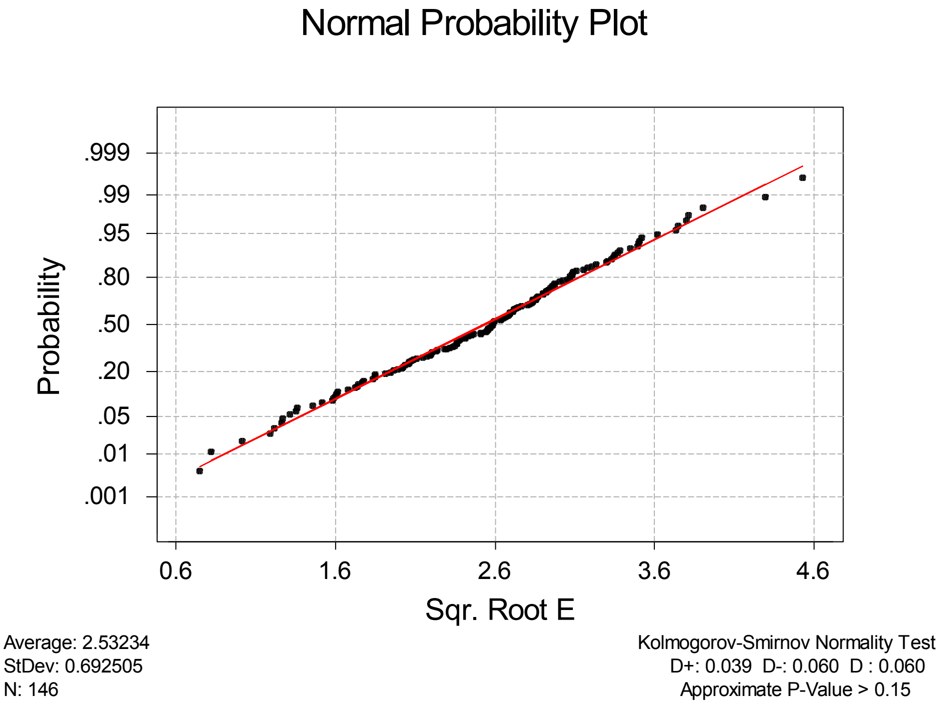


Figure 3-10. Square Root-transformed Percentage of Overweight Vehicles Normality Plot, Focused Enforcement Year

The square root transformation of the data achieves a normal distribution and hence, maintains the integrity of statistical inference from a two-sample t-test. However, a slightly modified hypothesis results:

H_0: $\mu_{\sqrt{b}} = \mu_{\sqrt{e}}$

H_1: $\mu_{\sqrt{b}} > \mu_{\sqrt{e}}$

where $\mu_{\sqrt{b}}$ is the square root of the mean percentage of overweight commercial vehicles statewide during the baseline year and $\mu_{\sqrt{e}}$ is the square root of the mean percentage of overweight commercial vehicles during the enforcement year.

To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0, a p-value ≤ 0.05 (one-tailed) suggests rejecting H_0: $\mu_{\sqrt{b}} = \mu_{\sqrt{e}}$ and accepting H_1: $\mu_{\sqrt{b}} > \mu_{\sqrt{e}}$, the square root of the mean percentage of overweight commercial vehicles during the enforcement year is significantly less than the square root of the mean percentage of overweight commercial vehicles statewide during the baseline year.

F-Test for Variance Equality. The formulation of the two-sample t-test statistic required to determine the sample p-values and draw conclusions related to the hypothesis varies depending on whether or not the variances of the two samples are equal:

H_0: $\sigma^2_{\sqrt{b}} = \sigma^2_{\sqrt{e}}$

H_1: $\sigma^2_{\sqrt{b}} \neq \sigma^2_{\sqrt{e}}$

where $\sigma^2_{\sqrt{b}}$ is the variance of the transformed baseline year sample and $\sigma^2_{\sqrt{e}}$ is the variance of the transformed enforcement year sample.

Again, to achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0, a p-value ≤ 0.025 (two-tailed) suggests rejecting H_0: $\sigma^2_{\sqrt{b}} = \sigma^2_{\sqrt{e}}$ and accepting H$_1$: $\sigma^2_{\sqrt{b}} \neq \sigma^2_{\sqrt{e}}$, the variance of the transformed baseline year sample is not equal to the transformed sample collected during the enforcement year. Used to determine sample p-values, the F-test statistic is:

$$F = \frac{s^2_{\sqrt{b}}}{s^2_{\sqrt{e}}}$$

where $s_{\sqrt{b}}$ is the standard deviation of the transformed baseline year sample and $s_{\sqrt{e}}$ is the standard deviation of the transformed enforcement year sample. Table 3-5 summarizes the results of this test. With the sample p-value ≤ 0.025, H$_0$: $\sigma^2_{\sqrt{b}} = \sigma^2_{\sqrt{e}}$ is rejected, the variance of the transformed mean percentage of overweight commercial vehicles statewide during the baseline year is not equal to the variance of the transformed mean percentage of overweight commercial vehicles statewide during the enforcement year.

For unequal variances between the two samples, the two-sample t-test test statistic is:

$$t = \frac{\bar{x}_{\sqrt{b}} - \bar{x}_{\sqrt{e}}}{\sqrt{\frac{s^2_{\sqrt{b}}}{n_{\sqrt{b}}} + \frac{s^2_{\sqrt{e}}}{n_{\sqrt{e}}}}}$$

where $\bar{x}_{\sqrt{b}}$ and $\bar{x}_{\sqrt{e}}$ are the mean percentages of overweight commercial vehicles in the transformed baseline and enforcement year samples, $s_{\sqrt{b}}$ and $s_{\sqrt{e}}$ are the standard deviations of the transformed baseline and enforcement year samples and $n_{\sqrt{b}}$ and $n_{\sqrt{e}}$ are the total number of commercial vehicles in the transformed baseline and enforcement year samples, respectively.

With a resulting p-value ≤ 0.05, H$_0$: $\mu_{\sqrt{b}} = \mu_{\sqrt{e}}$ is rejected, the transformed mean percentage of overweight commercial vehicles during the enforcement year is significantly less than the transformed mean percentage of overweight commercial vehicles statewide during the baseline year (see Table 3-6).

Table 3-5. F-test for Variance Equality (two-tailed): Square Root-transformed Mean Percentage of Overweight Commercial Vehicles Statewide, Baseline versus Focused Enforcement Year

	Square Root Transformed Baseline Year	Square Root Transformed Enforcement Year
Number of Observations	146	146
Sample Standard Deviation	1.0519	0.693
Sample F Statistic		2.307
Sample p-value		0.000

Table 3-6. Two-sample t-test (one-tailed): Square Root-transformed Mean Percentage of Overweight Commercial Vehicles Statewide, Baseline versus Focused Enforcement Year

	Square Root Transformed Baseline Year	Square Root Transformed Enforcement Year
Number of Observations	146	146
Sample Mean	2.77	2.532
Sample Standard Deviation	1.05	0.693
Sample t Statistic		2.31
Sample p-value		0.011

Mann-Whitney Nonparametric Test. Recall that a second approach to investigating the significance of the change in the mean percentage of overweight commercial vehicles between the baseline and enforcement years when the normal distribution assumption is violated is to use a nonparametric test such as the Mann-Whitney Nonparametric Test. Unlike the two-sample t-test that compares the equality of two independent sample means, the Mann-Whitney Test compares the equality of two independent sample medians:

H_0: $\eta_b = \eta_e$

H_1: $\eta_b > \eta_e$

where η_b and η_e are the median percents of overweight commercial vehicles in the traffic stream during the baseline and enforcement years, respectively. This test requires that the two sample distributions have the same shape and spread, but they do not need to follow a prescribed probability distribution (Devore 1995).

With a resulting p-value ≤ 0.05 (one-tailed), H_0: $\eta_b = \eta_e$ is rejected, the median percentage of overweight commercial vehicles during the enforcement year is significantly less than the median percentage of overweight commercial vehicles statewide during the baseline year (see Table 3-7).

This finding is consistent with previous findings using the transformed data approach to explore the aggregate change in overweight commercial vehicle percentages between the baseline and enforcement years. Both approaches suggest that *STARS*-directed enforcement efforts, when considered on an annual and statewide basis, resulted in a significant overall reduction in overweight commercial vehicle activity.

Table 3-7. Mann-Whitney Nonparametric Test (one-tailed): Mean Percentage of Overweight Commercial Vehicles Statewide, Baseline versus Focused Enforcement Year

	Baseline Year	Enforcement Year
Number of Observations	146	146
Median	7.165	6.665
Sample W Statistic		22,636.5
Sample p-value		0.0419

3.3.3 Commercial Vehicle Weight Distributions

STARS-directed enforcement resulted in an increased proportion of weight-compliant vehicles and a decrease in the proportion of overweight vehicles in the traffic stream. This result might be expected, as more trips would be required to move the same volume of freight if the amount of freight carried per vehicle is reduced (i.e., on legal versus overweight vehicles). Evidence of this behavior is seen in the frequency distributions by weight for selected truck configurations for months with and without *STARS*-directed enforcement. As before, trends in overweight vehicle behavior across the enforcement year were studied relative to sites that were frequently selected for enforcement (enforced more than six months), sites that occasionally were selected for enforcement (enforced one to six months) and sites that were not enforced. For each of these categories of sites, comparisons of the weight distributions for Class 6, 9, 10, and 13 vehicles during the baseline and enforcement years are presented in Appendix C. Selected weight distributions are presented and discussed below. In all cases, the weight distributions presented in these figures were generated using the data from each site for the entire year (baseline or enforcement), independent of the specific *STARS* enforcement activities being performed.

STARS Sites with More Than Six Months of Focused Enforcement. As might be expected, at the sites subjected to frequent enforcement activities (Four Corners/Gallatin, Ryegate, Stanford and Townsend) and for the vehicle classes that were the focus of these activities, an obvious reduction occurred in the proportion of overweight vehicles in the traffic stream during the enforcement year. Correspondingly, the proportion of legal weight vehicles in the traffic stream increased. These effects are evident in Figure 3-11, which shows the weight distributions for Class 9 vehicles at frequently enforced sites during the baseline and enforcement years. In

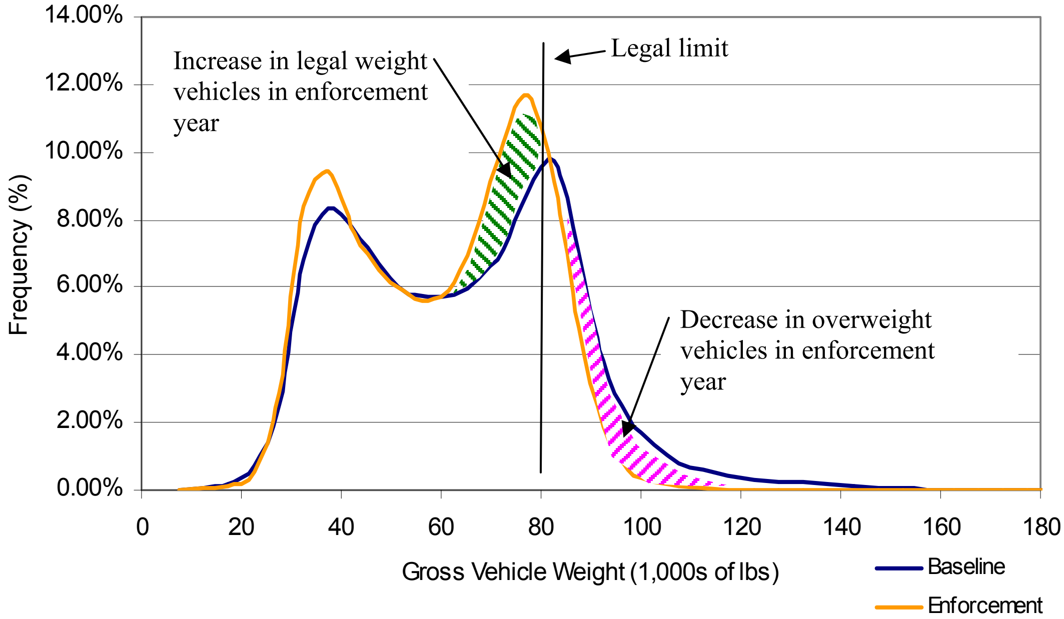


Figure 3-11. Class 9 Gross Vehicle Weight Distributions at **All *STARS* Sites with More than Six Months of Focused Enforcement**, Baseline and Focused Enforcement Year

general, as the proportion of overweight vehicles decreased, the proportion of vehicles operating close to, but below the legal load limit increased. This behavior suggests that the overweight vehicles were carrying divisible loads that could be relatively easily re-configured during enforcement periods to comply with legal load limits. Furthermore, the proportion of empty vehicles in the traffic stream also generally increased at the frequently enforced *STARS* sites during the enforcement year. This change suggests that more trips (with empty back hauls) were required during the enforcement year relative to the baseline year to accommodate the amount of freight to be moved. This situation is consistent with the idea that more trips are required to move the same amount of freight when weight-compliant versus overweight vehicles is used. Note that the trends discussed above were most pronounced for Class 9 and Class 13 vehicles and least pronounced for Class 10 vehicles.

The changes in the weight distributions described above to some extent suggest that the underlying population of overweight vehicles was primarily engaged in local (intrastate) rather than long distance (interstate) freight movements. That is, the increase in the relative proportion of empty trips as the proportion of legally loaded trips increased suggests that the enforcement activities were primarily affecting shorter trips, where empty back hauls are more common.

STARS Sites with One to Six Months of Focused Enforcement. At sites that were only occasionally selected for *STARS* enforcement (Arlee, Decker, Manhattan, Miles City East and Ulm), only nominal changes were observed in the weight distributions for the targeted vehicle classes between the baseline and enforcement years. To some extent, this situation supports the conclusion that the *STARS* enforcement activities only had limited residual effects on loading behaviors. That is, if the residual enforcement effects were significant, even a few months of enforcement activity would have been expected to have a noticeable effect on the vehicle weight distributions developed from the data for the entire year. The only pronounced difference in weight distributions for the sites occasionally selected for *STARS* enforcement was for Class 9 vehicles (see Figure 3-12). The weight distributions for these vehicles do show a reduction in the proportion of overweight vehicles in the traffic stream in the enforcement versus the baseline year, although the reduction is not as pronounced as for the frequently enforced *STARS* sites.

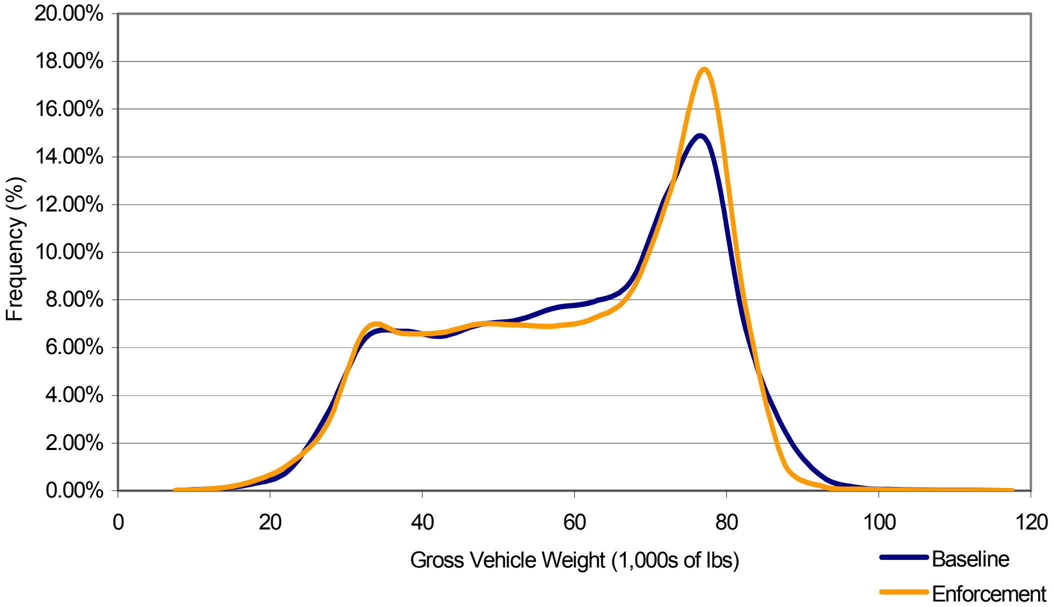


Figure 3-12 Class 9 Gross Vehicle Weight Distributions at **All *STARS* Sites with One to Six Months of Focused Enforcement**, Baseline and Focused Enforcement Year

STARS* *Sites not Selected for Focused Enforcement. Similar to the sites that were only occasionally selected for *STARS* enforcement, the weight distributions for the vehicles operating at sites not selected for enforcement (Broadview, Culbertson, Fort Benton, Galen, Havre East, Lima and Paradise) generally remained unchanged in the baseline and enforcement years. The weight distributions for the Class 9 vehicles actually show an increase in the proportion of overweight vehicles in the traffic stream during the enforcement year relative to the baseline year for this category of site (see Figure 3-13). This result supports the concern that overweight vehicle activity may have actually increased at some *STARS* locations during the enforcement year, as the available resources for enforcement were focused on a few critical sites, and some sites experienced less enforcement activity than in the baseline year.

