Title

Strategies for Successful Implementation of Virtual Weigh and Compliance Systems in California

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Strategies for Successful Implementation of Virtual Weigh and Compliance Systems in California

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1. Introduction

1.1 Background

Freight transportation, particularly by trucks, plays a crucial role in regional and national economy. Trucks account for three-fourths of the value and two-thirds of the weight of freight moved within the United States (BTS, 2005). The ability to efficiently handle truck traffic is essential to the overall economic vitality of the nation.

Fueled by demand for all types of goods mainly due to a population and economic growth, truck traffic has been rapidly increasing in most urban and rural roadways throughout the United States. Transportation statistics expose the growing magnitude of this situation. Since 1970, truck travel in the United States, as measured in vehicle-miles of travel (VMT), has increased by 216%, whereas overall vehicle travel (total VMT) has increased by 137% (BTS, 2001). Forecasts of future freight flows indicate that this growth trend will continue. The volume of domestic freight is projected to increase by 87% between 1998 and 2020, while the volume of international freight is projected to increase by 107% during the same period (FHWA, 2001). This implies additional volume of trucks on the roadway systems in the nation.

Increasing truck traffic poses many challenges for the agencies that construct, operate, and maintain the transportation system. These include:

- Traffic congestion, especially where activities such as loading and unloading and queuing spill truck traffic onto public roadways;
- Safety hazards, especially where heavy trucks are mixed with light-duty vehicles;
- Deterioration of infrastructure, as increasing numbers of heavy vehicles reduce the useful life of pavement;
- Degradation of the environment resulting from increased emissions, particularly of pollutants such as nitrogen oxides (an ozone precursor) and particulate matter associated with diesel truck engines;
- Impediments to economic development, especially in areas where public opposition has arisen to truck intensive development such as truck terminals and intermodal yards;
- Losses in productivity due to congestion, which can delay critical shipments, increase costs, and affect manufacturing schedules or shipping deadlines.

Transportation agencies are increasingly faced with the dilemma of needing to accommodate truck traffic to sustain economic growth and development, while minimizing the negative impacts of increasing truck traffic. The primary mission of commercial vehicle operations by public agencies is the safe and efficient movement of goods. Efficiency is assured when there is minimum interference by the agencies, only to the degree necessary to ensure the safety of the traveling public.

For the movement of goods to function properly, a set of clear guidelines and regulations should be consistently enforced. Regulations cover a large number of parameters that are necessary for safety, infrastructure preservation, security, and the environment, including commercial vehicle weight, maximum dimensions, speed, exhaust, and a multitude of other factors. Other regulations govern commercial drivers, such as work hours and correct licensure.

Overweight vehicles trigger serious safety and roadway maintenance challenges. A relatively small number of grossly overweight vehicles are causing an exorbitant amount of damage to the roadways resulting in excessive pavement rehabilitation costs that could be avoided if the compliance rate were improved. While truck traffic continues to grow, enforcement resources are shrinking. As such challenges have increased in importance, public agencies have begun to develop plans and implement strategies to address them. Weigh stations have been installed to ensure that commercial vehicles abide by weight limitations and other regulations. However, it is practically impossible to stop, inspect, and test every commercial vehicle that travels through an area in order to ensure that it meets all safety, security, and environmental regulations. Thus, traditional enforcement models have centered on selecting a random number of commercial vehicles for inspection at weigh stations. In this instance, commercial vehicles are taken out of the traffic flow and asked to park at the weigh station for inspection.

This enforcement method has been proven to be inefficient for several reasons. First, a substantial amount of time is lost in the inspection process, which must be recouped by the commercial vehicles. Of course, these costs are eventually borne by taxpayers, not to mention the impact of these delays on interstate commerce. Second, queuing commercial vehicles at weigh stations with their associated acceleration and deceleration maneuvers cause a significant increase of traffic congestion, accidents and air pollutants in the region around weigh stations. Third, large commercial vehicles stopping at weigh stations require substantial space for parking, especially in the vicinity of urban areas where space may not be available at any cost. And fourth, with the current and forecasted budgetary shortfalls, enforcement agencies can no longer afford to employ additional enforcement personnel and equipments for accommodating rapidly increasing truck traffic.

With the expected increase in the number of trucks on our roadways, coupled with modern logistic practices and the rapid growth in e-commerce, highway traffic flow characteristics may change significantly. This would require the application of new and innovative technologies to facilitate the monitoring of commercial vehicles in conformance with regulations governing weight, dimensions, and safety, as mandated by federal and state regulations.

As a leading state in the deployment of advanced technologies for commercial vehicle operations, California has adopted and is operating modern weigh-in-motion (WIM) systems that allow legal trucks to bypass weigh station without stopping, leading to greater benefits for goods movement and commercial vehicle enforcement. Even the WIM systems installed at fixed weigh stations expose an additional set of deficiencies. Some commercial vehicles that exceed safe weight limits often bypass the fixed weigh stations. With an increased need for enhanced safety and infrastructure preservation as well as the current budgetary limitations, there is now a huge demand for proven advanced compliance technologies to assist enforcement agencies.

These new compliance technologies come in the form of technologies used to provide fully automated weigh stations, referred to as '*virtual weigh stations*'. Virtual weigh stations may be placed at strategic locations, both on the mainline of roadways and at selected bypass routes, to enable enforcement agencies to plan the optimal use of their resources. Virtual weigh stations would use existing WIM system in combination with Automatic Vehicle Identification (AVI) technologies so that can monitor and communicate violations in an unattended manner. By automatically detecting attempts of overweight vehicles to bypass weigh stations, deployment of virtual weigh stations will lead to improved enforcement and more efficient utilization of enforcement resources. By removing overweight vehicles from our roadways, this new system ultimately will help public agencies achieve the goals of protecting infrastructure and enhancing safety and air quality while minimizing the delays at weigh stations for inspections.

California Department of Transportation (Caltrans) recently initiated a program aiming at the development of a virtual weigh and compliance system (VWCS) for better commercial vehicle monitoring and weight enforcement. For the successful development of the VWCS, it is first necessary to enhance knowledge baseline associated with the virtual WIM systems. This can be achieved by evaluating the current state of the practice that could aid enforcement agencies in the selection of appropriate operating methods and technologies. As an initial step of the program, Caltrans has teamed up with the Institute of Transportation Studies at the University of California at Irvine to document a synthesis for successful implementation of the virtual weigh and compliance systems.

1.2 Synthesis Objective and Scope

The objective of this synthesis is to document recent efforts and technologies associated with the automated monitoring and enforcement of commercial vehicles and to present the current state of the practice in dealing with overweight vehicle enforcement using advanced WIM technologies. To accomplish this goal, the synthesis identifies:

- Historical background and current state of commercial vehicle enforcement practices,
- Emerging new technologies and methods applicable to upgrade existing commercial vehicle weight enforcement methods,
- Basic concept of the virtual weigh and compliance system considered by the Caltrans,
- Key considerations when implementing the VWCS, and
- Strategies for successful implementation of the VWCS.

The information presented in this synthesis was based on literature survey related to weight enforcement practices and technologies. The literature was collected from a number of sources, including academic journals, government reports, and online materials. These are cited as references in the report.

1.3 Organization of Report

This synthesis is organized to provide better understanding of virtual WIM systems. It begins by reviewing historical background of vehicle weight enforcement using WIM technologies, continues with a discussion of the basic concept and benefits of virtual weigh and compliance systems with case studies conducted elsewhere in the U.S. Key factors that should be considered when developing and deploying the VWCS are then presented, which is followed by the strategies for successful VWCS implementation. Finally, the synthesis draws conclusions with a summary of findings identified in this research.

Section two includes historical background and evolution of weigh-in-motion systems for highway use, and reviews current commercial vehicle operations and enforcement practices in California. Emerging technologies applicable to improve existing enforcement methods are also included in this chapter.

Section three presents the basic concept of virtual weigh and compliance systems considered in California. Key system components and their functions are discussed, and expected benefits of the use of advanced WIM technologies are explained along with empirical evidence. This section also includes some case studies of other states directed toward accommodating advanced WIM technologies.

Section four identifies key factors that must be considered when implementing virtual weigh and compliance systems. These include physical requirements for WIM facility location, standard specification of system components, data requirements and accuracy, operational and maintenance issues, cost factors, and institutional and legal issues.

Section five focuses specifically on those strategies selected for successful implementation of the VWCS and presents the reasons for their selection. It also details the types of challenges for which these strategies are being considered.

Section six presents the conclusions of the report, including a summary of research findings and suggestions for the practical application of the information in the report.

Five appendices are provided. Requirements for commercial vehicle operations in California are summarized in Appendix A. A location map and list of existing commercial vehicle enforcement facilities currently operated in California is presented in Appendices B and C, respectively. Graphical representation and lists of weigh station bypass sites are also provided in Appendices D and E, respectively.

2. Review of Commercial Vehicle Operations and Enforcement

By the American Society of Testing and Materials (ASTM), 'Weigh-in-Motion (WIM)' is defined as the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination of these, by measurement and analysis of dynamic vehicle tire force (ASTM, 1994). Consequently, ASTM defines a WIM system as a set of sensors and supporting instruments, which measures the presence of a moving vehicle and the related dynamic tire force at specified locations with respect to time; estimates tire loads, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information.

As a weigh enforcement tool, a WIM system could be deployed on the ramp to a weigh station or on the mainline. In either case, based on a preset weight threshold, the WIM system typically sorts arriving trucks prior to entering a weigh station either on the mainline traveling at highway speeds or on off-ramps at reduced speed. Where truck volumes are low, static scales provide sufficient capacity to weigh most trucks passing through the facility. However, many weigh stations experience high volume of truck traffic that they do not have the capacity to weigh all trucks statically. In these cases, trucks that the WIM identifies as near the allowable weight limits are directed to the static scales, while all other trucks are allowed to bypass the weigh station. Such a bypass system has the potential to significantly improve the efficiency of commercial vehicle enforcement agencies that operate weigh stations, as well as the trucking companies that deliver the goods. Even in the event of weigh station closure, weight data could still be collected continuously by the WIM unit if it is deployed on the mainline.

When considering the development of advanced WIM systems, it is important to understand historical background behind the development of existing WIM systems. This section provides a brief overview of the evolution of WIM systems for highway use, including significant changes made in latest version of the industry standard for WIM systems –ASTM 1318-02: Standard Specification for Highway Weigh-in-Motion (WIM) Systems, and its implications for WIM vendors and users. This is followed by reviewing the current state of commercial vehicle enforcement practices in California. Emerging technologies and new methods for weight enforcement are also included in this section.

2.1 Historical Background and Evolution of WIM Systems

The first formal effort to develop a WIM system appeared in literature is an experiment of WIM equipment conducted in 1951 by the U.S. Bureau of Public Roads (BPR) in cooperation with the Virginia State Department of Highways and the Williams Construction Company (Mettler Toledo, 2002). The experiment involved the construction of a pit and slab for the load cells and electrical equipment to test WIM equipment on the Henry G. Shirley Memorial Highway. The experiment near the intersection with U.S. 1 led to the conclusion that a good possibility exists for improving accuracy to the point that weighing trucks in motion will provide data that is as accurate as weighing trucks statically.

Other significant events related to WIM evolution are as follows:

- 1960s: The California Department of Transportation becomes actively involved with weigh-in-motion research.
- 1983: The first National Weigh-in-Motion conference held
- 1987: Long-term Testing of Pavement Program initiated in 1987 as part of the Strategic Highway Research Program
- 1990: The first version of ASTM 1318 Standard Specification for Highway Weigh-in-Motion (WIM) Systems was published.
- 1994: Minor revisions were made to ASTM 1318.
- 1996: The first mainline electronic weight and credential screening system was installed in California.
- 1997: The U.S. DOT Federal Highway Administration (FHWA) published "Best Practices Weigh-in-Motion Handbook," written by the Center for Transportation Research and Education at Iowa State University.
- 2002: A second version of the ASTM 1318 Standard Specification for Highway Weigh-in-Motion (WIM) Systems was released.

The original edition of ASTM 1318 was published in 1990 in response to the need for a definition of performance standards for various types of WIM systems. Revisions to the standard were made in 1994. Extensive additional research and field experience identified the need for additional revisions, which were released in February, 2002.

Specifications for weigh stations and traffic data collection sites are typically written by State Department of Transportation Engineering Divisions. Weigh-in-Motion installation, performance, and acceptance test criteria are included in these specifications. ASTM 1318 has allowed state highway engineers to reference performance and installation practices that are now familiar to equipment vendors and contractors. Some state specifications call out ASTM 1318 sections, while others incorporate portions of ASTM 1318 into their specifications. ASTM 1318 has also provided a common performance standard from which equipment vendors and contractors can work, helping to prevent a proliferation of different systems supplied to different states.

The growth of the installed WIM base in a variety of environments has provided insight into the needed revisions to ASTM 1318. The major changes in ASTM 1318 released in 2002 and their impacts on WIM vendors and users are summarized in Table 1. The most significant changes have been driven by

- The growth of mainline weight sorting systems, which require that weight enforcement-related WIM systems function at higher speeds.
- Users experiencing inconsistent weight data accuracy stemming from temperature variations, which has compromised the accuracy of collected vehicle weight data.
- The realization that vehicles are not always centered over the weighing platform, and that weight readings from off-center vehicles can have significantly lower accuracy.
- Experience and research indicating that pavement smoothness and durability is critical to long-term accuracy of WIM systems as well as safe operations.

Table 1. Key Changes in ASTM 1318 and Their Impacts on Vendors and Users

Revision to ASTM 1318	Reason	WIM Vendor Impact	WIM User Impact
Increase in Type III operational speed to 80mph	Growth of mainline weight enforcement WIM	Need to ensure accuracy at higher speeds	More options on placement of WIM equipment
Suggestion to user to specify that sensor accuracy is met across 20°F to 120°F range	Finding that some sensors lose weighing accuracy at the high and low end of the temperature range	Need to ensure accuracy via data conditioning or other methods	Improved quality of weight data
Requirement to certify sensor accuracy across width of weighing platform	Experience that some sensors are less accurate for off-center applied loads	Need to design systems to maintain accuracy across width of weighing platform	Improved quality of weight data
Increase of smooth and level pavement surface to 200 ft in advance of WIM sensor (100 ft beyond sensor)	Experience that greater distance of smooth pavement increases WIM weighing accuracy	None	No net change to smooth pavement length, only WIM repositioning
Recommendation that WIM system be installed into Portland Cement concrete pavement only	Experience shoed improved accuracy and durability when using PCC vs. asphalt	None	Increase in initial construction cost with increase in system life and accuracy
Increase of minimum road width in advance of and beyond WIM system to 12 ft wide		None	Increase in construction cost
Increase in maximum allowable cross slope to 3° for Type I, II, and III		None	Decrease in construction cost
Data communication link between the WIM site and a remote host computer, allowing for remote setting adjustment	Prevalence of sites where operator is not near the WIM system and where users desire to change settings	Hardware and software requirement	Increased WIM functionality
Addition of vendor Type-Approval Test	Cases where WIM system could not meet accuracy requirements	Need to provide Type-Approval Test compliance	Assurance of WIM system capability
Acceptance test includes non-centered platform loading	Experience that some sensors are less accurate for off-center applied loads	Need to design systems to maintain accuracy across width of weighing platform	More accurate data under actual range of use conditions
Acceptance test does not require on-site static weights, but rather pre-weighed vehicles		None	Lower testing cost when no on-site static scales exist

Source: Mettler Toledo, 2002

2.2 Current Commercial Vehicle Enforcement Practice in California

2.2.1 General Requirements for Commercial Vehicle Operations in California

"Commercial vehicle" is defined in California Vehicle Code Section 260 as a motor vehicle of a type used or maintained for the transportation of persons for hire, compensation, or profit or designed, used, or maintained primarily for the transportation of property. Any vanpool or passenger vehicles which are not used for the transportation of persons for hire, compensation, or profit are not included in the definition of commercial vehicles.

