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16. ABSTRACT

This report documents a research effort to develop requirements and recommendations for establishing a Weigh-in-Motion Test Facility (WIMTF) in California. This study finds that the effectiveness of existing WIM stations needs to be improved. A WIMTF can facilitate an in-depth understanding of the characteristics of various WIM technologies, as well as the development of new methods for dynamic calibration of WIM scales in order to improve the WIM measurement accuracy, which is critical to the effectiveness and efficiency of WIM stations. To prepare for a WIMTF, several sets of requirements, including non-functional and functional requirements, interface requirements, and data requirements for the WIMTF were developed. Potential sites for the WIMTF were evaluated. Based on the requirements, a site recommendation was made. The study also evaluated the benefits and costs of a WIMTF, concluding that the benefits will far outweigh the costs of a WIMTF.

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Report To
California Department of Transportation

The Requirements and Recommendations for Development of a California Weigh-in-Motion Technology Test Facility

University of California at Berkeley
University of California at Irvine

California PATH Research report
UCB-ITS-PRR-2014-04

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List of Abbreviations

AASHTO: American Association of State Highway and Transpiration Officials
ASTM: American Society for Testing and Material
ATRI: American Transportation Research Institute
AVI: Automatic Vehicle Identification
BHL: Berkeley Highway Laboratory
BWIM: Bridge Weigh-in-Motion
Caltrans: California Department of Transportation
CHP: California Highway Patrol
ConOps: Concept of Operations
CRCP: Continuously Reinforced Concrete Pavement
CSA: Comprehensive Safety Analysis
CSFFM: California Statewide Freight Forecasting Model
CVEF: Commercial Vehicle Enforcement Facility
CVIEW: Commercial Vehicle Information Exchange Window
CVISN: Commercial Vehicle Information Systems and Networks
CVRA: Commercial Vehicle Registration Act
DCVEF: CVEF Data
DDOT: USDOT Reader Data
DFS: Vehicle Feature and Status Data
DLPR: License Plate Recognition Data
DMV: California Department of Motor Vehicles
DSI: Passage System and Information
DSRC: Dedicated Short-Range Communications
DW: Weight Data
GPS: Global Positioning System
GVW: Gross Vehicle Weight
ESAL: Equivalent Single-Axle Loads
ETA: Estimated Time of Arrival
FBD: Functional Block Diagram
FHWA: Federal Highway Administration
FMCSA: Federal Motor Carrier Safety Administration
HDMI: High-Definition Multimedia Interface
HMI: Human Machine Interface
IFTA: International Fuel Tax Agreement
IRP: International Registration Plan
JCP: Jointed Concrete Pavement
LPR: License Plate Reader
LTPP: Long-Term Pavement Performance
NCHRP: National Cooperative Highway Research Program
NF: Functional Needs
NI: Interface Needs
NN: Non-Functional Needs
NS: Site Needs
OCR: Optical Character Recognition

OOS: Out-of-service
OS/OW: Oversize/Overweight
PCC: Portland Cement Concrete
PCI: Peripheral Component Interconnect
PeMS: Performance Measurement System
RFP: Request for Proposals
RI: Interface Requirements
RG: Radio Guide
RN: Non-Functional Requirements
RS: Site Requirements
SEGB: Caltrans/FHWA Systems Engineering Guidebook
SHRP: Strategic Highways Research Program
TAG: Technical Advisory Group
TMC: Traffic Management Center
UC: University of California
UCR: Unified Carrier Registration
USB: Universal Serial Bus
USDOT: United States Department of Transportation
VWIM: Virtual Weigh-in-Motion
VWS: Virtual Weigh Station
WIM: Weigh-in-Motion
WIMTF: Weigh-in-Motion Test Facility

Executive Summary

Weigh-In-Motion (WIM) systems can greatly improve the efficiency and effectiveness of weight enforcement facilities, while minimizing the delays imposed on the trucking industry. To date, 145 Weigh-in-Motion (WIM) stations have been established by the California Department of Transportation (Caltrans). Thirty-five WIM stations are used as PrePass™ stations to prescreen trucks near static Weigh Stations or Commercial Vehicle Enforcement Facilities (CVEFs) by identifying, removing, and citing trucks that run overweight. The remaining stations are used as WIM Data Stations collecting truck operational data. Use of WIM systems has been recognized as a promising and cost effective way to reduce damage to highway infrastructure, and to support caltrans' planning, operation, and maintenance. The California WIM data has been provided to California Air Resource Board, California Highway Patrol, the Long Term Pavement Performance (LTPP) and Future Strategic Highway Research Program (SHRP2) programs administered by Federal Highway Administration.

With existing technologies continuously evolving and new technologies emerging, Caltrans is considering the development of a WIM Test Facility (WIMTF) to support the deployment of WIM and VWS. The WIMTF will support the evaluation of systems and technologies that are developed for roadside inspection, screening, and enforcement functions. More specifically, the WIMTF will serve as a platform to evaluate existing, new, and emerging technologies for WIM systems, as well as to produce a guide for supporting statewide deployment of WIM technologies. It will address the following issues:

- selection of appropriate WIM technologies for prescreening and data purposes;
- determination and evaluation of new and advanced calibration methods for improved accuracy of measurements;
- strategic selection of deployment sites across the state;
- infrastructural support for WIM/VWIM-related communication methods/technologies;
- methods for meeting the growing demand for data storage and management;
- methods for integrating improved and new technologies;
- compatibility between old and new technologies;
- maintenance and repair issues.

As a planning activity, this project was initiated to analyze and evaluate the needs, cost and benefits and feasibility for a WIMTF, and to develop the requirements and site recommendations for a California WIMTF. The project, sponsored by Caltrans and jointly carried out by researchers from the University of California at Berkeley and the University of California at Irvine, was initiated in early 2012 and completed in December 2013. A Technical Advisory Group (TAG) representing the stakeholders was formed to solicit and address their needs, knowledge, and recommendations.

The Need for a WIMTF

The project team evaluated the data collected from 106 WIM stations in California and found that the overweight trucks only account for 0.083 percent of approximately 78 million trucks weighed by the WIM system. The extremely low percentage of overweight truck activities detected by WIM stations most likely does not represent the overall number of the truck overweight incidents in California. An in-depth study revealed that PrePass™ stations in California have been set with biased thresholds that are a few percentage points higher than their corresponding truck overweight limits. The biased thresholds minimize mis-detecting compliant trucks that are flagged as overweight (false positive overweight trucks). As a result, a large number of overweight trucks continuously bypass the CVEFs, preventing the WIM PrePass™ stations from performing their intended pre-screening functions. For the rest of WIM data stations, the WIM thresholds are often biased as well as a result of the sensors not being calibrated frequent enough. The systematic errors in the data collected by WIM significantly hinder their intended purpose of providing traffic and weight data for better planning and management of maintenance and new construction activities

A WIMTF can facilitate the selection of WIM technologies that will weigh trucks in motion with a smaller standard deviation. It will also support the development of continuous and dynamic calibration methods for significantly more accurate WIM results, maximizing positive violation detection rates and minimizing unnecessary delays for the trucking industry. When the performance of WIM technologies is improved at the Prepass™ WIM stations, truck overweight activities could be significantly discouraged. This, in turn, would reduce overall road infrastructure damage and maintenance costs. The improvement in data quality at WIM data stations will also result in significant planning, operation, and maintenance of highway infrastructure costs benefits.

Recommendations

This study recommends that Caltrans establish a WIMTF in order to realize the full benefits described in this report. We further recommend the NB Nimitz PrePass™ WIM site on the I-880 freeway as the candidate site for the WIMTF.

Based on the investigation of WIM calibration methods, we recommend that the primary guideline for calibrating WIM/VWIM technologies at the WIMTF should remain on-site field calibration, as defined in ASTM E1318. Continuous calibration and emerging calibration methods have great potential for either becoming a primary calibration means, or for supplementing on-site field calibration methods for WIM systems. We recommend that continuous calibration methods be developed and verified under the WIMTF program to prepare such technologies for broader applications in California.

The study further recommends investigating approaches to changing existing policies and practices regarding the distribution of enforcement revenues collected from overweight truck fines, to enable the new revenues generated from improved WIM PrePass™ to offset the funding shortfall for preservation of the highway infrastructure.

A feasibility study of a networked WIM system in California is also recommended. We have concluded that the data collected by existing WIM stations are not sufficient statistically or qualitatively to be used for decision support for statewide highway planning and maintenance purposes. A comprehensive Data WIM network should be first established in regions of the State with the largest number of truck vehicle miles, including Southern California, the Central Valley, the Bay Area, and the Border Region. This will cover all highway segments maximally disallowing trucks to bypass WIM stations.

The project team recommends pursuing the Pooled Fund option for both research as well as planned development of WIMTF, as it will reduce the overall costs to California for establishing and operating WIMTF, allowing the results from the WIMTF to be shared among pooled-fund participating states.

Development of WIMTF Requirements

The research team assessed WIM operation concepts and technologies, in order to establish the necessary background and knowledge base to conduct this study, and subsequently conducted analyses germane to the development of requirements for WIMTF. Using a systems engineering approach, as recommended by Caltrans, the Federal Highway Administration (FHWA) Systems Engineering Guidebook, and IEEE 1233, the team developed a logical, systematic, and traceable methodology for documenting multiple system requirement sets for a WIMTF. Newly developed WIMTF requirements were based on stakeholder-identified general needs, as well as specified functional capabilities for a WIMTF. The requirement sets include:

- Non-functional requirements: general system requirements that address the operational conditions, the environmental constraints imposed on the design, and implementation of the WIMTF;
- The Site Requirements: based on specific test site needs provided by stakeholders and WIM standards;
- Functional Requirements: all required functions and components of a WIMTF, based on the functional needs;
- Interface Requirements: the interface between various functional elements of a WIMTF, and the interface between a WIMTF and external systems;
- Data requirements are derived from the functional and interface requirements to capture data needs for the reference system, as well as the systems to be tested.

Site Selection for the WIMTF

As recommended by Caltrans, the following options were considered for a new WIMTF:

(a) No need for establishing a new WIM test facility;
(b) Upgrade the Berkeley Highway Lab;
(c) Upgrade the I-405 facility;
(d) Upgrade an existing Commercial Vehicle Enforcement Facility;
(e) Offer a Pooled Fund Option;
(f) Use a National Laboratory in California;
(g) Use a site in California not currently part of the above 6 options;
(h) Use a PrePass™ WIM site at the I-15 Mountain Pass (this option was added to the list as described below).

The first seven options were specified by the Request for Proposals(RFP); option (h) was added during the execution of the project. As a result of the analysis that was conducted in the evaluation of the Caltrans-recommended site options, we determined that options (b), (d), (f), and (h) do not meet the necessary WIMTF requirements. Option (c) requires significant new infrastructure to meet the WIMTF requirements. Option (a) is not a site option, while (e) is not a specific site. These options were however evaluated under the benefit cost analysis. Additional site evaluation efforts were focused on option (g): a site in California not currently included in the recommended options.

In addition to analyzing the deployment of a WIMTF for highways, Caltrans also requested an investigation of potential sites for the deployment of WIMs for bridges. The project team has investigated bridge-in-motion technologies and found that though bridge WIM has been used in Slovenia and a few other locations in Europe and Asia, the suitability for use of these technologies on the bridge types in California has not been tested or demonstrated. After consulting with Caltrans project managers, the decision was made not to pursue a bridge WIM test facility under this study.

Based on the established WIMTF requirements, the research team screened several dozen potential test sites (a list of these sites is provided in Appendix B). Five criteria were used to evaluate the suitability of each site option:

- fulfillment of the geometric requirements for WIM sites, as defined in American Society for Testing and Materials (ASTM) E1318-09;
- proximity to a CVEF for validating axle weight measurements at the WIMTF as reference measures;
- existing requirements for accessible power at the site without the need for extensive trench work;
- existing communications to a CVEF infrastructure near the site;
- availability of a suitable overhead structure necessary for mounting validation sensors and equipment for monitoring trucks traversing the WIMTF.

The first four criteria were specified by Caltrans in the RFP. Our team added the fifth criterion to the list, in order to achieve more synergy with existing WIM facilities. This enabled us to focus our research efforts on the most cost effective options.

Comparing all the site options, we concluded that the PrePass™ WIM sites best fulfill and meet the proposed requirements for an optimal WIMTF site. PrePass™ WIM sites also possess additional attributes, including having a close proximity and existing communications with an associated CVEF, and are, therefore, desirable as a potential WIMTF site.

Benefit and Cost Analysis

This study used a Benefit Cost Ratio (BCR) to evaluate the benefit versus cost of setting up a WIMTF. To determine the BCR, costs and benefits need to be estimated separately in monetary form. The analysis took into account the direct WIMTF benefits achieved from savings in the operation of WIM stations, as well as the indirect benefits that will be attributed to improvements in WIM station performance as a result of research and development outcomes that will be obtained from the WIMTF. The estimated benefits are summarized in Table (a).

Table (a) Benefits from WIMTF

Items	**Savings Generation (per year)**
Savings from existing operation	
Savings in operation costs	$325k to $425k
Savings from Reduced Overweight Truck Activities due to WIM Prescreening	$111 million to $264 million
Savings through WIM for Infrastructure Planning, Design and Management	$85 million to $145 million
Savings by Applying WIM Data for Highway Maintenance	$340 million to $1.02 billion
Estimated Range of Savings	**~$861 million and ~$1.85 billion**
Savings to trucking industry	
Weighing for Freight/Trade Planning and Regulation	$64 million to 124 million
Estimated Savings to Trucking Industry	**$64 million to $124 million**

The costs for two types of candidate sites are evaluated. The first site was the I-405 facility recommended by Caltrans. The second was a typical PrePass™ station. An estimated cost of $442,500 is needed for initial instrumentation of the WIMTF at a PrePass™ station. In contrast, our team estimated that the I-405 facility would require $100 million to build both a WIM and a CVEF from scratch, plus any necessary instrumentation for WIMTF. The team also estimated that an annual budget of $815K is needed for operation and research purposes.

One of the main findings of our research is that the benefits for existing WIM systems — in terms of prescreening overweight trucks and providing invaluable traffic and weight data for better planning and management of maintenance and new construction activities — are seriously hindered by large WIM system errors. A major benefit of setting up a WIMTF is the development of calibration algorithms and new sensing technologies for achieving significantly smaller weigh scale system errors at WIM stations. However, the project team was unable to precisely determine the costs for upgrading the current PrePass™ stations to achieve the desirable error characteristics. These upgrades will need to be determined based on the results and recommendations produced by the research using the WIMTF. It is envisioned that these recommendations will range from the use of new calibration software developed by the WIMTF, to a combination of new WIM scales and infrastructure improvements. These anticipated updates would have a wide range of cost values, possibly between tens of thousand dollars to hundreds of thousands dollars per WIM station. We therefore have to make some assumptions in order to make the cost benefit analysis more realistic. The assumed values for the necessary upgrades to the California WIMs are between $40K (an average of $10K per scale for a four lane highway) to $200K (an average $50K per scale for a four lane highway). The total assumed costs for upgrading all 106 WIM stations would therefore be between $4.24M and $33.92M. It is assumed in this report that the costs for the initial instrumentation and the WIM upgrades will be amortized over 10 years.

Based on the above benefit and costs analysis, the BCR is calculated using the benefits attainable from the analysis on the savings from the existing operation as the baseline. Table (b) summarizes the Benefit Cost Ratio for establishing a WIMTF.

Table (b) Benefit Cost Ratio

	a typical WIM PrePass™
Minimum benefits from the current operation	$861 million
Minimum benefits for trucking industry	$64 million
Costs for instrumentation (amortized over 10 years)	$44,250
Costs for operation and maintenance	$815,000
Costs for upgrading PrePass™ stations	$424,000 to $2,120,000
BCR on savings from existing highway operation	290 to 670
Additional BCR for trucking industry	20 to 75

The resulting BCR indicate that the positive economic benefits resulting from setting up a WIMTF far outweigh the costs. The large BCR values should be tolerant to uncertainty and error introduced by the estimation nature of the cost and benefit values. The BCR calculation results show that the investment in a WIMTF will have a tremendous impact on preserving thousands of miles of interstate from premature wear, and reducing maintenance costs. A WIMTF can also indirectly generate significant savings for the freight industry.

The team has further investigated Caltrans' recommended WIMTF site options, except those determined to be infeasible. The benefits and costs for instrumentation and operating/maintaining a WIMTF at the I-405 facility and a generic Prepass™ station are about the same. However, when replacing the costs for upgrading a PrePass™ station with the $100M cost for establishing a new facility, the BCR for the I-405 facility is reduced by a factor between 4 and 9. Though the BCR is still positive, it is hard to justify the creation of a WIMTF facility on I-405, since it offers the same benefits with a significantly smaller BCR. This factor has been considered in the final site selection. As a result, an I-405 WIM facility was not selected.

The team also assessed two other no-site related options provided by Caltrans. Since none of the benefits discussed in this report will be achieved through the 'No need for a newly established WIMTF' option, we recommend against this option. The project team recommends pursuing the pooled fund option recommended by Caltrans, as it will reduce overall costs to California for establishing and operating a WIMTF, and the results from a WIMTF can be shared among the pooled-fund participating states.