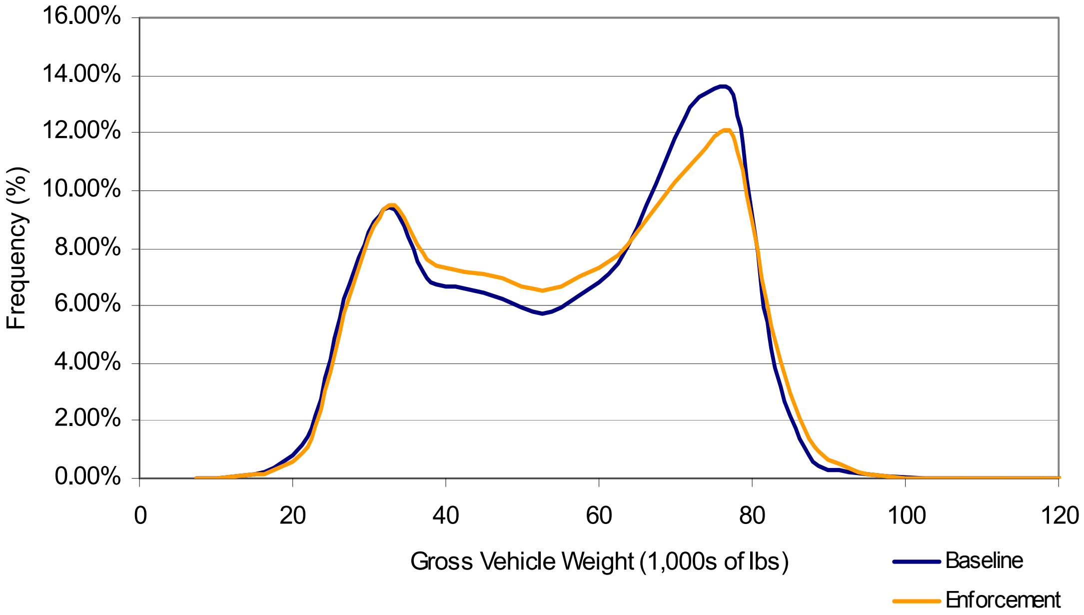


Figure 3-13 Class 9 Gross Vehicle Weight Distributions at **All *STARS* Sites not Selected for Focused Enforcement**, Baseline and Focused Enforcement Year

3.3.4 Average Commercial Vehicle Weight Exceedance

In addition to a noted reduction in the percentage of overweight commercial vehicles in the traffic stream under *STARS*-directed enforcement, a reduction in the average amount of the weight exceedance carried by these vehicles was also observed. In the baseline year, the average amount by which an overweight vehicle exceeded legal weight limits was 6,100 pounds; during the *STARS* enforcement year, this average exceedance decreased by more than 16 percent to 5,100 pounds. Trends with respect to where and when these reductions were realized closely paralleled the reduction in the proportion of overweight commercial vehicles in the traffic stream reported previously.

3.3.5 Statistical Confirmation of the Change in Commercial Vehicle Weight Exceedance

Two-sample t-test. A two-sample t-test was conducted to statistically confirm whether or not the statewide mean commercial vehicle legal weight exceedance significantly decreased between the baseline and enforcement years:

H_0: $\mu_b = \mu_e$

H_1: $\mu_b > \mu_e$

where μ_b and μ_e are the mean amount of legal weight exceedance statewide during the baseline and enforcement years, respectively. As with previous statistical analyses, questionable data due to WIM equipment failure or malfunction was removed from consideration.

Violation of the normal distribution assumption was once again problematic in conducting the two-sample t-test. To overcome this violation, the baseline and enforcement year samples were mathematically transformed by taking the logarithm of each individual weight exceedance observation. This transformation proved successful; the logarithm transformation of the baseline and enforcement mean overweight values achieved normally distributed data sets. In each case using the Kolmogorov-Smirnov Test for Normality, a p-value > 0.025 (two-tailed) confirmed that the mean amount of legal weight exceedance, in both the baseline year and the enforcement year, is normally distributed.

Though the data transformation maintains the integrity of statistical inference from a two-sample t-test, a slightly modified hypothesis results:

H_0: $\mu_{\log b} = \mu_{\log e}$

H_1: $\mu_{\log b} > \mu_{\log e}$

where $\mu_{\log b}$ and $\mu_{\log e}$ are the logarithm of the mean amount of legal weight exceedance statewide during the baseline and enforcement years, respectively.

To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0, a p-value ≤ 0.05 (one-tailed) suggests rejecting H_0: $\mu_{\log b} = \mu_{\log e}$ and accepting H_1: $\mu_{\log b} > \mu_{\log e}$, the logarithm of the mean amount of legal weight exceedance statewide during the enforcement year is significantly less than the logarithm of the mean amount of legal weight exceedance statewide during the baseline year.

F-Test for Variance Equality. The formulation of the two-sample t-test statistic required to determine the sample p-values and draw conclusions related to the hypothesis varies depending on whether or not the variances of the two samples are equal:

H$_0$: $\sigma^2_{\log b} = \sigma^2_{\log e}$

H$_1$: $\sigma^2_{\log b} \neq \sigma^2_{\log e}$

where $\sigma^2_{\log b}$ is the variance of the transformed baseline year sample and $\sigma^2_{\log e}$ is the variance of the transformed enforcement year sample.

Again, to achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H$_{0,}$ a p-value ≤ 0.025 (two-tailed) suggests rejecting H$_0$: $\sigma^2_{\log b} = \sigma^2_{\log e}$ and accepting H$_1$: $\sigma^2_{\log b} \neq \sigma^2_{\log e}$, the variance of the transformed baseline year sample is <u>not</u> equal to the transformed sample collected during the enforcement year. Used to determine sample p-values, the F-test statistic is:

$$F = \frac{s^2_{\log b}}{s^2_{\log e}}$$

where $s_{\log b}$ is the standard deviation of the transformed baseline year sample and $s_{\log e}$ is the standard deviation of the transformed enforcement year sample. Table 3-8 summarizes the results of this test. With the sample p-value ≤ 0.025, H$_0$: $\sigma^2_{\log b} = \sigma^2_{\log e}$ is rejected, the variance of the transformed mean percentage of overweight commercial vehicles statewide during the baseline year is <u>not</u> equal to the variance of the transformed mean percentage of overweight commercial vehicles statewide during the enforcement year.

For unequal variances between the two samples, the two-sample t-test test statistic is:

$$t = \frac{\bar{x}_{\log b} - \bar{x}_{\log e}}{\sqrt{\frac{s^2_{\log b}}{n_{\log b}} + \frac{s^2_{\log e}}{n_{\log e}}}}$$

where $\bar{x}_{\log b}$ and $\bar{x}_{\log e}$ are the mean legal weight exceedance amounts in the transformed baseline and enforcement year samples, $s_{\log b}$ and $s_{\log e}$ are the standard deviations of the transformed baseline and enforcement year samples and $n_{\log b}$ and $n_{\log e}$ are the total number of commercial vehicles in the transformed baseline and enforcement year samples, respectively.

With a resulting p-value > 0.05 (one-tailed), H$_0$: $\mu_{\log b} = \mu_{\log e}$ is accepted, the transformed mean amount of legal weight exceedance statewide during the enforcement year is <u>not</u> significantly different than the transformed mean amount of legal weight exceedance statewide during the baseline year (see Table 3-9). This finding changes if lower levels of confidence are assumed; at the 88th percent confidence level (p-value = 0.117), the difference in mean legal weight exceedance amounts between the baseline and enforcement years becomes significant.

Table 3-8. F-test for Variance Equality (two-tailed): Logarithm-transformed Mean Amount of Overweight Commercial Vehicle Exceedance Statewide, Baseline versus Focused Enforcement Year

	Logarithm Transformed Baseline Year	Logarithm Transformed Enforcement Year
Number of Observations	158	179
Sample Standard Deviation	0.191	0.146
Sample F Statistic		1.698
Sample p-value		0.001

Table 3-9. Two-sample t-test (one-tailed): Logarithm-transformed Mean Amount of Overweight Commercial Vehicle Exceedance Statewide, Baseline versus Focused Enforcement Year

	Logarithm Transformed Baseline Year	Logarithm Transformed Enforcement Year
Number of Observations	158	179
Sample Mean	0.744	0.715
Sample Standard Deviation	0.191	0.146
Sample t Statistic		1.57
Sample p-value		0.117

3.4 Changes in Pavement Preservation

The *STARS*-directed enforcement activities were scheduled based on the objective of minimizing the pavement damage caused by overweight vehicles. The success of these activities in achieving this objective was determined by comparing the pavement damage caused by all vehicles during the enforcement year with the pavement damage caused by all vehicles during the baseline year. As was done in prioritizing the focused enforcement activities, pavement damage was calculated using the AASHTO ESAL approach. A cost was assigned against the change in pavement damage between the baseline and enforcement years based on the fundamental cost to the state of constructing and maintaining the highway system.

Pavement damage attributable to overweight vehicles was found to decrease by 6-million ESAL-miles statewide during the enforcement year. This change in ESAL-miles of damage corresponds to a pavement cost of approximately $700,000. In arriving at these results, it was critical to identify those changes in pavement demands related to overweight vehicle operations that could be specifically attributed to the *STARS*-directed enforcement activities. Notably, traffic volumes vary from year-to-year, in response to the amount of freight that has to be moved in any given year. Correspondingly, the number of overweight vehicles involved in moving this freight changes from year-to-year, independent of any enforcement related activities. Ideally, to eliminate this confounding factor from the evaluation, the total volume of freight moved on the highway system should have been held constant during the baseline and enforcement years, so that the only variable between the two years was the percent of overweight vehicles in the traffic stream that hauled this freight.

Naturally, it was impossible to actually control the amount of freight moved on the highway system, so the effect of this variable had to be analytically removed from the evaluation. To neutralize the effect of this confounding factor, the traffic volume in the baseline year was adjusted by a factor designed to account for the differences in the basic amount of freight that was moved on the highway system between the baseline and enforcement years. The magnitude of this factor was primarily driven by the relative volume of traffic observed in each of these two years, with due consideration of the relative proportion of overweight vehicles in the traffic stream in each of the two years, as well as the average amount of overweight carried on these vehicles. Thus, for example, the magnitude of this adjustment factor increased as any one of the parameters of traffic volume, proportion of overweight vehicles in the traffic stream and the average amount of overweight carried by these vehicles increased in the enforcement year relative to the baseline year.

Viewed from a slightly different perspective, the above adjustment made it possible to calculate the pavement damage that would have occurred during the enforcement year under traditional enforcement conditions (that is, the pre-*STARS* enforcement traffic conditions during the baseline year). To evaluate the impact of *STARS*, this "baseline" pavement damage was subtracted from that which was actually experienced under *STARS* focused enforcement year during the enforcement year.

Note that ESAL calculations for this part of the analysis were performed using data from load spectrum reports from each *STARS* site, instead of data obtained directly from the *MEARS* reports. The change in ESALs at each site from the baseline to the enforcement year was calculated as the difference between the total ESALS from each year, with due consideration of the adjustments discussed above. The change in ESALs at each site was subsequently multiplied by the estimated length of highway (from Table 3-3) whose operations were affected by enforcement at that site, to obtain a measure of pavement damage in ESAL-miles. Finally, this pavement damage was multiplied by a unit cost factor to obtain a total cost impact.

3.4.1 Pavement Damage

Relative to the baseline year, pavement damage decreased by 6 million ESAL-miles during the year of *STARS*-directed enforcement. Changes in pavement damage by site and month as a function of *STARS*-directed enforcement activities (i.e., sites with more than six months, one to six months and without any focused enforcement) are described below. In general, the trends observed in changes in pavement damage as a function of *STARS* enforcement activities mirror the trends observed in the changes in the proportion of overweight vehicles in the traffic stream. Complete results by month and by site are reported graphically in Appendix D; a sample of the most illustrative sites are presented and discussed below. Detailed analyses of the statistical significance of these changes in pavement damage were not performed on a site-by-site and month-by-month basis. Notably, the statistical significance of the underlying changes in the proportion of overweight vehicles in the traffic stream in the baseline versus the enforcement year has already been established.

STARS Sites with More Than Six Months of Focused Enforcement. The four *STARS* sites with seven or more months of focused enforcement (Four Corners/Gallatin, Ryegate, Stanford and Townsend) clearly show the most dramatic reductions in pavement damage when compared to all other *STARS* sites. The change in pavement damage as a function of month and enforcement activity at the Four Corners/Gallatin, Ryegate and Stanford sites are presented in Figures 3-14, 3-15 and 3-16, respectively. Referring to these figures, those months with the most significant decreases in pavement damage generally correspond to months of *STARS*-directed enforcement. The changes in magnitude of the reductions in pavement damage at each site each month generally parallel changes in the volume of traffic at each site each month. Similar to the

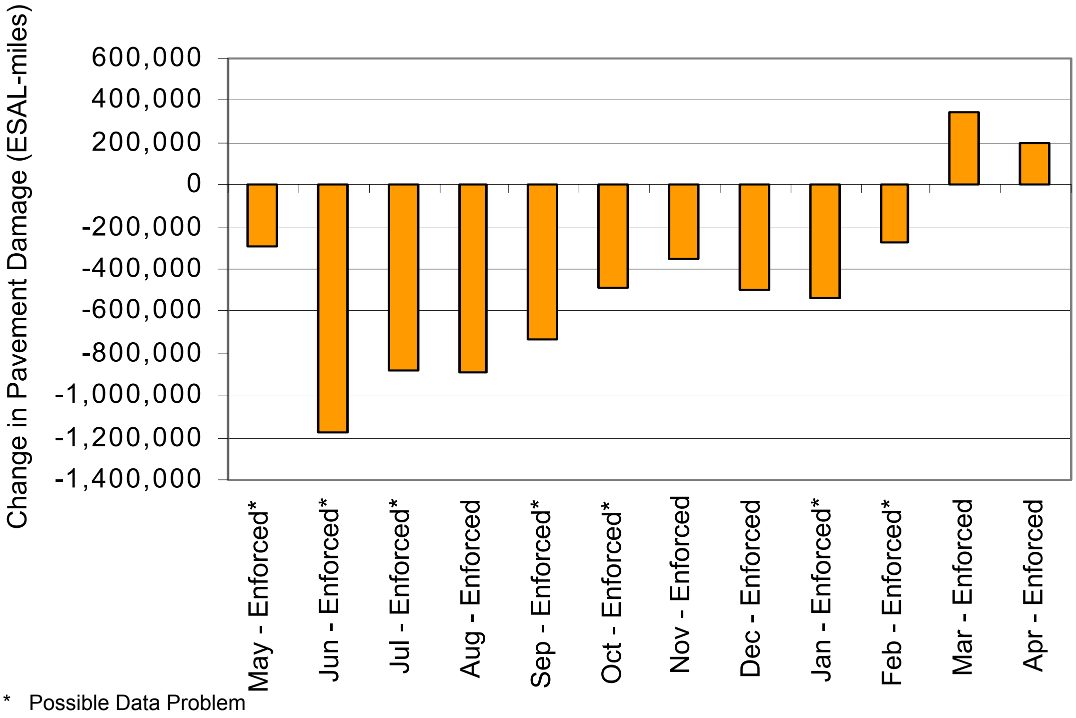


Figure 3-14. Change in Pavement Damage for the **Four Corners/Gallatin** *STARS* Site, Baseline to Focused Enforcement Year

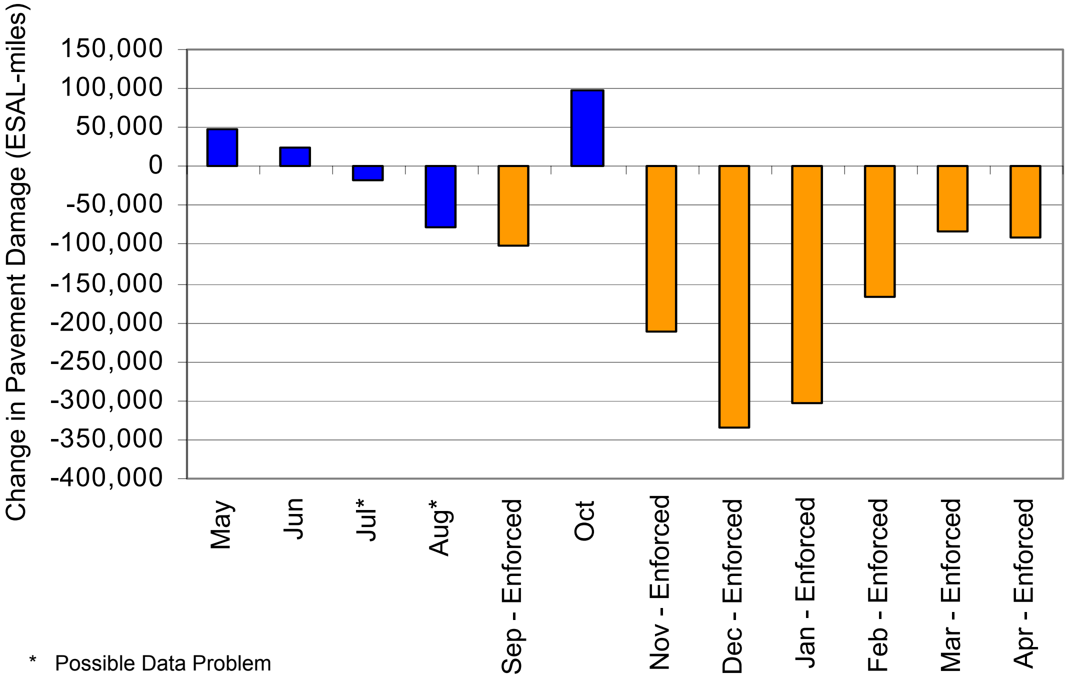


Figure 3-15. Change in Pavement Damage for the **Ryegate** *STARS* Site, Baseline to Focused Enforcement Year

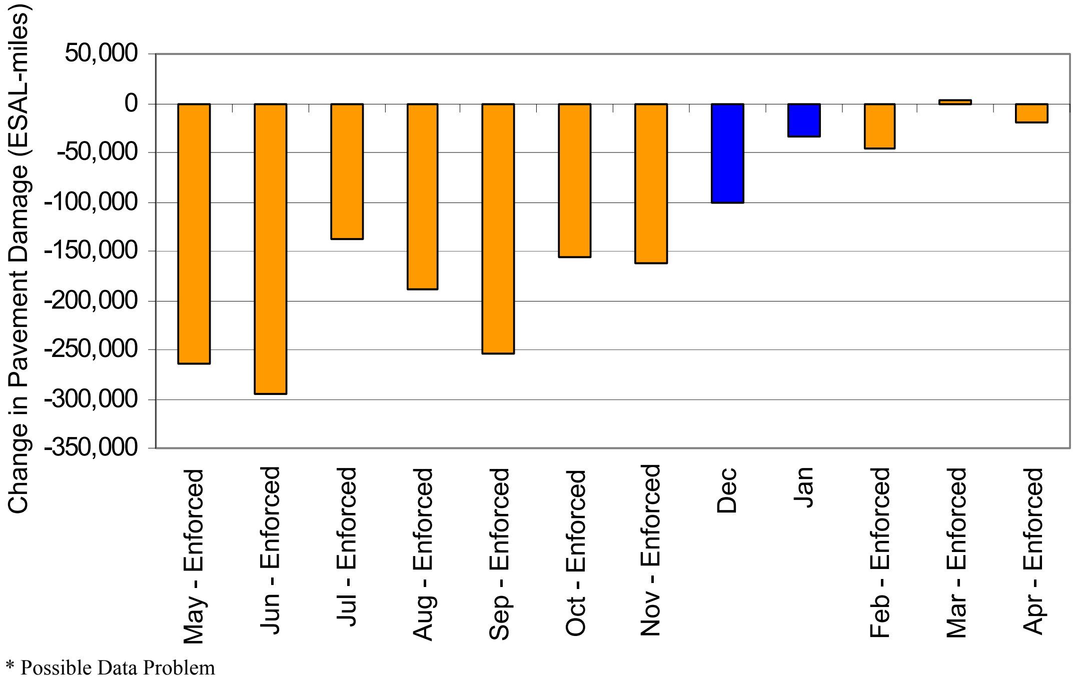


Figure 3-16. Change in Pavement Damage for the **Stanford** *STARS* Site, Baseline to Focused Enforcement Year