To operate commercial vehicles in California, the following documents must be carried and shown to enforcement personnel when requested:

- Drivers license documents and any related certificates.
- Registration documents (cab cards, permits, etc.).
- Proof of insurance.
- Special permits for oversize and overweight loads, if required.
- Hazardous materials shipping papers, if required.
- Fuel tax permits.
- Hours of service records (log book).
- Bills/Invoices etc. showing content and origin of agricultural products, if required.
- Proof of sales tax payment if applicable.

Commercial vehicle operators must comply with many of the applicable requirements listed in Appendix A.

2.2.2 Who must stop at Weigh Stations?

By California State law, any commercial vehicles entering and operating in California must stop for inspection of their size, weight and emissions at commercial vehicle enforcement facilities when signs are displayed requiring the stop. Commercial vehicle enforcement facilities are commonly called weigh stations or truck scales. These facilities are operated by the California Highway Patrol (CHP), not by Caltrans.

California Vehicle Code Section 2813 outlines who must stop at weigh stations and inspection stations as follows:

- **Code 2813: "***Every driver of a commercial vehicle shall stop and submit the vehicle to an inspection of the size, weight, equipment, and smoke emissions of the vehicle at any location where members of the California Highway Patrol are conducting tests and inspections of commercial vehicles and when signs are displayed requiring the stop. Every driver who fails or refuses to stop and submit the vehicle to an inspection when signs are displayed requiring that stop is guilty of a misdemeanor.*"

Highway pavement life depends upon the weight and frequency of the traffic carried. To illustrate the difference between cars and trucks, a road test sponsored by the American Association of State Highway Officials, established that it takes the passage of approximately 9,600 cars to equal the pavement damage caused by one legal 80,000 pound truck (CHP, 2001).

Based on a 1991 overweight vehicle fine schedule analysis, it is estimated that overweight vehicle alone increase the state highway system pavement maintenance and rehabilitation costs by $ 17,000,000 annually. If excessive weights were not controlled by the weigh stations, these figures would be substantially greater. The inspection program through weigh stations can also significantly increase the detection and apprehension of the impaired and fatigued commercial vehicle operator, consequently enhancing commercial vehicle safety.

For these reasons, the weight of commercial vehicles is strictly controlled by public agencies. Table 2 summarizes maximum allowable vehicle weight regulated in California (California Vehicle Code Sections 35550-35558).

Table 2. Maximum Allowable Commercial Vehicle Weight in California

	Unit	Maximum
Gross Weight	Vehicle Combination	80,000 pounds
Axle Weight	Single Axle	20,000 pounds
	Axle Group: - Less than 8’-6” between outer axles - 8’-6’’ and more between outer axles	 34,000 pounds 34,000 – 80,000 pounds

Source: California Department of Transportation, 2005

2.2.3 Facility Classification and Location

Based on primary function, staffing needs, size, location, and physical configuration, five classifications have been established to define the existing facilities for commercial vehicle enforcement (weigh stations): Class “A”, Class “B, Class “C”, and mini-sites (CHP, 2001). Currently there are 38 facility locations throughout the state with some locations having a facility in each direction of travel. There are a total of 53 facilities: 2 Class “A”, 17 Class “B”, 14 Class “C”, and 20 Class “D.” Additionally, there are 58 mini-sites. A map and list of the existing commercial vehicle enforcement facilities in California are presented in Appendices B and C, respectively.

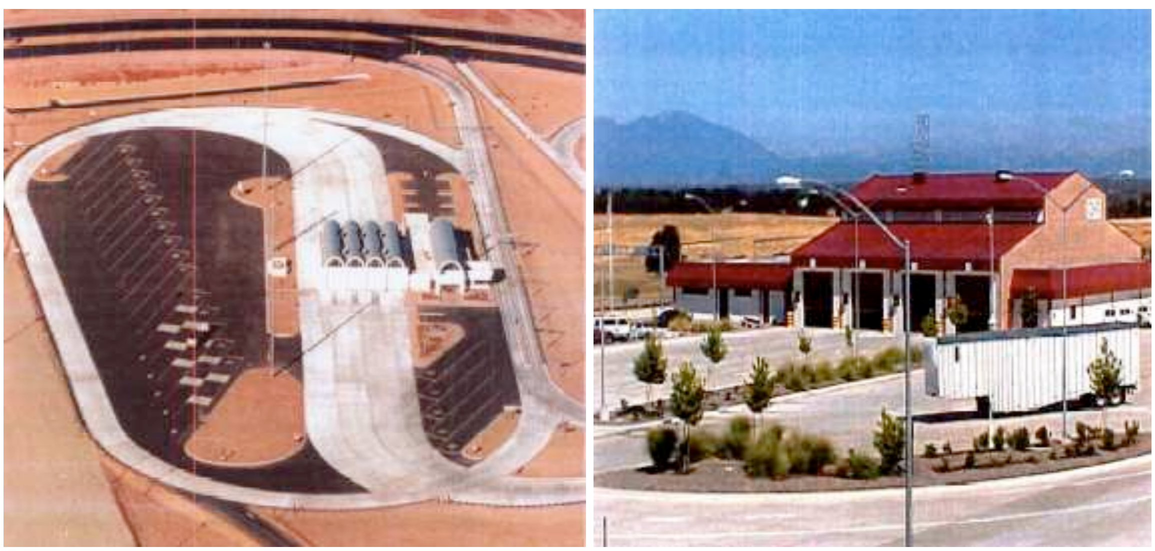
A. Class “A” and “B” Facilities

Class “A” facilities are located at strategic points of entry into the state, while Class “B” facilities are located along major highway routes. These facilities have independent CHP command identity, and normally operate 24-hours per day, 7-days per week. Class “A” and “B” facilities may be used by other state or local agencies as well as jointly used by bordering state representatives, such as the Air Resources Board, Board of Equalization, Department of Motor Vehicles, California Department of Food and Agriculture, and court clerk. Therefore, administrative office space should be included in the facility designed to accommodate allied agency use on a permanent of frequent basis. Accommodations and funding should also be included for the installation of the weigh stations.

Class "A" and "B" facilities generally have weigh-in-motion and static scales for the weighing of vehicles and cover areas for the inspection of vehicle equipment. The covered inspection area should be constructed with two or more bays (at least one designed without inspection pits). The number of bays is determined by the average daily truck traffic and projected long-term needs for the location. The facility should have an open storage area for legalizing loads, a parking area, and area to permit the turning of trucks for reweighing. These facilities are designed and staffed for a primary focus on the inspection of vehicle equipment and loads during all hours of operation.

Class "A" and "B" Facilities are intended to be operational 24-hours per day, 7 days per week. CHP staffing generally includes 1 lieutenant, 2 sergeants, 10 to 12 officers, 16-20 Commercial Vehicle Inspection Specialists, 1.5 clerks, and 1 maintenance worker and/or 1 janitor.

The following pictures depict a Class "A" facility and Class "B" facility, respectively.



(a) Class "A" Facility – Calexico (b) Class "B" Facility - Cottonwood

Figure 1. Pictures of Class "A" and "B" Facilities

B. Class "C" and "D" Facilities

Class "C" facilities are located at strategic points on major highway routes, while Class "D" facilities are located at strategic points on major and secondary highway routes. Operational hours of these facilities are based on such factors as the average daily truck traffic, peak truck traffic hours, and seasonal needs, normally operated up to 24-hours per day, 5 or 7 days per week.

Class “C” facilities should have static scales designed for vehicle weighing, areas for the inspection of vehicle equipment, open storage for legalizing loads, a parking area, and area to permit the turning of trucks for reweighing. Class “D” facilities also have static scales designed for the weighing of vehicles, but may have a limited open areas for the inspection of vehicle equipment. Accommodations and funding should be included for the installation of the mainline bypass system for facilities participated in this program.

Class “C” and “D” facilities are designed and staffed for a primary focus on the inspection of vehicle equipment and loads. The facilities not equipped with a covered inspection area and/or under-truck lighting should direct primary focus on vehicle inspection during daylight hours. During periods of darkness or inclement weather this focus would necessarily be redirected toward size, weight, and loading enforcement, as well as toward conducting Commercial Vehicle Safety Alliance Level II inspections of driver qualifications and topside vehicle equipment.

Class “C” and “D” Facilities are generally operational less than 24-hours per day, 5 or 7 days per week. These facilities are not “stand-alone” command facilities, and therefore are not staffed by managerial or supervisory personnel. The facilities are normally staffed with 2 to 6 officers. In addition, Class “C” facility staffing usually includes 1 to 3 commercial vehicle inspection specialists and 0.5 clerk. Class “C” and “D” facilities located in close proximity to Class “A” or “B” facilities become a portion of that command structure. Remaining facilities are under the direct command of the respective Division Special Services Commander and, in those instances where a sergeant has not been specifically assigned to the facility, are supervised by the Division commercial sergeant.

The following figure presents pictures of the Class “C” and “D” facilities.

(a) Class “C” Facility – E/B Antelop (b) Class “D” Facility – Keene

Figure 2. Pictures of Class “C” and “D” Facilities

C. Mini-Sites

Mini-sites are designed as safe locations for portable scale operations. Mini-sites are strategically located on highways with an above-average volume of commercial vehicle traffic to screen vehicles which may use bypass routes to avoid commercial facilities. There are no above-ground facilities at mini-sties. Mini-sites should be designed to accommodate portable scales and should include an area designed for truck inspections. The sites may be randomly used by either platform scale personnel or Mobile Road Enforcement officers.

Operational equipment for mini-sites is normally transported to the site. Traffic is directed into the site by traffic control signs and appropriate roadway markings. Mini-site locations are under the command of the facility commander or Division Special Services Commander who has supervisory responsibility for the officers using the site. Pit scales are included within the definition of the term “mini-site” since they are simply considered to be an earlier version of the mini-site.

Mini-sites are not staffed facilities. Personnel as well as needed operational equipment are transported to the site during hours of operation. Mini-sites are generally operated by Mobile Road Enforcement officers. Figure 3 illustrates a picture of a mini-site located at Southbound 99 North of Riego Road.

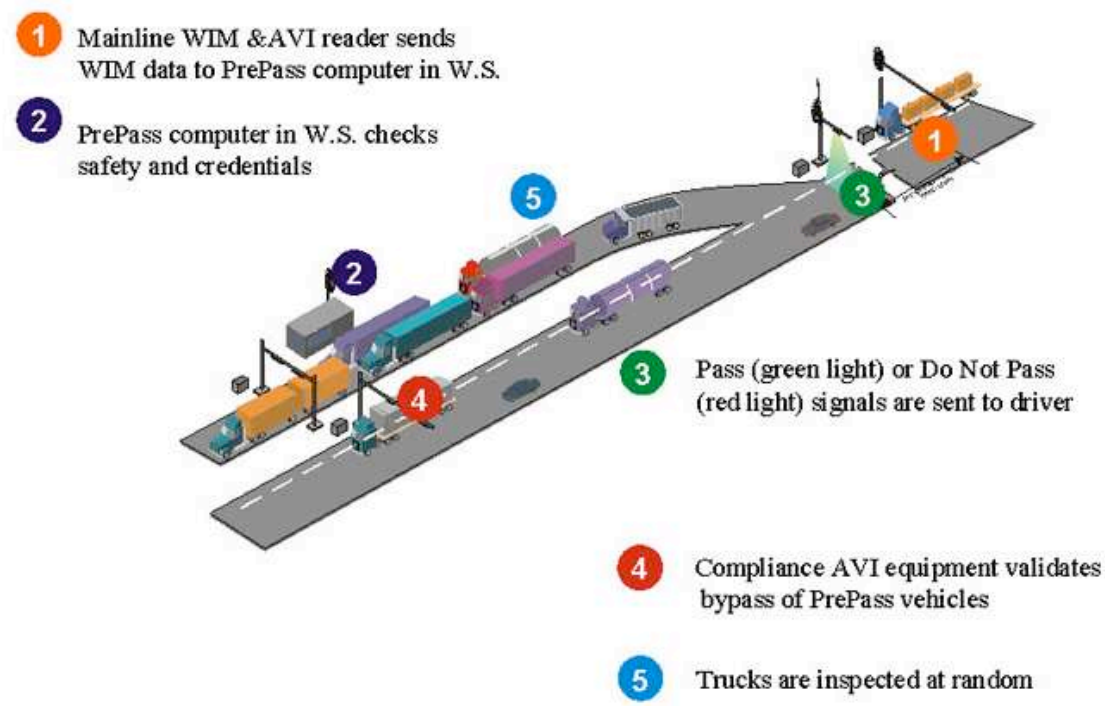
Figure 3. Pictures of Mini-Site Located S/B 99 North of Riego Road

2.2.4 Weigh Station Bypass Program: 'PrePass™'

For the purpose of enhancing the operational efficiency of weigh stations for commercial vehicle weight enforcement, California developed a weigh station bypass system called 'PrePass™' in 1994. The weigh station bypass system is an automated system allowing heavy vehicles that are registered in the program to legally bypass open weigh stations.

The bypass system requires carriers to obtain special transponders used for communication between computers in the weigh stations and the vehicles. If all requirements for weight, size, safety, etc. are met, the driver receives a green signal that allows the vehicle to bypass the weigh station. Otherwise, the driver receives a red signal which requires the vehicle to go through the weigh station. All heavy vehicles that are not registered in PrePass™ are required to pass through weigh stations that are open. The system has been in operation in California since 1994. Currently, there are 36 weigh stations across California deploying the PrePass™ technology (Caltrans, 2005). The location map of the California PrePass™ sites and the list including the location and status of all bypass sites are presented in Appendices D and E, respectively.

The following graphic diagram shows the overview of the PrePass™ system that explains basic operating process of the system.



Source: California Department of Transportation, 2005

Figure 4. Overview of the PrePass™ system

2.3 Emerging Technologies

The PrePass™ systems have the mainline WIM capability that automatically pre-screen commercial vehicles traveling at highway speeds up to 80 mph. By allowing for static scale to be used for only the most likely violators, the systems facilitate overweight vehicle enforcement activities, being effective especially in the region with high volume of truck traffic. However, the systems are limited to the transponder-equipped vehicles, still required for trucks without transponder to stop at the weigh stations for inspection.