The potential benefits of future applications of WIM were also analyzed, indicating that WIM with improved error characteristics can generate substantial revenues that may contribute to the highway preservation, as long as current policies and provisions for distribution of fine revenue collected from overweight trucks can be adjusted. This project lead to a recommendation for studies on policy issues related to distribution revenues overweight enforcement and the feasibility of a statewide network of WIM stations.

The benefit cost analyses lead to a positive recommendation for establishing a WIMTF in California.

Final Site Selection

Based on our initial site selection results and benefit and cost analyses, further analysis was conducted to derive final site recommendations, using the following criteria:

- Minimum Disruption: The WIMTF will require at least one non-adjacent, non-instrumented lane that can be open to traffic during installation of pavement-based sensors at the WIMTF.
- Safe Access: The WIMTF will require a safety pull-out that accommodates at least two vehicles within 100 ft. (30.48 m) of the WIM-system sensors.
- Multiple Test Pass: The WIMTF and CVEF should be located within 10 miles (16,093 m) of a freeway exit to permit safe turnaround of FHWA Class 9 trucks making multiple calibration passes.
- Speed Range: The WIMTF should contain at least two instrumented lanes with speeds ranging from 10 - 80 mph (16 - 130 km/h).

While the facility class may not appear critical, a better-equipped CVEF is expected to provide superior infrastructure for installation of the equipment required for matching trucks and validating axle weights. Therefore, we recommend North Bound Nimitz Interstate-880 PrePass™ WIM as the final candidate for the California WIMTF site.

1. Introduction

The volume of commercial truck traffic grows every year, demanding increased screening, inspection, and enforcement activities by the California Highway Patrol (CHP). Caltrans and CHP must streamline enforcement efforts by reducing the number of trucks that need to be inspected, while simultaneously identifying, removing, and citing trucks that run overweight. Use of Weigh-in-Motion (WIM) and Virtual Weigh Station (VWS) systems are a promising and cost effective way to accomplish these goals.

Caltrans is considering the development of a WIM Test Facility (WIMTF) to support the deployment of WIM and VWS. The planned WIMTF will serve as a platform to evaluate existing, new, and emerging hardware and software for WIM and Virtual WIM (VWIM) systems. As part of the planning effort, a project team consisting of researchers from the University of California at Berkeley and the University of California at Irvine studied the needs and requirements for a California WIMTF, assessing benefits and costs, evaluating site options, and developing recommendations. The project was initiated in early 2012 and ended in December 2013. This report documents the study's findings.

1.1 WIM and VWS Systems

WIM systems have been used for commercial vehicle operations in the United States for many years and are commonly deployed at weight enforcement facilities where static scales cannot handle truck traffic volumes. WIM has been used at PrePass™ stations as a weight enforcement tool to sort trucks on the mainline one mile upstream of a Commercial Vehicle Enforcement Facility (CVEF). PrePass™ stations use the transponder in the truck to signal the truck to bypass or pull in when suspected of exceeding maximum allowable weight limits, directing them to a static scale for compliance weighing. WIM has also been used to collect truck data in California.

Currently 145 data-WIM stations are operating throughout California. Several more are under construction, and further expansion of WIM systems is planned.[1] At the time of this report was written, data from 106 WIM stations are available and analyzed.

Caltrans WIM systems are configured to either measure or calculate gross vehicle weight (GVW), individual axle weights, vehicle speed, overall length, and axle spacing. As a vehicle moves across sensors or scales, the system measures approximate dynamic weights at each axle, determining gross vehicle weight and classification based on axle weights and spacing.

One hundred and five of the 106 Caltrans WIM system scales consist of bending plates on frames embedded in concrete. The other location uses a piezoelectric scale. Inductive loops are placed before and after the WIM sensor array to measure time for the vehicle to pass between loops. The WIM system then calculates vehicle speed and length. This data provides vehicle classification, including passenger vehicle, bus, or truck-tractor/semitrailer identification, and vehicle conditions that include when a truck is overweight.[2]

[1] http://www.dot.ca.gov/hq/traffops/trucks/datawim/index.html
[2] http://www.dot.ca.gov/hq/traffops/trucks/datawim/technical.html

A VWS is a roadside-enforcement facility that is remotely monitored and does not require continuous staffing. VWSs are established for a variety of tasks depending on the priorities and needs of each jurisdiction. Typically, this could include safety enforcement, data collection, security (e.g., homeland security and theft deterrence), size, and weight enforcement. These sites often use a variety of sensor components to collect data, such as WIM installations, camera systems, and wireless communications. No VWS facilities are currently installed or operating in California.

1.2 Project Scope

The objective of this project was to develop requirements and recommendations for a California WIMTF for rigorous, transparent, and replicable testing of new technologies. The project includes that following tasks:

Task 1. Project Management
Task 2. Form a Technical Advisory Group
Task 3. Evaluate Methods for Calibrating and Evaluating WIM/VWIM Technologies
Task 4. Establish Requirements for the WIM/VWIM Test Facility
Task 5. Explore Options for Establishing a WIM Facility
Task 6. Benefit/Cost of Various VWIM Test Facility Options
Task 7. Develop Site Selection Recommendations
Task 8. Final Report

As a first step of the systems engineering process, we worked with the stakeholders to synthesize their long-term vision, goals, and objectives for WIM/VWIM deployment. A carefully structured process was followed. It was, based on the systems engineering approach typically known as the "V diagram" and used to determine how best to proceed in defining the needs and requirements for a test facility that would support continuous testing, evaluation, and deployment/of WIM/VWIM systems and technologies.

Our investigation used both top-down and bottom-up approaches in an iterative fashion. In the top-down approach, the investigation was organized according to the functions of WIM/VWIM technologies. We derived a list of aspects of technical performance for each function, which included general aspects, such as accuracy, precision, data latency, and system maintainability, as well as technical aspects that are specific to individual functions. We then derived specific performance measures for each aspect of technical performance. In the bottom-up approach, correlations and interactions between aspects of a function, as well as between individual functions, were investigated. The overall system performance requirements were then examined as both a sanity check for the performance measures of individual functions and as a basis for the final comprehensive evaluation. The resulting lists of detailed performance measurements and requirements then guided the data analysis and technical performance evaluation.

A WIM Technical Advisory Group (WIM TAG) was created to include staff representatives from several divisions of Caltrans and the CHP, as well as other experts in WIM technologies and operations. The WIM TAG served as a mechanism for harnessing the wisdom and experience that Caltrans and other states have accumulated in the field of truck inspection and

WIM/VWIM systems. Monthly TAG meetings were conducted, when possible, to review project progress and guidance.

The project team investigated various methods for calibration and evaluation of the weight measurements, including subsystem calibration, bench-test-based calibration using analytical tools, continuous calibration and evaluation using CVEFs, and periodic calibration and evaluation using test trucks. The knowledge gained from the evaluation of calibration methods added important information to the WIM/VWIM requirements and test site selection recommendations.

A systems engineering approach was followed throughout, to develop the technical requirements and site requirements for the California WIMTF. The research team reviewed a suite of WIM systems and technologies and solicited customer needs from Caltrans, CHP, and members of the WIM TAG. Technical needs for validating WIM technologies were compiled and assessed, and formed the basis for developing the technical and site requirements. Specifically, the project team factored in the requirements for effective and efficient calibration and evaluation of WIM technologies to ensure the continuous validity of the WIM systems measurements. These included weight, vehicle size, and vehicle ID under various operating and environmental conditions, such as vehicle speeds, and varying weather factors.

The project team developed detailed requirements for the WIMTF to include non-functional requirements, functional requirements, site requirements, interface requirements, and data requirements. As part of the systems engineering approach, the requirements were reviewed and refined.

The research team also conducted a cost/benefit evaluation of the WIMTF to estimate projected savings from more effective overweight enforcement and more efficient planning, operation, and highway maintenance as a result of new WIM technologies and calibration methods facilitated by the WIMTF.

A key task was to explore site options for a new WIMTF. Working with Caltrans and the WIM TAG, five criteria were used to evaluate the suitability of the site options, including:

- Fulfilling the geometric requirements for WIM sites, as defined in American Society for Testing and Materials (ASTM) E1318-09;
- Proximity to a CVEF for validating axle weight measures at the WIMTF as reference measures;
- Existing power requirement for accessible power at the site without the need for extensive trench work;
- Existing communications to CVEF infrastructure available at the site for data communication with the CVEF;
- The availability of a suitable overhead structure necessary for mounting validation sensors and equipment for monitoring trucks traversing the WIMTF.

The first four criteria were provided by Caltrans in the Request for Proposal (RFP). The overhead structure criterion was added by the project team because many WIM stations in

California already have existing overhead structures for sensors and therefore meet the general WIMTF requirements. The overhead structure criterion enables us to focus our efforts on most cost effective options.

As a part of the RFP, the following site selection options have been given:

(a) No need for a newly established test facility;
(b) Upgrade the Berkeley Highway Lab;
(c) Upgrade the I-405 facility;
(d) Upgrade an existing Commercial Vehicle Enforcement Facility;
(e) Offer a Pooled Fund Option;
(f) Use a National Laboratory in California;
(g) Use a site in California not currently part of the above;
(h) Add a Planned PrePass™ WIM site at the I-15 Mountain Pass to the list.

The first seven options were provided in the RFP and (h) was added during the project. As a result of the analysis of the Caltrans-recommended site options, we determined that options (b), (d), (f) and (h) do not meet the WIMTF requirements. Option c requires significant new infrastructure to meet the WIMTF requirements. Options (a) and (e) are not site options. These options are evaluated under the benefit cost analysis. Additional site evaluation efforts have focused on option (g), a site in California not currently included in the recommended options.

Based on the requirements for a WIMTF developed under this study, the research team identified several dozen sites, including those identified by Caltrans. The team performed an initial screening of these potential test facility sites, which are listed in Appendix B. The initial screening was supplemented by an online examination of site characteristics with Google Earth and Google Maps, reducing the list to a manageable level.

1.3 Report Structure

All study outcomes, including requirements, benefit and cost analysis, and site recommendations for a California WIMTF, are documented here. An overview of WIM technologies and operations is provided in Section 2. The concept of the proposed California WIMTF is presented in Section 3. The requirements for such a facility are derived and elaborated in Section 4. Options for facility configuration and equipment, along with candidate sites in California, are described in Section 5, which is followed by the cost-benefit analysis in Section 6. Section 7 assesses suitability of site options. The report concludes with site recommendations in Section 8. Although this report is primarily intended for audiences in California, it will be published as a PATH report to be made available for readers both inside and outside of United States. We therefore used both US customary and metric units throughout the report.

2. Overview of Weigh-in-Motion Operations and Technologies

The project team assessed the WIM operation and technologies. As WIM technologies are central to the WIMTF, the project team conducted a thorough evaluation of the characteristics of existing WIM technologies and systems, and identified calibration as a critical process to the effectiveness and efficiency of WIM operation. Various methods for the calibration and evaluation of the weight measurements were also evaluated.

2.1 Functions of WIM/VWIM

In an effort to provide technical guidance to jurisdictions regarding their implementation of the Virtual Weigh Station (VWS) concept, the U.S. Department of Transportation funded a study[3] to define the Concept of Operations (ConOps) of Weigh-in-Motion/Virtual Weigh-in-Motion (WIM/VWM). This study provides a comprehensive summary of basic WIM functions and expanded WIM functions. Below is a synopsis of the WIM/VWIM functions from a WIM study sponsored by the United States Department of Transportation (USDOT).[3]

(a) Basic WIM functionality derives from the following **Operation Concept**:

- Use roadside technology to augment human enforcement resources;
- Deploy scarce enforcement resources as effectively and efficiently as possible;
- Accurately identify all commercial vehicles in real-time;
- Determine a commercial vehicle's weight to a degree of accuracy that is sufficient for its functional purpose;
- Deliver vehicle identification and weight data to enforcement personnel in real-time;
- Leverage other safety and credentialing data in screening criteria;
- Focus enforcement on commercial vehicles that pose the highest risk;
- Deploy VWS technology in an open and expandable way so that future technologies (e.g., enhanced vehicle identification systems, driver identification systems, Smart Roadside, Connected Vehicle/Commercial Vehicle Infrastructure Integration) can be integrated easily and cost effectively.

(b) WIM can be designed and implemented to support a wide variety of roadside enforcement functions. At a minimum, a VWS must support the following **Basic WIM Functionality**:

- Real-time weighing of a commercial vehicle: Determine a commercial vehicle's estimated axle weights as the vehicle moves across sensors, and calculate gross vehicle weight and classification based on the number of axles, as well as axle weights and spacing (which are calculated through WIM detection, vehicle presence, and speed measurements);
- Real-time identification of a commercial vehicle: Accurately identify all commercial vehicles that pass the site, using a combination of camera-based license plate recognition, Radio Frequency Identification (RFID), and other sensors;

[3] Cambridge Systematics, Concept of Operation for Virtual Weigh-in-Motion Station, Report to USDOT, June 2009

- Integration of real-time data for screening decisions; integrate commercial vehicle identification and weight data in real-time/near real-time, in order to support manual (i.e., decisions made by roadside enforcement personnel) or automated (i.e., decisions based on data processing by the system, then forwarded to a human) targeting of specific commercial vehicles for further enforcement action;
- Communication of data to enforcement personnel in real-time: Communicate VWS data (e.g., vehicle photo, weight data) to authorized users (e.g., mobile enforcement personnel stationed downstream from the VWS, enforcement personnel stationed at a fixed inspection site that could be dispatched to intercept an overweight vehicle) in a timely and secure manner.

(c) **Expanded WIM Functionality** is also identified to enable the current WIM deployment to support additional applications:

- Real-time identification of the motor carrier responsible for the operations of a commercial vehicle; identify the motor carrier responsible for the safe operation of the vehicle;
- Implementation of an expanded screening algorithm: Integrate additional criteria (e.g., motor carrier history of safety performance, motor carrier history of compliance with size and weight standards, current commercial vehicle credential status, current motor carrier credential/operating authority status, driver's license status) into the screening decision;
- Real-time verification of vehicle dimensions: Integrate additional sensors (e.g., gantry-mounted laser over-height detectors) to determine if a commercial vehicle exceeds legal height, width, and length regulations, and therefore would require an oversize/overweight permit;
- Availability of data to support resource planning: Provide commercial vehicle average daily trip data (e.g., volume, weight, vehicle classification) in order to support the scheduling of mobile enforcement activities, as well as to identify locations in need of fixed enforcement facilities.

(d) The USDOT's study also identified a series of **Additional Functionality** that could be supported by a WIM. These additional functionalities include:

- Real-time identification of the commercial driver operating a commercial vehicle and inclusion of driver information in the screening decision: Identify the individual driving a commercial vehicle and determine if that individual can legally operate the vehicle at that time (i.e., commercial driver's license is not revoked or suspended);
- Direct enforcement: Issue a citation or take other enforcement actions (e.g., prevent a commercial vehicle from being started) based on data from a WIM;
- Communication of real-time operational data to system managers: Serve as a conduit for onboard vehicle data (e.g., speed, windshield wipers on/off, air temperature) to be sent to traffic management centers in support of traffic/congestion monitoring and development of travel advisories;
- Communication of real-time traveler information to commercial drivers: Serve as the means by which real-time traffic (e.g., incident warning, congestion, weather advisories)

and truck parking (e.g., location, availability) information could be delivered to commercial vehicle drivers operating within a specific geographic area/corridor;

- Communication of commercial vehicle location data to authorized users: Accurately capture vehicle location data (i.e., date and time when it passed a VWS) in order to support private sector applications (i.e., asset tracking, estimated time of arrival (ETA) updates to the vehicle's motor carrier/shipper/receiver) and public sector applications (i.e., tracking of hazardous material by the Department of Homeland Security, and tracking of in-bond agricultural shipments by the United States Department of Agriculture).

Please note that the expanded functions discussed in (c) and potential additional functions (d) are desirable for an advanced WIM system. Most of these functions have not yet been implemented in the United States. WIM for direct enforcement is still in an exploratory stage through research efforts around the world and is only deployed for low-speed enforcement applications. Direct enforcement is not used in California at this time.

2.2 WIM Scale Technologies and Types of WIM Systems

WIM technologies will be the central element of the WIMTF. State-of-the-art WIM technologies and WIM systems are therefore evaluated here.

2.2.1 WIM/VWIM Scale Technologies

The most commonly used WIM weight sensor technologies are bending plates, piezoelectric sensors (quartz, polymer, and ceramic), load cells, and Bridge WIM. This section provides a brief overview of each technology.

A bending plate system incorporates strain gauges attached to the bottom of a steel plate. When a vehicle travels over the plate, the strain introduced by the loading is measured and converted to a dynamic weight. The static load is estimated by multiplying the measured load by its calibration factor.

Piezoelectric sensors measure the change in voltage induced as a vehicle passes over sensors. As with all WIM sensors, the static load is estimated by using the measured load and a calibration factor. The piezoelectric materials can be polymer molecular chains (e.g., polyvinylidene fluoride), ceramics (e.g., lead zirconate titanate) or crystals (e.g., quartz). Polymeric and ceramic piezoelectric are the least expensive WIM sensor alternatives, but these sensors are temperature sensitive. As compared to polymeric and ceramic piezoelectric sensors, quartz crystal piezoelectric sensors have been shown to have good linearity and remain stable under changing temperature conditions.