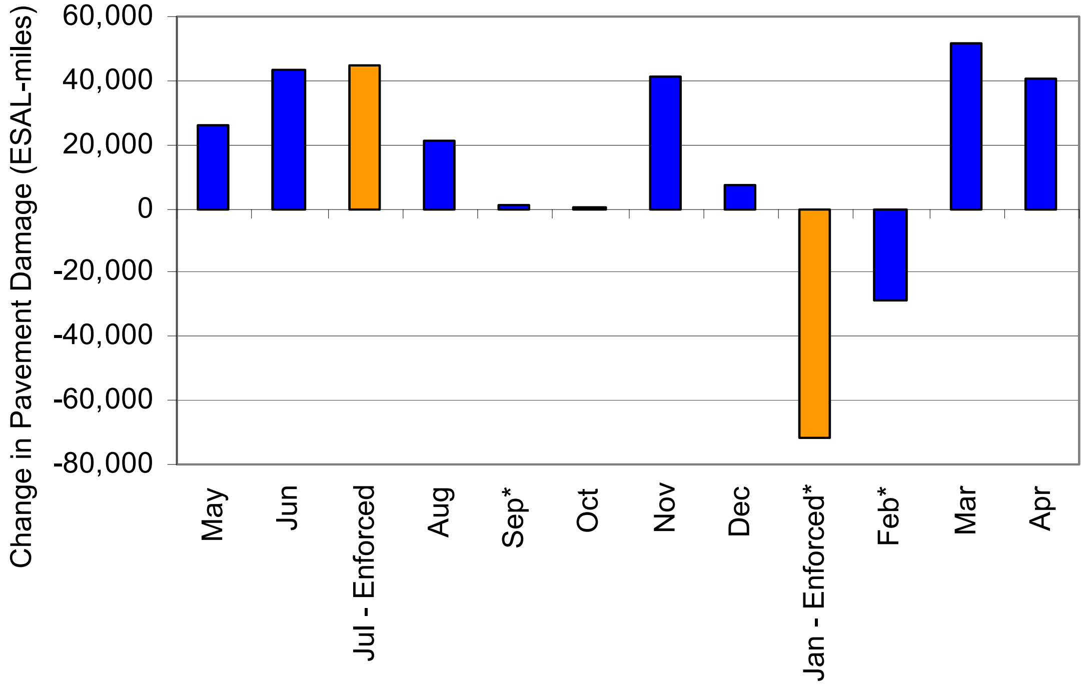
trend seen in the proportion of overweight vehicles in the traffic stream, an unexpected increase in pavement damage is seen in the last two months of focused enforcement (March and April 2002) at the Four Corners/Gallatin site. This behavior, observed at a few other sites, may again be related to a relaxation in enforcement effort toward the end of the evaluation, as well as a reduction in available enforcement resources due to an unanticipated staffing shortage.

In reviewing performance at the various sites, once again, the trend at Ryegate is worth noting (see Figure 3-15). A decrease in pavement damage occurred during the enforcement month of September followed by the opposite result in the non-enforced month of October. In the following months, when focused enforcement was resumed, another dramatic decrease in pavement damage occurred. At the Stanford site (see Figure 3-16), the non-enforced months of December and January show a potential residual effect of the *STARS* program; there is a continued decrease in pavement damage following several months of focused enforcement.

STARS Sites with One to Six Months of Focused Enforcement. *STARS* sites that had one to six months of focused enforcement include Arlee, Decker, Manhattan, Miles City East and Ulm. As might be expected, the effect of the pilot program on pavement damage from overweight vehicles are less pronounced at these sites with fewer months of focused enforcement, although the trend of decreasing pavement damage with *STARS* enforcement activity is still evident.

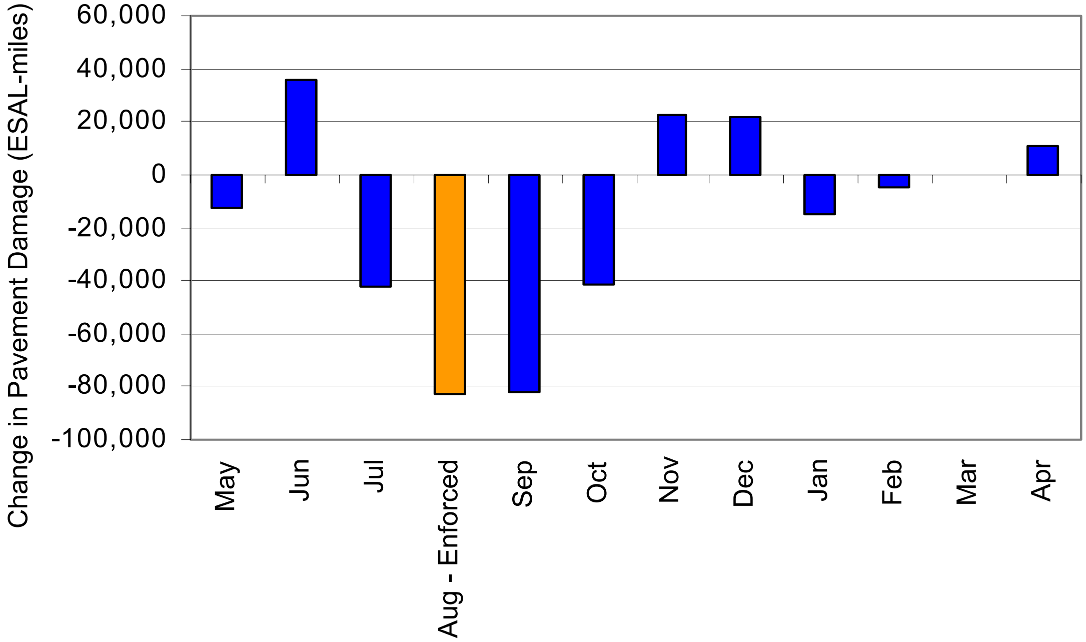
Noted reductions in pavement damage, for example, occurred during the focused enforcement months of January at the Arlee site (Figure 3-17) and August at the Miles City East site (Figure 3-18). An increase in pavement damage is seen, however, during the focused enforcement month of July at the Arlee site. At both the Arlee and Miles City East sites there is evidence of residual enforcement effects, namely, during the non-enforced month of February at Arlee and the non-enforced months of September and October at Miles City East, although at these and other sites there are an equal number of examples when no residual effects were evident.

STARS Sites Not Selected for Focused Enforcement. Broadview, Culbertson, Fort Benton, Galen, Havre East, Lima and Paradise were sites included in the *STARS* program, but that were never selected for focused enforcement. It is difficult to discern consistent trends in the changes



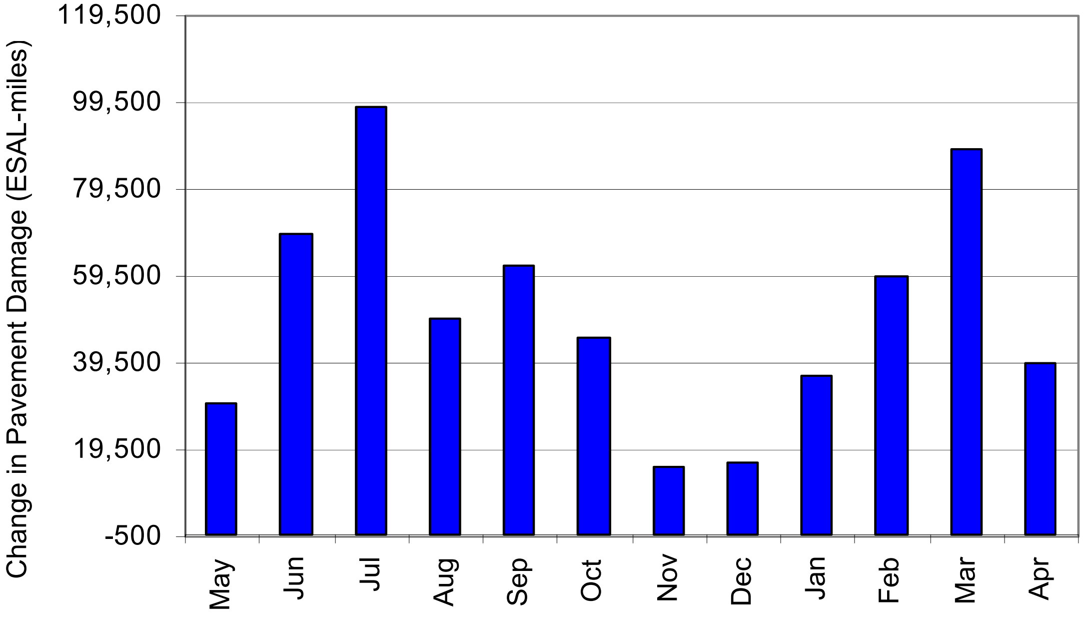
* Possible Data Problem

Figure 3-17. Change in Pavement Damage for the **Arlee** *STARS* Site, Baseline to Focused Enforcement Year



* Possible Data Problem

Figure 3-18. Change in Pavement Damage for the **Miles City East** *STARS* Site, Baseline to Focused Enforcement Year in the pavement damage from overweight vehicles at these sites. At two of these sites, Broadview and Fort Benton, pavement damage did increase every month during the enforcement year (the change in pavement damage at Broadview is shown in Figure 3-19). As previously mentioned, one explanation for this situation is that these sites received less attention during the enforcement year relative to the baseline year, as enforcement resource was redirected to higher priority sites under the *STARS* program. In evaluating the significance of this situation, it is important to note the relative magnitude of this increase in pavement damage compared to the decreases in pavement damage observed at other enforced sites. At the non-enforced site at Broadview, for example, the maximum increase in monthly pavement damage was approximately 2,000 ESALs (see Figure 3-19). At the frequently enforced site of Ryegate, the maximum monthly decrease in pavement damage during an enforced month was over 7,000 ESALs (see Figure 3-15).



* Possible Data Problem

Figure 3-19. Change in Pavement Damage for the **Broadview** *STARS* Site, Baseline to Focused Enforcement Year

At many of the non-enforced sites, no distinct pattern was seen in the change in pavement from overweight vehicles in the enforcement versus the baseline year. The change in pavement damage at Paradise presented in Figure 3-20 is typical of the response observed at these sites, with approximately an equal number of months experiencing increases and decreases in pavement damage.

Changes in Pavement Damage Statewide. As previously stated, avement damage from overweight vehicles statewide decreased by 6 million ESAL-miles as a result of the *STARS*-directed enforcement effort. The changes in pavement damage observed in the enforcement year across all the sites are presented in Figure 3-21. These results represent to a large extent the simple accumulation of the results by site and by month as presented above. In calculating the combined results across the entire year, however, adjustments were made to account for problems with the data at some of the sites (months with problem data are identified on the pavement damage figures presented in Appendix D). An algorithm was developed to

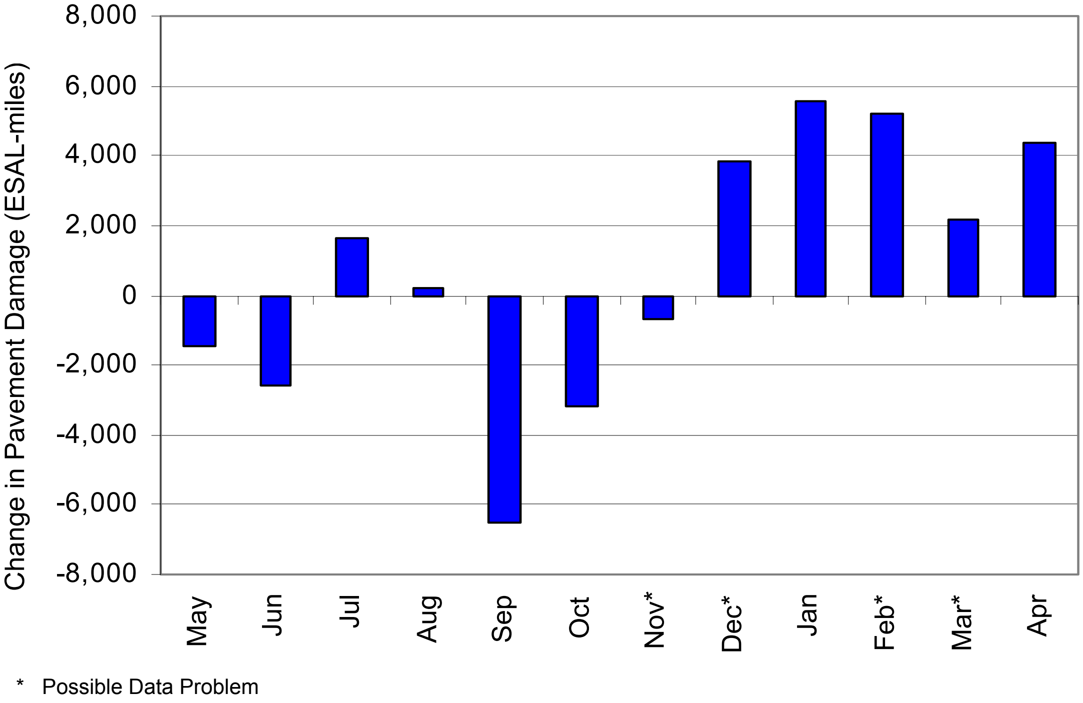


Figure 3-20. Change in Pavement Damage for the **Paradise** *STARS* Site, Baseline to Focused Enforcement Year

extrapolate pavement damage during periods for which no useful WIM data was available using data from contiguous time intervals. Note that across all the evaluation sites, useable data was available for 75 and 82 percent of the baseline and enforcement years, respectively.

Referring to Figure 3-21, those sites most often selected for focused enforcement (Four Corners/Gallatin, Ryegate, Stanford and Townsend) are among the sites with the greatest reductions in ESAL-miles of pavement damage. Some of the sites that were not selected for focused enforcement also show a decrease in pavement damage from the baseline year to the enforcement year (notably, Havre East and Lima). As previously stated, confounding factors such as short-term, non-recurring construction activities during the baseline year may offer explanation of this phenomenon.

Statewide changes in pavement damage from overweight vehicles in the baseline versus the enforcement year are presented by month in Figure 3-22. Pavement damage decreased every month except March and April. As previously mentioned, the results from March and April could reflect an unintentional relaxation in enforcement effort as the *STARS* pilot program. These results may also have been influenced by the reduction in enforcement resources available for *STARS* in these two months.

Changes in Pavement Damage by Vehicle Configuration. An analysis of the change in pavement damage as a function of vehicle class found that over 90 percent of the reduction in pavement damage was attributable to Class 9, 10, and 13 vehicles, which were the vehicles most frequently selected for focused enforcement.

3.4.2 Pavement Cost

The cost associated with the statewide reduction in pavement damage from overweight vehicles was calculated to be $700,000. Costs were assigned against the changes in pavement damage before and following *STARS* implementation based on the fundamental cost to the state of constructing and maintaining the highway system. Highways are designed and built to withstand, among other things, a certain number of ESALs. Thus, a cost can be established for

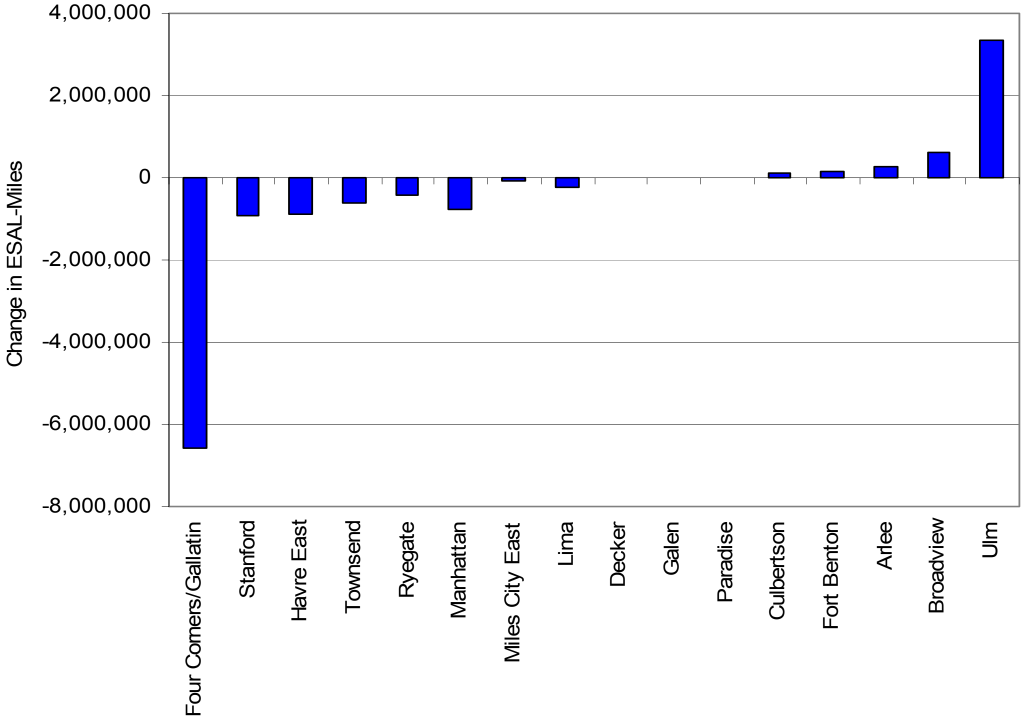


Figure 3-21. Total Change in Pavement Damage by Site, Baseline to Focused Enforcement Year

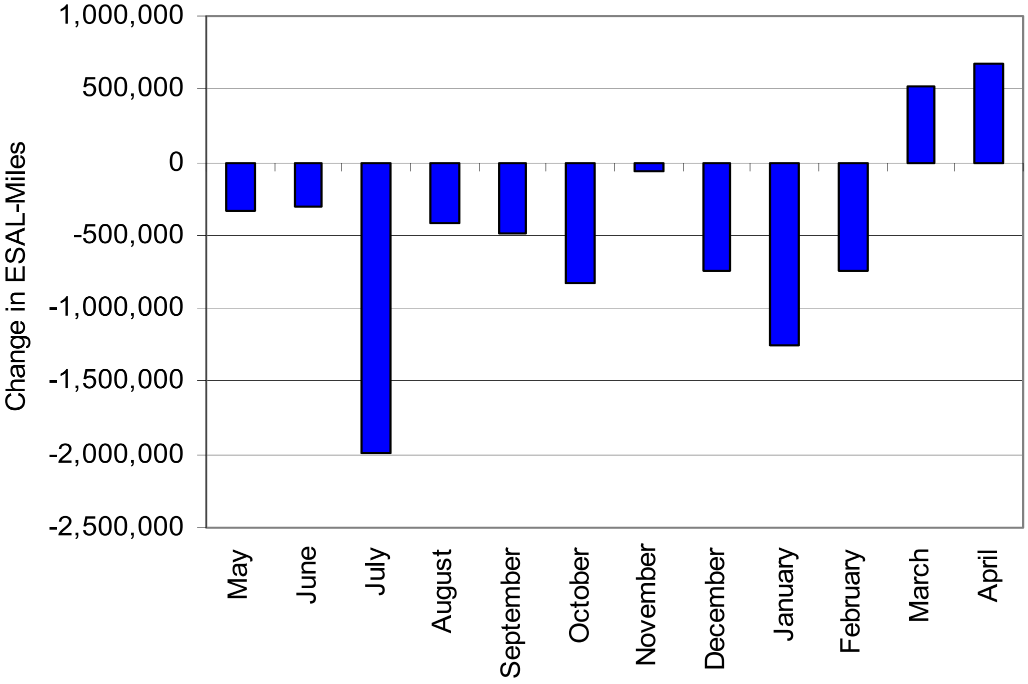


Figure 3-22. Statewide Change in Pavement Damage by Month, Baseline to Focused Enforcement Year

each ESAL that a highway is expected to carry. This cost was estimated from the results of a cost allocation study for the Montana highway system completed by Stephens and Menuez (2000).