Recent advances in sensor and communication technologies lead to the emergence of advanced WIM technologies that have the potential for further improvement of existing weigh station operations. New technologies involving WIM systems include Automated Vehicle Identification systems. Integration of AVI with WIM technology creates new methods of screening commercial vehicles traveling on the mainline at high speeds in an unattended mode for their conformity to weights, dimensions and other regulations. Newer forms of technology also include a photo WIM system, mainline automated clearance system, and new WIM scale developed by Omni Weight Corporation known as the Safe Load WIM.

2.3.1 Automated Vehicle Identification Systems

Automated vehicle identification (AVI) is the application of sensor technologies to make more informed screening decisions at weigh station for commercial vehicles. It may be described as containing three components, the transducer, a signal processing device, and a data processing device. The transducer detects the passage or presence of a vehicle or its axles. The signal processing device typically converts the transducer output into an electrical signal. The data processing device usually converts the electrical signal to traffic parameters.

A sensor is a key component of any AVI systems. Depending on the installation location, sensors are categorized into two types, intrusive and non-intrusive (Mimbela and Klein, 2000). Intrusive sensors are those that require the installation of the sensor directly onto or into the road surface, including inductive loops, magnetometers, microloop probes, pneumatic road tubes, piezoelectric cables and other WIM sensors. On the other hand, non-intrusive sensors are mounted overhead or on the side of the roadway. The video image processors, microwave radar, active and passive infrared sensors, and ultrasonic sensors fall in this category.

In Table 3, the strengths and weaknesses of the sensors are summarized with respect to installation, parameters measured, performance in inclement weather and variable lighting conditions, and suitability for wireless communication. The types of data typically available from each sensor technology are listed in Table 4, including coverage area, communication bandwidth requirements, and purchase costs. Several technologies are capable of supporting multiple detection zone applications with one or a limited number of units. These devices may be cost effective when larger numbers of detection zones are needed to implement the traffic management strategy.

Inductive loop detectors have been most widely used to monitor traffic flow and control signals because of their relatively low cost, maturity, aesthetics, and policy issues. Some of the overhead technologies, such as video image processing and multi-zone microwave and infrared sensors, may replace several inductive loops since the higher cost of the aboveground sensors can offset the costs associated with installing and maintaining multiple inductive loops. In addition, most overhead sensors have the advantages over intrusive sensors of being compact and not roadway invasive, thus making installation and maintenance relatively easy

AVI technologies have already been used to a limited extent in some locations, but it is expected that most WIM systems will eventually be integrated with this new technology. Properly implemented, electronic screening using AVI results in significant improvement of weigh station operations in a cost effective manner.

Table 3. Strengths and Weaknesses of Sensor Technologies

Technology	Strengths	Weaknesses
Inductive Loop	▪ Flexible design to satisfy large variety of application ▪ Mature, well understood technology ▪ Provides basic traffic parameters (e.g, volume, presence, occupancy, speed, headway, and gap) ▪ High frequency excitation models provide classification data	▪ Installation requires pavement cut ▪ Decreases pavement life ▪ Installation and maintenance require lane closure ▪ Wire loops subject to stresses of traffic and temperature ▪ Multiple detectors usually required to instrument a location
Magnetometer (Two-axis fluxgate Magnetometer)	▪ Less susceptible than loops to stresses of traffic ▪ Some models transmit data over wireless RF link	▪ Installation requires pavement cut ▪ Decreases pavement life ▪ Installation and maintenance require lane closure ▪ Some models have small detection zones
Magnetic (Induction or search coil mangetometer)	▪ Can be used where loops are not feasible (e,g. bridge decks) ▪ Some models installed under roadway without need for pavement cuts ▪ Less susceptible than loops to stresses of traffic	▪ Installation requires pavement cut or tunneling under roadway ▪ Cannot detect stopped vehicles
Microwave Radar	▪ Generally insensitive to inclement weather ▪ Direct measurement of speed ▪ Multiple lane operation available	▪ Antenna beamwidth and transmitted waveform must be suitable for the application ▪ Doppler sensors cannot detect stopped vehicles
Infrared	▪ Active sensor transmits multiple beams for accurate measurement of vehicle position, speed, and class ▪ Multizone passive sensors measure speed ▪ Multiple lane operation available	▪ Operation of active sensor may be affected by fog when visibility is less than >>20 ft or blowing snow is present ▪ Passive sensor may have reduced sensitivity to vehicles in its field of view in rain and fog

Table 3. Strengths and Weaknesses of Sensor Technologies (Continued)

Ultrasonic	▪ Multiple lane operation available	▪ Some environmental conditions such as temperature change and extreme air turbulence can affect performance. Temperature compensation is built into some models. ▪ Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds
Acoustic	▪ Passive detection ▪ Insensitive to precipitation ▪ Multiple lane operation available	▪ Cold temperatures have been reported as affecting data accuracy ▪ Specific models are not recommended with slow moving vehicles in stop and go traffic
Video Image Processor	▪ Monitors multiple lanes and multiple zones/lane ▪ Rich array of data available ▪ Provides wide-area detection when information gathered at one camera location can be linked to another	▪ Inclement weather, shadows, vehicle projection into adjacent lanes, occlusion, day-to-night transition, vehicle/road contrast, and water, salt grime, icicles, and cobwebs on camera lens can affect performance ▪ Require 50-to 60-ft camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement ▪ Some models susceptible to camera motion caused by strong winds ▪ Generally cost-effective only if many detection zones are required within the field of view of the camera

Source: Klein, 2001.

Table 4. Traffic Sensor Output Data, Bandwidth, and Cost

Technology	Output data					Multiple Lane, Multiple Detection Zone Data	Communication Bandwidth	Sensor Purchase Cost[1]
	Count	Presence	Speed	Occu-pancy	Classifi-cation			(Each in 1990 $)
Inductive Loop	X	X	X[2]	X	X[3]		Low to moderate	Low[9] ($500 to $800)
Magnetometer (Two-axis fluxgate)	X	X	X[2]	X			Low	Moderate[9] ($1100 to $6,300)
Magnetic (Induction or search coil)	X		X[2]	X			Low	Low to Moderate[9] ($385 to $2000)
Microwave radar	X	X[4]	X	X4	X[4]	X[4]	Moderate	Low to moderate ($700 to $3300)
Infrared	X	X	X[5]	X	X[6]	X[6]	Low to moderate	Low to high (passive:$700 to $1200; Active:$6500 to14000)
Ultrasonic	X	X		X			Low	Low to moderate (pulse model: $600 to $1900)
Acoustic array	X	X	X	X		X[7]	Low to moderate	Moderate ($3100 to 8100)
Video Image Processor	X	X	X	X	X	X	Low to high[8]	Moderate to high ($5000 to $26000)

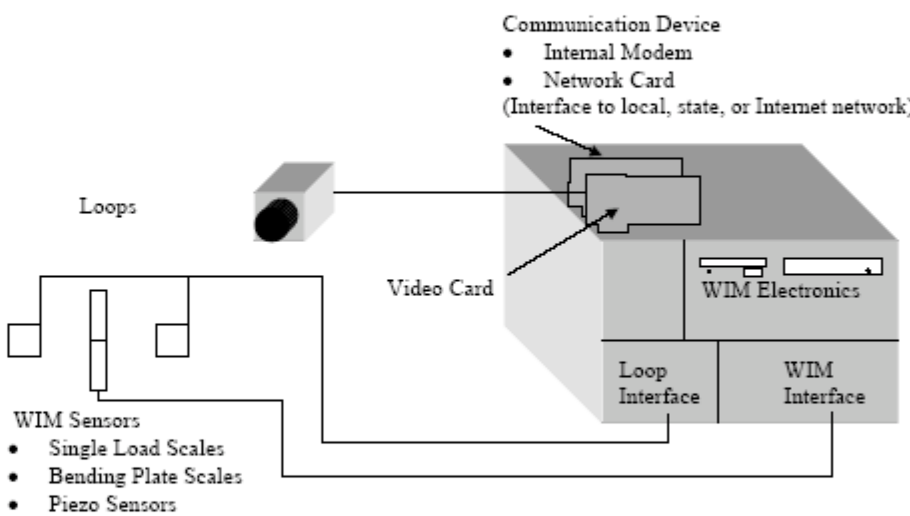
Note: 1. Installation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution as discussed in the text
Speed can be measured by using two sensors a known distance apart or by knowing or assuming the length of the detection zone and the vehicle
With specialized electronics unit containing embedded firmware that classifies vehicles
From microwave radar sensors that transmit the proper waveform and have appropriate signal procession
With multi-detection zone passive or active mode infrared sensors
With active mode infrared sensor
Models with appropriate beam forming and signal processing
Depends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the traffic management center.
Includes underground sensor and local receiver electronics. Receiver options are available for multiple sensor, multiple lane coverage.

Source: Klein, 2001

2.3.2 Photo WIM Systems

Dramatic improvement in video sensor technology and computing capability leads to the development of photo WIM systems. In fact, the use of video technology in combination with WIM is a concept that has been in existence since the mid-1980's and expanded considerably in recent years. The future potential of this technology is extensive.

As shown in Figure 5, a photo WIM involves the merging of two existing technologies: WIM and photo enforcement. The primary function of photo WIM systems is to detect vehicles that are of interest to the weight enforcement or planning agency, and to capture an image of those vehicles. Photo WIM operates in a similar fashion to photo radar or red light camera systems. Photo WIM systems can be installed in mainline or remote locations in either a permanent or portable application to monitor commercial traffic at a particular location in the road network. WIM sensors are used to measure vehicle weights and dimensions and a camera is used to capture and store a photographic image of the vehicles of interest. If digital images are used, the images can be immediately communicated electronically to a central office for real time deployment of enforcement personnel.



Source: Koenderink, et al., 2000.

Figure 5. The Overview of Photo Weigh-in-Motion system

Photo WIM can be used to augment permanent weigh station operations by providing images for mainline WIM pre-screening systems, monitoring vehicle compliance to WIM sorter traffic signals and traffic signs, and for monitoring weigh station evasion routes. Photo WIM may also be deployed in conjunction with mobile and remote weight enforcement as a pre-screening system, or as an automated stand alone monitoring system on remote routes. Data collected by photo WIM can provide weight enforcement agencies with a visual record from which to engage in discussions with particular carriers detected as chronic violators, or to assign preferred carrier status. Photo WIM may also be deployed in support of transportation planning activities to assist traffic engineers to evaluate future capital developments or help road asset managers plan preservation programs across specified segments of the road infrastructure. Other applications of photo WIM include urban weight enforcement and concentrated haul road weight enforcement.

With the increasing limitations on budgets for highway construction, maintenance and planning, the many applications of photo WIM provide transportation authorities with the enabling technology to significantly enhance the enforcement of commercial vehicle weights and dimensions, and protect the highway infrastructure in the most efficient manner.

2.3.2 Mainline Automated Clearance Systems

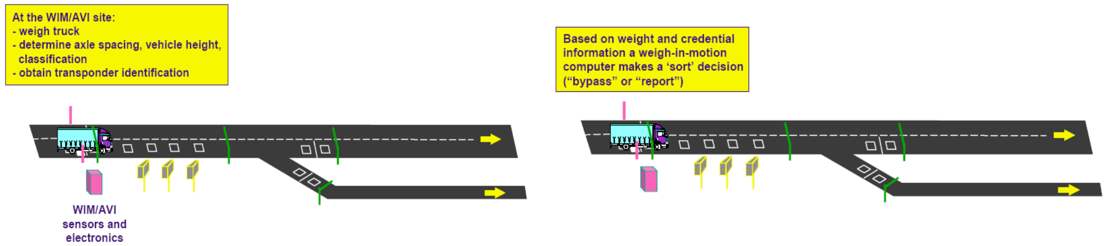
Advance in WIM technologies also provides enforcement agencies with additional capabilities associated with commercial vehicle monitoring and enforcement. Developed as a key component of the U.S. DOT's Intelligent Transportation Systems for Commercial Vehicle Operations (ITS/CVO) program, Mainline Automated Clearance Systems (MACS) can more efficiently monitor trucks' compliance with other regulations related to licensing and registration, permits, taxation, and safety, as well as size and weight regulations, as identified in Appendix A (McCall, et al., 1998).

Electronic screening through the MACS utilizes a vehicle-mounted transponder to detect and transmit a unique vehicle identification number or other regulatory information, as defined by the screening system requirements, to a stationary transceiver which relays the data to a local computer at the weigh station. The transceiver may also transmit to the vehicle a message to direct the operator to enter the weigh station or to bypass it. In electronic screening, Dedicated Short Range Communications (DSRC) is used to identify the vehicle, store and transfer other screening data, and signal the driver of the pull-in decision. Additionally, electronic Data Interchange (EDI) may be used to transmit safety and credentials history data, or snapshot data, from the information infrastructure to the roadside systems to assist in the screening decision.

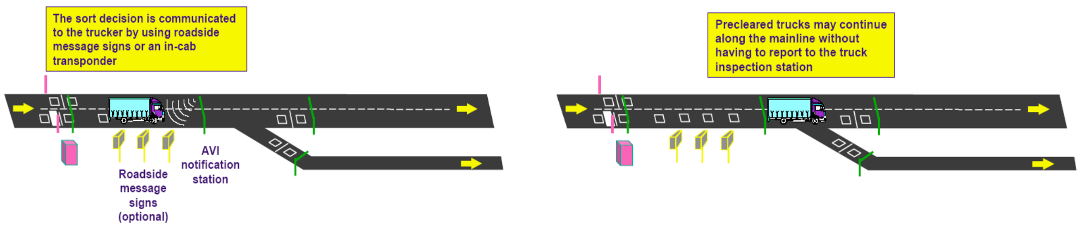
The system consists of a roadside AVI reader and WIM scale upstream of the weigh station. The reader and scale capture information about transponder-equipped trucks as they pass, including their identity, weight, and other regulatory information. Trucks that are in compliance are automatically signaled to bypass the station, while all other trucks are signaled to pull in to the weigh station unless the station is closed.

With mainline automated clearance systems, commercial vehicles can be monitored at highway speeds and asked to stop at the weigh station only when there is a need to statically weigh the vehicle. The truck would use the right-hand lane and using a combination of WIM sensors and AVI technology to determine whether the truck would need to bypass the static scale or to report to the static scale. Overhead signals or roadside sings notify the truck driver to let them know whether or not to bypass the static scale.

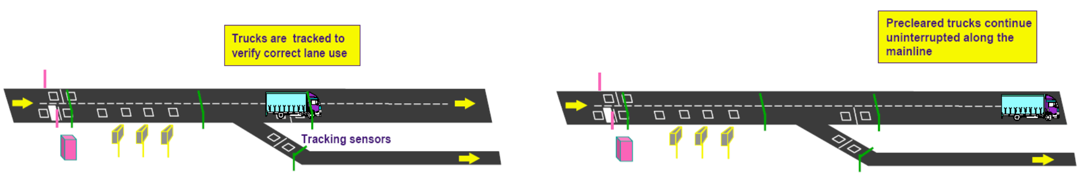
Figure 5 presents the basic concept of the mainline screening WIM systems.