In a load cell-based WIM sensor, a load cell is mounted centrally in each scale mechanism across the traffic lane. All loading on the weighing surface sensor is transferred to the load cell through load transfer tubes. Typically there are two six-foot long scales covering one lane width, which weigh wheels at both sides of an axle simultaneously. The scale is mounted in a frame installed in a vault, which is flush with the road surface.

Bridge weigh-in-motion (BWIM) is a non-intrusive method of determining a truck's weight as it crosses a highway bridge, by measuring the strain or deflection of the bridge's structural members. BWIM has typically been used under limited circumstances, specifically for bridges that are simply supported or have structures of short length that allow just one vehicle on the bridge at a time, as well as bridges with little skew and low traffic volumes. Moreover, Bridge WIM systems designed for a specific bridge type might not be effectively transferred to other bridges types.

Because the accuracy of a WIM scale depends not only on sensor technology but also on site conditions, truck characteristics, and driver behavior, it is difficult to precisely quantify the accuracy of each of the sensor technologies. Therefore, a qualitative comparison has been conducted by the Connecticut Academy of Science and Engineering ([1]) on such characteristics as ease of installation, maintenance, safety, and cost, along with accuracy in determining the technology or technologies. Table 2.1 shows a qualitative comparison of the four most common WIM sensors.[4]

[4] Based on the comparison, the study recommended using quartz piezoelectric sensors for Near Term Enforcement and Data Collection and using Bridge WIM for long-term potential application at some locations in Connecticut.

Table 2.1 Qualitative comparison of the four most common WIM sensors ([1])

	Quartz Piezoelectric Sensor	Polymeric and Ceramic Piezoelectric Sensors	Bending Plates	Load Cells	Bridge WIM
Performance	Can meet pre-screening enforcement requirements with two rows of sensors. Better accuracy can be achieved with three rows through averaging out of vehicle dynamics	Not acceptable – temperature sensitive	Can meet pre-screening enforcement requirements	Can meet enforcement requirements	More research needed to verify accuracy
Installation	Small road cuts one day to complete	Small road cuts one day to complete	Significant road cut with proper drainage; required multiple days to complete	Significant road cut with proper drainage required multiple days to complete	Non–intrusive Instrumentation
Maintenance	Must maintain surface smoothness and seal properly to achieve satisfactory performance	Must maintain surface smoothness and seal properly to achieve satisfactory performance	Required six-month checks and annual in-road inspection	Corrosion of load cell if not properly sealed	Minimal
Safety Issues	One day for system installation and during periods of in-road maintenance	One day for system installation and during periods of in-road maintenance	Multiple day system installation and during periods of in-road maintenance	Multiple days for system installation and during periods of in-road maintenance	None
Cost of System Including Installation	Low-medium cost	Low cost	Medium-high cost	High cost	Low Cost
Mature/Proven Technology	Yes	Yes	Yes	Yes	Not in US

2.2.2 Types of Highway WIM Systems

Highway WIM systems generally have three applications: collecting statistical traffic data, aiding enforcement, and enforcement, though the application for enforcement is only at its exploratory stage. The American Society for Testing and Materials (ASTM) "Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Method" (ASTM Designation: E 1318-09[5] [2]) classifies four types of WIM systems according to their application and gives related performance and user requirements for each type of system. The Standard lists user requirements that should be met to ensure that the WIM system functions properly. The four systems have different speed ranges, data gathering capabilities, and intended applications. Table 2.2 shows the information of the four types of WIM systems.

Type-I WIM systems shall be designed for installation in one or more lanes at a traffic data-collection site and shall be capable of accommodating highway vehicles moving at speeds from 10 to 80 mph (16 to 130 km/h), inclusive. For each vehicle processed, the system shall produce all data items shown in Table 2.2.

Type II WIM Systems shall be designed for installation in one or more lanes at traffic data-collection sites and should be capable of accommodating highway vehicles moving at speeds from 15 to 80 mph (24 to 130 km/h), inclusive. For each vehicle processed, all data items shown in Table 2.2, except wheel load, shall be produced by the system. All other features and options of the Type II WIM system shall be identical to those for the Type I WIM system.

Type III WIM Systems shall be designed with sensors installed in one or more lanes off the main highway lanes at weight-enforcement stations, or in one or more main highway lanes, to identify vehicles operating at speeds from 10 to 80 mph (16 to 130 km/h), inclusive, that are suspected of weight-limit or load-limit violation. For each vehicle processed, the system shall produce all data items shown in Table 2.2 except vehicle class, wheelbase, and ESALs and it shall also estimate acceleration while the vehicle is over the WIM-system sensors (see 7.3.6.1 of the ASTM E1318 Specification [2]). However, when the sensors are installed in the main highway lane(s), the Type III system will not be required to measure vehicle acceleration.

Type IV WIM Systems has not yet been approved for use in the United States, but for conceptual development purposes, it shall be designed for use at weight-enforcement stations to detect weight-limit or load-limit violations. Speeds from 2 to 10 mph (3 to 16 km/h), inclusive, shall be accommodated. A Type IV system that uses tire-force sensors that support the entire tire-contact area(s) of all tires on a wheel assembly simultaneously shall also be capable of indicating the wheel load(s), if applicable, and individual axle loads for a stationary vehicle. For each vehicle that is processed, the system shall produce all data items shown in Table 2.2, except vehicle class, lane and direction of travel, wheelbase, and ESALs; it shall also estimate acceleration (while the vehicle is over the WIM-system sensors).

Thirty-five WIM systems in California are deployed as Type III systems, while the remaining 71 WIM stations are used for Type II systems. All WIM systems are configured to collect and process GVW (gross vehicle weight), individual axle weights, weight violations, vehicle

[5] The ASTM E1318 specification cited in this report refers to E1318 – 09, which was last revised in 2009.

speed, overall length, axle spacing, and vehicle classification (such as passenger vehicle, bus, or truck-tractor/semitrailer).[6]

Accordingly, ATSM E1318 Specifications ([2]) define the detailed performance requirements for each type of WIM system. The performance requirements cover the following functions: accuracy (of wheel load, axle load, axle-group load, gross vehicle weight, speed, and axle spacing and wheelbase), vehicle class, site identification code, lane and direction code, date and time of passage, vehicle record number, wheelbase, ESALs, violations, acceleration, user-assignable codes, and the tire-force sensor.

As an example, Table 2.3 lists the accuracy requirements of the indicated functions each type of WIM system shall be capable of performing. The E1318 Specifications ([2]) further specify a test method for determining compliance with these requirements under prevailing site conditions described in Section 7. The stated accuracy should be maintained for ambient air temperatures at the WIM site from –20 to 120°F (–28 to 50°C); however, the user shall specify, at the time of system procurement, the range of temperatures within which the WIM system must operate properly.

Table 2.2 ASTM WIM System Classification ([2])

		Classification			
		Type I	Type II	Type III	Type IV
Speed Range		10 ~ 80 mph (16 ~ 130 km/h)	15 ~ 80 mph (24 ~ 130 km/h)	10 ~ 80 mph (16 ~ 130 km/h)	2 ~ 10 mph (3 ~ 16 km/h)
Application		Traffic Data Collection	Traffic Data Collection	Weight Enforcement Station	Weight Enforcement Station
Number of Lanes		Up to four	Up to four	Up to two	Up to two
Bending Plate		x	x	x	x
Piezoelectric Sensor		x	x		
Load Cell		x	x	x	x
WIM Data Outputs	Wheel Load[7]	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 Class	x	x		
	Site Identification Code	x	x	x	x
	Lane and Direction of Travel	x	x	x	
	Date and Time of Passage	x	x	x	x
	Sequential Vehicle	x	x	x	x

6 http://www.dot.ca.gov/hq/traffops/trucks/datawim/technical.htm
7 The data description is provided in Appendix A

	Record Number				
	Wheelbase (front to rear axle)	x	x		
	Equivalent Single-Axle Load	x	x		
	Violation Code	x	x	x	x

Table 2.3 Functional Performance Requirements for WIM Systems ([2])

Function	Tolerance for 95% Compliance[8]				
	Type I	Type II	Type III	Type IV	
				Value ≥ lb(kg)[9]	±lb (kg)
Wheel Load	±25%		±20%	5000 (2300)	300 (120)
Axle Load	±20%	±30%	±15%	12000 (5400)	500 (200)
Axle-Group Load	±15%	±20%	±10%	25000 (11300)	1200 (500)
Gross Vehicle Weight	±10%	±15%	±6%	60000 (27200)	2500 (1100)
Speed	±1mph (2 km/h)				
Axle Spacing and Wheelbase	±0.5ft (0.15m)				

2.3 Calibration of WIM/VWIM Technologies

The accuracy of WIM systems is critical to their efficiency and effectiveness. The calibration plays a critical role in controlling the accuracy of WIM systems.

2.3.1 The Impact of Calibration on the Performance of WIM

We can describe the WIM system accuracy using the mean and the variance of the measurement error, which is defined as a function of the vehicle's true static weight: (WIM-STATIC)/STATIC [3]. If a WIM system is installed in a sound road structure and is subjected to normal traffic conditions, the system errors are normally distributed. The calibration of a WIM system is determined by the arithmetic mean of WIM system measurement errors. If the arithmetic mean of the WIM measurement errors is zero, the WIM system is considered to be perfectly calibrated. Even when perfectly calibrated, some WIM systems have greater measurement errors than others. For example, typical standard deviations for the three most common WIM technologies − piezoelectric sensors, bending strain scales, and single load cell − are 10%, 5% and 1.5%, respectively, at one standard deviation (1σ), as depicted in Figure 2.1 [3].

Let's assume the trucks identified by the WIM as being over the maximum allowable weight are directed to the static scale for compliance weighing and possible citation, while trucks within legal weight limit are directed to bypass the static scale. If the calibration of a WIM system is biased to weigh either light or heavy, the sorting decisions made by the WIM system are correspondingly significantly biased. Figure 2.2 illustrates the effect a 5% calibration bias to weigh trucks light has on the sorting decision made by a bending strain scale WIM system for a truck that is at the legal weight limit [3]. As shown in Figure 2.2, if

[8] 95% of the respective data items produced by the WIM system must be within the tolerance.
[9] Lower values are not usually a concern in enforcement.

the bending strain WIM system is biased to weigh 5% light, the probability of a truck at the legal weight limit being called in for static weighing is reduced from 50% to approximately 16%. Similarly, if a piezoelectric WIM system and single load cell scale WIM system are biased to weigh 5% light, the probability of a truck at the legal weight limit being called in for static weighing is reduced from 50% to approximately 31% and 0.04%, respectively. As a result, it can be concluded that weigh-in motion system calibration is critical to optimizing heavy truck sorting efficiency.

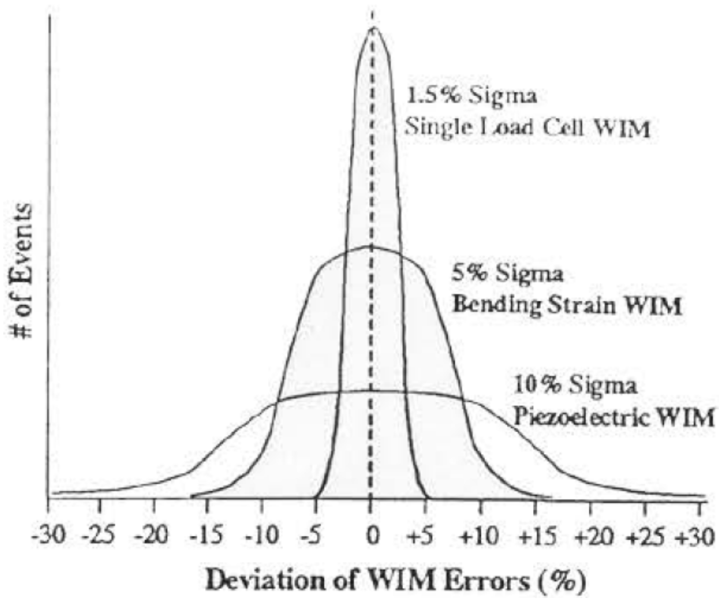

Figure 2.1 Typical WIM measurement errors distribution for GVW (assuming zero bias) ([3])

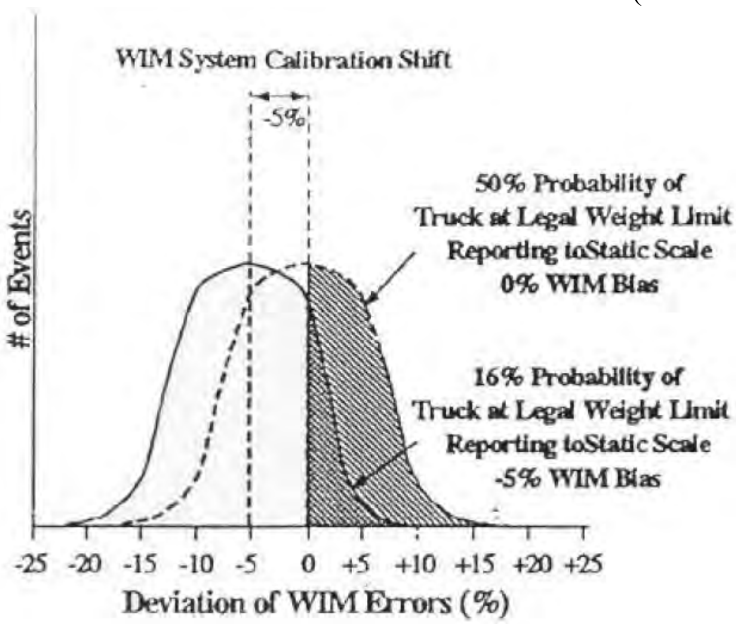

Figure 2.2 Effects of WIM System Calibration Shift (assuming a 5% standard deviation) ([3])

Thus, significant importance has been placed on initial and ongoing calibration activities to ensure an adequate level of WIM system performance. The tire-force sensors of a WIM system are typically designed to produce a signal, with respect to time, that is linearly proportional to the magnitude of the component of dynamic tire force applied perpendicularly to the road surface by the tires of a moving vehicle. The function of calibration is to define factors that are subsequently applied within WIM-system calculations to correlate the observed vehicle speed and tire-force signals with the corresponding tire-load, axle-spacing, and wheelbase values for the static vehicle. The dynamic tire force results from a complex interaction among the vehicle components, the WIM-system sensors, the road surface surrounding the sensors, and other factors.[10] Road-surface profiles and sensor installation are different at every WIM site, and every vehicle has unique tire, suspension, mass, and speed characteristics. Therefore, it is necessary to recognize the effects of these site-specific, speed-specific, and vehicle-specific influences on WIM-system performance, and attempt to compensate for their adverse effects as much as is practicable via calibration.

Field calibration procedures use vehicles of a known weight/configuration or a random sample of vehicles from the traffic stream measured, using both a WIM system and vicinity static scale to determine mean differences between the WIM system and known/static scale measurements. The WIM system is then adjusted until mean differences equate to zero. However, the WIM system can often shift out of calibration between periodic calibration efforts. Measurement errors occur once the WIM scale is out of calibration.

2.3.1 On-Site Calibration Procedure

The most commonly used calibration is the on-site calibration procedure defined in ASTM E1318 Standard Specification ([2]). It requires each of two loaded, pre-weighed and measured[11] test vehicles to make multiple runs over the WIM-system sensors in each lane at specified speeds. The recorded data is then used to calculate the difference in the WIM-system estimate and the respective reference value for the two test vehicles for each wheel-load, axle-load, tandem-axle load, gross-vehicle weight, speed, axle-spacing, and wheelbase value. A mean value is then computed for the differences for each set of values and used to determine the necessary changes to the WIM-system settings that will adjust the calculated mean value of the respective differences for each of these values to equal approximately zero. The purpose of this on-site calibration is to remove as much bias as feasible from the weight, load, speed, axle-spacing, and wheelbase estimates.

For example, for WIM systems that estimate wheel load (Type I and perhaps other types), the adjustment is to the settings that affect the wheel-load estimates on each side of the vehicles, separately. For systems that estimate axle loads and not wheel loads, the adjustment is to the settings that affect axle loads. WIM-system estimates for axle-spacing and wheelbase are usually calculated as the product of speed[12] and the measured time between successive axles on the moving vehicle actuating one chosen sensor. Therefore, assuming that vehicle speed is constant while the vehicle crosses over the sensors, proportional adjustments to the distance between the two sensors used to measure speed (an input value to software for the site) will result in proportional changes in the WIM-system estimates for axle spacing and wheelbase.

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[10] Such as road surface roughness, vehicle acceleration, out-of-round tires, dynamically-unbalanced wheels, tire inflation pressure, vehicle suspension, aerodynamic features, and wind.

[11] The reference value weighing and measuring of the two test vehicles shall be in accordance with the ASTM E1318 specifications as well.

[12] This is estimated by dividing the distance between two different sensors (an input value to software for the site) with the travel time of the vehicle (or an axle) between the two different sensors.