The total ESAL-miles of highway use reported in that study over a three-year period was divided by the pavement expenditures to obtain the cost of providing highway service in dollars per ESAL per mile for each highway system (e.g., Interstate, Primary, Secondary, etc.) in the state. The resulting costs were subsequently adjusted for inflation (results reported in Stephens and Menuez (2000) covered 1994 to 1996), to obtain costs ranging from \$0.05/ESAL/mile to \$0.31/ESAL/mile for the year 2000-2001, depending on the type of highway system. The appropriate unit cost at each site was subsequently multiplied by the change in total ESALs at the site from the baseline year to the enforcement year and by the estimated length of highway (from Table 3-3) whose operations were affected by enforcement at the site to obtain the cost impact.

The costs assessed against the reduction in pavement damage from overweight vehicles that resulted from the *STARS* focused enforcement effort are reported statewide by *STARS* site and by month of the year in Figures 3-23 and 3-24, respectively. As would be expected, these cost values closely parallel the underlying change in pavement damage by site and month, as reported in Figures 3-21 and 3-22, respectively. Referring to Figure 3-23, the *STARS* sites that were frequently enforced are among the sites with the greatest cost savings. Cost savings were realized across the entire enforcement year, with the exception of the months of March and April (see Figure 3-24), for reasons previously discussed.

Pavement Preservation Impacts Summary. As reported in Figure 3-25, pavement damage decreased by 6-million ESAL-miles between the baseline and enforcement years, with the majority of this change attributable to *STARS* enforced sites. Correspondingly, the cost savings associated with this change in pavement damage is again primarily attributable to the *STARS* enforced sites. The cost associated with this change in pavement damage was approximately \$700,000. During non-enforcement months, a slight increase in total pavement damage (approximately 750,000 ESAL-miles) and a decrease in related cost savings (approximately \$55,000) occurred in the enforcement versus the baseline year.

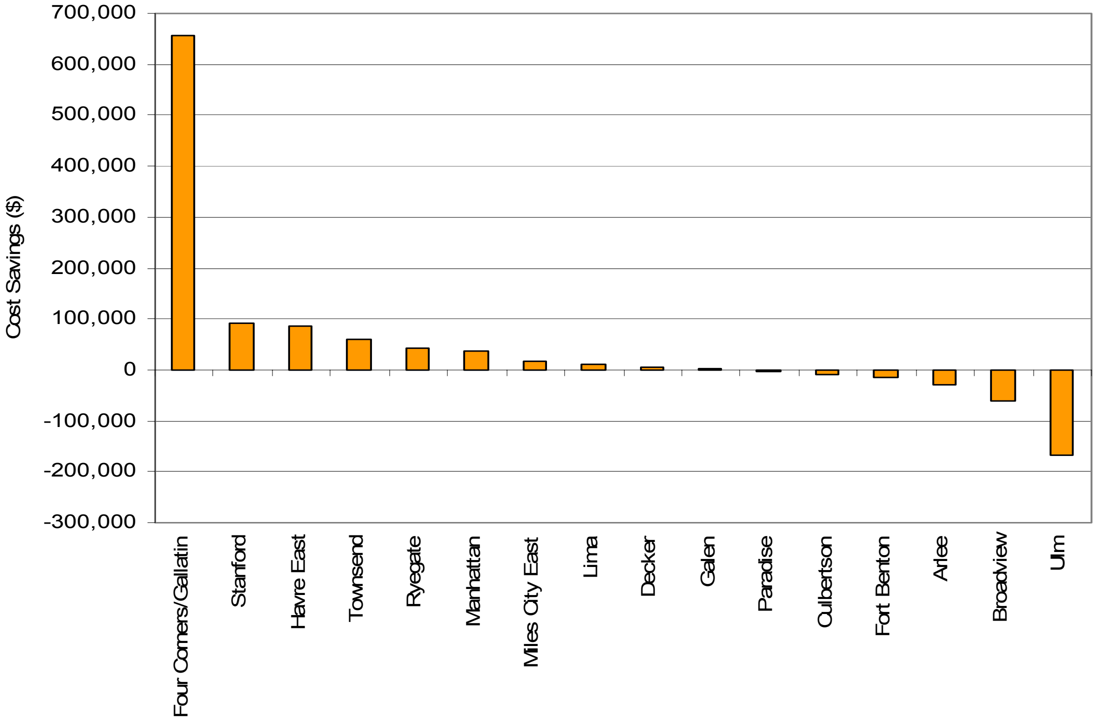


Figure 3-23. Total Cost Savings by Site, Baseline to Focused Enforcement Year

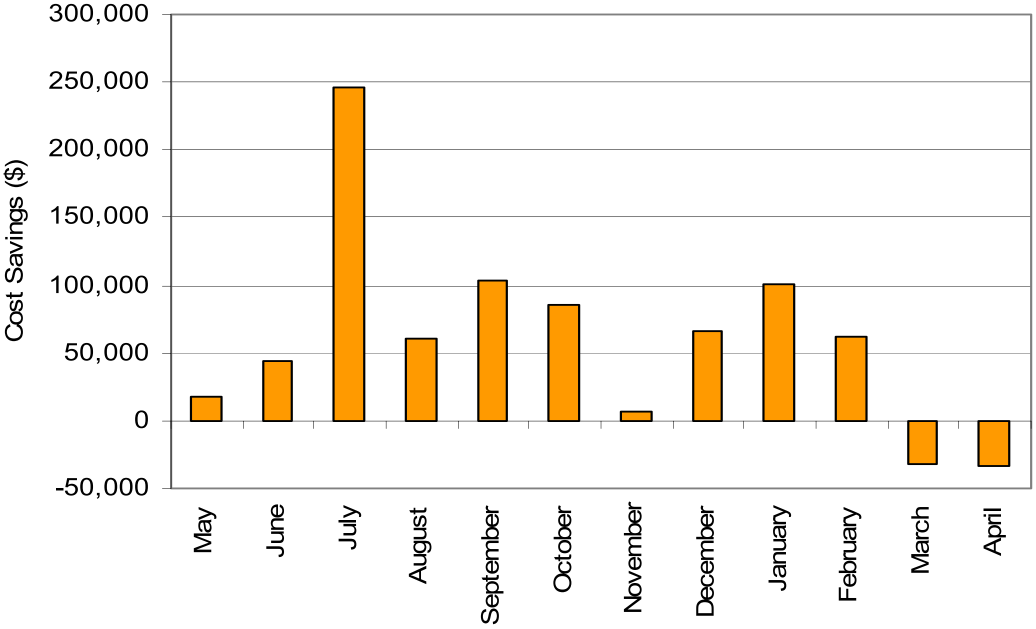


Figure 3-24. Statewide Cost Savings by Month, Baseline to Focused Enforcement Year

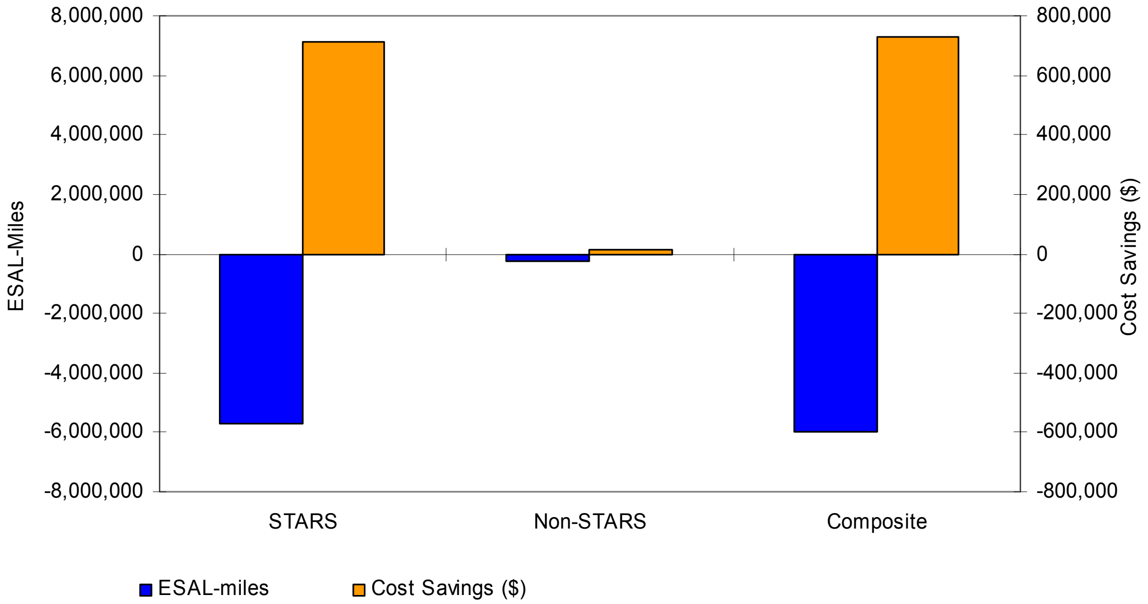


Figure 3-25. Change in Pavement Damage and Related Cost Savings Statewide, Baseline to Focused Enforcement Year

3.5 Influence of Bypass/Avoidance Activities on the Evaluation

In evaluating the effectiveness of *STARS*-directed enforcement, the possibility that reductions in overweight vehicle operations at focused enforcement sites might have been due to enforcement avoidance was also considered. Two types of avoidance strategies were considered: (1) traveling before or after scheduled enforcement activities during the day (enforcement activities typically only ran for eight hour periods, and these periods were often scheduled at the same time each enforcement day) and (2) using an alternate route to bypass the enforcement activity.

Parking and waiting for the *STARS* enforcement effort to end before resuming travel is suspected to have occurred during the enforcement year. The MCS mobile patrol officer at one site, for example, reported that on several days the frequent and normal vehicle activity declined when she began her scheduled enforcement activity. In this case, the officer was allowed to adjust the eight-hour window of scheduled enforcement within the day to better respond to these dynamic changes in vehicle operations. Note that while this action may have allowed her to be more effective, enforcement avoidance of this kind did not affect accurate evaluation of the focused enforcement effort. That is, effects of vehicles that ran overweight at off times to avoid enforcement activities were still captured in the WIM data, and their negative effect on enforcement effectiveness was accounted for in the evaluation process.

Use of alternate routes by overweight commercial vehicles to avoid focused enforcement activities could however bias the *STARS* evaluation. That is, the absence of these vehicles from the traffic stream would appear to reduce overweight vehicle operations, while in reality, these operations simply shifted to unmonitored routes. Note, with respect to bypass concerns, (1) MCS patrol officers devote a fixed percent of their normal enforcement time to combating bypass activities, and (2) practical bypass routes are not readily available in Montana due to mountainous conditions and seasonal considerations. Nonetheless, efforts were made to monitor activity on possible bypass routes using portable classifier and WIM equipment during some of the focused enforcement activities. In all cases, no substantial bypass activity could be detected; traffic volumes captured using portable WIM systems did not change significantly during periods of focused enforcement.

3.6 Changes in Citation Issuance

While not the primary focus of this investigation, a limited examination was made of statewide citation issuance activity during the baseline year and the year of *STARS*-directed enforcement. This examination found that there was not a statistically significant change in citation issuance between the baseline and enforcement years.

3.6.1 Statistical Investigation of the Change in Citation Issuance

Two-sample t-test. To statistically investigate the change in citations issued from the baseline year to the enforcement year, a two-sample t-test was again conducted.

H_0: $\mu_b = \mu_e$

H_1: $\mu_b > \mu_e$

where μ_b and μ_e are the mean number of citations per 100 hours worked per quarter during the baseline and enforcement years, respectively. Note that citation issuance was quantified in terms of the total number of citations per 100 hours worked by quarter for both years based on data reported by MCS.

To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H_0, a p-value ≤ 0.05 (one-tailed) suggests rejecting H_0: $\mu_b = \mu_e$ and accepting H_1: $\mu_b > \mu_e$, the mean number of citations per 100 hours worked per quarter during the enforcement year is significantly less than the mean number of citations per 100 hours worked per quarter during the baseline year.

F-test for Variance Equality. The F-test for Variance Equality was again performed to determine the appropriate formulation of the two-sample t-test test statistic:

H_0: $\sigma_b^2 = \sigma_e^2$

H_1: $\sigma_b^2 \neq \sigma_e^2$

where σ_b^2 and σ_e^2 are the variances of baseline and enforcement year data, respectively.

A p-value ≤ 0.025 (two-tailed) suggests rejecting H_0: $\sigma_b^2 = \sigma_e^2$ and accepting H_1: $\sigma_b^2 \neq \sigma_e^2$, the variance of the number of citations per 100 hours worked per quarter during the baseline year is <u>not</u> equal to the variance of the number of citations per 100 hours worked per quarter during the enforcement year. Used to determine sample p-values, the F-test statistic is:

$$F = \frac{s_b^2}{s_e^2}$$

where s_b is the standard deviation of the baseline year sample and s_e is the standard deviation of the enforcement year sample. Table 3-10 summarizes the results of this test. With the sample p-value > 0.025, H_0: $\sigma_{\sqrt{b}}^2 = \sigma_{\sqrt{e}}^2$ is rejected, the variance of the baseline year data is <u>not</u> equal to the variance of the enforcement year data.

Table 3-10. F-test for Variance Equality (two-tailed): Citation Issuance, Baseline versus Focused Enforcement Year

	Baseline Year	Enforcement Year
Mean (Citations/100 hrs.)	2.27	1.44
Variance	0.22	0.50
Observations	3	3
Sample F-statistic		0.44
p-value		0.31

For unequal variances between the two samples, the two-sample t-test statistic is:

$$t = \frac{\bar{x}_b - \bar{x}_e}{\sqrt{\frac{s_b^2}{n_b} + \frac{s_e^2}{n_e}}}$$

where $\bar{x}_b$ and $\bar{x}_e$ are the mean number of citations per 100 hours worked per quarter in the baseline and enforcement year, s_b and s_e are the standard deviation of the baseline and enforcement year data, and $n_b = n_e = 4$, representing the number of quarters in the baseline and enforcement years.

Again, with a resulting p-value > 0.05, H_0: $\mu_b = \mu_e$ is accepted, the mean number of citations per 100 hours worked per quarter during the baseline year and the enforcement year is <u>not</u> significantly different (see Table 3-11). The difference in the number of citations issued between baseline and enforcement years was not statistically significant.

Table 3-11. Two-sample t-test (one-tailed): Citation Issuance, Baseline versus Focused Enforcement Year

	Baseline Year	Enforcement Year
Mean (Citations/100 hrs.)	2.27	1.44
Variance	0.22	0.50
Observations	3	3
Sample t-statistic		1.68
p-value		0.19

4 PAVEMENT DESIGN IMPACTS

In addition to investigating the impact of *STARS* on preserving the existing highway infrastructure, this evaluation also examined the potential impact that *STARS* may have on future infrastructure designs. Potential changes in future designs may result from: (1) a noted reduction in anticipated pavement damage from overweight commercial vehicle activity attributable to focused enforcement efforts and (2) an improvement in the quantity and quality of commercial vehicle weight data (WIM system vs. traditional weigh station) available for the design process. As was the case when investigating preservation impacts, future design-related impacts considered only pavements (as opposed to bridges); the majority of MDT's infrastructure expenditures are on pavements. Furthermore, design impacts attributable to *STARS* will occur in the fatigue (i.e., traffic demand) portion of the design process, with design life, reliability, material characteristics and serviceability assumed constant. Fatigue load histories are effectively what the *STARS* WIM system is collecting for the highways around the state, as individual axle loads are measured and recorded for each vehicle as it crosses the WIM installation.

The evaluation methodology used herein consisted of determining what changes would occur in pavement designs using fatigue related traffic demands determined from (1) *STARS* and (2) weigh station data. These potential impacts on pavement design were further expressed in terms of any attendant changes that might occur in future costs of pavement projects. That is, an estimate was formulated for what would be spent annually on new pavement projects relative to existing expenditures, if these projects were designed using load related traffic demands calculated from *STARS* data.

Before directly quantifying the estimated changes in pavement designs and costs described using the methodology introduced above, some general remarks are made on the general improvements in commercial vehicle weight data quantity and quality resulting from collecting this data using WIM systems as compared to weigh stations. WIM systems are increasingly being acknowledged as the best method available for collecting traffic demand information for pavement design, and, in the future, MDT is proposing to determine the ESAL factors used in the pavement design process from *STARS* WIM data (Bisom 2003). FHWA and various states began researching the value of WIM data for pavement design and other purposes in the mid-1980's (e.g., Krukar 1986, U.S. Department of Transportation 1990, Hajek, et al 1992). As a result of this work over the past 15 years, many states have shifted to using WIM data to determine fatigue demands for pavement design purposes. The mechanistically-based *2002 Pavement Design Guide* being developed by AASHTO as a successor to their existing empirical design approach, assumes pavement designers will have WIM data available to them to characterize fatigue demands (Transportation Research Board/National Cooperative Highway Research Program 2001). Suggestions on the type of WIM sensor (i.e., piezoelectric, bending plate, etc.) appropriate to support data collection for pavement design and other purposes are readily available in the literature (e.g., Oak Ridge National Laboratory 2002; McCall and Vodrazka 1997).