(a) Detection of Vehicle at the WIM/AVI site



(b) Sort Decision and Report to the Truck



(c) Verification and Truck Bypass

Source: International Road Dynamics, 1998.

Figure 6. Truck Bypass Concept in Mainline Screening WIM Systems

2.3.4 Omni Weight Corporation Safe Load System

New form of WIM scale, known as the Safe Load WIM, has been developed by the Omni Weight Corporation. The Safe Load System is a dynamic scale automated truck weigh station developed under ASTM guidelines as a Type III and IV WIM system. The system has several benefits of saving capital cost in installation by not requiring concrete slabs for the WIM sensors, providing weighing and classification software in one element, and providing a maintenance-free rugged element without load bearing sensors. The system has been installed on the Smart Road in Blacksburg, Virginia, and being monitored by the Virginia Tech Transportation Institute (Katz and Rakha, 2002).

3. The Concept of Virtual Weigh and Compliance Systems

The availability of advanced WIM technologies in conjunction with improved sensor and communication technologies had lead to the development of virtual (unattended) weigh stations. Virtual WIM systems provide enforcement agencies with a cost-effective tool to monitor and enforce truck weights on bypass or secondary routes as well as major highways, and new opportunities for easily accommodating increased truck traffic volumes while significantly reducing the costs of expanding the physical weigh stations.

This section presents the basic concept of virtual weigh and compliance systems considered in California. Key system components and their functions are described. Expected potential benefits of the virtual weigh and compliance systems are discussed along with empirical evidence. Case studies of other states directed toward accommodating advanced WIM technologies are also included in this section.

3.1 Basic Concept of Virtual Weigh and Compliance Systems

Depending on the traffic characteristics and enforcement objectives, in general, a variety of weight enforcement strategies can be considered and WIM systems vary widely in functionality and level of complexity. Weight enforcement options to be applicable for different traffic conditions and enforcement levels include

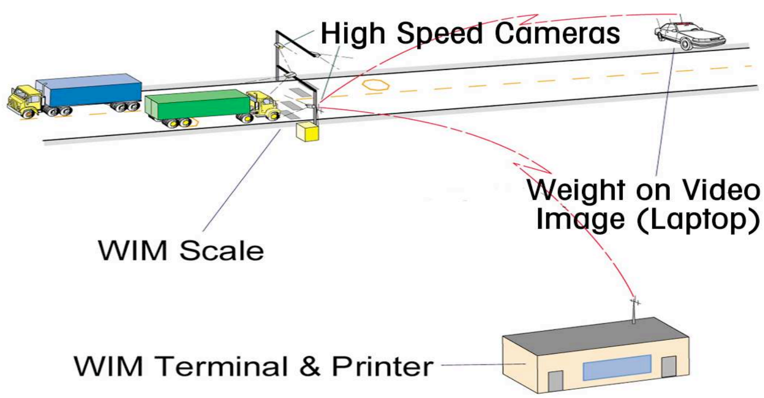
- Portable Scales
- Virtual Weigh Stations using WIM
- Fixed Facility Weigh Stations with Static Scales
- Fixed Facility Weigh Stations with Ramp WIM
- Fixed Facility Weigh Stations with Mainline WIM

Traditionally, secondary roads and bypass routes have been randomly monitored by mobile enforcement officers. Given the time consuming process of weighing trucks with portable scales, there is a need to pre-screen which trucks should be weighed statically in order to maximize a mobile enforcement officer's effectiveness. To address the need for low cost, continuous monitoring of lower volume secondary roads or bypass routes, a "virtual weigh station" can be used.

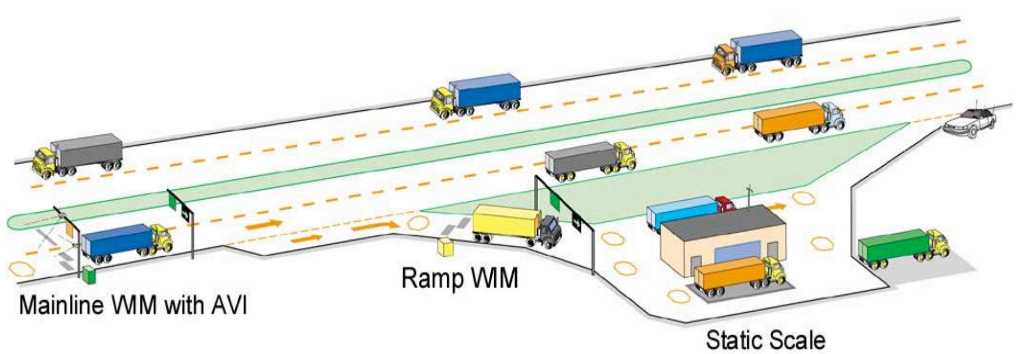
Designed to help provide effective truck weight enforcement on secondary and bypass roads as well as highways, the virtual weigh station is a new method for overweight vehicle enforcement that integrates WIM technology with other technologies including AVI, video sensor, and wireless communication. It operates in an unattended mode, weighs and classifies vehicles, and retains images of weight violators along with their weight data, time and date information.

A weigh-in-motion system is installed across the lanes of a bypass road. As vehicles cross the WIM scale, a photo overview image of the vehicle including license plate of the vehicle, are captured if the vehicle is overweight. Images and weight data are stored for remote retrieval, or instantly transmitted via a wireless communication network to a laptop computer in a nearby patrol car. Another option is wireless or landline transmission to a weigh station located nearby the bypass road, or to a centralized traffic control center. The weigh station or traffic control center can then dispatch an enforcement officer to intercept the violating vehicle (See Figure 5-(a)).

As shown in Figure 5- (b), the virtual weigh station can be also applied to complement existing fixed WIM sites. It can automatically pre-weigh vehicles and transmit a photo image with the vehicles' weights and/or dimensions to an enforcement officer downstream of the WIM or to a central facility. Based on vehicle information, vehicles suspected of being overweight can be either stopped and weighed using portable scales or can be directed to the nearest fixed facility weigh station with static scales for more accurate weighing, while allowing vehicles in compliance to continue on their way. The use of virtual weigh stations would significantly improve existing bypass systems as in the PrePass™ program by allowing even trucks without transponders to bypass the fixed weigh station if they satisfy enforcement requirements.



(a) Virtual Weigh Station on Bypass Roads



(b) Virtual Weigh Station on Fixed Weigh Station

Source: Mettler Toledo, 2005

Figure 5. Typical Configuration of Virtual Weigh-in-Motion Systems

3.2 System Components and Functions

Designed to realize unattended weight enforcement of overweight trucks, a virtual weigh station consists of a set of components that must perform together for the system to work successfully. These include WIM sensors, video image processing system, wireless communication and portable communication devices, and WIM cabinet. Depending on the applications, additional options can be added, such as an interface to a static scale, message signs and over-height detectors. Key system components and their functions of a virtual WIM system are as follows. These are described in detail in next chapter.

3.2.1 WIM Sensors

A WIM system functions to provide preliminary dynamic weight readings which can be used to pre-clear and automatically sort vehicles. According to enforcement objectives, WIM systems can vary widely in functionality and level of complexity. The most important component of WIM systems is a WIM scale that measures the gross vehicle weight of a vehicle as well as the portion of this weight that is carried by each wheel assembly, axle and axle group on the vehicle. Several types of WIM scales are currently available, including single load cell scales, bending plate scales, and piezoelectric, quartz and fiber optic sensors (portable and permanent). The categories of WIM systems are listed in Table 5 along with the corresponding data each provides. Other components in WIM systems include inductive loop sensors to detect approaching vehicles, electronics to interpret the signals, a computer for data processing and storage, and a computer display screen. At weigh stations, the ultimate goal of the WIM system is to enhance weight enforcement operations by enabling low to high speed dynamic weighing to complement static weighing.

3.2.2 Video Image Processing Systems

Video image processing systems typically consist of one or more cameras, a microprocessor-based computer for digitizing and processing the imagery, and software for interpreting the images and converting them into traffic flow data. As vehicles go across the WIM scale, the systems automatically capture a photo overview image of the vehicle of interest and extract information for commercial vehicle operations. If the vehicle is overweight, the overview image of the vehicle with weight and speed data is stored for remote retrieval, or instantly transmitted via a wireless connection to a laptop computer in a nearby patrol car. Conceptual video image processing for vehicle identification is presented in Figure 6.

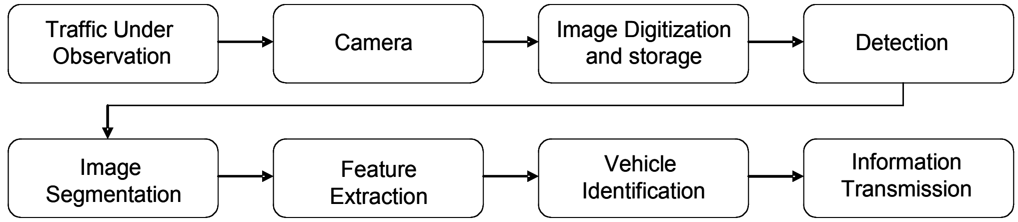


Figure 6. Conceptual Video Image Processing for Vehicle Identification

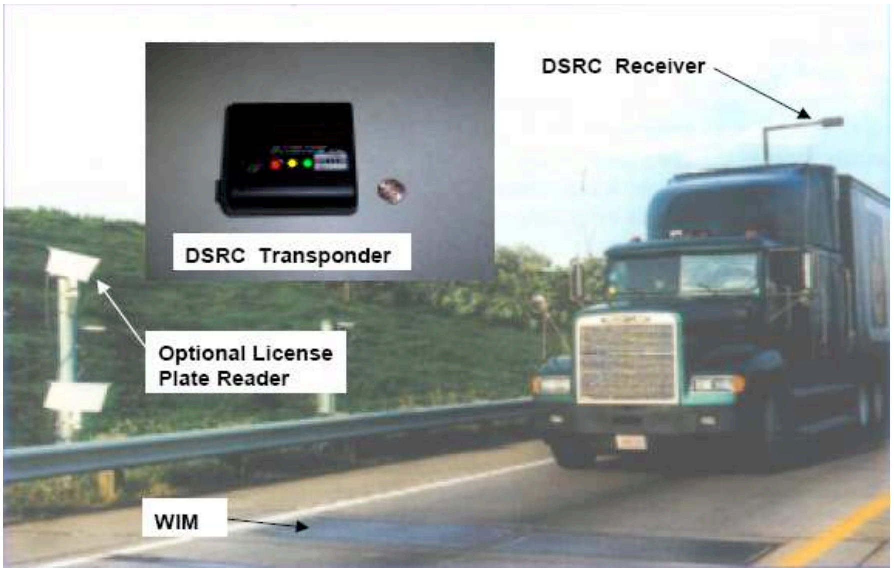
Table 5. WIM System Categories, Applications, and Data Items

	Type I	Type II	Type III	Type IV
Speed range	16 to 113 km/h (10 to 70 mi/h)	16 to 113 km/h (10 to 70 mi/h)	24 to 80 km/h (15 to 50 mi/h)	24 to 80 km/h (15 to 50 mi/h)
Application	Traffic Data Collection	Traffic Data Collection	Weight Enforcement	Weight Enforcement
No. of lanes	Up to 4	Up to 4	Up to 2	Up to 2
Bending Plate	X	X	X	X
Piezoelcectric	X	X		
Load Cell	X	X	X	X
Wheel load	X		X	X
Axle load	X	X	X	X
Axle-group load	X	X	X	X
Gross vehicle weight	X	X	X	X
Speed	X	X	X	X
Center-to-center axle spacing	X	X	X	X
Vehicle classification	X	X		
Site identification code	X	X	X	X
Lane and direction of travel	X	X	X	X
Date and time of passage	X	X	X	X
Sequential vehicle record number	X	X	X	X
Wheelbase (front-to-rear axle)	X	X		
Equivalent single-axle load	X	X		
Violation code	X	X	X	X
Acceleration estimate			X	X

Source: ASTM, 1994.

3.2.3 Wireless Communication Systems

Information associated with vehicle captured by WIM sensors and video image processing system needs to be communicated between roadside WIM controller and vehicles for conveying screening decision, and between the WIM controller and patrol car or weigh station for monitoring and enforcement. Wireless communication system plays a role of transmitting the information to vehicle, a portable wireless device in a patrol car or a local computer at nearby weigh station. As shown in Figure 7, Dedicated Short Range Communication (DSRC) is a typical one commonly used in electronic screening of transponder-equipped vehicles.



Source: Richeson, 2000

Figure 7. Electronic Screening Using DSRC Technology

3.2.4 Other Components

WIM cabinet is also a key part of virtual weigh station, which includes roadside data acquisition electronics that convert the scale readings to vehicle information.

Optionally, other components can be added, including multiple inductive loops for vehicle tracking, one or more static scales, directional signs, over-height detectors, and automatic vehicle identification equipments.

- Over-height Detector: This identifies heights of vehicles entering the truck weighs station. The detection of over-height vehicles shall take place along with the in-motion weight measurement.
- Static Scale: It provides fully unattended operation of both the WIM and static scale allowing for more efficient personnel use.
- Directional message signs: The system readily identifies overview image of the truck, providing information on the axle weights, gross weights, class, speed, date, time, and any weight violations.

3.3 Expected Benefits of Virtual Weigh and Compliance Systems

Compared to those of static weighing and low-speed WIM installed at a fixed weigh station, the use of virtual WIM systems for monitoring and enforcement of commercial vehicles has a range of advantages for both enforcement agencies and trucking companies. The expected benefits of virtual WIM systems include prevention of overloading, decrease of delays at weigh stations, enhancement of safety and air quality, as well as cost savings.

3.3.1 Prevention of Overloading

In traditional weigh station operations based on static scales, all trucks are required to stop at the weigh stations for visual inspection and/or weighing. At busier routes and/or during peak time periods, it is normal for trucks to fill the stations such that they must close temporarily until the queues diminish. The temporary closure of the stations is necessary to prevent traffic backups onto the highway and to avoid the safety hazards of having immobile vehicles adjacent to vehicles traveling at high speeds. When the stations are closed, some trucks are able to bypass the weighing process even though they may be overweight, causing many problems related to overweight vehicles discussed earlier.

By implementing virtual WIM systems, all trucks can be weighed in an unattended manner. Thus no overweight trucks are allowed to bypass, leading to a decrease in the number of overweight trucks. Table 6 provides empirical evidence that shows a significant decrease in overweight violation rates at high enforcement levels, compared to that of low enforcement levels. A decrease in the number of overweight trucks immediately indicates a reduction in infrastructure damage and deterioration attributed to overweight trucks.

Table 6. Impacts of Enforcement Level on Overweight Violation Rate

State	Violation Rate (%)	
	At High Enforcement Level	At Low Enforcement Level
Virginia	0.5-2.0	12-27
Maryland	1.0	34
Arizona	1.5	30
Wisconsin	1.0	20
Idaho	11.9	32
Florida	1.4	13
Montana	1.0	29

Source: Kishore and Klashinsky, 2000.