The ASTM E1318 Specification ([2]) requires that this on-site calibration procedure be applied immediately after the initial installation of a Type I, Type II, or Type III WIM system at every site. Furthermore, the calibration procedure shall be applied again when a system is reinstalled or whenever site conditions or WIM-system components (including software and settings) have changed significantly. Recalibration shall be performed no less frequently than annually.

2.3.2 Continuous Calibration using Static Measurements from Enforcement Activities

Although the on-site calibration procedure described above could provide the best results, it is costly to perform and hence, may occur infrequently. As a result, methods that do not require controlled runs of pre-weighted vehicles have been explored for continuous monitoring and calibration. Enforcement officials in France and The Netherlands utilize continuous, ongoing calibration procedures to ensure an adequate level of WIM system performance [4]. Under this procedure, static axle weight records obtained by enforcement officials during their scheduled enforcement activities are directly compared for accuracy to the axle weight records captured by the WIM system for the same vehicles. Static measurements are relayed in near-real time to personnel at the WIM site using unique vehicle identification information (i.e., vehicle silhouette and license plate images) and Dedicated Short-Range Communications (DSRC). If an unacceptable level of WIM data error is observed (in The Netherlands, WIM axle weight error rates cannot exceed ±15% for 95% of the aggregate vehicles measured), the problem can be quickly corrected through system calibration or other remedial action. Periodic comparisons between static and WIM system weight records can also be performed on an ongoing basis using archived data records.

A similar calibration method that has been explored uses the static measurements at nearby CVEFs. This method typically involves associating the measurements from the WIM system with the static weight measurements of the same vehicles through Automated Vehicle Identification (AVI). A study [5] conducted by Washington State University used the AVI facilities developed for the Heavy Vehicle Electronic License Plate project on the I-5 corridor. In this study, the static axle load of AVI-equipped vehicles was obtained from the Oregon DOT for two sites (Woodburn south-bound and Ashland northbound); WIM load data was obtained from the database maintained by Lockheed Martin for Information Management System (IMS) for all WIM systems on the I-5 corridor. The data was analyzed to sort-out AVI numbers, dates, and times of weighing. Time limits for traveling between sites were established to ensure that trucks had no time to stop and load/unload cargo between sites. Direct comparisons between WIM and static axle loads were effected by matching the AVI numbers of transponder-equipped vehicles at static and WIM weighing locations, and then by cross-checking date and driving time between them. Subsequently, errors were calculated as the percent difference between WIM and static loads for individual axles/axle groups, and calibration factors were derived to set the mean axle weigh error to zero. The results showed that, with few exceptions, the median errors for both northbound and southbound WIM locations were all negative and had substantial magnitudes. Accordingly, the calibration factors were developed through regression by considering the static load as the dependent and the WIM load as the independent variables. As a result, this study was able to show the potential of developing continuous calibration methods by using static measurement at nearby CVEFs through AVI.

2.3.3 Emerging Methods in WIM System Calibration

One emerging method is to develop automatic calibration on the continuous basis to reduce the costly procedure of on-site calibration. The key enabler is that the static measurements of the vehicles together with the vehicle ID information will need to be communicated to the WIM station. The WIM system controller (or a separate computer) can then automatically associate the WIM measurements with the static measurement by matching vehicle identification from the WIM system with the static measurement. Accordingly the WIM system controller can (periodically) determine and apply calibration factors to maintain the accuracy of WIM measurements.

Another emerging method looks at how to simplify the on-site calibration procedure to make it easier to implement (thereby allowing it to be conducted more frequently). As metrological laws and specifications are based on static weight measurements, traditional WIM system calibration methods require conversion of the true dynamic load to a static measure, with a concomitant loss in accuracy. In The Netherlands, a specially-designed vehicle was developed to allow calibration of a dynamic measure to the true dynamic load [4]. The dynamic calibration vehicle consists of a three-axle tractor and a five-axle trailer; one axle is instrumented and the remaining four axles are steerable and liftable. The trailer load can be incrementally adjusted using up to 44 2,204 lbs. (1,000 kg) mass pieces. The dynamic calibration vehicle measures, while driving, the dynamic forces exerted on the WIM system by the instrumented axle using strain gauges. Accelerometers mounted on the axle correct for the influence of inertia from the wheels, hub, and braking system. Measurements captured by the dynamic calibration vehicle are compared with those of the in-road WIM system at speeds of 6 to 62 mph (10 to 100 km/h), for axle loads between 11,023 and 33,070 lbs. (4535.9 to 13607.8 kg), with an accuracy of ±5%. The dynamic calibration vehicle[13] can also be used to calibrate traditional static weight bridges [4].

A third method of calibration can be explored by focusing on developing novel sensor configurations and smarter estimation algorithms. As a vehicle travels, the dynamic load applied to the road varies significantly due to vehicle bouncing, acceleration or deceleration, and shifting of the load either physically or just in its distribution through the suspension system. The combination of all these loading factors is what is actually measured by a WIM system. Thus, in addition to the error in the measuring device, the dynamic effects of weighing a vehicle at high speeds contributes to a second error in the WIM weight measurements. Therefore, a WIM system that can better remove those dynamic effects is likely to have better accuracy. As the number of axles and the vehicle class are estimated, the structure of the corresponding vehicle dynamic model can then be determined. If the key parameters in the vehicle model can be identified from the dynamic load measurement, we can estimate the dynamic effects and approximately remove them to achieve a more accurate estimate of the static load of the vehicle. For some sensors, such as the piezoelectric sensors, this could require multiple sensors to provide additional measurements of the dynamic load for vehicle model identification. For other sensors, such as bending plate scales, this could

[13] At the time this report is prepared, only one of these dynamic calibration vehicles exists; it is located in Europe.

require a higher sampling rate to have more measurements while the tires travel through the span of the plate. Meanwhile, the estimation algorithm will need to integrate the measurements of multiple axles in the model identification and static weight estimation.

2.3.4 Quality Control Methods

In addition to calibration methods, various quality control methods for monitoring and evaluating WIM performance have been developed or investigated. In The Netherlands, transportation officials issue a formal Quality Assurance Statement – that includes the number of axles measured, period of measure, and inaccuracy (compared to static weights) for every weight record and in aggregate − with every data request, including routine data disseminations. Provision of this Quality Assurance Statement allows individual data users to determine the sufficiency of data quality based on their individual needs [4].

Sponsored by the Indiana DOT, a project that aimed to develop a quality control program to improve the accuracy of the data produced from the WIM system was conducted by Nichols and Bullock of Purdue University [6]. This quality control program provides a mechanism for assessing the accuracy of vehicle classification, weight, speed, and axle spacing data, and monitoring it over time. In this project, robust metrics were identified for the quality control program; these metrics can be continuously monitored using statistical process control procedures that differentiate between sensor noise and events that require intervention. Examples of the robust metrics include the following:

- The accuracy of speed and axle spacing can be assessed by examining the drive-tandem- axle spacing of the Class 9 vehicle. The population average of this metric should range between 4.30 and 4.36 feet.
- The weight accuracy can be assessed by examining the total steer-axle weight and left-right-steer axle residual of the Class 9 vehicle population. The population average steer- axle weight should range between 9,000 and 11,000 lbs. (4082 to 4989 kg) depending on the percentage of loaded vehicles. The population average left-right residual should range between -6% and +6% depending on the cross-slope of the roadway.
- The sensor error rates can be assessed and monitored by computing the proportion of errors relative to the number of vehicles.

Using these robust metrics, system accuracy charts include the average values for each WIM lane in the WIM system that can be derived. If a lane's value is outside the target range, a statistical process control chart (developed in this project) can be used to determine whether the deviation is attributed to random variation or a sensor problem.

Both the Oregon DOT study (described earlier in Section 2.2.2) and the above Indiana DOT study found that WIM sensor measurements frequently drift out of calibration. Therefore, for WIM systems to be effective, it is critical to maintain a high level of WIM data accuracy and reliability through continuous calibration and rigorous quality control in addition to on-site calibration.

3. Approach to Establish Requirements for the WIM/VWIM Test Facility

In this section, we describe the approach we took defining the WIMTF and developing the requirements for the WIMTF. We started with the general needs for the WIMTF based on inputs from the stakeholders. Following a review of the WIM/VWIM Concept of Operation2, we derived the operational concept for the WIMTF and established the functional capability of the WIMTF.

3.1 General Needs for a WIM/VWIM Test Facility

The envisioned WIMTF is intended to serve as a test bed for evaluation and validation of commercial technological products that are crucial to the operation of future WIM/VWIM stations. It adds, for testing purposes, a suite of capabilities to test the list of functionalities needed for a basic or expanded WIM/VWIM station. The WIMTF will also facilitate and enable the investigation of existing and emerging components, sub-systems, software tools, as well as integrated functions of a WIM/VWIM station. According to the stakeholders, including Caltrans and CHP, who provide us with the overall needs of the test facility, the WIMTF will need to support the following rigorous, transparent and replicable testing of new technologies:

- Evaluate new and emerging WIM/VWIM technologies
- Evaluate and analyze calibration needs, frequency, and techniques
- Compare technologies, one against another, including Bridge WIM
- Investigate data mining accuracy and calibration, including identification of data patterns that indicate the need for calibration, or pending failure
- Evaluate new and emerging communications methods/technologies
- Evaluate various camera technologies, including LPR and OCR
- Evaluate new and emerging sensors to replace loops for WIM
- Evaluate sensors for hot/cold brakes

3.2 Operational Concept of the WIM/VWIM Test Facility

The WIMTF will support typical WIM application scenarios, which involve collecting all necessary data to measure the weight of each individual truck ‘on-the-fly’ when it passes through a segment of highway where WIM technologies are installed. A WIM station will first identify the truck, weigh the truck at normal highway operational speeds, establish the dimension of the truck, make a screening decision, then share the data with appropriate stakeholders. A typical operational procedure for the baseline WIM station is illustrated by the left side of the block diagram in Figure 3.1.

The WIMTF, on the other hand, will be designed to verify the quality of data collected by various WIM system features, including vehicle identification, weight, dimension, as well as the screen decision. Because WIMTF systems serve as instrumental tools, all components of the WIMTF need to be calibrated using the continuous calibration tools and will undergo periodic on-site calibration. Furthermore, the WIMTF will be located where all passing heavy trucks can be weighed and truck status data can be captured, that is, near a CVEF, so that samples of trucks that are detected by the WIMTF will be directed to the CVEF, allowing data collected by the WIMTF and the CVEF to be compared.

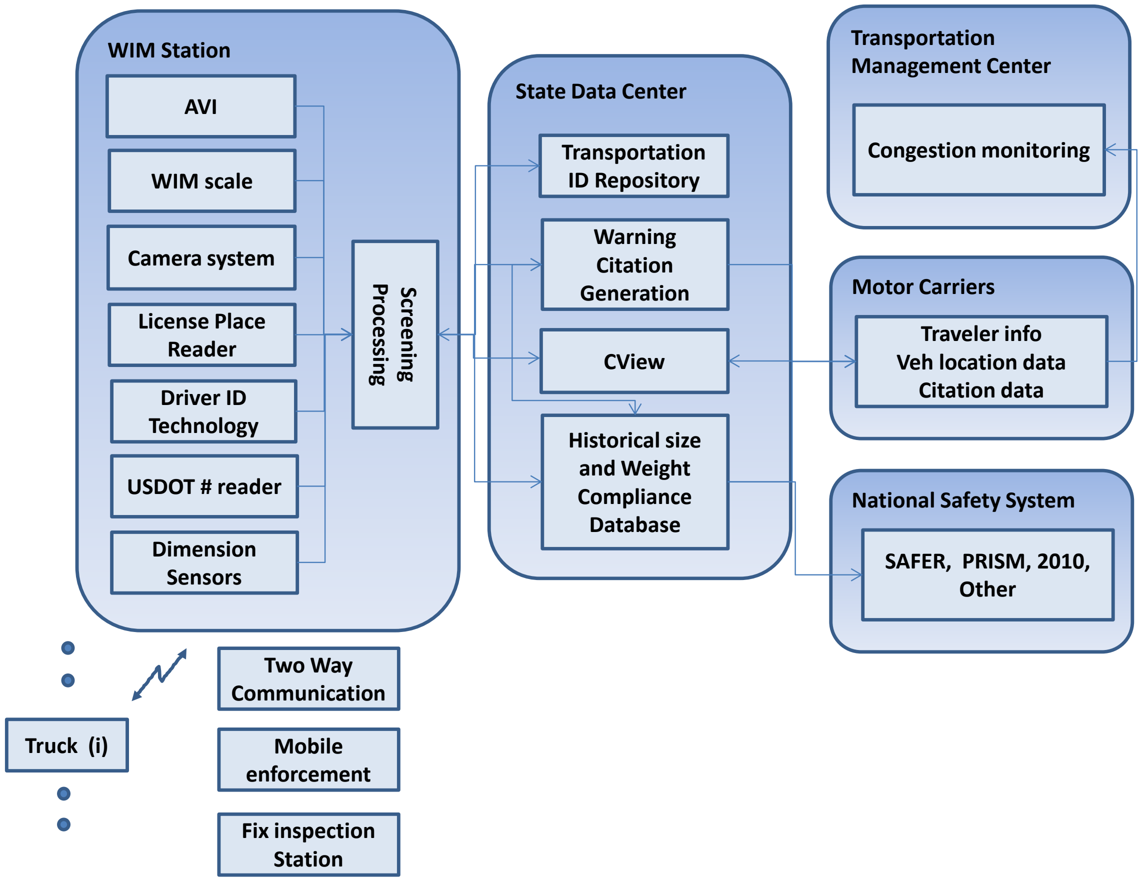


Figure 3.1 Typical Operational Procedure of a Baseline WIM and the Baseline Functionality of the WIM/VWIM Test Facility

The above scenario represents the baseline functionalities of the WIMTF, which will support verification and validation of the functions for WIM technologies and tools. Accordingly, the WIMTF will need to possess the capabilities for verifying or validating a suite of functions or WIM technologies, including:

- Verification[14] of technologies and tools:
  - Weigh scale technologies
  - Speed measurement technologies
  - Vehicle identification technologies
  - Dimension measurement technologies
  - Data synchronization and archiving technologies
  - Screening tools
  - Technologies for other measurements
- Validation[15] of:

[14] Verification ensures that the product has been built according to the requirements and design specifications. Simply stated, verification ensures that "you built it right."

  - Sensor calibration
  - Camera (digital imaging) system
  - Screening software
  - Communication infrastructure
    - Network availability and/or reliability
  - LPR and/or USDOT number reader system
  - CVIEW (future function to be added)
  - Repository of past weight performance
  - Driver identification system (future function to be added)
  - Two-way communication to verify
    - Communication latency
    - Message transmission loss

Reference sensors, devices, and communication systems to accomplish the above-identified functions are to be included in WIMTF functions for collecting data for verification and validation of the commercially available systems, and for supporting research and development of new technologies. Note that WIM systems in California are currently configured to collect and process GVW (gross vehicle weight), individual axle weights, weight violations, vehicle speed, overall length, axle spacing, and vehicle classification (such as passenger vehicle, bus, or truck-tractor/semitrailer).[16] As the priority of the WIMTF is to enhance the existing operational WIM systems in California, the WIM technologies that are in use for WIM will be first instrumented at the WIMTF. Figure 3.2 shows the functionalities of the baseline WIMTF. Additional functionalities are to be added as the needs grow.

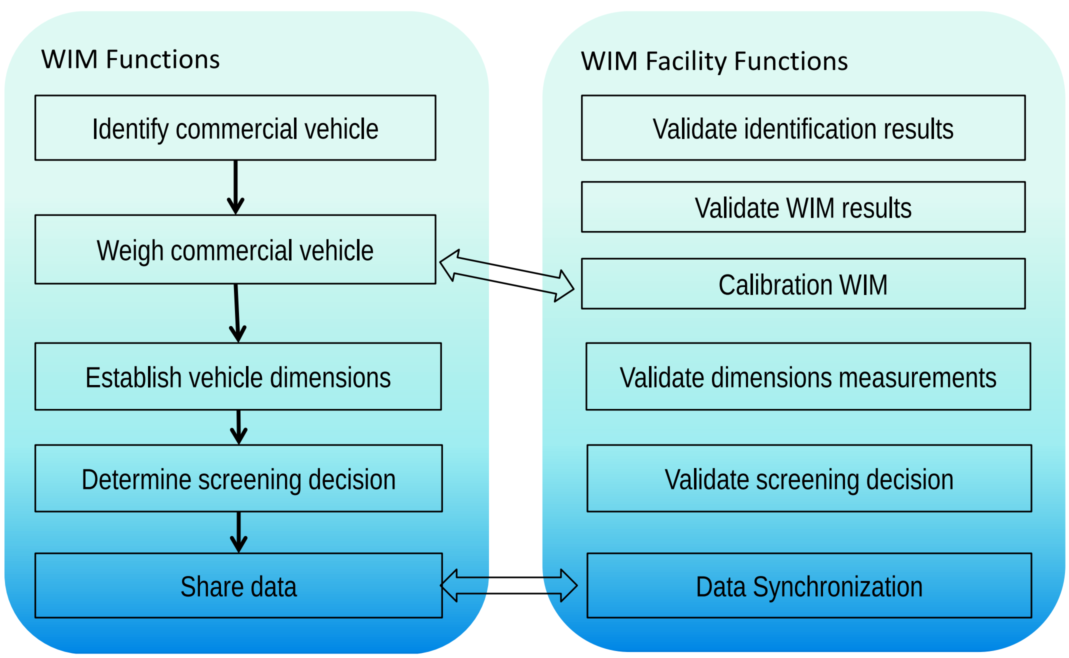


Figure 3.2 Expanded WIM System Functionalities

[15] Validation ensures that the product actually meets the user's needs, and that the specifications were correct in the first place. Simply stated, validation ensures that "you built the right thing," or confirms that the product, as provided, will fulfill its intended use.
[16] http://www.dot.ca.gov/hq/traffops/trucks/datawim/technical.html

As the WIMTF is not an operational facility, reference systems and data archiving tools are only required to be reliable enough to support the evaluation and research purposes.