4.1 Improved Commercial Vehicle Weight Data Quality and Quantity

WIM systems are increasingly being used to collect pavement design (as well as other traffic information) because this approach, to a large extent, overcomes the data collection concerns that exist with using weigh stations for this purpose. The problems with weigh station versus WIM data collection are discussed in the following sections of this report. In particular, consideration is given to weigh station evasion and bypass, the extent of geographic and temporal coverage of traffic operations provided by Montana's weigh station and *STARS* WIM facilities, and WIM equipment performance.

As a side note, the use of WIM systems for data collection produce additional benefits unrelated to data quality. When data is collected at weigh stations, commercial vehicles must exit and re-enter the traffic stream, increasing the potential for vehicle conflicts and safety problems. Vehicle operators have also raised the issue of productivity losses when they are stopped at a weigh station. WIM systems collect data without interfering with the flow of traffic because they are installed directly in the traveling lanes of the roadway and can capture measurements unobtrusively at normal highway speeds. Benefits such as these that are unrelated to data quality, while possibly substantial, will not be discussed further in the context of this report.

It is important to note that WIM systems complement existing weigh station functions and will not be a substitute for weigh stations in the future. While WIM systems collect better data for pavement design purposes than can be collected by weigh stations, Montana law does not allow the issuance of a citation based on WIM measured weights (presumably due to issues of accuracy). Further, WIM systems do not fulfill all of the functions of a weigh station, as weigh stations offer the opportunity for enforcement personnel to check other aspects of vehicle operation and operator condition.

4.1.1 Weigh Station Evasion and Bypass

WIM systems capture the weight of *every* vehicle in the traffic stream; problems associated with overweight commercial vehicles avoiding weigh stations and thus being under-represented in the data sample used for pavement design are eliminated. Furthermore, any possible biasing of the data sample collected at the weigh stations is eliminated. Notably, during busy periods, empty or obviously weight-compliant vehicles occasionally are allowed to roll over the scale to minimize unsafe queuing onto the mainline roadway. Evidence exists to confirm that the weigh station data collected in Montana for pavement design has suffered from both these problems.

An early study done for MDT (Straehl 1988) on WIM system performance found that weigh station evasion was significant in some regions of the state. This conclusion has been echoed by other departments of transportation around the country that have investigated weigh station evasion by overweight vehicles (e.g., Cunagin, et al. 1997, Jessup and Casavant 1996, Strathman and Theisen 2002). This phenomenon results in an under-representation of overweight commercial vehicles in the data sample used for pavement design.

Contrary to this effect, the operational constraints at many weigh stations that occasionally result in empty or obviously weight-compliant commercial vehicles rolling over the scale (without recording a weight) produce a bias towards heavier/loaded commercial vehicles in the data sample used for pavement design. While this data bias phenomenon has been an ongoing concern of MDT data collection personnel (Bisom 2002), it has not previously been studied. In an effort to more definitively investigate this issue, weight distributions were generated for Class 9 vehicles using WIM system and weigh station data collected during the same time period and for the same traffic stream (i.e., at locations where a WIM site and a weigh station were in close proximity). These weight distributions are presented in Figures 4-1 and 4-2 for locations on the Interstate and non-Interstate NHS/Primary systems, respectively.

Referring to Figures 4-1 and 4-2, the weight distributions from the weigh station data are obviously skewed toward heavier commercial vehicles relative to those from the WIM data. This difference is believed to be the result of weigh station personnel focusing on heavily-loaded vehicles during periods of high commercial vehicle activity (as mentioned above). The difference in WIM and weigh station based weight distributions is decidedly more pronounced on the non-Interstate NHS/Primary systems (see Figure 4-2), in part because there are more unloaded vehicles in the traffic stream on the non-Interstate NHS/Primary system relative to the Interstate system. A greater percentage of the commercial vehicles operate empty on their back hauls on the non-Interstate NHS/primary system compared to the vehicles on the Interstate system due to the intrastate nature of many of their trips. Finally, note that on both highway systems, the proportion of the vehicles reported to be operating above legal limits in the weigh station data is negligible, whereas the WIM data clearly indicates a small, but obvious fraction of these vehicles operate overweight.

4.1.2 Geographic and Temporal Coverage

Ideally, new pavement designs would be based on traffic loadings measured at each project site and continuously over time. Due to resource constraints, however, load data from which fatigue demands are calculated for design purposes is generally collected at relatively few locations around the state. Furthermore, as outlined in Chapter 2, the load data traditionally used for pavement fatigue design is only collected at these sites at selected times during the year. This type of data sampling plan would be adequate if traffic was relatively uniform at all locations across the state throughout the day, month and year. Data collected from the *STARS* WIM sites, however, indicates that traffic and traffic demands on the state's highways vary significantly both geographically and temporally (particularly on the non-Interstate NHS and Primary systems).

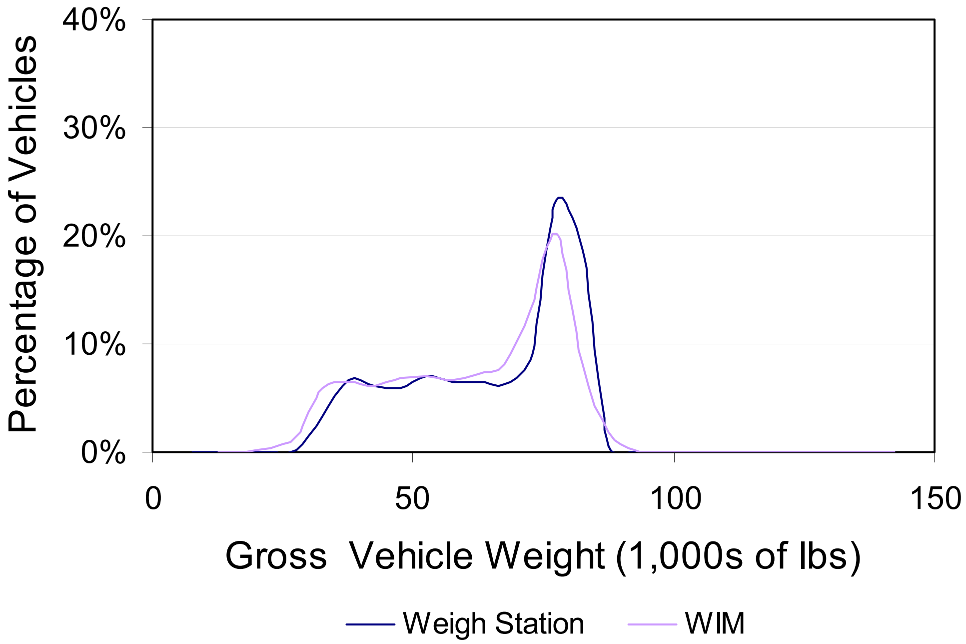


Figure 4-1. Class 9 Commercial Vehicle Weight Distributions, Weigh Station versus WIM System Data, Interstate System

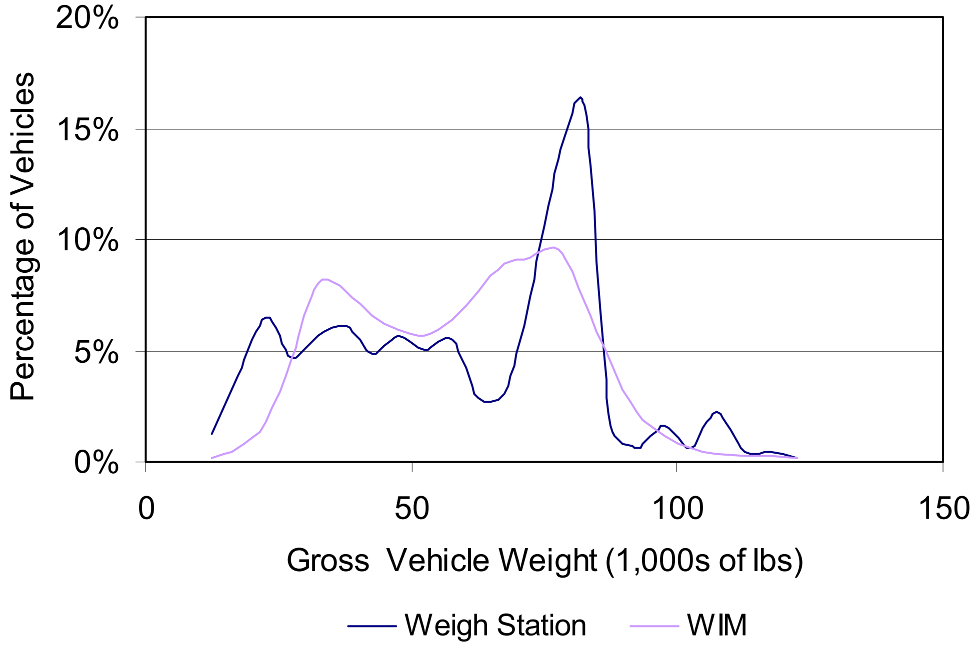


Figure 4-2. Class 9 Commercial Vehicle Weight Distributions, Weigh Station versus WIM System Data, Non-Interstate NHS/Primary Systems

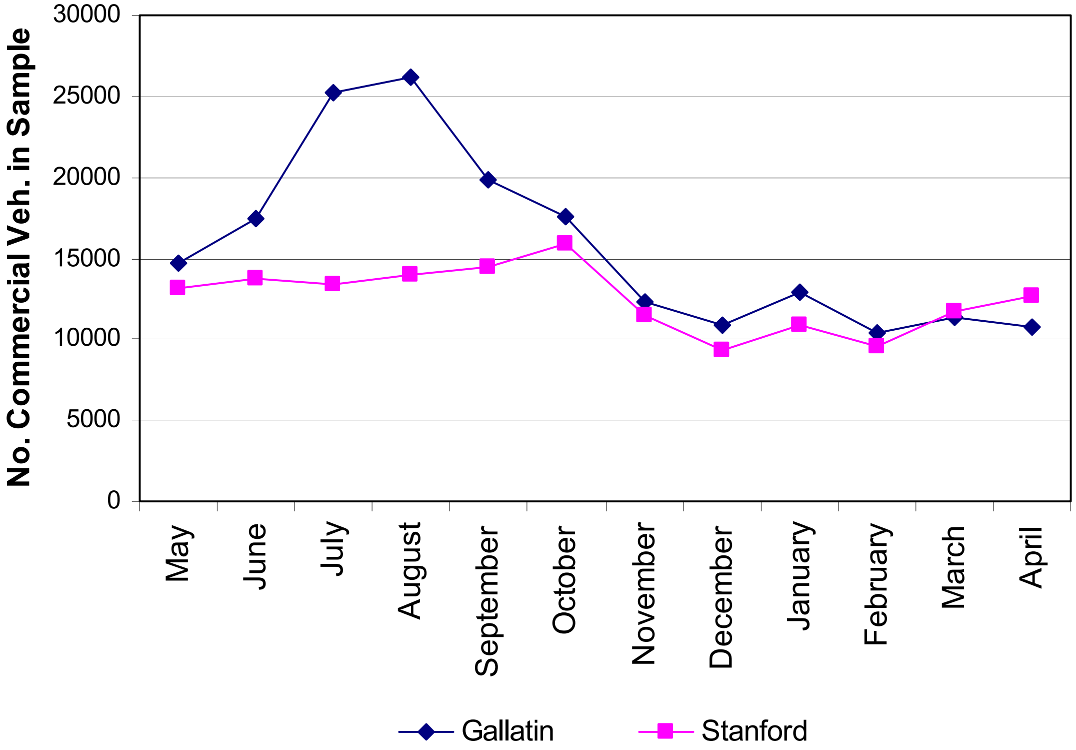


Figure 4-3. Commercial Vehicle Traffic Volume Variation by Month at Gallatin and Stanford

To demonstrate the variation in traffic demand experienced across the state, commercial vehicle volumes by month for two typical non-Interstate NHS/Primary sites are shown in Figure 4-3 for the year of *STARS*-directed enforcement. Referring to Figure 4-3, the variation in the relative volume of traffic between these two sites (which are on different routes) is obvious. Commercial vehicle traffic at the Gallatin site exceeds that at the Stanford site (which is approximately 150 miles away) by a maximum of 85 percent in July and August and an average of 24 percent across the year. Temporal variations in traffic loadings month-by-month are also evident at the two sites. Traffic volumes by month vary by up to 60 and 40 percent across the year at the Gallatin and Stanford sites, respectively. These sites are representative of the monthly variations in commercial vehicle traffic volumes observed across the state on the non-Interstate NHS and Primary systems. These variations are believed to occur in response to seasonal intrastate movement of construction, agricultural and natural resource based commodities. Commercial vehicle traffic volumes are generally more uniform on the Interstate system.

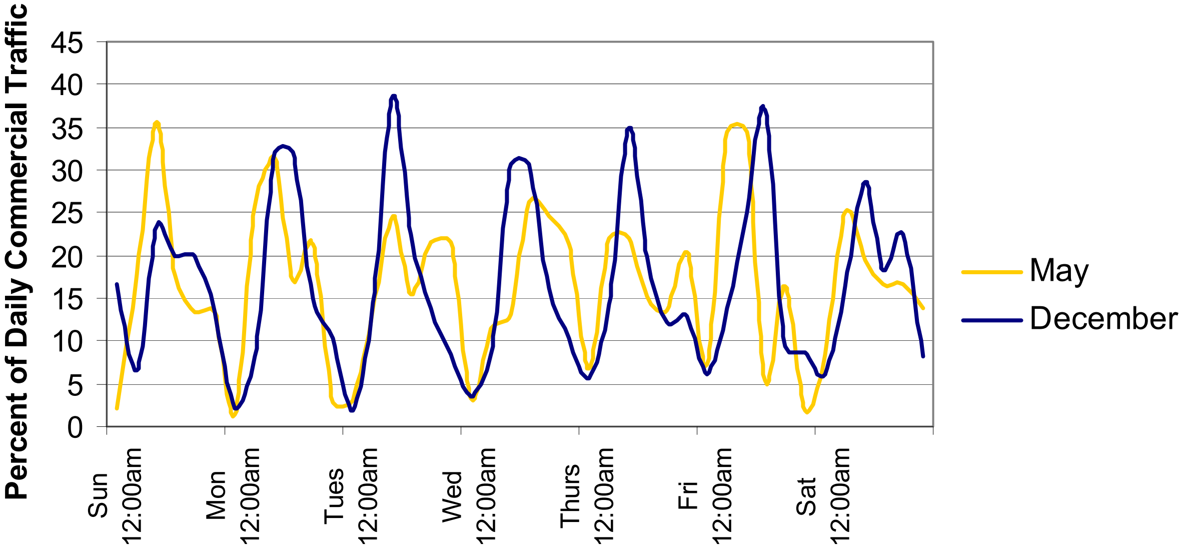


Figure 4-4. Commercial Vehicle Traffic Volume Variation by Day of the Week and Time of the Day at Townsend

Additional temporal variations in traffic levels are seen at all sites as a function of hour of the day and day of the week, as illustrated in Figure 4-4. Traffic patterns by day of the week and hour of the day also change with the month of the year, again as illustrated (although to a lesser degree) in Figure 4-4.

In light of this observed variability in commercial vehicle traffic geographically and temporally around the state, the current sampling scheme used to capture data for fatigue demand calculations for pavement design may be inadequate (even if the sample was not already shown to be biased based on weigh station avoidance by overweight vehicles and bypass by lightly loaded vehicles). As described in Chapter 2, this sampling scheme consists of collecting data for one eight-hour period per month at selected weigh stations around the state.

From a geographical and temporal perspective, the *STARS* program offers a significant increase in coverage of commercial vehicle operations on the state's highways relative to the existing weigh stations. Commercial vehicle weight data by axle and axle group is now routinely and continuously collected at 28 permanent WIM sites around the state (with 62 pre-planned sites at which data can be collected on an intermittent basis). Weight monitoring of the State's highway system provided by both weigh stations and *STARS* is quantified in Table 4-1 in terms of CVMT

Table 4-1. Weight Monitoring on Interstate and Non-Interstate NHS/Primary Systems

Highway System	Coverage of Vehicle Operations (CVMT per hour of operation)	
	Weigh Station	*STARS*
Interstate	14,000	14
Non-Interstate NHS/Primary	25,000	12

per hour of data collection. Referring to Table 4-1, lower values indicate greater scrutiny of the traffic stream with respect to collecting information on the weights of the vehicles using the State's highways. *STARS* increases coverage by factors of 1,000 and 2,000 on the Interstate and non-Interstate NHS/Primary systems, respectively, relative to coverage by weigh stations.

4.1.3 WIM System Performance

While WIM systems may offer greater temporal and spatial coverage of commercial vehicle operations on the state's highways, the accuracy of the data collected by these systems continues to be debated and studied. The discussion/commentary presented thus far has assumed that weigh station scales and WIM systems provide equally useable and accurate data. The accuracy of the static scales is well established; while the general level of accuracy of WIM systems is known, research on the accuracy of specific systems and installations under various environmental conditions is still being researched. Montana presently has two field studies underway investigating the performance of piezoelectric and bending plate WIM systems (Carson and Stephens 2003; Bylsma and Carson 2002) and many other studies have been completed in this regard (International Road Dynamics, Inc. 2001, Larsen and McDonnell 1999, Barnett, Benekohal and Tirums 1999, Cottrell 1991, U.S. Department of Transportation 1990). These studies have generally concluded that with proper calibration, WIM systems provide acceptable data for pavement design purposes. Note that MDT routinely calibrates both types of devices (static scales and WIM systems) following standardized calibration procedures (Bisom 2002). Furthermore, and as mentioned earlier, algorithms are used to automatically check the reasonableness of each WIM measurement. Some of the reports generated by *MEARS* specifically report on WIM calibration and WIM record error checking so that the analyst can be alerted to any anomalies in the collected data (see Table 2-7).

While WIM systems are usually capable of capturing every vehicle event, gaps occasionally occur in coverage due to equipment malfunctions. In this investigation, it was found that 25 and 18 percent of the data collected by the *STARS* WIM systems during the baseline and enforcement years was unusable due to such problems. Generally, these gaps are well-documented through the internal error checks performed by the WIM system itself. While such gaps could potentially bias the collected data, in this case, due to where and when they occurred, they were expected to have little impact on the evaluation. Gaps in the measurement process allow for the possibility that important events are absent in the collected data. In a study conducted by Wright, et al. (1997), while such gaps were cited as a source of concern, they rarely had a significant effect on the subsequent fatigue demands calculated from the data set. As might be obvious, Wright and his colleagues point out that the impact of missing data is dependent on the magnitude of the underlying variability in the traffic demands. Note that the most extreme case of missing data encountered by Wright, et al. in the WIM files they examined was approximately 180 days, which still left substantially more days in the data sample than historically has been used in the MDT weigh station files.