3.3.2 Decreasing Delays at Weigh Stations

In traditional weigh station operations, even trucks with legal weights experience unnecessary delays at the weigh stations. It has been documented that on average, each truck experiences a delay of approximately 5 minutes for weight compliance checks (Benekohal, et al., 1999). This delay increases with the traffic at the weigh stations, ranging from 8.7 to 137.6 minutes. Such long delays resulting from the inefficient operation of weigh stations often reduce the productivity of the trucking industry and may cause significant truck cargo delivery problems.

The delays at weigh stations can be considerably reduced by implementing virtual WIM stations. With an interface with AVI technologies, virtual WIM systems can identify and measure the characteristics of the vehicles traveling at normal highway speeds in an unattended manner, including weights and, where applicable, credentials. The systems can also sort all vehicles and direct only out of compliance vehicles to the nearest fixed weigh stations or mobile stations for further inspection. All other trucks are allowed to bypass without stopping at the stations. The fully automated vehicle weighing process makes possible the significant enhancement of weigh station capacity, thus decreasing the delays at weigh stations.

A simulation study by Kamyab (1998) shows the potential impacts of virtual WIM systems in terms of travel time savings. In the study, two alternatives were considered for capacity improvement of an existing fixed weigh station with static scale. One is physical expansion of a fixed weigh station by adding a ramp WIM scale, a sorter and a bypass lane. The other is electronic screening on mainline without expanding physical infrastructure of the weigh station, assuming that some of heavy trucks are equipped with in-cab transponders. The simulation results indicate that physical expansion could improve operational efficiency of a weigh station to some extent in a shorter amount of time than electronic screening programs. Electronic screening, however, reduces inefficiency at the weigh station gradually, but has the potential to permanently eliminate it as the number of transponder-equipped trucks increases.

Fewer delays at weigh stations means that carriers can deliver goods on time without the disadvantage of competing against carriers who attempt to cheat the system to gain financially by overloading their trucks. Eventually, this benefit will lead to the increased productivity of trucking companies that comply with the vehicle weight enforcement.

3.3.3 Enhancement of Safety and Air Quality

As addressed earlier, the commercial vehicle enforcement must be balanced with public concerns for safety and air quality. In the past, truck weight enforcement has been performed by forcing vehicles to enter and exit the highway to travel through a weigh station. The chance of accidents increases around weigh stations due to disruption of the traffic stream as well as general truck characteristics such as the need for longer acceleration and deceleration distances and larger turning radii.

A survey of commercial vehicle drivers conducted in Illinois shows the potential benefits of Virtual WIM systems in terms of safety enhancement. By assessing the driver acceptance level of WIM systems, this survey concluded that 91 percent perceived the WIM system reduce the hazards of merging and diverging at weigh stations and 88 percent advocated the installation of WIM systems (Benekohal, et al., 2000).

Although there appears to be little about the literature that measured the environmental benefits of WIM technologies, virtual WIM systems can also help minimize truck emissions and maximize fuel efficiency by limiting the number of idling trucks at weigh stations.

3.3.4 Saving Taxpayers' Money

WIM systems help enforcement agencies easily monitor and keep weights under control in a cost effective way. With virtual WIM systems, enforcement agencies can target violators with less enforcement personnel, leading to the enhanced operational efficiency and safety, infrastructure protection, and less emissions and less delay of trucks. All these benefits mean savings to the taxpayer through better roads, cheaper goods, and more efficient enforcement operations.

3.3.5 Collection of Valuable Data

Virtual WIM systems provide valuable data for future transportation planning and maintenance activities. The WIM systems collect traffic data continuously, even while the weigh stations are closed. Information on peak times, traffic volumes, type of vehicles and weight of vehicles allows transportation planners to improve existing systems and design better future systems. In addition, the data collected from the WIM system can be used for scheduling truck weight enforcement resources and details, both geographically and temporally (i.e., by time of day).

For example, the current WIM systems installed at key locations in California highways provide 24-hour traffic information. The primary information collected from the WIM systems includes axle weights and gross weight, axle spacing, vehicle classification and speed. The information gathered is essential for the pavement studies, highway monitoring and capacity studies, accident rate calculations, and analysis of truck transport practices.

3.4 Case Studies

This section presents case studies of planning activities of other states directed toward accommodating advanced WIM technologies. These examples were selected to indicate the types of activities being undertaken with different technologies in a range of geographic areas across the United States.

3.4.1 Florida's Weigh Station Bypass Detection System

In Florida, as with many states in the United States, commercial vehicles are required to meet legal requirements for weight and size. As the Virtual Weigh Station (VWS) concept is propagating throughout the United States, Florida Department of Transportation (FDOT) plans to utilize this strategy for screening overweight trucks and the successive apprehension and citation issuance for those violators. Two major activities deserve special attention.

First, FDOT has teamed up with the Center for Advanced Transportation Systems Simulation (CATSS) at the University of Central Florida to deploy an "outdoor" lab to evaluate selected technologies for a virtual weigh station (FDOT, 2004). There is an abundance of vendors marketing technologies and devices to serve the needs fulfilled by virtual weigh stations. However, there is a deficiency of deployment studies that could aid state agencies in the selection of appropriate proven technologies. This lab will serve as a unique facility in the nation, evaluating hardware and software enforcement technologies. Vendors are invited to submit their hardware and software systems for an unbiased evaluation of operational characteristics – not from an indoor lab but rather from an environment that mimics the exact operational characteristics where these systems will be deployed. The evaluation results will be shared with transportation and research agencies. This research project has two additional objectives, namely, the development of a framework for virtual weigh stations and the deployment of a Web-based public database to serve as a reference for available technologies, vendors, and evaluation results.

Second, FDOT is implementing a weigh station bypass detection system designed to detect possible overweight vehicles which exit before the weigh station and re-enter the highway afterwards. Although WIM scales are very accurate for determining the commercial vehicle's weight, most states including Florida only allow citations to be written based on static scale measurements. The weigh station system works fine as long as the commercial vehicles come through the weigh station. However, there is a high probability in reality that if a commercial vehicle is deliberately running overweight, the driver may decide to take a route that avoids the weigh station. Because of primary and secondary roads, there is usually at least one alternative route around every weigh station. In response to this reality, FDOT initiated a pilot project to develop a weigh station bypass detection system.

The first installation will be near the Punta Gorda weigh station located on I-75 in Charlotte County. This system is designed to screen all commercial vehicles using the exit and entrance ramps before and after the weigh station and to categorize them as either "potential violator" or "non-violators." Law enforcement personnel will focus their attention toward potential violators that appears to violate Florida's weight or dimension requirements or intentionally avoid the weigh station.

The weigh station bypass detection system will be automated, determining commercial vehicle weights using WIM technology. If the commercial vehicle is shown to be overweight, this will trigger optical character recognition (OCR) cameras that will record license plate numbers and capture a digital image of the vehicle. The system will then merge these three pieces of data and send an image, via wireless communication, to an enforcement officer's patrol car laptop and to the computer located at the Punta Gorda weigh station. The image will consist of a digital photo of the offending commercial vehicle superimposed with WIM data and the license plate number. This system will also have a random component which will be set by law enforcement personnel to randomly flag a commercial vehicle for further review even though none of the other violator criteria is met. License plate numbers of commercial vehicles bypassing the Punta Gorda weigh station will be stored in a database for future use.

Once the system is developed and brought on-line, the system's database will be integrated into Florida's Commercial Vehicle Information Exchange Window (CVIEW) system Florida's CVIEW will provide Florida's commercial vehicle regulatory agencies with a single database that contains all information used in the regulation of commercial vehicles operating in Florida. By utilizing existing infrastructure to the greatest extent possible, the system is a very cost-effective method of augmenting the current FDOT weight enforcement efforts. This will greatly enhance the efforts of finding and dealing with unsafe or illegal commercial operators.

3.4.2 Kentucky's Remote Monitoring System and Virtual Weigh Station

To provide effective roadside enforcement, Kentucky has invested in state-of-the-art enforcement stations, providing a high level of enforcement on the route segment where they are located. However, much of Kentucky's truck traffic is on routes not monitored by fixed weigh stations. Even on monitored routes, routes for detour are often available to bypass the weigh station. Mobile enforcement has been used to augment fixed weigh stations, but Kentucky Vehicle Enforcement has concerns about its effectiveness because truckers know where the mobile enforcement is set up, and thus they can avoid it. Furthermore, limited staffing restricts the number of routes that can be monitored.

In response to this problem, Kentucky developed a virtual weigh station that combines the Remote Monitoring System (RMS) with a weigh-in-motion system (Crabtree, 2003). To automatically check commercial vehicles' credentials, taxes, and safety rating, the Remote Monitoring System was first developed and deployed on US-25 in Kenton County, Kentucky. The system uses roadside photo equipments installed for the RMS that capture images of passing trucks and transmit those images to the "Image Review Station" at the Kenton County weigh station. From this image, enforcement personnel can read the USDOT number, enter the number into Kentucky's observation system, and instantaneously check the motor carrier's registration, tax status, and safety record.

Later, researchers in Kentucky Transportation Center identified the potential of combining the RMS with a WIM system to create a virtual weigh station. The virtual weigh station consists of an image capture system provided by Computer Recognition Systems (CRS) and a WIM system of Quartz Piezo provided by International Road Dynamics (IRD). All system components were installed in December 2002, providing the same functionality as the fixed weigh stations at lower cost by not requiring continuous staffing, nor continuously monitoring. The system also provides covert enforcement, thus making it more difficult for violators to avoid enforcement.

Based on the data collected from 48 hour enforcement in June 2003, a preliminary evaluation of the system's effectiveness showed that only 34% of total 493 system transactions triggered by trucks was readable for USDOT number. This low efficiency was resulted from some deficiencies of the system, including blurry images, numbers too small to read, poor contrast between numbers and background, location and timing of image capture, and lighting and shadowing. Although some challenges still remain to be solved, the system turns out to be very cost effective. The potential value of virtual weigh station was evaluated for fraction of the cost of a fixed weigh station to be $100K to $130K versus $3-5 million. This implies that approximately 40 virtual weigh stations could be installed at the same cost for a new fixed weigh station. It can also spread enforcement coverage to many routes where fixed station may not be feasible.

3.4.3 Montana's STARS Program

The Montana Department of Transportation (MDT) developed a 10-year WIM plan in 1997, and initiated a virtual weigh station project to develop "State Truck Activity Reporting System (STARS)." The project aimed at improving the efficiency and effectiveness of truck weight enforcement activities performed by the Motor Carrier Services (MCS) Division of MDT, and providing MDT access to improved truck-related data for use in pavement design and planning applications.

STARS consists of an array of WIM and AVI sensors deployed across the Montana highway system that feed data to customized software programs, including system of 26 piezo-based WIM recorders, portable WIM program at 64 sites, comprehensive calibration program and a software program dealing with the collected data. 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 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 and transportation planning.

One of unique features of the STARS is the capability of automatically identifying overweight incidents and dispatching enforcement personnel to individual overweight incidents in real time. To identify these locations, MDT developed a software program, called "Measurement of Enforcement Activity Reporting System (MEARS)" that processes the STARS data specifically to obtain information on commercial vehicle and overweight vehicle activity.

A pilot project to evaluate the effectiveness of Montana's STARS has shown that a significant reduction was seen in the percent of overweight vehicles in the traffic stream (Stephens, et al, 2003). Statewide, throughout the extensive network of highways covered by STARS, the percent of overweight vehicles in the traffic stream dropped by 22 percent. The average amount of overweight on each vehicle was also decreased by 16 percent. The overall reduction in pavement 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 per year.

3.4.4 Indiana's Photo Virtual Weigh Stations

Virtual weigh station project initiated by Indiana Department of Transportation (INDOT) and Purdue University in 2000 was originally motivated by the need to have more dynamic procedures for catching habitual overweight trucks that bypass port-of-entry fixed scale houses (Nichols, et al., 2003). Originated as Strategic Highway Research Project and Long Term Pavement Performance Project sites, WIM systems were installed at 42 WIM sites to collect continuous vehicle data to be used for research, highway design and planning. Indiana State Police (ISP) wanted a method for using the WIM systems for dynamic weight enforcement efforts.

Using existing WIM equipment, a laptop computer, and wireless communication technology, early concept of the virtual weigh station developed in Indiana was that ISP commercial vehicle enforcement mobile units connect wirelessly to WIM cabinets to see real-time truck weight data. The WIM reading is used to screen vehicles to be pulled over and weighed with certified portable scales. For the virtual weigh station to function, radio equipments were installed in 2 WIM sites, I-65 in Merrillville and US-24 in Fort Wayne, Indiana, and ISP has 4 radio units to use during enforcement efforts.

More recently, a collaborative effort between INDOT, ISP, Mettler Toledo and Purdue, has developed advanced virtual weigh station with image capturing capability. The photo virtual weigh station was installed and is tested on SR-1 in southeast Indiana – 2lane road with high truck volumes between I-74 and I-275. The objective of the system is to develop a virtual WIM system that can record picture of overweight truck at WIM site and transmit the image to a police cruiser downstream. The Photo WIM system developed in Indiana is at the early stage of development and thus should only be viewed as work in progress. When using WIM data for enforcement, enforcement personnel desire more accuracy than traditionally required for performance monitoring. To create more reliable online reports on various sites for ISP enforcement scheduling purposes, Purdue is conducting large-scale analysis of database from all Indiana WIM sites.

3.4.5 Virtual Weigh Station Project for the GCM Corridor

A virtual weigh station project designed for the Gary-Chicago-Milwaukee (GCM) corridor, one of the busiest commercial vehicle corridors in the United States, provides a good example that shows how multiple agencies cooperatively plan and deploy ITS technologies for commercial vehicle operations and enforcement.

The GCM Corridor is one of four multi-agency ITS coalitions formed as a result of the Intermodal Surface Transportation and Efficiency Act of 1991. Officially started in 1993, the GCM Corridor is comprised of all of the major transportation agencies in the 16 county area connecting Gary, Indiana through Chicago, Illinois to Milwaukee, Wisconsin. The GCM Corridor includes the three state departments of transportation, 16 counties, and numerous local agencies, as well as the Federal Highway Administration. The objective of the GCM Corridor Program is to improve the efficiency and effectiveness of the Corridor's transportation infrastructure through the planning, design, deployment, and evaluation of leading edge ITS applications. As part of the GCM Corridor program, a virtual weigh station pilot project was recently initiated by a collaborate efforts of the GCM corridor agencies (GCM Corridor, 2004).

The virtual weigh station pilot project involves the deployment of virtual weigh stations (VWS) at three sites, one each in Wisconsin, Illinois and Indiana. The objective of this project is to introduce the use of WIM sensor and communication technologies to the GCM corridor agencies in an effort to encourage greater compliance with truck weight restriction laws. The project calls for the development of a central operating system that would monitor and control multiple sites across the three states. Besides the central dispatch computer, the VWS system also includes high-speed WIM scales, digital camera, communication systems, police-vehicle computers and inspection sites. The computer in the enforcement vehicles will enable enforcement officers to screen large numbers of trucks on multiple routes in order to single out the gross offenders who will then be pulled over and weighed along the roadside using conventional portable static scales. Digital cameras will record images of non-compliant vehicles the moment they are screened for weight to help the enforcement officers identify them several miles downstream. This allows enforcement officials to screen large numbers of vehicles with a minimal impact on the flow of truck traffic.