3.3 Requirement Development Process

The project team developed the WIMTF requirements based on the general needs identified by the stakeholders (Section 4.1), and general functional capabilities for the WIMTF (Section 4.2). Using the systems engineering approach defined by the Caltrans/FHWA systems engineering guidebook (SEGB) and IEEE 1233, the team developed a logical, systematic, and traceable methodology for documenting the WIMTF systems requirements, including (a) non-functional requirements, (b) site requirements, (c) functional requirements, (d) interface requirements, and (e) data requirements.

3.3.1 Development of System Requirements

Development of Non-functional requirements: Non-functional requirements were developed based on a set of needs derived from the WIMTF, needs defined by the stakeholders within the context (or constraints) of environmental and operational conditions for both the technologies to be tested and the reference systems.

Development of site requirements: Test site requirements were developed based on a specific set of test site needs provided by Caltrans.

Development of functional requirements: A two-step development process, as shown in the dotted line in Figure 1.1, was utilized for the development of WIMTF functional requirements, including a 'needs-driven' requirement development process and a requirement verification process using functional analysis. The following steps were taken in developing the needs-driven requirements:

1) Decompose corridor needs: The non-functional, site, functional, and interface needs were decomposed from the WIMTF needs identified in the ConOps, to the level that requirements can be identified.
2) Identify functional requirements: Each functional requirement was derived from the WIMTF functional needs.
3) Build requirements: Through analysis, detailed requirements were extracted and refined from the high-level requirements to obtain well-formed requirements.
4) Categorize functional requirements: Similar requirements were combined and the functional requirements were categorized into an ordered set of requirements according to the data flow in the WIMTF.

A functional analysis was conducted to verify the completeness of the functional requirements, to:

1) Identify major WIMTF functions (capabilities): A set of major WIMTF functions was identified based on the WIMTF goals/objectives.
2) Identify WIMTF functions: From the major WIMTF functions, functional decomposition was conducted to derive lower level functional requirements and were also developed based on the relationships among various functions identified by using Functional Block Diagrams (FBD).

3) Validate requirements using functional analysis: Each requirement item developed under the 'needs'-driven requirement process was mapped into the FBD to verify if such a function was indeed needed, and if any functions were missing.

Development of Interface Requirements: Requirements for interfaces among functions within the WIMTF and interfaces among WIMTF functions and outside functions were identified.

Development of Data Requirements: Data requirements were derived from the functional and interface requirements to capture data collected by the systems to be tested and the reference systems.

Figure 3.3 depicts the requirements process taken by the team for the development of WIM requirements.

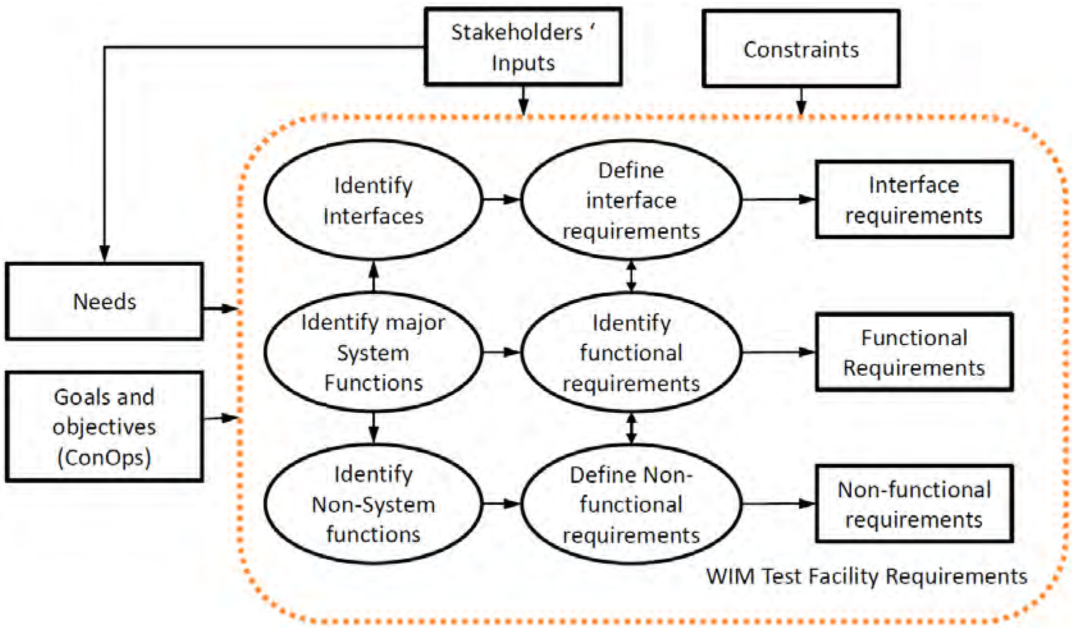


Figure 3.3 Process for Developing WIMTF Requirements

3.3.2 Traceability Method and Criticality Assignments

These WIMTF requirements were developed based on a set of functional, non-functional, and interface needs derived from stakeholder input. Accordingly, a traceability method has been established to trace between the needs and functional and data requirements, between the design/implementation needs and non-functional requirements, and between functional requirements and interface requirements. The requirements that are prioritized with level of criticality to the WIMTF are denoted as highly critical (H), medium level critical (M), and low critical (L) in the requirements table.

3.3.3 Requirement Verification Methods and Terminologies

All requirements must be verifiable through one of the following methods:

A = Analysis

I = Inspection
D = Demonstration
T = Operational test

Requirements may have other attributes that generally fall under the following categories:

S = Similarity
TBS = To be submitted by Supplier
N/A = Not Applicable

3.3.4 Normative References

IEEE Guide for Developing System Requirements Specifications, IEEE 1233 (1998 Edition) and Caltrans/Federal Highway Administration (FHWA) Systems Engineering Guidebook are used.

3.4 Guidelines and Procedures for Calibrating WIM/VWIM Technologies

An effective calibration and evaluation means is critical to the assessment of performance and reliability of WIM/VWIM technologies and is therefore central to the WIM/VWIM test facility. Based on the WIM calibration and evaluation methods reviewed in Section 3.4, the guidelines for calibrating WIM/VWIM technologies at the WIMTF were derived. Accordingly, the recommended calibration procedures were provided. To facilitate incorporation of the guidelines and procedures into the requirements for the WIMTF, calibration needs for the WIMTF were identified. These guidelines and needs will be considered and incorporated into the WIMTF requirements and site selection recommendations in the subsequent tasks of this project.

3.4.1 Guidelines for Calibrating WIM/VWIM Technologies at the WIMTF

Since the WIMTF is intended to serve as a platform for evaluating existing, new, and emerging hardware and software for WIM and VWIM systems, the WIMTF should have the capability of supporting both existing and emerging methods for WIM calibration and evaluation. As described in Section 2.2, the WIM calibration methods include on-site field calibration, continuous calibration using static measurements from enforcement activities, and emerging methods, such as online automatic calibration, dynamic calibration using specially designed vehicles, and smart estimation algorithms based on vehicle dynamics. Since the continuous calibration methods and the emerging new methods are still in their development (and validation) stages, they are the technologies that will likely be evaluated at the WIMTF. Thus, the primary guideline or principle for calibrating WIM/VWIM technologies at the WIMTF should still be the on-site field calibration, as defined in the ASTM E1318 Specification ([2]). The continuous calibration using static measurements from enforcement facilities and the emerging calibration methods should be used as secondary calibration methods; the WIMTF should be able to obtain some types of ground truth data (e.g., measurements from enforcement facilities, or from a well-calibrated reference WIM system) to facilitate the evaluation of these calibration methods.

As the WIMTF differs from a standard WIM site, it has a few unique considerations related to on-site field calibration. First, multiple WIM systems are likely to be installed at the WIMTF simulatneously. When one WIM system needs testing or recalibrating, it would be advantageous to conduct the tests or calibration runs for all other WIM systems at the WIMTF, and collect the data for either re-calibrating or evaluating those other WIM systems.

Second, we recommend that the WIMTF have a reference WIM system installed, whose weight measurements and estimates could serve as a reference (i.e., an approximate ground truth) to evaluate the performance of new WIM weight sensing technologies and WIM systems. For this reference WIM system[17], strictly following the tests and on-site calibration procedures (described in Section 2.3.2) becomes even more critical to ensure accuracy. In particular, the reference WIM system can be recalibrated whenever a WIM system needs tests or recalibration.

Third, the tests and calibration procedures defined in the ASTM E1318 Specification ([2]) can be anticipated to be applicable to most new and emerging sensing technologies, since they are defined independently of the specific WIM sensing technologies. However, in the few cases where it cannot be applied, the tests and calibration procedures can be provided by the system developers or vendors.

Fourth, the ASTM E1318 Specification ([2]) requires that WIM system recalibration should be conducted no less frequently than annually. However, one purpose of the WIMTF is to allow the refinement and evaluation of continuous calibration using static measurements from enforcement activities, as well as the development, testing, and verification of emerging calibration methods. As those calibration methods mature, recalibration with on-site field calibration could be performed less frequently to evaluate the longer-term effectiveness of the new calibration methods.

3.4.2 Procedures for Calibrating WIM/VWIM Technologies

Calibration of the WIM/VWIM technologies at the WIMTF should include the following test and calibration procedures, as defined in the ASTM E1318 Specification ([2]):

(1) A Type-Approval Test should be conducted for any new or modified type (or model) of WIM system that is to be installed at the WIMTF;
(2) An on-site Acceptance/Verification Test should be conducted for newly-installed or recently-modified equipment at the WIMTF;
(3) An on-site Acceptance/Verification Test should be conducted for verifying the performance of an in-service system at the WIMTF;
(4) A Calibration Procedure for on-site calibration should be conducted at the time of system installation or whenever site conditions or equipment have changed. This Calibration Procedure is not only a stand-alone calibration procedure, but also a fundamental part of every Type-Approval Test, as well as a recommended component in every On-site Acceptance/Verification Test;
(5) The Calibration Procedure for on-site calibration should be conducted no less frequently than annually.

[17] A bending plate system identical to those used by Caltrans will likely be the on-site reference system.

Users conducting these tests and calibration procedure should refer to the current ASTM E1318 Specifications ([2]) for the detailed procedures.

3.4.3 Preliminary needs for the WIMTF based on Calibration Guidelines

To incorporate the calibration guidelines and procedures into the requirements for the WIMTF, we identified the needs from the perspective of WIM calibration as follows:

- Need for calibration of all types of WIM systems (Type I ~ Type IV WIM systems, as defined in the ASTM E1318 Specification ([2]));
- Need for calibration using data from traditional CVEFs;
- Need for calibration using test methods defined in the ASTM E1318 Specification ([2]);
- Need for advanced calibration and self-calibration methods;
- Need for data monitoring and evaluation.

Each of the above calibration needs can be translated into equivalent site needs, functional needs, non-functional needs, and interface needs. Each need is uniquely labelled to facilitate tracing the needs to the requirements; the labels are exactly the same as those used in the requirement development in Section 4[18].

- Need for calibration of all types of WIM systems (Type I ~ Type IV WIM systems as defined in the ASTM E1318 Specification ([2]))
  - Site needs: need for accommodating all WIM types
  - Functional needs: need for calibrating WIM using static weight measurements for all WIM types (NF-03)
- Need for calibration using data from traditional CVEFs
  - Site needs: need for proximity to an existing CVEF
  - Interface needs: need for access to the CVEF data
  - Functional needs:
    - need for recording WIM data (including vehicle identification)
    - need for associating WIM data with the CVEF data
- Need for calibration using test methods defined in the ASTM E1318 Specification ([2])
  - Site needs: need for conducting field test methods (type-approval tests, on-site acceptance tests, on-site calibration)
- Need for advanced calibration and self-calibration methods
  - Site needs: need for accommodating multiple WIM sensors and WIM systems
  - Interface needs
    - need for remote access to the WIM data as well as raw and semi-processed WIM sensor data (preferably at least daily)
    - need for remote calibration of WIM sensors or systems
    - need for remote software upgrade
  - Functional needs:
    - need for storage of raw and semi-processed WIM sensor data
    - need for off-line calibration methods

[18] The needs are reorganized in Section 4 and some needs are further broken down. Therefore, the labels shown below are not sequential and some needs may have multiple labels.

        - need for on-line calibration methods
- Need for data monitoring and evaluation
    - Interface needs: need for remote access to the WIM data as well as raw, and semi-processed WIM sensor data (preferably at least daily)
    - Functional needs:
        - need for storage of raw and semi-processed WIM sensor data
        - need for off-line data monitoring and evaluation capabilities
        - need for on-line data monitoring and evaluation capabilities

The above identified needs have been fully incorporated into the functional and non-functional needs and are used to generate requirements for the WIMTF in the subsequent Task 4. The traceability is provided between the full sets of needs and requirements defined in Section 4. The purpose of documenting a subset of needs based on calibration guideline is to provide an example of the analytical approach we have taken in developing the needs for the WIMTF.

4. Needs and Requirements for the WIM/VWIM Test Facility

This section details the WIMTF needs and requirements developed following the approach described in Section 3. As mentioned in Section 3, the WIMTF requirements can be grouped into five categories:

- General requirements (i.e., non-functional requirements)
- Site requirements
- Functional requirements
- Data requirements
- Interface requirements

The general requirements contain non-functional requirements, which impose constraints on the design or implementation (such as performance requirements, quality standards, or design constraints). The functional requirements provide a complete description of the behavior of the WIMTF system to be developed. Interface requirements specify the requirements imposed on one or more WIMTF subsystems, including the reference system and technologies to be tested by the WIMTF to achieve the complete purpose of the WIMTF. The Data requirements define the information needed to perform the desired functions.

Development efforts of the WIMTF requirements have benefited greatly from stakeholder participation and contributions through the Technical Advisory Committee.

4.1 Non-Functional Requirements

This section describes the needs and associated requirements for the non-functional aspects of the WIMTF.

4.1.1 WIMTF Non-Functional Needs:

A set of non-functional needs (NN) for the WIMTF are identified here. These non-functional needs form the basis for a set of non-functional requirements (RN), which impose constraints on the design and implementation. The identified needs are indicated by multiple categories, as shown in Table 4.1. All corresponding requirements are traced to one or more of these needs.

Table 4.1 WIMTF Non-Functional Needs

NN-01 Needs for a reliable system
NN-02 Needs for a durable system
NN-03 Needs for a maintainable system
NN-04 Needs for a modifiable system
NN-05 Needs for intuitive designs
NN-06 Needs for policy and regulations for data sharing
NN-07 Needs for a quality information processing infrastructure
NN-08-01 Performance
NN-08-02 Function 24/7
NN-08-03 Function at least 90% of the time
NN-08-04 Process user authentication within two seconds
NN-08-05 Provide user information storage for up to 30 days
NN-08-06 Provide data acquisition configuration capability for up to five WIM test scales and Y sensors and detection data sources
NN-08-07 Provide network configuration to allow remote operation
NN-09 Needs for security
NN-09-01 Operations center firewall
NN-09-02 Physical security
NN-10 Needs for documentation
NN-10-01 Maintenance documentation
NN-10-02 Operator manuals
NN-10-03 Administration Manuals
NN-10-04 User Manuals
NN-11 Needs for training
NN-11-01 Maintenance training
NN-11-02 Operator training

4.1.2 WIMTF Non-Functional Requirements

According to the needs above, a set of non-functional requirements, labeled as RN, are developed and documented in Table 4.2 to accompany the functional, interface, and data requirements discussed in the next few sections.