Concerns have been voiced that the use of WIM data in weight enforcement could ultimately result in compromised information quality for design and planning purposes (Wisconsin Department of Transportation 2000). Notably, if overweight vehicle operators recognize the role of these sites in enforcement, they may develop strategies to avoid detection that diminish the reliability of the collected data. Therefore, WIM data should be routinely reviewed for any anomalies that would indicate operators are employing such avoidance strategies. In the event such strategies become prevalent, and if they cannot be countered by reconfiguring the WIM system, a decision may have to be made on the relative value of this information in planning and design versus weight enforcement.

4.2 Fatigue Demands for Pavement Analysis and Design

Due to the obvious differences in the sampling methodologies that are used to collect vehicle load data for pavement design (i.e., data collected at weigh stations versus WIM sites), differences were also expected to exist in the fatigue demands calculated from the two different samples. Possible differences in design fatigue demands were evaluated in terms of the average

ESAL factor generated for each vehicle class from each source of data. These ESAL factors were calculated using the axle and axle group weights contained in the individual vehicle records following the procedure outlined in Chapter 2 of this report. While the methodology used for these calculations was the same for the data from both sources, the weigh station data was processed using an FHWA mainframe program (Bisom 2003), while the WIM data was processed using *TRADAS* (a commercial program developed for this purpose by Chaparral Systems Corporation, Santa Fe, New Mexico). MDT personnel provided the results of both these calculations.

The data in both the weigh station and the WIM system samples were from selected locations around the state (i.e., not all the available weigh stations or WIM sites were included in these calculations). The WIM sites used in these calculations are given in Table 4-2 (the sites used in assembling the weigh station data were previously reported in Table 2-5). These sites were judged by MDT (from among all the available sites) to provide a representative aggregate sample of commercial vehicle operations across the state. Note that for each site, the WIM data was collected continuously (with the exception of limited interruptions due to equipment problems).

MDT currently calculates separate ESAL factors for non-Interstate principal arterials and minor arterials, though the data sample compiled to date for minor arterials is of limited size, containing less than five records to represent some of the less common vehicle classes. Because of the similarity in ESAL factors for the better-represented vehicle classes on non-Interstate minor arterials and principal arterials, the decision was made to consider the ESAL factors derived for non-Interstate principal arterials to also be applicable to minor arterials. Furthermore, this category of highways was judged to be equivalent to the non-Interstate NHS/Primary designation used with the weigh station and traffic data, allowing for a direct comparison of the results obtained from the data collected from the two sources (weigh station and WIM systems).

Table 4-2. WIM Sites Used in Calculating ESAL Factors for Pavement Design

WIM Site			
2000		2001	
Interstate	Non-Interstate NHS/ Primary	Interstate	Non-Interstate NHS/ Primary
Manhattan	Townsend	Manhattan	Townsend
Big Timber	Arlee	Big Timber	Arlee
Ulm	Gallatin	Ulm	Gallatin
Bad Route	Broadview	Bad Route	Broadview
Lima	Ryegate		Ryegate
	Stanford		Stanford
	Havre East		Havre East
			Four Corners
			Fort Benton

4.2.1 ESAL Factors by Vehicle Class, Weigh Station versus WIM System

The ESAL factors determined aggregately across the WIM sites are reported in Table 4-3 and 4-4 by year for Interstate and non-Interstate NHS/Primary highway systems, respectively. The ESAL factors determined from the WIM system and weigh station data are graphically compared by vehicle configuration in Figures 4-5 through 4-10. Referring to Figures 4-5 through 4-10, the ESAL factors determined from the weigh station data are greater than those determined from the WIM data in almost every case. The greatest difference in the WIM system and weigh station ESAL factors occurred for Class 5 vehicles on the Interstate system (265 percent); the smallest difference was observed for Class 9 vehicles on the Interstate system (2 percent). Viewed collectively, Figures 4-5 through 4-10 reveal no obvious trends in the differences in WIM system and weigh station based ESAL factors based on vehicle configuration and element of the highway system.

In reviewing any differences in ESAL factors attributable to the data source (i.e., weigh station or WIM system), it is important to recognize that ESAL factors based on a single year of weigh station data include a considerable degree of uncertainty (for the various reasons discussed

Table 4-3. Typical WIM System ESAL Factors, Interstate Systems (Bisom 2002)

	2000		2001		Two-year Average (2000 – 2001)	
FHWA Vehicle Class	No. of Vehicles in Sample (1,000's)	ESAL Factor	No. of Vehicles in Sample (1,000's)	ESAL Factor	No. of Vehicles in Sample (1,000's)	ESAL Factor
5	319	0.160	333	0.148	652	0.154
6	51	0.439	41	0.449	92	0.444
7	5	0.653	3	0.792	7	0.723
8	45	0.359	45	0.354	91	0.356
9	1380	1.224	1401	1.330	2781	1.277
10	97	0.874	103	0.939	200	0.907
11	18	1.367	18	1.413	36	1.390
12	21	0.659	22	0.687	43	0.673
13	145	1.396	158	1.568	302	1.482

Table 4-4. Typical WIM System ESAL Factors, Non-Interstate NHS/Primary Systems (Bisom 2002)

	2000		2001		Two-year Average (2000 – 2001)	
FHWA Vehicle Class	No. of Vehicles in Sample (1,000's)	ESAL Factor	No. of Vehicles in Sample (1,000's)	ESAL Factor	No. of Vehicles in Sample (1,000's)	ESAL Factor
5	234	0.221	228	0.188	462	0.204
6	77	0.645	87	0.485	164	0.565
7	4	1.017	5	0.698	9	0.858
8	30	0.474	39	0.363	68	0.419
9	443	1.497	529	1.133	972	1.315
10	89	1.027	108	0.834	198	0.931
11	4	1.398	4	0.913	9	1.155
12	8	0.868	9	0.700	17	0.784
13	143	1.662	175	1.351	319	1.507

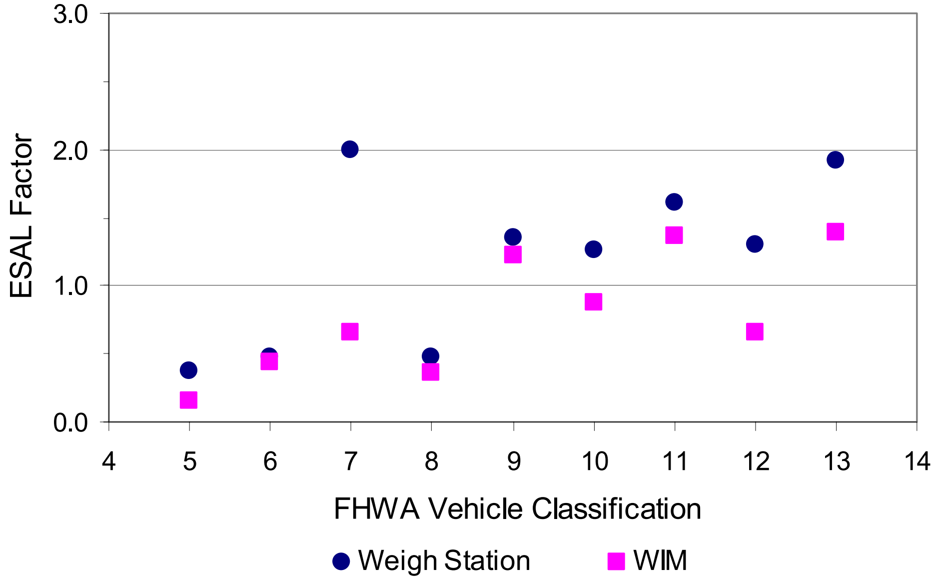


Figure 4-5. Interstate System ESAL Factors for 2000, Weigh Station versus WIM System Data

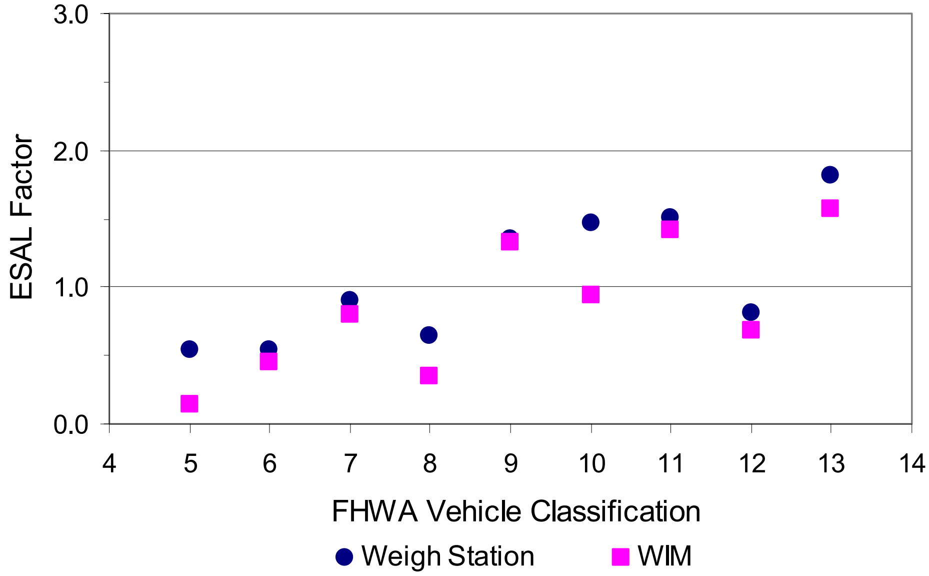


Figure 4-6. Interstate System ESAL Factors for 2001, Weigh Station versus WIM System Data

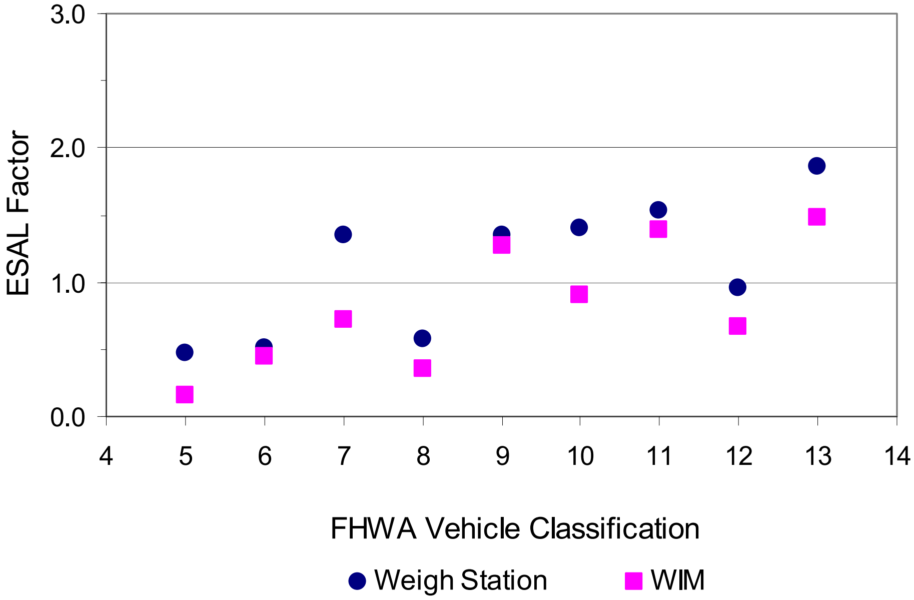


Figure 4-7. Interstate System ESAL Factors for 2000 and 2001, Weigh Station versus WIM System Data

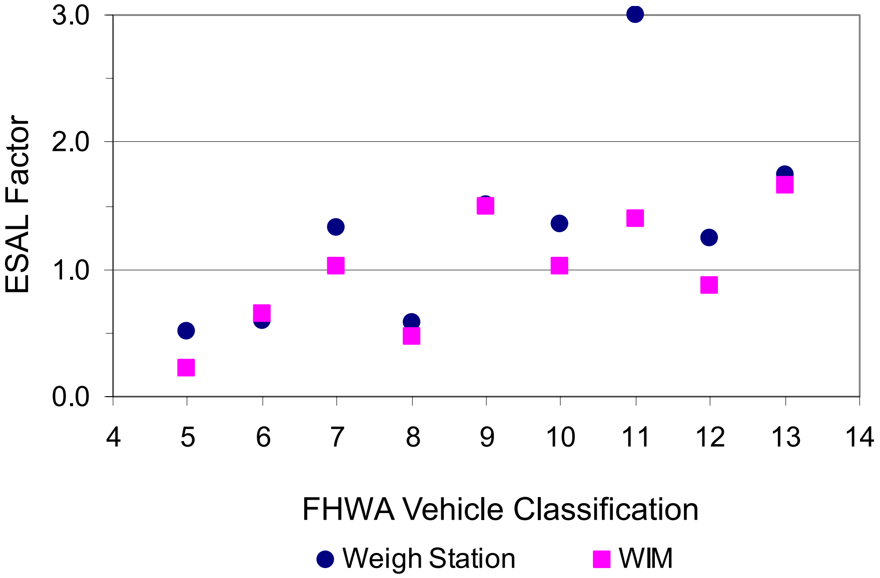


Figure 4-8. Non-Interstate/Primary System ESAL Factors for 2000, Weigh Station versus WIM System Data

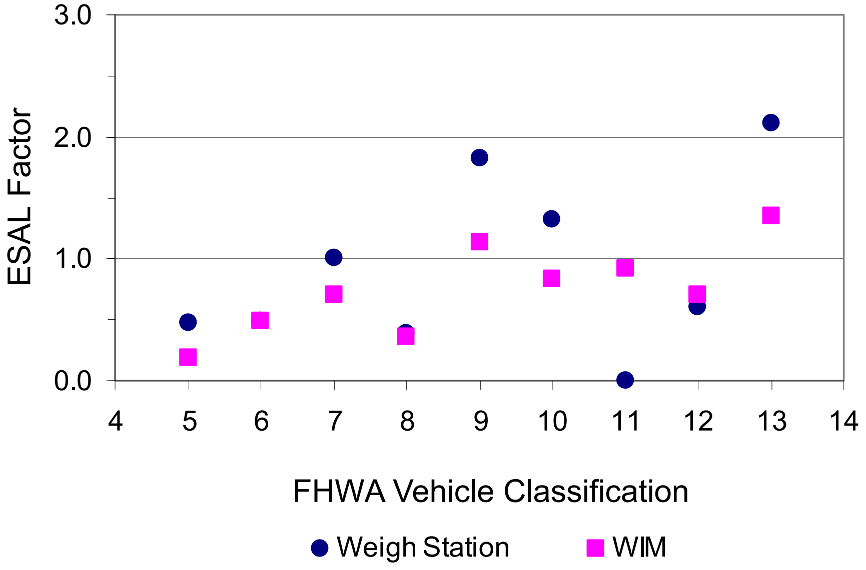


Figure 4-9. Non-Interstate/Primary System ESAL Factors for 2001, Weigh Station versus WIM System Data

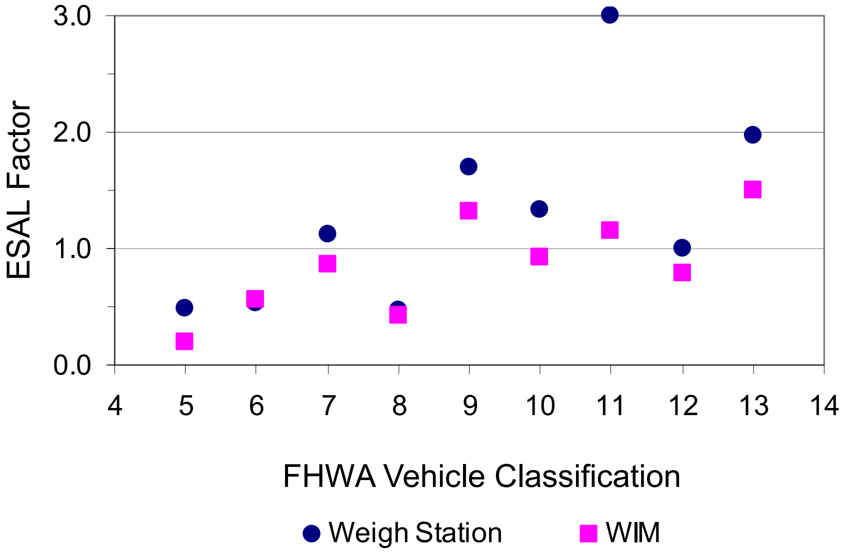


Figure 4-10. Non-Interstate/Primary System ESAL Factors for 2000 and 2001, Weigh Station versus WIM System Data

above). For this reason, weigh station ESALs are averaged over a 10-year period when used in design. WIM system data should also be averaged over several years of commercial vehicle operation. Vehicle activity in Montana can vary significantly year-to-year in response to short-term or one-time trip generating activities. Notably, traffic volumes are low enough at some sites that major industrial or highway construction activities, for example, can have a significant impact on the ESAL factors calculated for any given year. In light of the fact that only two years of data were available for this evaluation, more significance should be attached to the direction and order of magnitude of any observed changes in ESALs by data source, rather than their specific numerical values.

4.2.2 Statistical Investigation of the Difference in Class 9 ESAL Factors, Weigh Station versus WIM System

To account for the variability in traffic demands, limited statistical analyses were performed to determine the statistical significance of the differences observed in the ESAL factors as derived from the WIM system and weigh station data. Efforts focused on those vehicle configurations that contribute substantially to total fatigue demands on the state's highway system. As such, Class 9 ESAL factors, determined from WIM system data and weigh station data for the year 2001 on non-Interstate NHS/Primary systems, were statistically compared. Specifically, two-sites were considered; Gallatin and Arlee.

The data available for analysis exhibited a bimodal distribution with observations centering on empty and fully-loaded vehicles. Hence, statistical analyses used thus far that rely on assumptions of normally distributed data are invalid. Further, mathematical transformations to achieve normality are precluded by the bimodal nature of the data. Instead, assuming that the bimodal distributions observed in the weigh station data and the WIM system data were similar in shape and spread, the less-restrictive nonparametric Mann-Whitney Nonparametric Test was applied.

Mann-Whitney Nonparametric Test. Unlike the two-sample t-test that compares the equality of two independent sample means, the Mann-Whitney Test compares the equality of two independent sample medians:

H$_0$: $\eta_{WS} = \eta_{WIM}$

H$_1$: $\eta_{WS} \neq \eta_{WIM}$

where η_{WS} and η_{WIM} are the median Class 9 ESAL factors derived from the weigh station data and the WIM system data, respectively. As mentioned previously, this test requires that the two sample distributions have the same shape and spread, but they do not need to follow a prescribed probability distribution (Devore 1995).