Depending on the placement of the WIM systems, any roadways in the corridor could be monitored by virtual station enforcement personnel. Since the three states have limited permanent weight enforcement facilities within the GCM corridor, this initiative is seen as a cost-effective solution that can be developed in a reasonably short time.

3.4.6 Bi-National Virtual Weigh Stations for Cross-border Mobility

Rapid growth in trade and commercial truck traffic across the Washington State-British Columbia border has strained border crossing facilities and enforcement agencies. As a result, commercial vehicles are often delayed at the border, and long queues of trucks waiting to cross in either direction are a common sight. It has been estimated that $40 million in business productivity is lost annually due to the border crossing delays (SAIC, 2003). To alleviate these problems, the public and private stakeholders in Washington State and British Columbia established the International Mobility and Trade Center (IMTC) partnership in 1997. The IMTC is a coalition of over 60 U.S. and Canadian business and government entities whose mission is to identify and pursue improvements to cross-border mobility.

The IMTC has supported the development of a network for assimilating and exchanging information between British Columbia and Washington State motor vehicle enforcement agencies to enable bi-national weigh-in-motion information exchange, referred to as "*Bi-National Virtual Weigh Station*." With this CVISN-based system, both northbound and southbound trucks operating in the IMTC will be monitored for safe and legal compliance, allowing eligible carriers to bypass IMTC corridor weigh stations on both sides of the border.

Based on statistical weigh station usage data provided by the WSDOT and the ICBC, and focused on five weigh stations along the IMTC corridor, a benefit-cost analysis was conducted to quantify the potential benefits and costs associated with the WIM data sharing system to IMTC stakeholders (SAIC, 2003). The analysis showed that travel time savings for motor carriers associated with bypassing weigh stations are expected to be between $25.6 and $61.7 million over the next 10 years. The corridor bypass time savings occur as driver/vehicle/shipment are screened initially via electronic means or through physical inspection, then are cleared from further inspections along the corridor. This information is then passed electronically to other weigh/inspection sites along the corridor, subject to verification via WIM and AVI transponder technologies.

Additionally, resource savings and safety benefits were also estimated for the enforcement agencies. This would be expected since resource efficiencies to the agencies would be realized through the elimination of "double weigh-ins" of "safe and legal" trucks along the IMTC corridor, allowing additional resources to be focused on non-transponder-equipped trucks, and especially carriers considered "high risk". Based on this, the safety benefits associated with this operational concept are estimated to be between $21.1 and $50.9 million over the next 10 years.

Overall, the virtual weigh station deployment at the border crossing facilities showed significantly positive benefit-cost ratios ranging from 4.0:1 to 8.5:1, and the benefits of employment of the virtual weigh station operational concept in a bi-national border region range from approximately $35 to $102 million, as moving from low to high ITS scenarios. The estimated payback periods for the weigh station ITS deployments are 2 years for the low and medium ITS scenarios, and 1 year for the high ITS scenario. As this technology is currently just being deployed, it will be interesting to examine how this concept is actually deployed in the field, and if the benefits estimated in this evaluation study can be validated.

The IMTC public-private partnership provides an international model for development of freight border ITS/CVO projects across international borders. The IMTC model involves successful interactions with federal, state, and local governments from two countries to fund and deploy major border ITS solutions for commercial vehicle operations and enforcement activities. The IMTC structure, functions, processes and real-world deployment of advanced WIM technologies can serve as an input or point of discussion to other bi-national stakeholder communities in border regions with significant freight flows such as the United States – Mexican border.

4. Key Considerations in the Development and Deployment of VWCS

Weigh-in-motion systems can be defined as the tools that estimate static loads of the vehicles using dynamic load impact force measurements. Virtual WIM systems are a new set of weight enforcement tools where the mainline weigh-in-scales are used as screening rules. In this exposition, key considerations required in the implementation processes of Virtual Weigh and Compliance Systems (VWCS) will be looked into. The key factors can be categorized depending on the time of implementation.

4.1 Overview of Issues in Development and Deployment of VWCS

Before implementation, the WIM facility location has to be closely surveyed to meet necessary physical requirements for VWCS. Based on this site, the system components required for VWCS will also be specified. An in depth knowledge of the VWCS systems available commercially has to be known for proper selection. The other essential criterion is the budgetary considerations involving VWCS setup and operating costs. The VWCS system set up has to be planned and an effort must be made to teach the execution aspects to the personnel and other agencies involved in the handling of the system to set up a workable “quality assurance program”.

Upon on the choice of implementation, tests (dry runs) must be made to look into the data requirements and accuracy of the system. After the implementation of the system, the systems need constant maintenance and personnel for handling the system. After the implementation an effort must be made to improve the operational efficiency of the system. The information gathered from the weigh stations must be translated into suitable formats for information dissemination and sharing among different agencies involved. The various issues to be considered in the deployment and development of VWCS are summarized in Table 7.

Table 7. Issues in Development and Deployment of VWCWS

Stages	Issues under consideration
Before implementation	· Physical requirements for WIM facility location · Standard specification of system components · Costs and personnel requirements · Justification and feasibility
During implementation	· System Installation · System calibration · Data requirements and accuracy
After implementation	· Operations and maintenance · Information collection, Dissemination and sharing · Quality assurance program

4.2 Physical Requirements for WIM Facility Location

Although the actual system characteristics of different WIM systems are different, the layout and the considerations that should be made are essentially the same. Generally speaking, cost will most likely be a key concern, but it is also important to carefully study the location that is chosen for the WIM system. The design speed of WIM systems is an important issue in designing the geometric of a WIM facility. In evaluation of the geometric design of the location, horizontal grade, roadway grade, cross slope, lane width must be within acceptable levels. In cases where a long design life for pavements is established, the reliance on the WIM data will most likely be high (McCall and Vodrazka, 1997). Additional considerations for a good site location are availability of access to power and phone, adequate location for the controller cabinet, proper drainage facilities and freeway traffic conditions.

In the preliminary site evaluation, steps need to be taken to find that there are no alternative routes to circumvent the system by overweight trucks. The site chosen should be such that it is not a point of high congestion such that more delays may creep into the highway traffic. Table 8 shows some the general checklist site selection criteria.

Table 8. WIM Site Selection Criteria

Criterion	Objective	Criteria
1	Distance from controller unit	Drive time (minutes)
2	Roadway geometry	Alignment, cross-slope, lane width
3	Pavement structure	Thickness
4	Traffic mix	Percent trucks and total volume
5	Multiple lanes	Number of lanes
6	Power and communication	Distance to service
7	Right-of-way	Distance to safe parking
8	Adjacent space	Park calibration truck
9	Space for structure	Area for building
10	Sign bridge structure	For mounting overhead Devices
11	Roadside pole	For mounting overhead Devices
12	Lighting	Security and night visibility
13	Pavement condition	Rutting, cracking, Smoothness
14	Pavement rehabilitation	Rehabilitation schedule
15	Circuit time for calibration truck	Cycle time
16	Sight distance	For clear visibility of traffic
17	Proximity to highway patrol and enforcement site	For ground truth weights
18	Access to satellite sites	Distance from primary site
19	Safety features	Longitudinal barriers
20	Traffic congestion	Free-flow or stop-and-go
21	Bending plate WIM	Existing, buildable, or not buildable

Source: Middleton, et al., 2004

Other exogenous criteria that must be met for locating a single weigh station, include avoiding environmental impact, minimizing avoidance of the weigh station, avoiding the need to weigh all trucks statically, and minimizing the staffing requirements needed.

The nature of pavement also becomes a critical part of site location as it produces variable bounce causing impact forces thus bringing about variations in the instantaneous axle measurements. The ASTM has designated guidelines in the ASTM standard E 1318-94 for geometric design for different types of weigh in motion sensors and nature of pavement surface as shown in Table 9 (ASTM, 1994).

Table 9. ASTM Standard Geometric Design Requirements

Characteristic	Type I	Type II	Type III	Type IV
Horizontal Curvature	Radius ≥ 1740m 46m before/after	Radius ≥ 1740m 46m before/after	Radius ≥ 1740m 46m before/after	Radius ≥ 1740m 46m before/after
Roadway Grade	≥ 2% 46m before/after	≥ 2% 46m before/after	≥ 2% 46m before/after	≥ 1% 46m before/after
Cross Slope (lateral)	≥ 2% 46m before/after	≥ 2% 46m before/after	≥ 2% 46m before/after	≥ 1% 46m before/after
Lane Width	3 to 4.5m 46m before/after	3 to 4.5m 46m before/after	3 to 4.5m 46m before/after	3 to 4.5m 46m before/after

Source: ASTM, 1994

Another important consideration of the sites is availability of access to power, telephone or other communication utilities. These utilities are dependent on the range of operations and amount of data collected at the weigh station. Power source is essential and any source like AC or solar power can be used. Communication can be done using telephone or cellular wireless, though wireless communications involve more costs. The choice of controller cabinet (CC) depends on the design life of the site. The CC must be protected from elements like runoff from heavy rains, irrigation and drainage facilities. It should be placed such that vehicles leaving the roadway do not hit it and protect the servicing technicians from danger. Care must be taken so as to properly place the CC with good sight distances near the sensors to diminish any possible errors in calibration. Traffic conditions are also critical for WIM station deployment. The site should ensure a smooth flow of traffic. Traffic conditions like stop and go traffic, slow moving, lane changing should be minimized.

4.3 Standard Specification of System Components

The VWCS systems proposed require an integration of AVI and WIM technologies, so that the weight and safety check of commercial vehicles and drivers can be done in real time on highway main lanes under normal traffic speed. Weigh-in-Motion systems generally have four main elements, roadway component, vehicle component, data & communications unit and weight enforcement center. The roadway component includes detectors to check for vehicle presence as well as for vehicle speed, a WIM scale, and an over-height detector. The roadway system also consists of a control assembly, directional signals, and variable message signs. Finally, for the tracking, a series of inductive loops, one upstream to the WIM detector and one downstream are placed. The computer component consists of a desktop computer, a display, and a printer.

4.3.1 WIM Scales

As shown in Table 5, WIM systems are mainly classified in to four different types according to their application and details about their respective functions, performance, and user requirements. The classification mainly depends on the speed of the vehicles, type of application, number of lanes. Some of the existing WIM scales used in real world practices include bending plates, piezoelectric sensors, and load cells.

Bending Plate System

Bending plate WIM systems have plates with strain gauges attached to them. These sensors are placed perpendicular to the direction of travel and when a vehicle moves over them the strain gauge readings are used to calculate the dynamic load (McCall and Vodrazka, 1997). The system needs extensive calibration to convert the dynamic load measurements to the required actual static loads. The bending plates systems can either be portable or permanent. The portable systems are useful for high-speed WIM applications and maybe employed at a adjacent WIM stations instead of mainline WIM stations. Depending on the intended usage, a bending plate system can be classified as ASTM Type I, II, III, or IV. The systems consists at least one scale and two inductive loops. An inductive loop placed at the upstream detects the incoming vehicles and sends a signal to the WIM sensor. The axle spacing is determined by vehicle speed is determined by three methods: weighpad to inductive loop, weighpad to axle sensor, and weighpad to weighpad, if the weighpads are staggered. The on-site processor is used to analyze the data emanating form the WIM system.

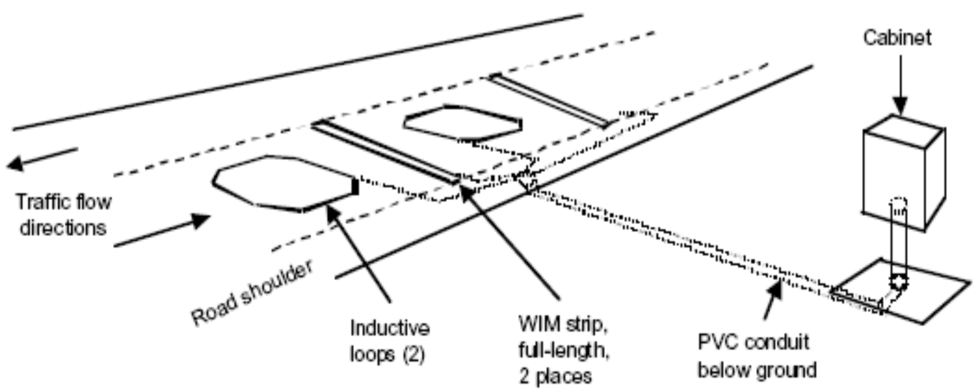
Piezoelectric System

The Piezoelectric sensor as the name specifies uses Piezoelectronic sensors to estimate the static loads. The sensors detect the changes in voltage caused by the pressure exerted by a moving vehicle, and calculate the dynamic load (McCall and Vodrazka, 1997). Similar to the bending plate systems the calibration methods and dynamic load measurements are used to estimate the static loads. The Piezo WIM systems consist of one or more sensors placed on the traffic lane which may or may not be wrapped in an epoxy-filled metal channel, usually made of aluminum. The whole system typically consists of one sensor and at least inductive loop. These are placed perpendicular to the traffic lane. In case of more than one inductive loop, an upstream inductive loop is used to detect the approach of incoming vehicles and the downstream loops to determine the speed of the vehicles. Again, this information can be analyzed from a site processor with operating software and can be saved in a manner so that the information can be downloaded on site or through a computer.

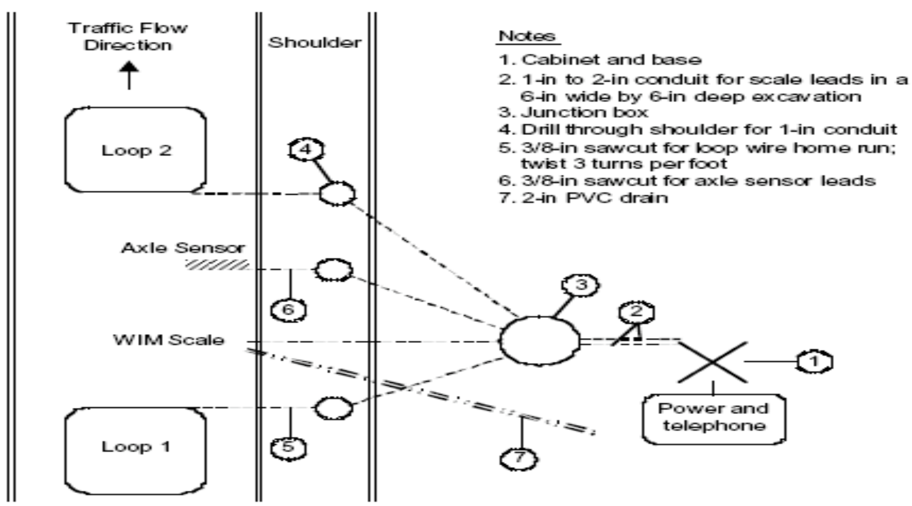
Load Cell System

The load cell WIM system consists of a load cell with scales, placed across the traffic lane (McCall and Vodrazka, 1997). The scales are used to detect an axle weigh both the right and left sides at the same time. The sum of the right and left sides measurements are used to determine the weight of the vehicle. The two in-line scales operate independently. Depending on the design of the system, it can be classified as ASTM Type I, II, III, or IV. In addition to the load cell, at least one inductive loop and one axle sensor are fitted to this system. The inductive loops usually placed upstream are used to detect the incoming vehicle. Sometimes a downstream inductive loop is placed to determine the axle spacing to measure the vehicle speed. The axle sensor is placed downstream determines the axle spacing and the velocity of the vehicle. Again, the data is analyzed from the site processor and software and saved in a format available for download.