Table 4.2 WIMTF Non-Functional Requirements

ID	***Title***	***Requirement***	***Traceability***	***Comment***	***Testability***	***Criticality***
RN-01	*Availability*	*The WIMTF shall be available 24 hours a day, 7 days a week.*	*NN-01*		*T*	*H*
RN-02	*Durability*	*The WIMTF subsystems shall be designed to last TBD years.*	*NN-02*		*T*	*H*
RN-03-01	*Working environment*	*The WIMTF subsystems and components shall be operational between -40^{o}C and 70^{o}C outdoors.*	*NN-01* *NN-02*		*T*	*H*
RN-03-02	*Working environment*	*The WIMTF subsystems and components shall be operational between 0^{o}C and 50^{o}C (31^o and 122^{o}F) in a roadside cabinet.*	*NN-01* *NN-02*		*T*	*H*
RN-04-01	*Reliability*	*The WIMTF shall have a Mean Time Between Failures (MTBF) greater than 180 days for major system failures*	*NN-01*		*T*	*H*
RN-04-02	*Reliability*	*The WIMTF shall have a MTBF greater than 30 days for minor system failures.*	*NN-01*		*T*	*H*
RN-05	*Hardware maintainability*	*The major WIMTF hardware shall be replaceable through plug-and-play process.*	*NN-03* *NN-04*		*T*	*H*
RN-06	*Software maintainability*	*The software components of the WIMTF shall be maintainable with maximum down time, not to exceed 30 minutes.*	*NN-03*		*T*	*H*
RN-07	*HMI design*	*The Human-Machine Interface of the WIMTF shall be designed in such a way that new-user training will not exceed 48 hours.*	*NN-05*		*A*	*H*
RN-08	*Authentication*	*The WIMTF shall process user authentication within two seconds after user log information is received.*	*NN-08-04*		*T*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RN-09-1	*Data acquisition capability*	*The WIMTF shall provide data acquisition configuration capability for up to five WIM subject scales*	*NN-08-06*		*T*	*H*
RN-09-2	*Data acquisition capability*	*The WIMTF shall provide data acquisition configuration capability for up to 20 additional sensors and detection systems.*	*NN-08-06*		*T*	*H*
RN-10	*Storage capability*	*The WIMTF shall provide an onsite storage capability for saving data up to 30 days.*	*NN-08-05*		*A*	*H*
RN-11	*Additional storage capability*	*The site shall allow additional data storage capacity to be added to store the relatively large amount of raw or semi-processed data.*	*NN-08-05*		*A*	*H*
RN-12	*Remote data access*	*The WIMTF shall support remote access to the data in real time (or, as needed).*	*NN-08-07* *NF-05*		*D*	*H*
RN-13	*Data download*	*The WIMTF shall support data downloading from both primary and additional data storages.*	*NN-08-07* *NF-05*		*D*	*H*
RN-14	*Administration*	*The administration of the WIMTF shall be performed by an on-site operator, with the capability of remote operation when the on-site operator is not available.*	*NN-08-02* *NN-08-07*		*D*	*H*
RN-15	*Communication protocol*	*Communication protocols shall be developed for the WIMTF allowing effective communication from permitted remote terminals.*	*NN-08-07*		*D*	*H*
RN-16	*Firewall*	*The WIMTF operations center shall have a firewall for security purposes.*	*NN-09-01*		*D*	*H*
RN-17	*Documentation for maintenance*	*The WIMTF shall have documentation for maintenance.*	*NN-10-01*	.,	*I*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RN-18	*Operation manual*	*The WIMTF shall have operator manuals.*	*NN-10-02*		*I*	*H*
RN-19	*Administration manual*	*The WIMTF shall have administration manuals.*	*NN-10-03*		*I*	*H*
RN-20	*On-line training for maintenance personnel*	*The WIMTF shall have features allowing online training for maintenance personnel*	*NN-11-01*		*I*	*H*
RN-21	*On-line training for operators*	*The WIMTF shall have features allowing on-line training for system operators.*	*NN-11-02*		*I*	*H*
RN-22	*User manual*	*The WIMTF shall have a user manual describing data type, format, and basic data processing.*	*NN-10-04*		*I*	*H*

4.2 Site Requirements

This section describes the site needs and associated requirements for selecting candidate sites for the WIMTF. The identified needs are organized into three main categories: WIM technology, operational, and safety needs, respectively. All corresponding requirements have been designed and are traced to one or more of these needs.

4.2.1 WIMTF Site Needs

A set of site needs (NS) for the WIMTF is identified and listed in Table 4.3. These needs form the basis for a set of site requirements (RS), which impose constraints on the design and implementation.

Table 4.3 WIMTF Site Needs

NS-01	WIM Technology Needs
NS-01-01	Needs to meet all site condition requirements for all WIM types, as per ASTM E1318-09
NS-01-02	Needs to accommodate multiple WIM systems for evaluation
NS-01-03	Needs to support the development of new methods for WIM system design, signal processing, and calibration/evaluation tests.
NS-02	Operational Needs
NS-02-01	Needs to facilitate validation of truck axle weight measures between the WIMTF and static scale
NS-02-02	Needs to work with a wide range of traffic conditions for evaluating WIM and associated technologies
NS-02-03	Needs to have provision for installation of roadside and overhead equipment and provide validation of test equipment
NS-02-04	Needs to facilitate minimum delay/inconvenience to general traffic during installation of in-pavement sensors
NS-02-05	Needs to meet requirements for all test methods defined in ASTM E 1318-09
NS-03	Safety Needs
NS-03-01	Needs to provide safe access by research and maintenance personnel
NS-03-02	Needs to be safe from exposure to general traffic

4.2.2 WIM Site Requirements

The requirements corresponding to the above site needs are identified and listed in Table 4.4.

Table 4.4 WIMTF Site Requirements

ID	***Title***	***Requirement***	***Traceability***	***Comment***	***Testability***	***Criticality***
RS-01	Horizontal Alignment	The horizontal curvature of the roadway lane for 200 ft. (60.96 m) in advance of, and 100 ft. (30.48 m) beyond the WIM-system sensors shall have a radius of not less than 5700 ft. (1737.36 m) (according to 6.1.1 in the ASTM E1318-09).	*NS-01-01* *NS-02-01*	To prevent lateral load transfers on axles	I	*H*
RS-02	Longitudinal Alignment	The longitudinal gradient of the road surface for 200 ft. (60.96 m) in advance of and 100 ft. (30.48 m) beyond the WIM system sensors shall not exceed 2 percent (according to 6.1.2 in ASTM E1318-09).	*NS-01-01*		I	*H*
RS-03	Cross Slope	The cross-slope of the road surface for 200 ft. (60.96 m) in advance of and 100 ft. (30.48 m) beyond the WIM-system sensors shall not exceed 3 percent (according to 6.1.3 in ASTM E1318-09).	*NS-01-01* *NS-02-01*	To prevent lateral load transfers on axles	I	*H*
RS-04	Lane Width	The width of the paved roadway for 200 ft. (60.96 m) in advance of and 100 ft. (30.48 m) beyond the WIM-system sensors shall be between 12 and 14 ft. (3.66 m and 4.27 m) (according to 6.1.4 in ASTM E1318-09).	*NS-01-01*		I	*H*
RS-05	Lane Markings	The edges of the lane for 200 ft. (60.96 m) in advance of, and 100 ft. (30.48 m) beyond the WIM-system sensors shall be marked with solid white longitudinal pavement marking lines 4 to 6 in. wide (according to 6.1.4 in ASTM E1318-09).	*NS-01-01*		I	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RS-06	Surface Smoothness	The surface of the paved roadway 200 ft. (60.96 m) in advance of and 100 ft. (30.48 m) beyond the WIM-system sensors shall be smooth before sensor installation and maintained in a condition such that a 6-in (0.15-m) diameter circular plate 0.125-in (3.17-mm) thick cannot be passed beneath a 16-ft. (4.88-m) long straightedge when the straightedge is positioned and maneuvered (according to 6.1.5.1 in ASTM E1318-09).	*NS-01-01*	To allow reliable WIM-system performance	I	*H*
RS-07	Pavement Structure	Consideration should be given to provide a 300-ft. (91.44-m) long continuously reinforced concrete pavement (CRCP) or a jointed concrete pavement (JCP), with transverse joints spaced 16 ft. (4.88 m) or less apart (according to 6.1.6 in ASTM E1318-09).	*NS-01-01*	To accommodate WIM-system sensors throughout their service life	I	*H*
RS-08	Roadside Clearance	The WIMTF shall have adequate roadside clearance for the installation of the equivalent of at least nine (9) 332-style traffic controller cabinets.	*NS-01-02* *NS-02-01* *NS-02-03*	To house controller equipment for WIM, roadside and overhead sensors	I	*H*
RS-09	Multiple WIM Systems	The WIMTF site shall contain adequate space to allow installation of at least five distinct WIM system sensors[19] to be installed and operable at the same time.	*NS-01-02*		*I*	*H*

[19] To include a reference WIM system and four WIM systems under evaluation.

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RS-10	Calibration	A site for weighing vehicles statically and measuring center-to-center axle spacing between adjacent axles and wheelbase shall be available within 10 miles (16093 m) of the WIM site.	*NS-02-01*		D	*H*
RS-11	Vehicle Identification	The WIMTF shall be equipped with the same vehicle identification means as the nearby CVEF and the vehicle identification shall be associated with the WIM measurements.	*NS-01-06* *NS-02-01*		I	*H*
RS-12	Available Power	There shall be adequate power available to support all equipment at the WIMTF.	*NS-02-01* *NS-02-03*		I	*H*
RS-13	Available in-system Communications	The WIMTF shall have available communications to the associated CVEF.	*NS-02-01* *NS-02-03*		D	*H*
RS-14	Available out-system Communications	The WIMTF shall have available communications to the Worldwide Web.	*NS-02-01* *NS-02-03*		D	*H*
RS-15	Speed Range	The WIMTF shall contain at least two lanes suitable for instrumentation with range of speeds between 10 and 80 mph (16 to 130 km/h).	*NS-02-02*		I	*H*
RS-16	Overhead Equipment	The WIMTF shall include a gantry to allow safe access to overhead equipment without lane closure.	*NS-02-03* *NS-03-01*		I	*H*
RS-17	Minimum Disruption	The WIMTF will have at least one non-instrumented lane open to traffic during installation of pavement-based sensors at the WIMTF, in addition to the two lanes in RS 14.	*NS-02-04*		I	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RS-18	Multiple Test Pass	The WIMTF and CVEF shall be located within 10 miles of freeway exits that permit safe turn around of FHWA Class 9 trucks for making multiple passes.	*NS-02-05*		I	*H*
RS-19	Temporary Traffic Control	The WIMTF site shall have a lane layout that allows traffic to be controlled safely around the site for testing purposes during sensor and/or equipment installation, and on-site sensor calibrations.	*NS-02-05*		I	*H*
RS-20	Safe Access	The WIMTF shall have a safety pull-out within 100 ft. of the WIM-system sensors that accommodates at least two support, or staff vehicles, not trucks being weighed.	*NS-03-01*		I	*H*
RS-21	Equipment Protection	The equipment at the WIMTF shall be protected from damage by vehicle impact.	*NS-03-02*		*I*	*H*

4.3 Functional Requirements

This section describes the functional needs and associated requirements for the WIMTF.

4.3.1 WIMTF Functional Needs:

A set of functional needs (NF) for the WIMTF are identified. These functional needs form the basis for a set of functional requirements (RA through RD), which impose constraints on thedesign and implementation. The identified needs are indicated by multiple categories, as shown in Table 4.5. All corresponding requirements are traced to one or more of these needs.

Table 4.5 WIMTF Functional Needs

NF-01 Needs for the WIMTF to collect independent measurements
NF-01-01 Needs to identify heavy vehicles from the traffic
NF-01-02 Needs to acquire status data from subject vehicles
NF-01-03 Needs to acquire vehicle characteristics data from the subject vehicles
NF-01-04 Needs to acquire weight outputs from the WIMTF
NF-01-05 Needs to acquire all relevant raw and semi-processed sensing data from the WIMTF
NF-01-06 Needs to acquire weight outputs from the CVEF
NF-01-07 Needs to acquire vehicle identification from the CVEF
NF-01-08 Needs to acquire vehicle brake temperature
NF-02 Needs for the WIMTF to support evaluation of WIM unit under test conditions
NF-02-01 Needs to acquire outputs (including relevant raw sensing data) from WIM units under test conditions
NF-02-02 Needs to collect data from non-weight sensing units under test conditions
NF-02-03 Need to assess WIM outputs by comparing outputs from the CVEF and the WIMTF reference systems
NF-02-04 Needs to assess data from non-weight sensing unit under test data by comparing it with relevant WIMTF sensing data
NF-03 Needs to assess and calibrate accuracy of the WIMTF
NF-04 Needs to store all related raw and processed data
NF-05 Needs to support online and offline data analysis and (online) monitoring for evaluation of WIM performance
NF-06 Needs to support the development of new methods for WIM system design, signal processing, and calibration/evaluation tests
NF-07 Needs to support WIM test methods defined in ASTM E1318

4.3.2 WIMTF Functional Requirements:

The requirements corresponding to the above functional needs are listed in Table 4.6.

Table 4.6 WIMTF Functional Requirements

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RA-xx		**Acquire Data**				
RA-01	Acquire vehicle speed	The WIMTF shall acquire vehicle speed at a designated location or locations within the range of 5 meters or 5.1 yards of the reference WIM scale, with a measurement error no greater than +/-1 mph (+/-1.6 km/h).	*NF-01-02*		*D*	*H*
RA-02	Acquire vehicle dimension	The WIMTF shall acquire the dimensional characteristics of the subject vehicle with error no greater than +/-3 ft (+/-0.91 m).	*NF-01-03*		*I*	*H*
RA-03	Acquire vehicle axle spacing	The WIMTF shall acquire the vehicle axle spacing the subject vehicle with error no greater than +/-0.5 ft (+/-0.152m).	*NF-01-03*		*I*	*H*
RA-04	Acquire truck identification	The WIMTF shall acquire vehicle type and identify trucks from other vehicles with error no greater than 1/100.	*NF-01-01*		*I*	*H*
RA-05	Acquire vehicle license number	The WIMTF shall acquire the vehicle license numbers, with an error rate less than 1%	*NF-01-03*		*I*	*H*
RA-06	Acquire vehicle vertical motion	The WIMTF shall acquire distance and frequency of vertical motion at the designated location or locations within the range of 5 meters or 5.1 yards of the reference WIM scale, with a measurement error no greater than 5 mm.	*NF-01-02*		*D*	*H*
RA-07	Acquire truck weight data by the WIMTF	The WIMTF shall acquire the weight data from an independent WIM scale, with error no greater than 1000 lbs. (453.5 kg). or +/-1.5 % of total weight within 1 standard deviation.	*NF-01-04*		*D*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RA-08	Acquire all relevant raw sensing data	The WIMTF shall acquire all relevant raw and semi-processed data from an independent WIM scale located onsite.	*NF-01-05*		*D*	*H*
RA-09	Acquire weight from subject WIM scale	The WIMTF shall acquire the weight data from a nearby stationary CVEF (for ground-truth data).	*NF-01-06*		*D*	*H*
RA-10	Acquire vehicle identification from subject WIM scale	The WIMTF shall acquire the vehicle identification data from a nearby stationary CVEF (for associating the weight data from WIM with that from the weigh station).	*NF-01-07*		*D*	*H*
RA-11	Acquire vehicle data from reference testing truck of known weight	The WIMTF shall acquire vehicle status information, at least to include weight, speed, and vertical motion from the testing truck.	*NF-02-02*		*D*	*H*
RA-12	Acquire vehicle weight from reference testing truck of known weight	The WIMTF shall acquire vehicle weight from the testing truck.	*NF-02-02*		*D*	*H*
RA-13	Acquire vehicle speed from reference testing truck of known weight	The WIMTF shall acquire vehicle speed at the time of inquiry from the testing truck.	*NF-02-02*		*D*	*H*
RA-14	Acquire vertical motion from reference testing truck of known weight	The WIMTF shall acquire vehicle vertical motion at the time of inquiry from the testing truck.	*NF-02-02*		*D*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RA-15	Acquire vehicle dimension from reference testing truck of known weight	The WIMTF shall acquire vehicle dimension information vehicle length from the testing truck.	*NF-02-02*		*D*	*H*
RA-16	Acquire vehicle axle spacing from reference testing truck of known weight	The WIMTF shall acquire vehicle axle spacing from the testing truck.	*NF-02-02*		*D*	*H*
RA-17	Acquire driver identity	The WIMTF will acquire driver identification.	*NF-02-02*		*D*	*H*
RA-18	Acquire vehicle speed (subject system)	The subject WIM equipment shall acquire vehicle speed.	*NF-02-02*		*D*	*H*
RA-19	Acquire vehicle dimension (subject system)	The subject WIM equipment shall acquire vehicle dimension characteristics.	*NF-02-02*		*I*	*H*
RA-20	Acquire truck identification (subject system)	The subject WIM equipment shall identify trucks.	*NF-02-02*		*I*	*H*
RA-21	Acquire weight data (subject system)	The WIMTF shall acquire the weight data from subject WIM scale.	*NF-02-02*		*D*	*H*
RA-22	Acquire vehicle license plate (subject system)	The subject WIM equipment shall acquire the vehicle license plate numbers.	*NF-02-02*		*I*	*H*
RA-23	Acquire relevant raw data	The WIMTF shall acquire all relevant raw data from the subject WIM equipment	*NF-02-01*		*D*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RA-24	Acquire brake temperature	The WIMTF shall acquire vehicle brake temperature through remote detection.	NF-01-08		*D*	*M*
RB-xx		**Processing Functions**				
RB-01	Process speed	The WIMTF shall determine vehicle speed at each WIM scale, with error no greater than +/-1 mph (+/-1.6 km/h).	*NF-02-04*		*D*	*H*
RB-02	Process vehicle size	The WIMTF shall estimate vehicle size, with error less than +/-3 ft. (+/-0.91 m).	*NF-02-04*		*D*	*H*
RB-03	Identify trucks	The WIMTF shall identify trucks, with error less than 1%.	*NF-02-04*		*D*	*H*
RB-04	Associate all data for subject vehicle	The WIMTF shall associate vehicle status and WIM measurements with subject vehicles.	*NF-02-04*		*D*	*H*
RB-05	Estimate WIM error	The WIMTF shall estimate WIM weigh-scale error.	*NF-02-04*		*D*	*H*
RB-06	Determine weight	The WIMTF shall determine the weight data from an independent WIM scale, with error no greater than 1000 lbs. (453.5 kg). or +/-1.5 % of total weight within 1 standard deviation (TBD) .	*NF-02-03*		*D*	*H*
RB-07	Estimate calibration factors	The WIMTF shall estimate calibration factors.	*NF-03*		*A*	*H*
RB-08	Calibrate WIM	The WIMTF shall calibrate the reference WIM by automatic means.	*NF-03*		*A*	*H*
RB-09	Calibrate WIM	The WIMTF shall enable calibration of the reference WIM by an operator.	*NF-03*		*A*	*H*
RB-10	Compare WIMTF measurements with reference truck	The WIMTF shall compare the status and weight of reference truck with WIMTF measurements.	*NF-03*		*A*	*H*