To achieve a minimum 95-percent confidence level in the decision to accept or reject the null hypothesis, H$_0$, a p-value ≤ 0.025 (two-tailed) suggests rejecting H$_0$: $\eta_{WS} = \eta_{WIM}$ and accepting H$_1$: $\eta_{WS} \neq \eta_{WIM}$, the median Class 9 ESAL factor derived from the weigh station data is significantly different from the median Class 9 ESAL factor derived from the WIM system data.

With resulting p-values ≤ 0.025 (two-tailed), H$_0$: $\eta_b = \eta_e$ is rejected, the median Class 9 ESAL factor derived from the weigh station data is significantly different from the median Class 9 ESAL factor derived from the WIM system data at both the Gallatin site and the Arlee site (see Tables 4-5 and 4-6, respectively).

Table 4-5. Mann-Whitney Nonparametric Test (one-tailed): Class 9 ESAL Factors, Weigh Station versus WIM System

	Gallatin	
	Weigh Station	WIM
Number of Observations	370	N/A
Sample Median	1.695	1.045
Sample W Statistic		11,224,000
Sample p-value		0.000

Table 4-6. Mann-Whitney Nonparametric Test (one-tailed): Class 9 ESAL Factors, Weigh Station versus WIM System

	Arlee	
	Weigh Station	WIM
Number of Observations	392	N/A
Sample Median	3.125	0.445
Sample W Statistic		21,172,936.5
Sample p-value		0.000

4.2.3 Average ESAL Factors, Weigh Station versus WIM System

To simplify comparisons of the WIM system and weigh station based ESAL factors, an average ESAL factor (independent of vehicle configuration) was calculated from each data source by year and element of the highway system. This factor was calculated as the weighted average of the ESAL factors by individual vehicle configuration. These ESAL factors are reported in Table 4-7.

The ESAL factors determined from the weigh station and WIM system samples should be the same, as the samples are drawn from the same vehicle population. This study found, however, that the ESAL factors (and thus, the fatigue demands) determined using the WIM system data were consistently lower than those calculated from the weigh station data by 6 to 37 percent (see Table 4-7). Considering the combined ESAL factors over two years, the change in ESAL factors (weigh station versus WIM system) is more pronounced for the non-Interstate NHS/Primary system (-26 percent) relative to the Interstate system (-11 percent). This result is consistent with the general bias of the weigh station data toward heavier (but not overweight) vehicles, with this bias being more pronounced on the non-Interstate NHS/Primary system relative to the Interstate system.

This outcome was somewhat unexpected, due to the general belief that weigh station data underestimates overweight vehicle operations because of weigh station avoidance. In this case, however, the absence of overweight vehicles in the weigh station data was more than

Table 4-7. Average ESAL Factors Derived From Weigh Station and WIM System Data

Year	System	Average ESAL Factor		Percent Change in Average ESAL Factor
		Weigh Station	WIM	
2000	Interstate	1.20	1.01	-15
	Non Interstate NHS - Primary	1.21	1.09	-10
2001	Interstate	1.23	1.16	-6
	Non Interstate NHS - Primary	1.40	0.88	-37
Combined	Interstate	1.22	1.08	-11
	Non Interstate NHS - Primary	1.32	0.98	-26

compensated for by a bias in this data toward the heavier commercial vehicles in the traffic stream (as previously discussed). Note that Siffert also reportedly observed that pavement demands estimated from WIM data can be less than those estimated from other sources (Quilligan 2003).

Arguably, differences between the 2000 and 2001 derived ESAL factors and subsequent pavement designs are attributable to the combined effects of improved commercial vehicle weight data quantity and quality (WIM system vs. traditional weigh station) and a noted reduction in overweight commercial vehicle activity attributable to focused enforcement efforts. That is, the WIM system ESAL factors for 2000 characterize traffic conditions prior to the *STARS*-directed enforcement effort. The WIM system ESAL factors for 2001, to some degree, characterize traffic conditions under *STARS*-directed enforcement that began in May 2001 (i.e., *STARS*-directed enforcement occurred for eight months in 2001, May through December). Further, *STARS*-directed enforcement occurred at 4 of the 9 sites used in calculating the WIM-based ESAL factors. The ESAL factors for the non-Interstate NHS/Primary systems decreased between 2000 and 2001, consistent with a noted reduction in overweight commercial vehicle activity attributable to *STARS*. The magnitude of this decrease (19 percent, from 1.09 to 0.88) seems fairly large, however, in light of the relatively modest reduction in total ESALs at the *STARS* sites during the enforcement year (approximately 3 percent). The ESAL factor for the Interstate system actually increased by 16 percent from 2000 to 2001. This result is difficult to explain, and may simply illustrate the variability in the ESAL factor results, even for the WIM system data.

A further implication of the observed reduction in design fatigue demands as determined from WIM versus weigh station data samples is that fatigue demands historically have been overestimated in the pavement design process. This observation, in turn, leads to the conclusion that roadways in the state have been over-built. This conclusion, however, presumes that fatigue is the controlling failure mechanism for the roadway's performance. This assumption is critical in generally assessing how reasonable the conclusion is that the state's highways have been over-built. Notably, many highways obviously wear out before their design life is reached. Often, however, their loss of functionality is not caused by, or it is only indirectly caused by, fatigue failure. Failures unrelated to fatigue include thermal cracking, frost heaving, long term settlement, cracking at cold joints, etc. Such distresses are commonly observed in highways relative to distresses resulting from traffic demands. In a study conducted in Minnesota on the performance of 15 different pavement sections, for example, of the 8 sections with below average to poor ride performance at eight years of age, 7 of the sections were judged to be performing below average relative to thermal cracking while only 3 of the sections were judged to be performing below average relative to traffic related cracking (Palmer, et al. 2002). Certainly, once deterioration begins, it can be accelerated by traffic loads. Even when fatigue is the first failure manifested, it may have initiated prematurely due to circumstances such as the undetected presence of poor subbase materials, the use of substandard materials in construction and/or the use of poor construction practices. Note that with respect to Montana's highways, all these situations are observed (Gustafson and Shea 2003).

4.3 Future Pavement Costs

The effect on future pavement projects and their cost of using WIM versus weigh station based fatigue demands in the design process was determined by redesigning some existing projects (originally designed using weigh station based data) using the new WIM-based ESAL factors. The purpose of this exercise was to develop a generic relationship between changes in the fatigue demands used in designing a roadway and the subsequent changes in the cost of building that roadway. This relationship was then used to extrapolate the expected change in annual expenditures on new pavements across the entire state in a WIM-based design scenario.

To investigate the relationship between design ESALs (ESAL factors multiplied by the anticipated traffic loadings over the life of the pavement) and subsequent pavement costs, a collection of typical paving projects was redesigned using design ESALs estimated from both weigh station data and WIM system data. This approach accounted for the fact that fatigue demand is only one factor that influences pavement designs. As stated in Chapter 2, resistance to environmental effects or geometric constraints related to construction practices, for example, can control pavement infrastructure design. In both cases, the resulting design could offer substantially more fatigue-related capacity than would be required given the anticipated traffic on the roadway. Thus, a decrease in design ESALs could result in no comparable reduction in facility costs or a substantial increase in design ESALs could be required before any increase in cost resulted.

For each construction project, costs were calculated for the redesigned projects and compared to costs of the original projects. MDT personnel (Gustafson and Shea 2003) conducted this analysis for the Interstate system and the combined non-Interstate NHS/Primary systems. Ideally, this analysis would have been done on a large sample of projects, as every paving project is unique. This analysis, however, is resource intensive, so the decision was collectively made with MDT that a few projects would be selected for this purpose that were generally representative of the design situations encountered in the state with respect geographic location, levels of traffic and type of work being performed.

The projects used in this analysis are listed in Table 4-8, along with the results obtained for each project when different levels of ESALs were used for design. Note that the specific ESAL levels used in the redesign process were not arbitrarily selected. The original design ESALs listed for each project were calculated using standard MDT procedures, in which the ESAL factors by vehicle configuration were based on weigh station measurements of vehicle axle weights by vehicle configuration. Early results from this investigation indicated that ESAL demands might decrease by 5 to 25 percent if *STARS* data were used in the design process (with 5 percent correlating with simply using *STARS* data versus weigh station data in the design process and 25 percent correlating with the combined effect of using *STARS* data and *STARS* focused enforcement). Therefore, redesigns were done for each project using approximately these reductions in ESALs of demand.

Changes in the costs of these projects as a function of changes of in design ESALs are reported in Table 4-8 and are plotted in Figures 4-11 and 4-12 for the Interstate and non-Interstate NHS/Primary systems, respectively. While the points in Figures 4-11 and 4-12 show considerable scatter, it is apparent that pavement costs increase as design ESALs increase above a certain threshold. A trend-line was fit to the data to grossly predict the percent change in pavement project cost for various changes in ESALs of demand.

Changes in total annual pavement construction expenditures if WIM-based ESAL factors were used in the design process were calculated by multiplying the percent change in project costs estimated from Figures 4-11 and 4-12 for a given change in design ESALs, by MDT's total annual expenditures on pavement construction on the Interstate and non-Interstate NHS/Primary systems. These calculations were done for MDT's pavement expenditures in the year 2000-2001 which were estimated to be \$48 million and \$133 million for the Interstate and non-Interstate/Primary systems, respectively. These estimates assume that total roadway construction and pre-construction costs in 2001 were \$299 million, coupled with information available from MDT on expenditures by highway system (MDT 2002) and information on the percent of construction expenditures by activity determined in a previous study on financing Montana's highways (Stephens and Menuez 1999).

Reductions in projected construction costs if future pavement projects were to be constructed from designs based on WIM system rather than weigh station based fatigue demands range from approximately \$0.1 to \$1.0 million on the Interstate system and from \$1.5 to \$4.0 million on the non-Interstate NHS/Primary system (see Table 4-9). These projections are based on ESAL factor comparisons from single-year data samples (2000 and 2001) and are susceptible to bias from sampling errors and short-term traffic events. More significance should be attached to the direction and order of magnitude of the changes in pavement costs reported in this table than in

Table 4-8. Change in Project Cost as a Function of Changes in ESALs of Design Demand

Location	System	Project Type	Design ESALs[a]	Change in Design ESALS (%)	Change in Project Cost ($)	Change in Project Cost (%)
Yellowstone Park	Non-Interstate NHS	Repave	375	-	-	-
			355	5.3	0	0
			273	27.2	149,466	3.76
Dixon-Ravalli	Primary	Reconstruction	130	-	-	-
			121	6.9	30868	0.51
			96	26.2	92,603	1.52
Frazer–E and W	Non-Interstate NHS	Widen and Repave	101	-	-	-
			92	8.9	138,533	2.42
			75	25.7	277,066	4.84
Browning-Meriwether	Non-Interstate NHS	Reconstruction	110	-	-	-
			102	7.4	29,727	0.45
			80	27.3	127,400	1.91
East Helena–E	Non-Interstate NHS	Repave	294	-	-	-
			274	6.8	6,231	0.45
			213	27.5	62,309	4.55
Vaughn S. River–E and W	Non-Interstate NHS	Reconstruction	328	-	-	-
			307	6.31	16,987	0.18
			239	27.0	50,960	0.53
Lothair-E	Non-Interstate NHS	Reconstruction	112	-	-	-
			106	5.4	7,774	0.09
			82	26.8	56,361	0.62
Conrad-N and S	Interstate	Resurface	528	-	-	-
			453	14.1	232,205	4.38
			402	23.9	375,951	7.09
Powder River-E	Interstate	Repave	745	-	-	-
			677	9.1	159,734	1.96
			599	19.6	372,722	4.57
Custer-W	Interstate	Paving	1275	-	-	-
			1108	13.1	0	0.00
			981	23.1	0	0.00
Alberton-E and W	Interstate	Paving	612	-	-	-
			541	11.6	0	0.00
			479	21.7	0	0.00

[a] Entries for each project correspond to original design demand, approximately 5 percent decrease in design demand, and approximately 25 percent decrease in design demand, respectively

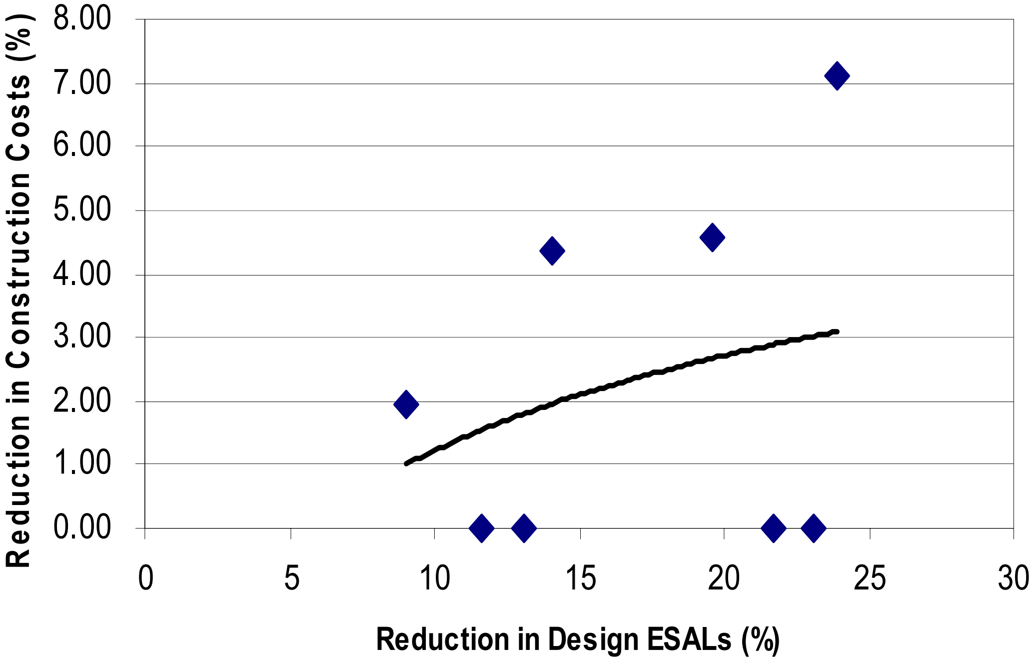


Figure 4-11. Reduction in Construction Costs as a Function of Reduced Design ESALs, Interstate System

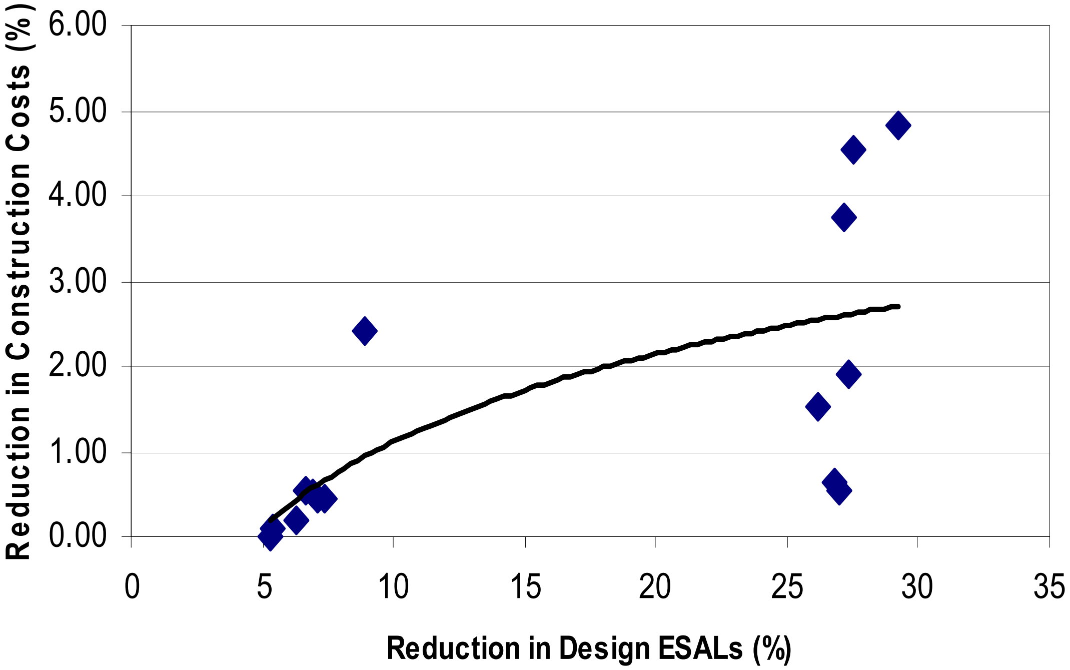


Figure 4-12. Reduction in Construction Costs as a Function of Reduced Design ESALs, Non-Interstate NHS/Primary Systems

Table 4-9. Projected Cost Impacts of Fatigue Demands in Pavement Design, Weigh Station versus WIM System

Year	System	Change in Design ESALs (%)	Change in Annual Construction Costs[a] (%)	Change in Annual Construction Costs[a] ($)
2000	Interstate	-15	2.1	1,036,118
	Non-Interstate NHS/Primary	-10	1.1	1,454,427
2001	Interstate	-6	0.2	115,444
	Non-Interstate NHS/Primary	-37	3.1	4,061,239
Combined	Interstate	-11	1.4	700,187
	Non-Interstate NHS/Primary	-26	2.5	3,367,681

[a] 2002 dollars

nominally better projection of changes in pavement costs. These results indicate that use of WIM-based ESAL factors in the design process would result in approximately a \$0.7 million and a \$3.5 million reduction in pavement construction costs on the Interstate and non-Interstate NHS/Primary systems, respectively.

5 DATA ENHANCEMENT

While demonstrated thus far with respect to commercial vehicle weight enforcement and pavement infrastructure design, the usefulness of WIM data crosscuts the organizational structure of transportation agencies. Despite an initial reluctance to share data (i.e., if WIM sites are used jointly for planning and enforcement, commercial vehicles may avoid these locations resulting in unrepresentative data samples), national experience suggests considerable success in sharing WIM technology and data (Wisconsin Department of Transportation, 2000). Hajek, et al. (1992) suggests that WIM data should be considered "corporate" data and should be managed accordingly with facilitated data storage and retrieval as a service to potential users. Schmoyer and Hu (1996) further suggest that data sharing among states is a good idea.