Figure 8 presents a typical design of WIM scale and other component installation.



(a) Piezoelectric Sensor



(b) Typical Bending Plate or Load Cell WIM system

Source: Mimbela and Klein, 2000

Figure 8. WIM Scale Installation Schemata

4.3.2 Data Communication Unit

Data transmission and communication between various units in this integrated system is of utmost necessity and can be achieved by the application of the following various technologies.

Wired or Wireless LAN
Wireless LAN technology, which is used widely in ITS applications, is used for relatively short distances. The frequency of 2.45GHz, belongs to the ISM (Industrial, Medical, and Science) band, is introduced for use under the "ad-hoc" mode of the IEEE802.11b protocol and spread spectrum. Wired LAN technology using Ethernet architecture is generally used for long distance data transmission in this system, such as multi-DMVs transmissions, multi-WHCCs transmissions, and between WHCC and CSC. This technology is also an alternative while the on-site conditions are not suitable for wireless LAN. WAN technology is used between the system and any other private components, such as ISP and truck company's surveillance centers. A common hypertext protocol is adopted with standard internet browser as the interface.

Dedicated Short Range Communication (DSRC)
DSRC technology using infrared or microwave is adopted for data transmission between the MSS and the OBU. It is suggested that the same technology used for the Electronic Toll Collection (ETC) project should be used in this system.

4.3.3 Vehicle Identification Technologies

Loop detectors
Traditional loop detectors are able to provide fundamental traffic parameters such as volume, occupancy, and speed by determining if inductance changes are significant enough to indicate a vehicle passing over the loop. The output signal is usually binary, such as either 0 for non-presence or 1 for presence. In addition, other information including arrival time, duration, lane, and speed for individual vehicles can be collected.

Video Image Processing
It has been reported that one of video image sensing techniques is able to produce individual vehicle information. The proposed system uses overhead cameras that automatically take a picture of every passing vehicle and process the image to extract useful information including vehicle length, width, and color. The extracted information from both upstream and downstream detection stations can be correlated, and then re-identify vehicles.

Automatic vehicle identification (AVI)
AVI technologies are based on license plate identification and the use of transponder tags. Road infrastructure capable of reading in-vehicle tags identifies individual vehicle information including unique ID, speed, and location, and transmits the information to the central computer. A RFID transponder replaces the traditional paper-parking permit. Enforcement is conducted by scanning the RFID.

4.4 Weigh-in-Motion System Costs

The design and selection of WIM systems are based on the considerations such as initial capital cost, accuracy, life span, permit requirements, and maintenance costs. Each of the three primary WIM systems has different costs, life spans, and accuracies. For example, Bushman and Pratt (1998) compared the three types of technologies with respect to accuracy, life span and cost, as summarized in Table 11. The study concluded that the piezoelectric systems are the least accurate at of the three technologies "15% and also offer the lowest expected life span at 4 years. In general, the study concluded that as the accuracy of the system increases, the cost increases; however, the system also has a longer expected life span. The most accurate system analyzed was the single load cell system with 6 percent accuracy at a 95 percent confidence level and offers the longest life span. However, an installation cost of the single load cell system is higher than that of bending plate system, while it has much lower maintenance cost than bending plate.

WIM system costs may be expressed in terms of the life cycle cost consisting of initial capital cost (in-road WIM equipment, installation labor and materials, initial calibration, and traffic control), and life cycle maintenance costs (labor and materials, traffic control, and system recalibration). Table 10 contains budgetary initial capital costs for piezoelectric, bending plate, and load cell technologies assuming typical road, traffic, and weather conditions. These costs may vary from manufacturer to manufacturer and with sensor model. Roadside cabinets, WIM electronics, power and communication connections, etc are not included as these are common to all the technologies.

Table 10. **Budgetary Initial Capital Costs of WIM Systems**

Cost Component	Piezoelectric	Bending Plate	Load Cell
Accuracy (95% confidence)	± 15 %	± 10 %	± 6 %
Expected Life	4 years	6 years	12 years
In-road equipment	$4,500	$13,000	$34,000
Installation labor and materials	$3,500	$6,500	$10,500
Traffic control	$1,000 (1 day)	$2,000 (2 days)	$4,000 (4 days)
Total capital cost	$9,000	$21,000	$48,000

Source: Bushman and Pratt (1998) and Bergan, et al. (1997)

The life cycle maintenance costs vary due to differences in traffic volumes and truck weights, weather, original installation procedures, roadbed condition, onsite quality control, etc. Table 11 presents WIM system life cycle maintenance and repair costs averaged over North American installations. They assume that annual routine maintenance (e.g., road inspection and crack filling) is performed on the roadbed surrounding the WIM system. Piezoelectric sensors are assumed to require replacing every 3 years, bending plate refurbishing every 5 years, and single load cell replacing every 5 years. Life cycle maintenance costs may also vary with manufacturer and sensor model.

Table 11. **Life Cycle Maintenance Costs of WIM Systems**

Cost Component	Piezoelectric	Bending Plate	Load Cell
In-road equipment	$4,000	$6,000	$1,000
Installation labor and materials	$4,000	$5,500	$500
Traffic control	$1,500 (1 day)	$1,500 (1 day)	$750 (1/2 day)
Total maintenance cost	$9,500	$13,000	$2,250

Source: Bergan, et al., 1997

The WIM system life cycle costs may be amortized over the life cycle. Based on the initial installation and life cycle maintenance costs shown in Tables * and ** and a discount rate of 10% over a 20 year WIM system life cycle, the average annual cost for each WIM technology system is estimated as

- Piezoelectric: $3,092 per year
- Bending Plate: $4,636 per year
- Single Load Cell: $5,982 per year

These figures show that the incremental cost for improved WIM system accuracy, durability, and reliability is small when compared to the annual operating budget of a weight enforcement facility. Costs over other life cycle intervals may be computed as required.

4.5 WIM System Installation

The WIM system has to be installed and maintained based on the recommendations of the vendor. All of the necessary equipment, materials, WIM components, and site plans should be on-site and tested before the procedure is started. The installation process depends on the type of scale used for weigh in motion. Table 12 provides guidelines suggested by Minnesota Department of Transportation for installation of the WIM system.

Table 12. Minnesota DOT Checklist for Installation of WIM System

· Hand sketched map · Direction o All lanes, shoulder, intersecting roads, reference post number o Width of lanes, medians, shoulders, lead lengths needed o Power, phone o Cabinet location (door facing north preferred) o Drainage, ditches o Parking spot · Roadway history o Age of pavement o Planned rehab o Type of pavement o Smoothness, crown	· Sketch layout · Location o Roadway name o Reference post o Relative position to nearest intersection o Relative position to nearest city o Directions from central office · Calibration truck route

Source: Middleton et al., 2004

4.6 WIM System Calibration

WIM system calibration is used to ensure that the estimation of the static weight produced by the WIM system is as close to the static weight as possible. A system is calibrated to offset the effects of site conditions such as pavement temperature, vehicle speed, and pavement conditions. Calibration of Weigh-In-Motion (WIM) systems is still a major concern. Improper calibration leads botched estimation of recorded axle loads resulting in insufficient fatigue calculations, pavement thickness designs that are too thin and hence premature pavement failure.

Calibration of WIM sensors is especially important, because even small errors in vehicle weight measurements caused by poorly calibrated sensors result in significant errors in estimated pavement damage when those axle weights are used in pavement design analyses.

ASTM procedures recommend an eight-step process to calibrate WIM systems (ASTM, 1994). First, all WIM system settings should be adjusted to the vendor's recommendations or to a best estimate of proper setting based on previous experience. Second, vehicles that go through the system for calibration purposes must be forced into the static scales at the site or a nearby facility to obtain static weight data. With a radar gun or other means, speed data should be taken to measure the speed that the truck moves through the WIM sensors. Third, tire loads and axle spacing should be recorded at the static scales. Fourth, the difference should be calculated between the WIM system estimate and the reference value for the speeds, wheel loads, axle loads, axle group loads, gross vehicle weights, and axle spacing measurements. The differences should be expressed in percents and a mean value should be obtained for each set of measurements.

Fifth, the calibration factors should be entered into the WIM system. Sixth, it should be determined whether or not the calibrated system can be expected to perform at the necessary tolerances. Seventh, if a large number of differences for the data occurs and does not meet the tolerances levels shown in the ASTM values for the specified system, the system will most likely not perform to a beneficial level. Eighth, precision and bias information should be noted although at this time, no procedure has been developed to determine what effect this data has on WIM system performance. MNDOT and CALTRANS have calibration procedures slightly different from the ASTM guidelines (McCall and Vodrazaka, 1997).

4.7 Accuracy of WIM System

Accuracy in terms of weigh-in-motion refers to the closeness between a quantity measured or estimated by a WIM system and an accepted reference value (ASTM, 1997). It is important to decide the necessary accuracy needed before deciding the type of WIM to purchase. The ASTM gives accuracy limits for each type of WIM system as a standard to be set. Additionally, there have been many experimental studies to show the level of accuracy of the various WIM systems.

The ASTM establishes functional requirements for WIM system accuracy. Table 13 presents these functional performance requirements of WIM systems as defined by ASTM (ASTM, 1994). As shown in the table, Types I, II, and III tolerances are given in terms of percentage of the original known value, while the tolerance is given for Type IV in terms of the number of pounds over or under the actual weight.

Table 13. ASTM Performance Requirements for WIM Systems

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				Value ≥ lb (kg)	± lb (kg)
Wheel load	± 25%		± 20%	5,000 (2,300)	250 (100)
Axle load	± 20%	± 30%	± 15%	12,000 (5,400)	500 (200)
Axle load group load	± 25%	± 20%	± 10%	25,000 (11,300)	1,200 (500)
Gross vehicle weight	± 10%	± 15%	± 6%	60,000 (27,200)	2,500 (1,100)
Speed	± 1mi/h (± 2 km/h)				
Axle spacing	± 0.5ft (± 150 mm)				

Source: ASTM, 1994.

Guidelines given by the ASTM do not only go into detail concerning accuracy guidelines for existing systems, but also consider procedures for acceptance testing of new systems. Some states such as California in Table 14 may impose more strict requirements (McCall and Vodrazka, 1997).

Table 14. Performance Requirements for WIM Systems in California

Parameter	Mean	Standard Deviation
Vehicle Weight		
- Single Axle	± 5%	8%
- Tandem Axle	± 5%	6%
- Gross Weight	± 5%	5%
Axle Spacing	± 150 mm (6 inch)	300 mm (12 inch)
Vehicle Length	± 300 mm (12 inch)	460 mm (18 inch)
Vehicle Speed	± 1.6 km/h (1 mi/h)	3.2 km/h (2 mi/h)

Source: McCall and Vodrazka, 1997.

For testing a Type I or Type II system, it is recommended that two vehicles loaded with a non-shifting load plus 51 additional vehicles that are selected from the traffic stream be utilized. The two test vehicles make multiple passes over the WIM sensors at a minimum speed, a maximum speed, and an intermediate speed. This allows for the evaluation of WIM systems over the full range of speeds and allows for making sure that reference values of tire-load measurement procedures give values that can be reproduced. The other vehicles are used to subject the system to various vehicle classes, just as it would be used in the travel stream.

For a Type III system, the system must be able to detect a weight limit or load-limit violation as well as control traffic control devices to direct overweight vehicles to a static scale and to allow other vehicles to proceed. Test loading allows variability and accuracy to be analyzed. All vehicles used for test loading must be weighed statically at certified scales at the location in which the acceptance test is performed. For a Type IV system, the acceptance test determines whether or not the system produces results consistent with the tolerance levels shown above. This should be tested using test vehicles at a static speed and up to 10 mph (16 km/h). The overall method for measuring accuracy is thus essentially the same.

4.8 Weigh Station Operations

To consider:

- Long queues
- Delays for legal trucks
- Habitual offender being caught
- Accident delays

Similar to any transportation facility, a weigh station has characteristics such as capacity and delay that show how efficient the station operates. Long vehicle queues can cause excessive delay to the facility and at times to the adjoining highway that the weigh station is monitoring. Additionally, where traffic must enter and exit a roadway, accident rates also increase. Weigh-in-Motion has the potential to increase weigh station capacity and thus can reduce queue length and system time.

4.9 Maintenance

In order to ensure that a weigh-in-motion (WIM) system performs throughout the established site design life, states need to perform maintenance at each site. Corrective maintenance is performed after a problem is detected in the system. Preventive maintenance is performed in an attempt to circumvent future equipment and site problems.

4.10 Information Collection, Dissemination and Sharing

In a VWCS systems there are various entities involved and a proper system must be in placed so that effective co-operation and information dissemination to take place.

- Various agencies involved:
- Transportation agencies
  - U.S. Federal Highways Administration
  - U.S. Federal Railroad Administration
  - U.S. Federal Transit Administration
- Inspection agencies
- Municipalities
- Non government organizations
- Other government organizations
- Private sector

5. Conclusions

Finally, as part of this research project we developed a prototype simulation model for the I-710 corridor which is the main access corridor to the Long Beach and Los Angeles Ports Complex. This model can be used to examine the benefits of locating a VWCS at some point in this corridor.