ID	***Title***	***Requirement***	***Traceability***	***Comment***	***Testability***	***Criticality***
RB-11	Screen overweight trucks	The WIMTF shall integrate commercial vehicle identification and weight data to screen overweight trucks.	*NF-02-04*		*D*	*H*
RB-12	Associate WIM outputs with outputs from CVEF	The WIMTF shall associate WIM outputs with outputs from CVEF, based on vehicle identification from both WIM and nearby CVEF.	*NF-02-03*		*A*	*H*
RB-13	Compare WIM outputs with outputs from CVEF	The WIMTF shall compare WIM outputs (including weight estimates and vehicle characteristics, etc.) with those from the CVEF.	*NF-02-03*		*A*	*H*
RB-14	Assess WIM accuracy	The WIMTF shall determine WIM accuracy based on the comparison of data from WIM and CVEF.	*NF-02-03*		*A*	*H*
RB-15	Monitoring WIM operations	The WIMTF shall monitor real-time WIM data and detect abnormal operations sensor data.	*NF-05*		*D*	*H*
RB-16	Monitoring WIM operations	The WIMTF shall also be able to record any equipment malfunctions through HMI .	*NF-05*		*D*	*H*
RB-17	Supporting ASTME1318	The WIMTF shall support all test methods defined in ASTM E1318.	*NF-05*		*D*	*H*
RB-18	On-line Data Analysis	The WIMTF shall conduct online data analysis to compute statistics of WIM data.	*NF-05*		*D*	*H*
RB-19	On-line Data Analysis	The WIMTF shall evaluate on-line data against robust metrics to assess the WIM data quality.	*NF-05*		*D*	*H*
RC-xx.xx		**Archive Data Functions**				
RC-01	Synchronize data	The WIMTF shall synchronize raw and processed data.	*NF-04*		*D*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RC-02	Archive data	The WIMTF shall archive relevant raw and processed data.	*NF-04*		*D*	*H*
RD-xx.xx		**Validation/Verification Functions**				
RD-01	Validate vehicle speed measurements	The WIMTF shall validate speed measurements of subject detections.	*NF-02-04*		*D*	*H*
RD-02	Validate vehicle dimension measurements	The WIMTF shall validate dimension characteristics of subject detections.	*NF-02-04*		*D*	*H*
RD-03	Validate truck id	The WIMTF shall validate truck identification results.	*NF-02-04*		*D*	*H*
RD-04	Validate truck license plate reading	The WIMTF shall validate license plate identification results from subject detections.	*NF-02-04*		*D*	*H*
RD-05	Validate Subject WIM Weight measurements	The WIMTF shall validate WIM measurements from subject detections.	*NF-02-04*		*D*	*H*

4.4 Interface Requirements

This section describes the interface needs and associated requirements for the WIMTF.

4.4.1 WIMTF Interface Needs:

A set of interface needs (NI) for the WIMTF are identified. These interface needs form the basis for a set of interface requirements (RI) which impose constraints on the design and implementation. The identified needs are indicated by multiple categories, as shown in Table 4.7. All corresponding requirements are traced to one or more of these needs.

Table 4.7 WIMTF Interface Needs

- NI-01 Needs for interfacing with existing CVEF
  - NI-01-01 Needs for interfacing with AVI (provided by the WIMTF) at the existing CVEF
  - NI-01-02 Needs for providing Human Machine Interface (HMI) for user input at CVEF
  - NI-01-03 Needs for communicating CVEF data to the WIMTF
- NI-02 Needs for interfacing with data centers & remote users
  - NI-02-01 Needs for scheduled daily data download from the WIMTF to the state data center
  - NI-02-02 Needs for HMI for remote users to conduct remote data management (e.g., archiving, on-demand data download, and so on)
  - N1-02-03 Needs for remote software update
  - N1-02-04 Needs for scheduled daily download of weight data from reference WIM to the Caltrans Performance Measurement System (PeMS)
- NI-03 Needs for interfacing with WIMTF subsystems
  - NI-03-01 Needs for providing power to WIM systems and subsystems
  - NI-03-02 Needs for wired and/or wireless network to interface with the servers of the commercial/prototype WIM systems
  - NI-03-03 Need for industry standard interfaces, including, but not limited to, Serial Port (e.g., RS232, RS422, RS485), Universal Serial Bus (USB), Peripheral Component Interconnect (PCI), (Radio Guide) RG coaxial cable, High-Definition Multimedia Interface (HDMI), and Ethernet interface capabilities for interfacing with WIM sensors and subsystems.
- NI-04 Needs for user interface
  - NI-04-01 Needs for real-time information display and replay
  - NI-04-02 Needs for system configuration

4.4.2 WIMTF Interface Requirements:

Table 4.8 below describes the requirements corresponding to the interface needs.

Table 4.8 WIMTF Interface Requirements

ID	Title	Requirement	Traceability	Comment	Testability	Criticality
RI-01		**Interface with existing CVEFs**				
RI-01-01	Interface with LPR system at CVEFs	The WIMTF shall provide interface to the LPR system at the CVEF[20] to obtain the vehicle license number (as well as the date and time of access if available).	*NI-01-01*		*D*	*H*
RI-01-02	HMI for user input at CVEFs[21]	The WIMTF shall provide human-machine interface (including a keyboard and a display) for manual input at CVEF (e.g., vehicle weight, class, axle number, etc.).	*NS-01-02*		*D*	*H*
RI-01-03	Storage of CVEF data	The WIMTF shall provide a local module at the CVEF to receive and store the vehicle ID (e.g., license plate) with manual input (including weight and vehicle characteristics) for at least up to 31 days of data.	*NI-01-03*		*D*	*H*
RI-01-04	Secure communication	The local module at CVEF shall support secure communication with the WIMTF server.	*NI-01-03*		*D*	*H*
RI-01-05	Scheduled upload of CVEF data	The local module at the WIMTF shall perform scheduled transmission of the CVEF data to the WIMTF server at least daily.	*NI-01-03*		*D*	*H*
RI-01-06	On-demand upload of CVEF data	The local module at the WIMTF shall transmit CVEF data to the WIMTF server upon request of the WIMTF server.	*NI-01-03*		*D*	*H*
RI-02		**Interface with Remote Data Center**				

[20] Most California CVEF locations do not have an LPR system already installed; therefore, it is likely that an LPR system will need to be installed at the CVEF that is close to the WIMTF.
[21] The HMI is intended to be used by researchers or technicians working at the WIMTF. It shall not be part of the normal operation for CVEF operators.

ID	Title	Requirement	Traceability	Comment	Testability	Criticality
RI-02-01	Secure communication	The WIMTF shall support secure communication with the remote server at the State Data Center.	*NI-02*		*D*	*H*
RI-02-02	Scheduled data upload	The WIMTF shall perform scheduled data uploads to the remote server at the State Data Center at least daily.	*NI-02-01*		*D*	*H*
RI-02-03	On-demand data upload	The WIMTF shall perform data uploads to the remote server at the State Data Center per request of the remote server.	*NI-02-01*		*D*	*H*
RI-02-04	Remote desktop	The WIMTF server shall support a remote desktop connection from the remote server at the State Data Center.	*NI-02-02*		*D*	*H*
RI-02-05	Remote software update	The WIMTF server shall perform scheduled and on-demand software updates by checking and downloading new versions from the remote server.	*NI-02-03*		*D*	*H*
RI-02-06	Download to PeMS	The WIMTF server shall support daily data downloading to Caltrans PeMS.	*N1-02-04*		*D*	*H*
RI-03		**Interface with WIMTF subsystems**				
RI-03-01	Mechanical Installation	The WIMTF shall satisfy space requirements for installing at least five WIM systems (including the reference bending plate system and four systems under evaluation) without any interference among them.	*NI-03-01*		*D*	*H*
RI-03-02	Electrical Power Supply	The WIMTF shall satisfy power requirements for at least five WIM systems, plus all needed common functions, such as, but not limited to, communications.	*NI-03-01*		*D*	*H*
RI-03-03	Secure communication	The WIMTF server shall have secure communication to interface with commercial or prototype WIM systems.	*NI-03-02*		*D*	*H*
RI-03-04	Local Area Network	The WIMTF shall support a LAN with more than six communication devices (i.e., the WIMTF server, at least five WIM systems, as well as other systems on the gantry).	*NS-03-02*		*D*	*H*

ID	*Title*	*Requirement*	*Traceability*	*Comment*	*Testability*	*Criticality*
RI-03-05	Interface with WIM weighing sensors	The WIMTF shall be capable of directly interfacing with at least 5 WIM weighing sensors.	*NS-03-03*		*D*	*H*
RI-03-06	Interface with inductive loop sensors	The WIMTF shall be capable of directly interfacing with at least 12 inductive loop sensors.	*NI-03-03*		*D*	*H*
RI-03-07	Interface with imaging systems	The WIMTF shall be capable of directly interfacing with at least 5 imaging systems (including vehicle overview imaging, license plate imaging, and USDOT# imaging).	*NI-03-03*		*D*	*H*
RI-03-08	Interface with AVI systems	The WIMTF shall be capable of directly interfacing with at least 5 AVI systems (including LPR systems, USDOT # OCR systems, RFID systems and related systems).	*NI-03-03*		*D*	*H*
RI-04		**Interface with users**				
RI-04-01	Interface with on-site users	The WIMTF shall provide a HMI including at least a display and keyboard for user operations.	*NI-04*		*D*	*H*
RI-04-02	Real-time monitoring	The WIMTF shall provide a GUI that displays real-time operating information.	*NI-04-01*		*D*	*H*
RI-04-03	Information Reply	The WIMTF shall provide a GUI that allows a user to request data for a specific time period.	*NI-04-01*		*D*	*H*
RI-04-04	Information Reply	The WIMTF shall provide a GUI that allows a user to receive data for a specific time period during at least the last 31 days.	*NI-04-01*		*D*	*H*
RI-04-05	System setup and configuration	The WIMTF shall provide a GUI for users to configure data acquisition, storage and management.	*NI-04-02*		*D*	*H*

4.5 Data Requirements

This section describes the data needs and associated requirements for the WIMTF.

4.5.1 WIMTF Data Needs:

A set of data elements for the WIMTF are identified, as shown in Table 4.9. The data description is based on ASTM E1318-09 Specifications ([2]).

Table 4.9 WIMTF Data Descriptions

Item #	Data Name	Data Description
1	Wheel Load	The sum of the tire loads on all tires included in the wheel assembly on one end of an axle; a wheel assembly may have a single tire or dual tires
2	Axle Load	The sum of all tire loads of the wheels on an axle; a portion of the gross-vehicle weight
3	Axle-Group Load	The sum of all tire loads of the wheels on a defined group of adjacent axles; a portion of the gross-vehicle weight
4	GrossVehicle Weight	The total weight of the vehicle or the vehicle combination, including all connected components; also, the sum of the tire loads of all wheels on the vehicle
5	Speed	Speed in miles per hour
6	Center-to-Center Spacing Between Axles	The distance between the centers of the adjacent axles on the vehicle
7	Vehicle Class (via axle arrangement)	The FHWA Vehicle Types[22]
8	Site Identification Code	A 10-character alphanumeric site identification code for each data-taking session
9	Lane and Direction of Travel	A number beginning with 1 for the right-hand northbound or eastbound traffic lane and continuing until all the lanes in that direction of travel have been numbered; the next sequential number shall be assigned to the lanes in the opposite direction of travel, beginning with the left-hand lane and continuing until all lanes have been numbered
10	Data and Time of Passage	The date[23] and time[24] a vehicle passed the WIM system
11	Sequential Vehicle Record Number	The WIM system shall provide sequential-numbering (user-adjustable) for each recorded vehicular data set; this number must be unique for each set of data and not be repeated.
12	Wheelbase	The distance between the front-most and the rear-most axles on a vehicle, or combination that has the tires on these axles in contact with the road surface at the time of weighing.

[22] See U.S. Department of Transportation Traffic Monitoring Guide for the complete description of FHWA Vehicle Type.

[23] In the United States, the MM/DD/YYYY format, where MM is the month, DD is the day, and YYYY is the year, is generally accepted.

[24] The time shall be in the following format: hh:mm:ss, where hh is the hour beginning with 00 at midnight and continuing through 23, mm is the minute, and ss is the second.

13	Equivalent Single-Axle Loads (ESALs)	The cumulative number of applications of the chosen standard single-axle load that will have an equivalent effect on pavement serviceability as all applications of various axle loads and types by vehicles in a mixed-traffic stream. (The WIM systems shall compute ESALs using American Association of State Highway and Transportation Officials [AASHTO] axle-load equivalence factors for single, tandem, and triple axles for flexible or rigid pavements [2].)
14	Violation Code	A two-character violation code used for each detected violation of all user-set parameters.[25]

[25] Provision shall be made for the user to define up to 15 violation codes. Examples of the violation code are WL (for wheel-load violations), AL (for axle-load violations), AG (for axle-group-load violations), and so on.

4.5.2 WIMTF Data Contents:

The data types and their contents are described in Table 4.10 below. They are categorized into weight data (DW), vehicle features and status data (DFS), passage system and information (DSI), CVEF data (DCVEF), LPR Data (DLPR), and USDOT reader data (DDOT).

Table 4.10 WIMTF Data Contents

ID	**Data Element Name**	**Source of data**	**Unit**	**Frequency of data from source**	**Characteristics, such as accuracy, validity, timing, and capacity**	**Ways to derive data value**	**Testability**	**Comments**
DW	Weight data from WIM (subject WIM scale X N channels)							
DW-01	Weight for individual wheels	Measured by WIM scale, and captured and recorded in WIM database computer	Pounds and Kg	Once per passing, unless re-weighing is conducted	Accuracy: % or difference of measurement to ground truth	Direct from scale measurement	D Accuracy will vary between calibrations; testable with a load of a known weight	Calibration needed periodically to tune scale sensors
DW-01-01	Weight for left wheel	Measured by WIM scale, and captured and recorded in WIM database computer	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above
DW-01-02	Weight measurement for right wheel	Measured by WIM scale, and captured and recorded	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above

ID	Data Element Name	Source of data	Unit	Frequency of data from source	Characteristics, such as accuracy, validity, timing, and capacity	Ways to derive data value	Testability	Comments
		in WIM database computer						
DW-02	Individual axle weights	Measured by WIM scale, and captured and recorded in WIM database computer	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above
DW-03	Gross vehicle weight	Measured by WIM scale, and captured and recorded in WIM database computer	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above
DW-04	Time stamp	WIM computer system clock	Seconds, minutes, hour, date	Time stamp recorded for each passing of a vehicle	Accuracy and time drift of WIM system clock versus a referenced time (such as Global Positioning System (GPS) standard time or a reference clock)	Time stamp created and stored at computer records of vehicle passing or time of measurement	D If each record contains time stamps of system time, as well as standard time (such as GPS), the irregularity of time can be tested.	A system with GPS time can be synchronized regularly; alternatively, a network connection to an online source may also provide periodic sync.
DFS	Vehicle features and							

ID	**Data Element Name**	**Source of data**	**Unit**	**Frequency of data from source**	**Characteristics, such as accuracy, validity, timing, and capacity**	**Ways to derive data value**	**Testability**	**Comments**
	status data							
DFS-01	Direction of travel	Indicated by the direction or road side of CVEF or WIM, unless noted; otherwise, by special situations	A numeric value (to designate a direction relative to referenced infrastructure), which can be translated into N, S, E, or W	One per vehicle passing	Correspond to highway direction	If direction is not spelled out explicitly, a numeric value matches to a designated direction	D Only testable or verifiable, if vehicle trajectory is recorded or reported	Must be compatible with current practice in California
DFS-02	Trailer detection	By the measurement of total vehicle length and axle configuration	1 or 0 (or other chosen values) to designate presence or absence	One per vehicle passing	Corresponds to each passing truck	Direct sensor output (such as gap between tractor and trailer) or processed data (such as passing time and number of axles)	D Testable within the limit of known or pre-defined types of vehicle configuration	Presence of trailer can be inspected by images or multiple sensors; must be compatible with current practice
DFS-03	Number of axles	Reading of axle weight in each vehicle passing; alternatively, a laser or other device can be utilized for measurement	Numeric value corresponding to number of axles	One output number per vehicle passing	Actual versus measured number	By direct measurement or by processed reading of axle passing time and sequence	D Testable within the limit of known or pre-defined types of vehicle configuration	