Figure 5-1 represents the flow of truck-related data through MDT and the types of truck-related data typically used by each area. Potential agency-wide data enhancements resulting from the *STARS* program were detailed using a survey questionnaire distributed to various sections or divisions within MDT. Specifically, information related to the extent of benefits that may result from expanded and improved truck-related data was sought. Representative responses were obtained from the areas of:

- Planning
- Engineering
  - Geometric Design
  - Safety
- Motor Carrier Services
- Pavements and Materials and
- Bridges.

The survey questionnaire, reproduced in Appendix E, solicited information related to data use, data elements, data sources, data quality, data improvements and the overall benefit of an increase in the quantity and quality of truck-related data. As might be expected, the responses varied greatly from one area to the next.

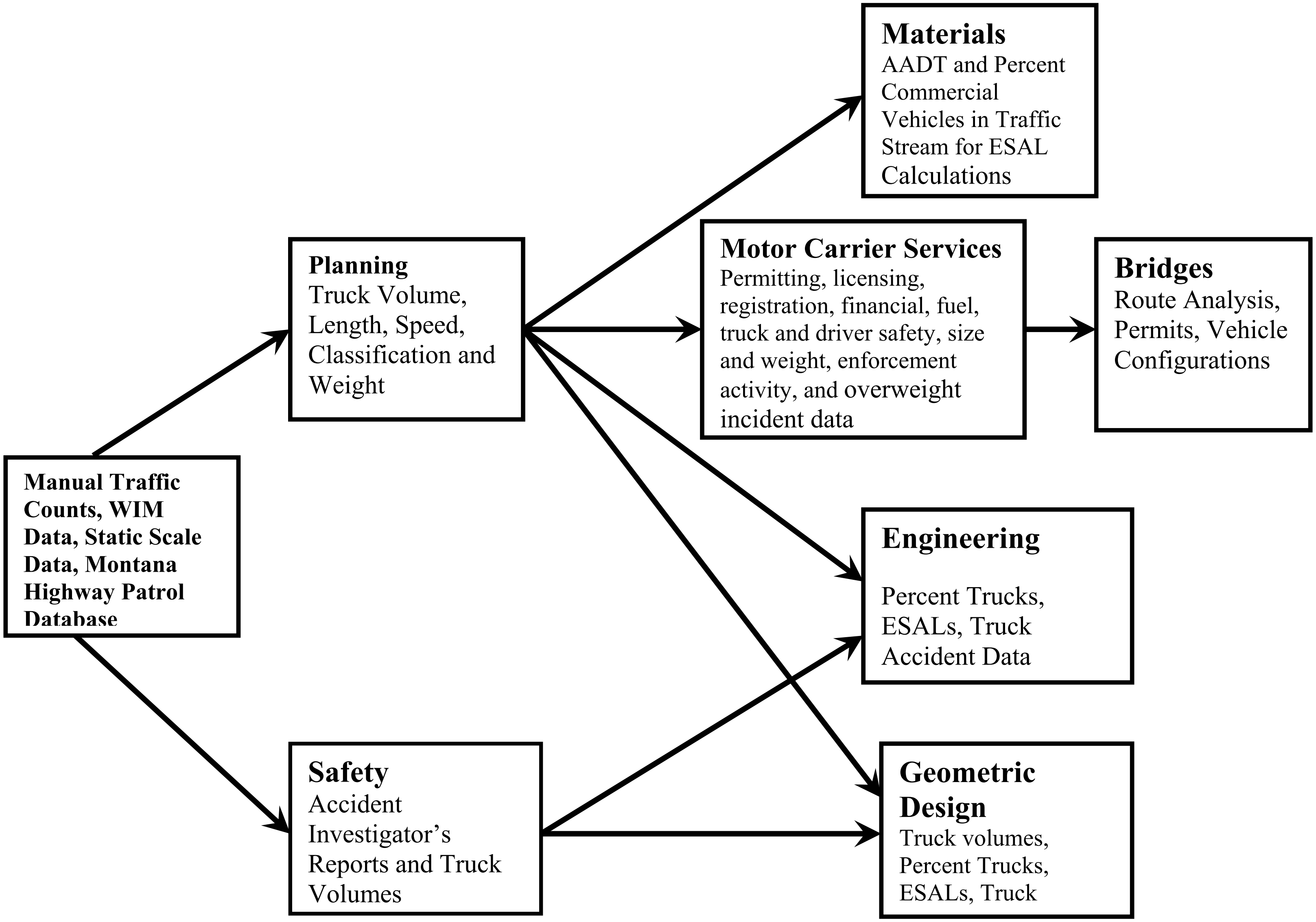


Figure 5-1. Departmental Flow of Truck-related Data

The approach taken in this investigation to document potential data enhancements for the Montana Department of Transportation mimics earlier work conducted by Sebaaly, et al. (1991) for the Pennsylvania Department of Transportation (PennDOT) and by Hajek, et al. (1992) who identified a number of specific WIM data application areas including planning and programming of transportation facilities, pavement design and rehabilitation, apportionment of pavement damage, compliance with vehicle weight regulations, development of geometric design standards, compliance and regulatory policy development of truck dimensions, safety analysis, traffic operation and control and analysis related to highway bridges.

5.1 Planning

The Planning Division collects and provides truck-related data to other divisions within MDT. This information includes Commercial Average Daily Traffic (CADT), Commercial Vehicle Miles Traveled (CVMT), Equivalent Single Axle Loads (ESALs), Percent Large Trucks of AADT, Percent Commercial Trucks of AADT and Traffic Stream Distribution. This data was historically captured using manual counts, portable classifiers and static scale information, but has recently been supplemented with WIM system information. The Planning Division favors using WIM equipment because of its accuracy in weight and classification capture. As such, MDT's Planning Division anticipates that the enhanced data available from the *STARS* program will "Substantially Benefit" their day-to-day activities. Note that in addition to supporting in-house data needs, the Planning Division responds to data requests from users outside of MDT, many of whom they believe will benefit from the enhanced data available from *STARS* (Bisom 2003).

Participants were asked to list any shortcomings that they have experienced with the data that they currently access or collect and utilize. The most direct complaint about truck-related data was voiced by the Planning Division: "We spend all year collecting data and at the year's end, we need more data." This comment is significant because the Planning Division provides several other divisions with the truck-related data they need for their day-to-day activities. This response is not unique. Liu, Sharma and Anderson (2002) considered data shortcomings for the Saskatchewan Department of Highways and Transportation. With a focus on operations and planning, individual interviews revealed that the most important traffic data included average annual daily traffic (AADT), percent trucks in the traffic stream and truck volume growth rates; but that more detailed data on vehicle classification, truck weight and configuration, truck traffic seasonal variation and goods movements was desired. Goods movement data includes origin-destination and truck route data, commodity transported, cargo value crossing the border and type of truck used for grain movements in the Province.

5.2 Engineering

The Engineering Division currently relies on truck-related data for site-specific design and safety applications but speculate that WIM technologies providing, "seasonal fluctuations in truck volumes and origin/destination information may be useful for route segment planning" and may improve access to existing types of data. As such, the Engineering Division reported an anticipated "Benefit" from the *STARS* program but did not cite any specific shortcomings with existing data; essential data is already available and sufficiently detailed for day-to-day functions.

5.2.1 Geometric Design

The Geometric Design Section, within the Engineering Division, currently uses the percent volume of trucks in the traffic stream, ESALs and truck dimensions to determine turning radii and lane widths. In addition, they use truck-related data in determining truck climbing lane warrants and in some cases the maximum grades for a facility. The data is also useful in developing justification for passing lanes on two-lane/two-way facilities.

The Geometric Design Section requested more detailed data describing vehicle dimensions and characteristics (i.e., sizes, number of axles) and an accurate inclusion of previously unreported (after hours) truck volumes and overweight vehicles for ESAL and traffic volume determinations.

5.2.2 Safety

The Safety Management Section, within the Engineering Division, primarily uses truck crash information for safety reviews, for crash cluster analyses and to review locations with a high number of truck crashes. The Safety Management Section supplements information obtained from MDT's Planning Division with data from the Montana Highway Patrol database, the Transportation Information System (TIS) Road Log, *TRADAS* (traffic volumes), and/or manual traffic counts. As a future application of WIM data, the Safety Management Section is interested in vehicle miles traveled by truck class and roadway classification, truck class volumes by route and by season and truck speed data by time of day and roadway classification.

5.3 Motor Carrier Services

The Motor Carrier Services (MCS) Division relies on truck-related data on a daily basis. MCS is responsible for Montana's oversize/overweight permitting program; all Interstate and "fleet" commercial vehicle licensing and registration done in Montana; enforcement of Montana's diesel fuel tax laws; enforcement of state and federal commercial vehicle safety laws and regulations; annual certification of Montana's size and weight enforcement program to the FHWA (PLAN/CERT); annual certification to the FHWA of Montana's compliance with the Heavy Vehicle Use Tax (HVUT) requirements; administration of the International Registration Plan (IRP) for Montana; administration of the federal Single State Registration System (SSRS) for Montana and development and implementation of the federally mandated Commercial Vehicle Information System Network (CVISN) program in Montana. All of these activities and responsibilities involve the use of various types of truck-related data.

The Motor Carrier Services Division gets much of its truck-related data directly from *STARS* and *MEARS* that provides information on overweight commercial vehicle activity, average commercial vehicle weights by configuration and indicators of system performance for WIM sites. The only complaint regarding this data is that it is not always easily accessible and requires the assistance of a technician to obtain.

Not surprisingly, the Motor Carrier Services Division anticipates that the improvements in data from *STARS* will "Substantially Benefit" their day-to-day activities. According to the Motor Carrier Services Division, "*STARS* provides MCS Managers with the ability to focus enforcement resources on a section of highway and at a time of day when overweight vehicles are known to have been in operation." They go on to say that, "Prior to *STARS*, this was a guessing game at best."

5.4 Pavements and Materials

The Materials Bureau currently uses 20-year ESAL information provided by the Planning Division to generate pavement designs and as part of their Pavement Management System. The ESALs for the Pavement Management System are estimated based on a formula using AADT and percent commercial vehicles. The Materials Bureau, interested in having actual ESALs for their Pavement Management System to support the generation of axle load spectra for the 2002 AASHTO Pavement Design Procedure, felt that STARS would "Benefit" what they do.

5.5 Bridges

The Bridge Bureau provides professional engineering vehicle and route analysis services to the Motor Carrier Services (MCS) Division on an "as requested" basis. This process may involve the full vehicle configuration including distances between axles, axle group weights, and application of the Federal Bridge Formula as appropriate.

The Bridge Bureau was the only area that didn't think the improvement in truck-related data would benefit what they do. (The Bridge Bureau did not respond to many of the questions contained in this survey.)

6 CONCLUSIONS AND RECOMMENDATIONS

The findings of this investigation indicate that the objectives of the *STARS* program have been met. The information provided by *STARS* on commercial vehicle weight operations on the state's highways:

(1) was successfully used to reduce infrastructure damage from overweight vehicles in a pilot program that used this information to schedule some of MDT's weight enforcement activities,

(2) offered a more comprehensive and accurate characterization of traffic related fatigue demands on the highway system than is available from traditional sources (weigh station sampling efforts), which should result in a better match of future pavement designs against actual traffic demands, and

(3) was found to be beneficial to several divisions within MDT with respect to many of the analyses they are tasked to perform, and is expected to be useful to outside users of MDT data.

With respect to using *STARS* to reduce infrastructure damage from overweight vehicles, MDT developed and executed a pilot project in which a portion of their weight enforcement efforts were directed to those locations and at those times at which the greatest overweight vehicle problems were known to historically exist. These locations were identified from *STARS* data. The effectiveness of this enforcement strategy was evaluated by comparing the characteristics of the vehicles in the traffic stream and the associated pavement damage they caused during a year of *STARS*-directed enforcement to these same parameters as determined during the previous baseline year.

The proportion of overweight vehicles in the traffic stream decreased by 22 percent during the year of *STARS* focused enforcement from 8.8 percent to 6.9 percent during the enforcement and baseline years, respectively. This decrease in the proportion of overweight vehicles was found to be statistically significant (95-percent confidence level), with the majority of locations at which a reduction in the proportion of overweight vehicles in the traffic stream was observed corresponding to *STARS* focused enforcement sites. The average amount of overweight was also found to decrease in the enforcement relative to the baseline year from 6,100 to 5,500 lbs (with a statistical confidence of 88 percent).

The reduction in pavement damage observed during the year of *STARS* focused enforcement was calculated to be 6 million ESAL-miles. Based on that part of the cost of providing highway service that is attributable to the fatigue demands of traffic, the cost associated with this amount of pavement damage was found to be approximately $700,000. Once again, the majority of locations at which a reduction in pavement damage was observed corresponded to those locations that were frequently the subject of *STARS* focused enforcement.

The WIM systems deployed as part of the *STARS* program provide significantly more comprehensive data on fatigue demands for pavement design than is currently available from weigh stations. Weigh station data is collected only for selected periods of time during the year, while WIM systems collect data continuously at all sites. Due to the variability of traffic volumes around the state and throughout the year, the ability of the weigh station data to accurately capture and represent commercial vehicle use across the year is questionable. Furthermore, the weigh station data appears to be biased toward heavier vehicles due to the manner in which it has to be collected. Thus, MDT's intention to determine the ESAL factors used in the pavement design process from *STARS* WIM data (Bisom 2002) rather than weigh station data is well supported by the results of this evaluation.

The problems encountered in collecting traffic/fatigue related pavement design information at weigh stations are carried forward into the fatigue demands that are subsequently determined from this information. In this investigation, fatigue demands calculated from WIM-based traffic data were lower than those calculated from weigh station-based traffic data by 11 and 26 percent, respectively, on the Interstate and non-Interstate NHS/Primary systems. These results indicate that pavement designs that are based on traditional sources of traffic load information (i.e., weigh stations) are overbuilt with respect to fatigue demands (note that traffic related fatigue demand is only one of many demands pavements must be designed to resist). Pavements designed with improved WIM-based fatigue demands should be better optimized relative to the actual demands they will experience in-service. Further analyses found that if pavements were designed using WIM-based rather than weigh station-based fatigue demands, pavement construction costs would decrease annually on the order of magnitude of $0.7 million and $3.4 million, respectively, on the Interstate and non-Interstate NHS/Primary systems.

With respect to engineering and planning benefits attributable to *STARS*, the degree to which benefits can be realized varies from one area within MDT to another. Motor Carrier Services and Planning Divisions perceive the greatest resulting benefit, while the Engineering Division anticipates a lesser degree of benefits. External users of the data collected by MDT are also expected to benefit from the improved quality and quantity of information available from *STARS*.

The information available from *STARS* on commercial vehicle operations on Montana's highways is substantial, and work should continue on further developing the system, itself, and on fully exploiting its use. As this process begins, the costs and benefits of the *STARS* program should be revisited. This evaluation highlighted the benefits that *STARS* offers; the value of these benefits (only some of which were quantified in this evaluation) needs to be balanced against the cost of the system. As might be obvious, in contemplating future investments in the system, consideration should be given to the cost of such work versus the benefits realized by the data users.

With respect to general system development, future tasks include establishing new sites (and possibly retiring existing sites), as necessary, to ensure that information on commercial vehicle operations is being collected at the most critical locations around the state. While certain divisions within MDT may have an obvious interest and role in site selection (e.g., Planning, Pavements and Materials, Motor Carrier Services), other divisions may discover uses for *STARS* information and develop their own suggestions for new sites (e.g., Bridge). Furthermore, the portable WIM systems that are part of the *STARS* program are a powerful tool for short-term, site-specific, traffic (and other) investigations. Once again, while certain divisions of MDT may have obvious uses for these systems, non-traditional users might realize significant benefit from their use, if they know they are available. In addition to establishing new *STARS* sites, consideration will have to be given to upgrading the system hardware in the future in light of technological advances that offer improvements in the quality and/or the types of information that are available from *STARS*.

With respect to optimizing the use of the information available from *STARS*, the first step in this process is simply to make sure the various divisions at MDT are aware of the capabilities of *STARS* and the availability of the data it produces. The *STARS* data may see more exposure and use if it is readily accessible by geographic information systems. A more specific future task related to optimizing the use *STARS* data may include developing task-specific software, as necessary, to process the raw data into a user friendly format. *MEARS* is an example of task-specific software that acts on raw *STARS* data to produce information for the use of Motor Carrier Services. Note that the volume of raw data being generated by *STARS* is large, and it will be less cumbersome to use this information in *MEARS* and other programs if it can be processed to reduce the size of the data files without affecting the nature of their content.

On a more specific level, one of the uses of *STARS* information that was evaluated in this project was its use in vehicle weight enforcement. In discussions with MCS following the pilot enforcement project, they indicated a strong interest in continuing to investigate the use of WIM in weight enforcement. Note that the pilot project looked at only one strategy/approach for using the *STARS* WIM data in weight enforcement, and considered only one possible implementation of this strategy. Thus, MCS could go in many other directions regarding the use of *STARS* in weight enforcement. Remaining questions for future investigation include the following:

(1) Is it cost effective to use *STARS* data in weight enforcement?

(2) Should the basic strategy employed in the pilot project be continued, with revisions as necessary to ensure its continued effectiveness?

(3) What are potential benefits of establishing *STARS* sites on bypass routes adjacent to existing weigh stations?

(4) Can bypass activity at a regional corridor level be determined using *STARS* data? Bypass of a weight enforcement activity by overweight vehicles is often evaluated with respect to roads in the immediate vicinity of the enforcement activity. For weigh stations and extended roadside enforcement activities, vehicle operators have the opportunity to plan

their bypass routes at a more regional level. It may be possible to monitor this type of bypass using a coordinated deployment of WIM sites and/or the coordinated processing of WIM data along such routes.

(5) How can *STARS* data be used to evaluate the effectiveness of short term enforcement activities? While *STARS* data was used in this project to evaluate the effectiveness of the pilot enforcement program, the evaluation was tailored specifically to the pilot program, which focused on statewide activities over a two period. What are possible strategies to detect and react to site specific problems of overweight vehicle activity? Is it possible to develop a general methodology for using *STARS* data to evaluate the effectiveness of any type of enforcement activity of any duration? Can this methodology produce sound information in a timely fashion for use by MCS managers and mobile enforcement personnel?

(6) What is the optimum use for the portable WIM systems that are part of the *STARS* program in data collection and weight enforcement?

(7) How can the presence of permitted vehicles operating at weights in excess of standard load limits be factored into MEARS?

In closing this investigation, the concept of using *STARS* to guide and evaluate the state's weight enforcement program as a possible performance-based alternative to the system currently used by the FHWA (Federal Highway Administration) is being put forth. By shifting the existing performance metric from overweight vehicle capture and citations issued to the reduction in pavement damage, a more direct, effective, objective and nationally-comparable state enforcement program may result.

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