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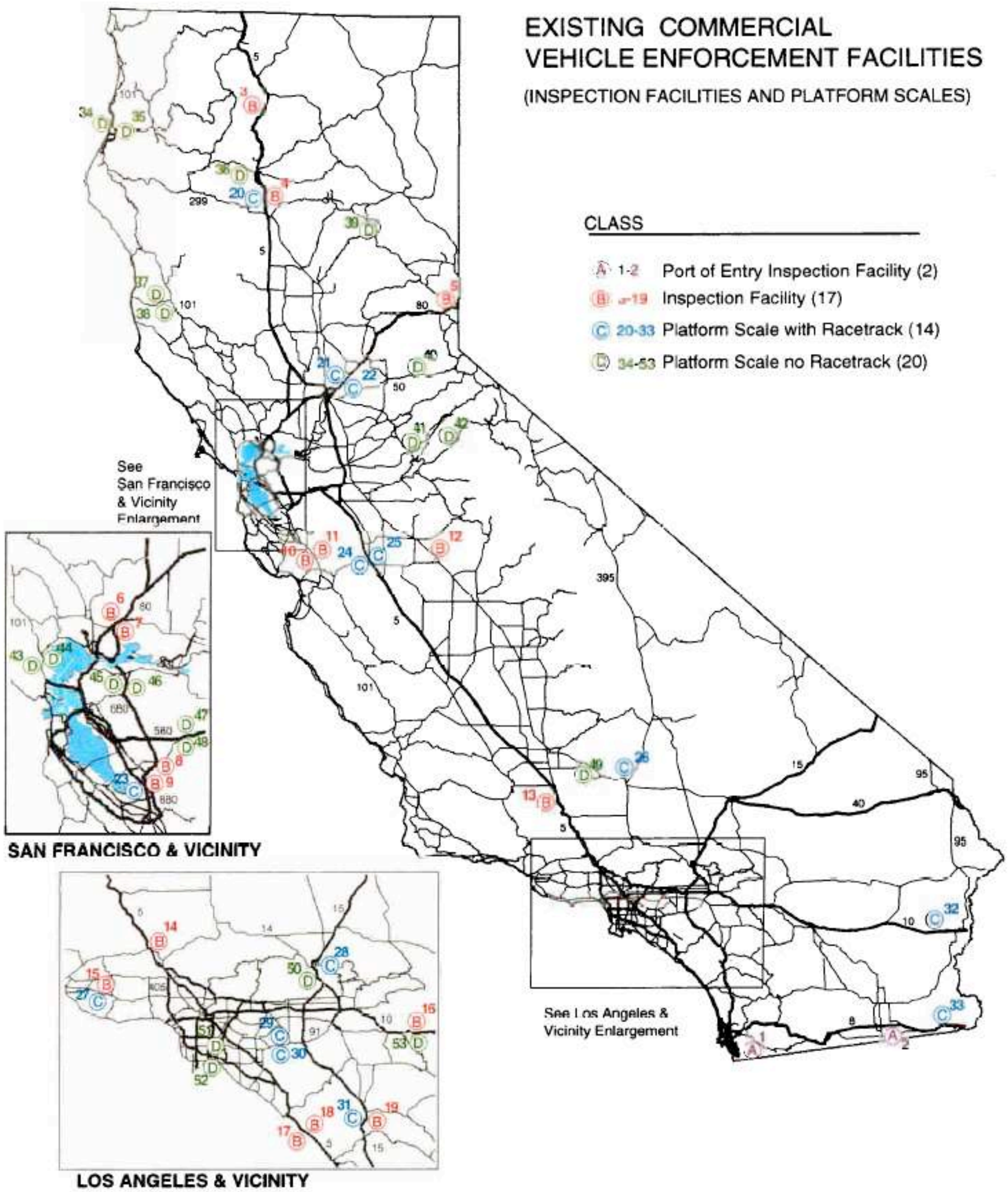
Appendix A. Requirements for Commercial Vehicle Operations in California

Purpose	Documents or Permits	
Identification	Federal US DOT Number	An out-of-state-domiciled commercial vehicle must have a federal U.S. DOT number to operate in California.
	CA Number	Commercial vehicles must have a CA number to operate within California.
	Trade Mark	Each vehicle must have a name or trademark displayed on both sides.
Permits / Licensing / Registration	Commercial Driver License (CDL)	A driver of a commercial vehicle operated in California must possess a valid commercial driver license.
	Vehicle Registration	Each vehicle must be registered.
	Motor Carrier Permit (MCP)	Commercial vehicles must have a motor carrier permit to operate within California.
	Fuel Taxes (IFTA/CFTP)	Commercial vehicles need a fuel license.
	Insurance	Must provide proof of adequate insurance.
Safety	Logbook / Hours of Service	Must maintain a log book and comply with hours-of-service laws.
	Alcohol / Drug Testing	Must comply to test for alcohol and controlled substances.
	Safety Equipment	Commercial vehicles must be equipped with safety equipment.
Protection of Infrastructure	Legal Size and Weight	Vehicle and load must meet standards for length, width, height and weight.
	Oversize / Overweight Permits	If load cannot meet standards for length, width, height or weight, it may qualify for an "extra-legal" permit. This applies to single item, non-reducible loads.
Environment	Air quality	Vehicle must meet air quality standards.
Special Cargo	Hazardous Cargo	If hauling hazardous waste, explosives, corrosives, petroleum products, or other hazardous materials, you may need additional permits and insurance.
	Produce	If hauling fresh fruits, nuts or vegetables, vehicle may need to obtain a certificate of compliance regarding the quality and labeling of your cargo. Bills/invoices etc. must show content and origin of agricultural products.

Source: California Department of Transportation, 2005

Appendix B. Existing Commercial Vehicle Enforcement Facility Location Map



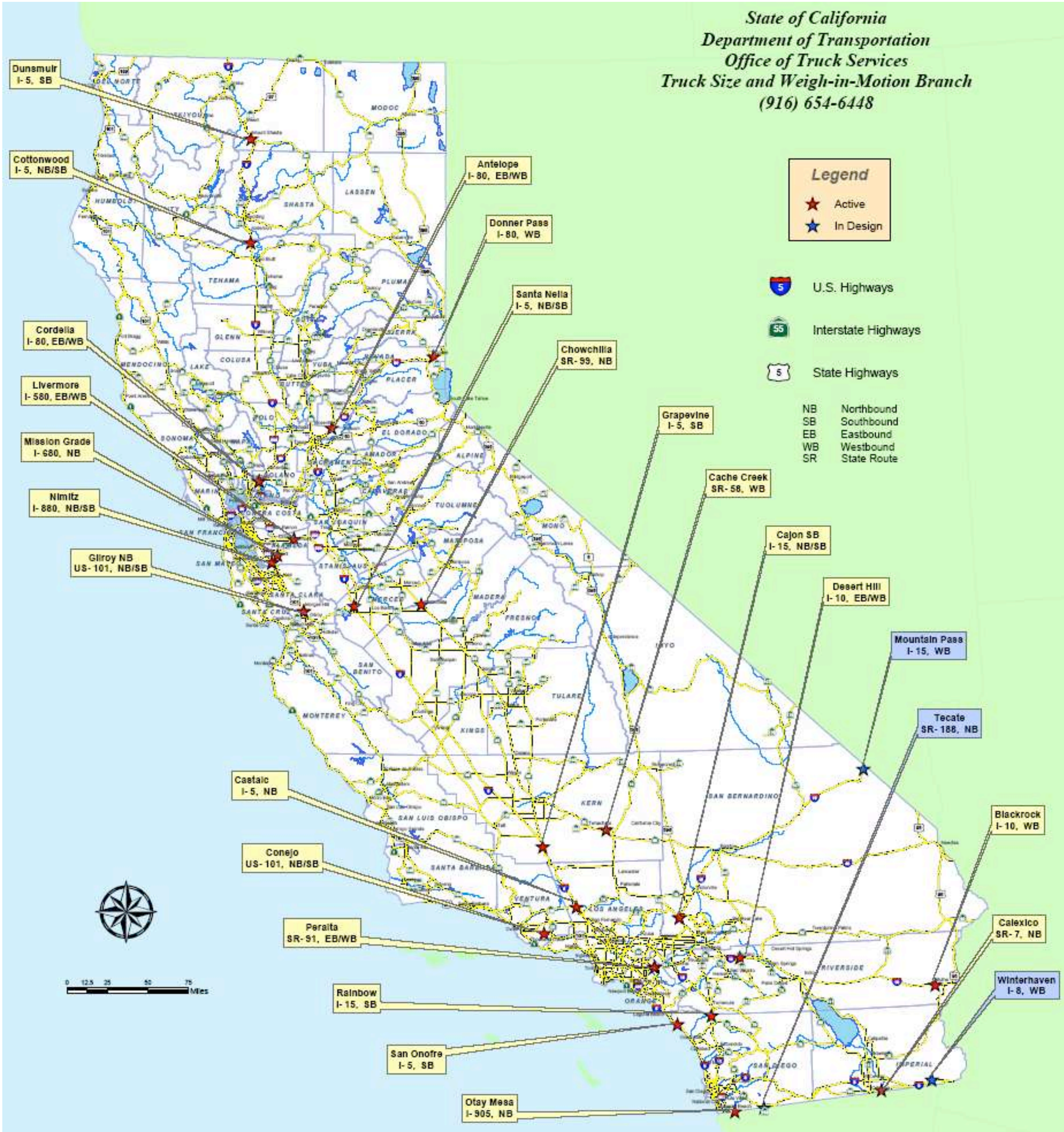
Source: Department of California Highway Patrol, 2001

Appendix C. Commercial Vehicle Enforcement Facility Location List

No.	Class	Rte.	Name	Dir.	Location	Dir.	Location
1	D	4	Murphys	WB	10-Cal-4-29.72		
2	C/C	5	Santa Nella	SB	10-Mer-5-23.44		
3	C/B	5	Cottonwood	SB	2-The-5-40.81	NB	Mer-23.45
4	B	5	Dunsmuir Gr.	SB	2-Sis-5-R7.15	NB	The-5.40-40.61
5	B	5	Grapevine	SB	6-Ker-5-11.87		
6	B	5	Castaic				
7	B/B	5	San Onofre	SB	11-SD-5-R67.41	NB	7-LA-5-R54.43
8	A	7	Calexico			NB	SD-5-R67.08
9	C	8	Winterhaven	WB	11-lmp-8-R89.51	NB	11-lmp-7-0.1
10	B/D	10	Desert Hills	WB	8-Riv-10-R15.00		
11	C	10	Blythe	WB	11-Riv-10-R144.49	EB	Riv-10-R15.54
12	D/C	15	Cajon	SB	8-SBd-15-R20.86		
13	C/B	15	Rainbow	SB	11-SD-15-53.5	NB	SBd-15-R20.62
14	D	20	Two Rock			NB	8-Riv-15-R1.0
15	D	50	Camino	WB	3-ED-50-27.08	EB	1-Men-20-28.67
16	D	58	Keene				
17	C	58	Cache Creek	WB	9-Ker-58-105.5	EB	9-Ker-58-81.0
18	D	70	keddie	WB	2-Plu-70-32.98		
19	B/B	80	Cordelia	WB	10-Sol-80-14.42	EB	Sol-80-14.16
20	C/C	80	Antelope	WB	3-Sac-80-16.24	EB	Sac-80-15.91
21	B	80	Donner Pass	WB	3-Nev-80-18.8		
22	C/C	91	Peralta	WB	12-Ora-91-13.81	EB	Ora-91-R13.62
23	B	99	Chowchilla Riv.			NB	10-Mer-99-0.9
24	D	101	Willits	SB	1-Men-101-48.71		
25	D	101	Little River	SB	1-Hum-101-97.26		
26	D	101	St. Vincents	SB	4-Mrn-101-15.24		
27	D	101	Terra Linda			NB	4-Mm-101-14.12
28	B/B	101	Gilroy	SB	4-SCI-101-8.8	NB	4-SCI-101-11.4
29	C/B	101	Conejo	SB	7-Ven-101-9.19	NB	Ven-101-8.96
30	D	108	Lyons Dam	WB	10-Tuo-108-17.17		
31	D	299	Whiskeytown			EB	2-Sha-299-12.64
32	D	299	Buckhom	WB	1-Hun-299-R7.38		
33	D/D	405	Carson	SB	7-LA-405-12.17	NB	LA-405-11.70
34	D/D	580	Livermore	WB	4-Ala-580-R8.87	EB	Ala-580-R9.17
35	B	680	Mission Gr.			NB	4-Ala-680-R.9.17
36	D/D	680	Walnut Crk.	SB	4-CC-680-15.99	NB	CC-680-15.89
37	C/B	880	Nimitz	SB	4-Ala-880-3.74	NB	Ala-880-4.22
38	A	905	Otay Mesa			NB	11-SD-905-12.0

Source: Department of California Highway Patrol, 2001

Appendix D. Weigh Station Bypass Sites in California



Source: California Department of Transportation, 2005

Appendix E. Weigh station Bypass Systems

Weigh Station	Direction	DIST-CO-RTE-PM	AADTT	Status
Antelope	EB	3-Sac-80-16	2,700	Completed 08/98
Antelope	WB	3-Sac-80-16	2,700	Completed 01/98
Blackrock	WB	8-Riv-10-R144	3,948	Completed 11/97
Blythe	WB	8-Riv-10-144	-	Proposed
Cache Creek	WB	6-Ker-58-105	2,756	Completed 10/97
Cajon	NB	8-SBd-15-R21	4,758	Completed 05/99
Cajon	SB	8-SBd-15-R21	4,758	Completed 08/99
Calexico	NB	11-lmp-7-0.1	535	Re-activated 08/02
Castaic	NB	7-LA-5-R54	6,378	Completed 06/95
Chowchilla	NB	10-Mer-99-1	3,870	Completed 09/97
Conejo	NB	7-Ven-101-9	1,300	Completed 09/00
Conejo	SB	7-Ven-101-9	1,300	Completed 09/00
Cordelia	EB	4-Sol-80-14	2,997	Completed 07/97
Cordelia	WB	4-Sol-80-14	2,997	Completed 07/97
Cottonwood	NB	2-Teh-5-41	2,585	Completed 12//95
Cottonwood	SB	2-Teh-5-41	2,585	Completed 05/99
Desert Hill	EB	8-Riv-10-R16	6,588	Completed 01/96
Desert Hill	WB	8-Riv-10-R16	6,588	Completed 12/96
Donner Pass	WB	3-Nev-80-19	1,843	Completed 05/98
Dunsnuir Pass	SB	2-Sis-5-R7	2,260	Completed 10/00
Gilroy	NB	4-SCI-101-11	2,241	Completed 10/00
Gilroy	SB	4-SCI-101-9	2,241	Completed 12/94
Grapevine	SB	6-Ker-5-12	6,916	Completed 12/96
Livermore	EB	4-Ala-580-R9	6,026	Completed 12/96
Livermore	WB	4-Ala-580-R9	6,026	Completed 12/96
Mission Grade	NB	4-Ala-580-R9	2,797	Completed 12/99
Mountain Pass	WB	8-Sbd-15-184	-	Proposed
Needles	WB	8-SBD-40-131	-	Proposed
Nimitz	NB	4-Ala-880-4	1,190	Completed 01/99
Nimitz	SB	4-Ala-880-4	1,190	Completed 01/99
Otay Mesa	WB	11-SD-905-12	1,100	Completed 06/00
Peralta	EB	12-Ora-91-14	3,549	Completed 04/01
Peralta	WB	12-Ora-91-14	3,549	Completed 04/01
Rainbow	SB	11-SD-15-53	2,691	Completed 05/99
San Onofre	SB	11-SD-5-R67	2,466	Completed 12/94
Santa Nella	NB	10-Mer-5-23	3,791	Completed 03/93
Santa Nella	SB	10-Mer-5-23	3,791	Completed 11/94
Tecate	NB	11-SD-188-0.1	-	Proposed
Winterhaven	WB	11-lmp-8-140	-	Proposed

Notes: 1. AADTT= average annual daily truck traffic for 5+axle trucks (vehicles per day)
2. Directions: NB: Northbound, SB: Southbound, EB: Eastbound, WB: Westbound
3. Counties: Als= Alameda, Imp= Imperial, Ker= Kern, LA= Los Angeles, Mer= Merced, Nev= Nevada, Ora= Orange, Riv= Riverside, Sac= Sacramento, Sbd= San Bernardino, SCI= Santa Clara, SD= San Diego, Sis= Siskiyou, Sol= Solano, Teh= Tehama, Ven= Ventura

Source: California Department of Transportation, 2005