ID	Data Element Name	Source of data	Unit	Frequency of data from source	Characteristics, such as accuracy, validity, timing, and capacity	Ways to derive data value	Testability	Comments
DFS-04	Inter-axle spacing	Pairs of sensing devices or processed passing times between axles, if speed is known	Feet or meters	One per pair of passing axles	Actual versus measured number	Direct measurement or processed data, if speed is known	I	Must be compatible with current practice
DFS-05	Vehicle length	Direct (from forward and rear-facing sensors or side sensors) or processed passing times between axles, if speed is known	Feet or meters	One per passing vehicle	Actual versus measured number	By direct measurement or processed data, if speed is known	I	Must be compatible with current practice
DFS-06	Vehicle class	Processed reading of axle passing and Vehicle ID	Numeric value	One per vehicle passing	Actual versus measured number	Processed reading of axle passing and Vehicle ID	I	Must be compatible with current practice
DFS-07	Vehicle violation	Weight Violation: Comparison of processed data versus regulated threshold of weight or	Numeric value	One per passing		Comparison of data versus pre-defined thresholds	D	

ID	Data Element Name	Source of data	Unit	Frequency of data from source	Characteristics, such as accuracy, validity, timing, and capacity	Ways to derive data value	Testability	Comments
		other indicators; size violation is monitored by thresholds of lengths and widths						
DFS-08	Vehicle speed	Direct measurement or derived	mph or km/h	Can vary during one passing, but likely reduced to one, or limited number of readings	% or absolute difference of measurement	Direct measurement or derived	D	Calibrated speed sensors needed
DFS-9	Total wheelbase	Processed reading of first and last axles	Feet or meters	Once per passing		Processed reading of axle passing and relative positions (passing time)	I	
DFS-10	Dual tires		Numeric value (such as 1 or 0)	One per axle			I	Must be compatible with current practice
DSI	Passage and system information							
DSI-01	Site identification	Value designated to	Alphabetical or numerical	One per site		Entered and recorded in	I	Associated with fixed CVEF or

ID	**Data Element Name**	**Source of data**	**Unit**	**Frequency of data from source**	**Characteristics, such as accuracy, validity, timing, and capacity**	**Ways to derive data value**	**Testability**	**Comments**
	code	site	value			system		variable as mobile or mini site
DSI-02	Unique vehicle count number	Recorded number of vehicle passing	Numeric value	A numeric value assigned for each period		Recorded number in system at site	D Testable only within the limit of test conditions	
DSI-03	Lane number	Value designated to specific lane	Numeric value	One per site		Entered and recorded in system	I	
DSI-04	Time & date	System clock	Date, hours, minutes, and seconds	Updated for each record		Direct reading from system clock	I	Synchronization needed with a reference clock
DSI-05	Vehicle trigger message	WIM Sensors	Message set	Updated for each record		Direct reading from sensor	I	
DSI-06	Sensor status message	Sensors	Message set	Updated for each record		Direct reading from sensor	I	
DSI-07	System status	System	Message set	Updated for each record		Direct reading from system	I	
DSI-08	Vehicle gap	System	Numeric value	Updated for each record	% or absolute difference of measurement	Processed	D	
DCVEF	CVEF data content							
DCVEF-	Vehicle			Updated				

ID	**Data Element Name**	**Source of data**	**Unit**	**Frequency of data from source**	**Characteristics, such as accuracy, validity, timing, and capacity**	**Ways to derive data value**	**Testability**	**Comments**
01	identification			for each record				
DCVEF-02	Vehicle image	Available if camera or video is present at CVEF	Image file	One or more image files per vehicle passing	Quality (clarity, resolution, coverage, target area)	Direct use of stored images	D Testable, only if images are used to generate additional information	Images are for records but can be used for LPR system
DCVEF-03	Vehicle class	By weight, size, and axle number measurement	An alphabetical or numeric value	One per vehicle passing			I	
DCVEF-04	Number of axles	By detection of axle readings	A numeric value	One per vehicle passing	Actual versus measured		I	
DCVEF-05	Individual axle weight	Measured by CVEF scale, and captured and recorded in CVEF database computer	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above
DCVEF-06	Gross vehicle weight	Measured by CVEF scale, and captured and recorded in CVEF database computer	Pounds and Kg	Same as above	Same as above	Same as above	Same as above	Same as above
DCVEF-07	Time stamp	CVEF computer	Seconds, minutes, hour,	Time stamp	Accuracy and time drift of	Time stamp created and	D If each record	A system with GPS time can

ID	Data Element Name	Source of data	Unit	Frequency of data from source	Characteristics, such as accuracy, validity, timing, and capacity	Ways to derive data value	Testability	Comments
		system clock	date	recorded for each passing of a vehicle	CVEF system clock versus a referenced time (such as GPS standard time, or a reference clock)	stored at computer records of vehicle passing or time of measurement	contains time stamps of system time, as well as standard time (such as GPS), the irregularity of time can be tested.	be synchronized regularly; alternatively, a network connection to an online source may also provide periodic synch.
	LPR system data content							
DLPR-01	License plate number	Taken image of license plate and image processing	Sequence of alphabetical or numeric characters	One per passing	Accuracy reading of character string	Optical character recognition from taken image or by vehicle record	D	
DLPR-02	Time stamp	CVEF computer system clock	Seconds, minutes, hour, date	Time stamp recorded for each passing of a vehicle	Accuracy and time drift of WIM system clock versus a referenced time (such as GPS standard time or a reference clock)	Time stamp created and stored at computer records of vehicle passing or time of measurement	D If each record contains time stamps of system time, as well as standard time (such as GPS), the irregularity of time can be tested.	A system with GPS time can be synchronized regularly; alternatively, a network connection to an online source may also provide periodic synch.
DLPR-03	Image of the vehicle	Image taken by system camera	Image file	One or more per passing	Quality (clarity, resolution, coverage, target	Optical character recognition or	D	

ID	**Data Element Name**	**Source of data**	**Unit**	**Frequency of data from source**	**Characteristics, such as accuracy, validity, timing, and capacity**	**Ways to derive data value**	**Testability**	**Comments**
					area)	manual review		
DDOT	USDOT# reader data content							
DDOT-01	USDOT number	On-vehicle marking	Sequence of alphabetical or numeric characters	One per passing	Accuracy checks of character string	Optical character recognition from taken image or by vehicle record	D	
DDOT-02	Time stamp	CVEF computer system clock	Seconds, minutes, hour, date	Time stamp recorded for each passing of a vehicle	Accuracy and time drift of WIM system clock versus a referenced time (such as GPS standard time or a reference clock)	Time stamp created and stored at computer records of vehicle passing or time of measurement	D If each record contains time stamps of system time, as well as standard time (such as GPS), the irregularity of time can be tested.	A system with GPS time can be synchronized regularly; alternatively, a network connection to an online source may also provide periodic synch.
DDOT-03	Image of the vehicle side showing the USDOT	Image taken by system camera	Image file	One or more per passing	Quality (clarity, resolution, coverage, target area)	Optical character recognition	D	

5. Options for a California WIM Facility

This section summarizes the efforts conducted by the project team in the development of the system requirements for the WIMTF. It describes the approach the team took in developing the potential site options, and the analysis performed to obtain the reduced set of candidate sites.

5.1 Site Options Recommended by Caltrans

Caltrans specified seven site options for the WIMTF in the RFP. During the course of this study, Caltrans also informed the research team that a new Mountain Pass PrePass™ WIM site is planned for construction, in conjunction with a new CVEF, to be located, along southbound I-15 near the California-Nevada state border. The team carefully reviewed these options, comparing each with the WIMTF needs and requirements developed during this project. The analyses of the Caltrans-recommended options are summarized below,

(a) No need for a newly established test facility;

Since a WIMTF facility does not exist in California, this "do-nothing option" does not satisfy existing needs. However, this option is evaluated in the cost benefit analysis section.

(b) Upgrade the Berkeley Highway Lab;

The Berkeley Highway Laboratory (BHL) is a test site spanning approximately two miles (3,218 m) of I-80, immediately east of the San Francisco-Oakland Bay Bridge between Gilman and Powell Streets. It is a Caltrans-sponsored facility, equipped with eight cameras, 16 directional dual-inductive-loop-detector stations, and an array of Sensys wireless detectors, all dedicated to monitoring traffic for research purposes.

However, the location of the BHL is not suitable for consideration as a WIMTF, primarily because the nearest CVEFs are more than 10 miles (16,093 m) from the site (see Figure 5.1). The nearest CVEF located along the same route is in Cordelia, 30 miles from the site. In addition, there is no safe place near the Berkeley Highway Lab to build a WIMTF. For these reasons the BHL was not considered in our site option analysis.

(c) Upgrade the I-405 facility

The traffic detector testbed on the northbound I-405 freeway in Irvine was designed as a real-world laboratory for the development and evaluation of emerging traffic detection technologies. It has an overhead bridge and pole for testing and developing overhead-mounted and side-mounted detectors, respectively (see Figure 5.2). Each lane is also equipped with dual inductive loop sensors and Sensys wireless detectors, as shown in Figure 5.3

Figure 5.1 Berkeley Highway Lab and corresponding nearest CVEF locations

Figure 5.2 Overhead- and side-mounted detectors at I-405 Detector Testbed in Irvine, California (image source: http://www.ctmlabs.net/facilities/detector-testbed)

Figure 5.3 I-405 Detector Testbed in Irvine, California (image source: http://www.ctmlabs.net/facilities/detector-testbed)

The I-405 detector testbed has a safe access area away from the freeway, which could accommodate several vehicles, as shown in Figure 5.4. However, similar to the BHL, it is located far from the nearest CVEFs, and is not on the same route as any of them (see Figure 5.5). A WIMTF at this site would need to be built from scratch to include CVEFs. Making the I-405 site into a viable WIMTF would require incurring significant costs. This option is further evaluated in the cost-benefit analysis.

Figure 5.4 Safe access area for I-405 Detector Testbed in Irvine, California

Figure 5.5 I-405 Detector Testbed and corresponding nearest CVEF locations

(d) Upgrade an existing Commercial Vehicle Enforcement Facility;

Building the WIMTF inside a CVEF will not support testing sensors at mainline highway speeds. Furthermore, there is no WIM station within 10 miles proximity of the commercial vehicle enforcement facility. This option does not meet the requirements for WIMTF.

(e) Offer a Pooled Fund Option;

This is not a site option. It is evaluated under the cost-benefit section.

(f) Use a National Laboratory in California;

None of the National Laboratories have facilities with CVEFs that would support testing sensors at mainline highway speeds. Therefore, this is not an option for the WIMTF.

(g) A site in California that is not currently part of the above;

There are several current WIM sites that could be viable candidates for the WIM test facility. These sites are evaluated in the next section.

(h) Planned PrePass™ WIM site at the I-15 Mountain Pass:

The planned Mountain Pass PrePass™ WIM site will be built along southbound I-15 near the California-Nevada state border in conjunction with a new CVEF, shown in Figure 5.6. This site possesses the benefits of PrePass™ WIM sites. Since the site has not been constructed, it offers the opportunity to make changes to the design of the weigh station to ease truck re-identification for the WIM Test Facility. However, since this site is far from the metropolitan areas, it is unlikely that it will experience significant congestion. Therefore, this will not be a site observing large numbers of trucks traveling at the range of speeds required to evaluate new WIM sensor technologies. In addition, the I-15 freeway along this corridor has only two-lanes in each direction. Hence, any construction activity associated with in-pavement WIM sensor installation would require full closure of the freeway in the affected direction.

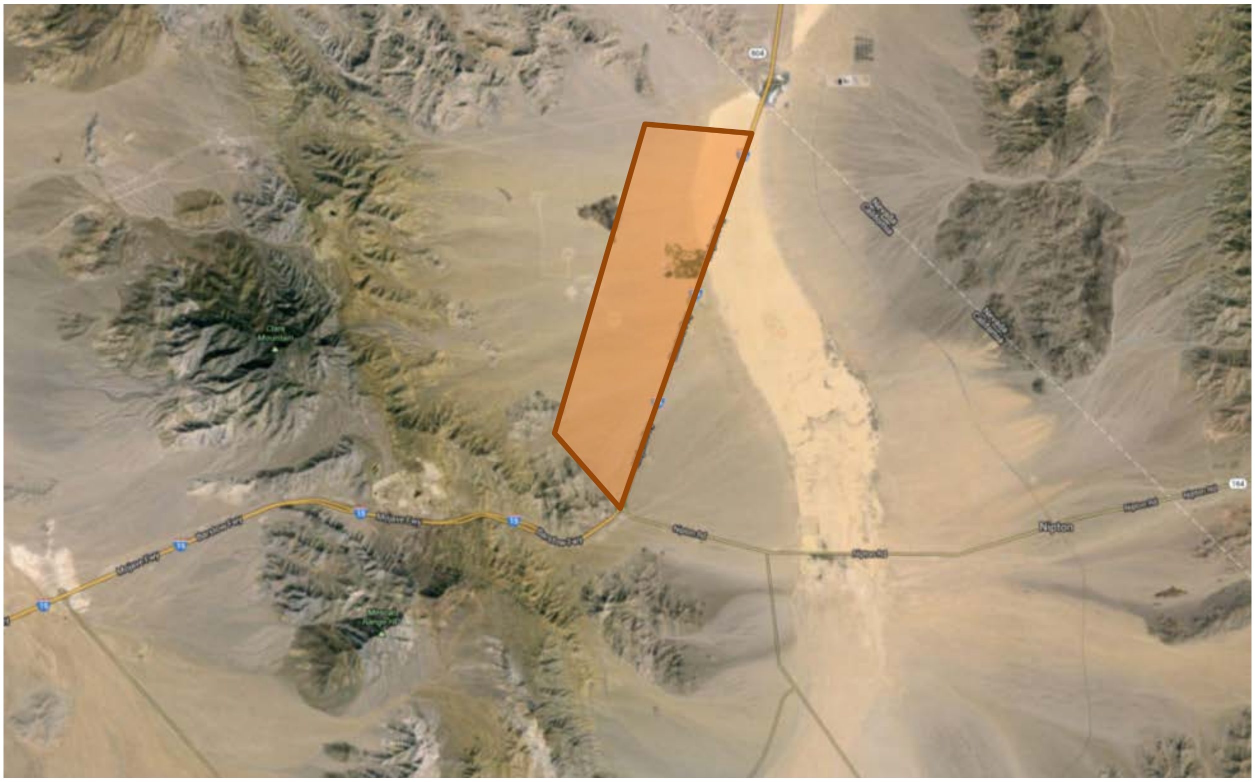


Figure 5.6 Planned location of Mountain Pass PrePass™ and CVEF

As a result of the analysis of the Caltrans-recommended site options, we determined that options (b), (d), (f) and (h) do not meet the WIMTF requirements and therefore are not viable options. Option (c) require significant new infrastructure to meet the WIMTF requirements, Option (e) is not a site option but should be considered as a funding approach for establhsing the WIMTF. Therefore, we have focused our site evaluation on option (g), a site in California not currently included in the recommended options.

In addition to the WIM for highways, the RFP also requested investigating potential bridge-WIM sites. The project team found that the existing WIM technologies for bridges are not reliable and do not meet the general requirements of WIM systems. After consulting with Caltrans project managers, the decision was not to pursue a bridge WIM test facility under this study.

5.2 Candidate Site Options

Site options, in addition to Caltrans recommendations, were selected based on their ability to meet key site requirements, as defined in Section 4. Three types of sites were considered as follows:

- Existing overhead bridges
- Existing WIM data sites
- Existing PrePass™ WIM sites

The subsequent sub-sections provide a detailed description of each of these site types and the associated data pre-processing.

The site section effort has focused on the typical arrangement where the WIM is located upstream of a static scale. There are several reasons why the WIMTF was not considered downstream of a static scale. It was advised during one of the TAG meetings that validation of trucks would not be ideal if the WIMTF was placed downstream of a static scale. More significantly, PrePass^{TM} WIM sites – by far the best candidates for a WIMTF due to their existing infrastructure – are always located upstream of static scales.

5.2.1 Existing Overhead Bridges

Existing overhead bridges were considered for the WIMTF because they met the site requirement of having an overhead structure that potentially facilitates safe installation of the overhead test and validation equipment needed to operate the WIMTF without lane or road closures. In addition, site candidates exist within close proximity of existing CVEFs.

The candidate overhead bridges were obtained through a spatial and visual data reduction analysis of the state bridges spatial data layer containing 12,751 bridge structures in the State of California. This data was obtained via Caltrans Earth[26], using the following procedures:

i. Identification of bridge structures close to existing CVEF locations: A 10-mile buffer region was added around Class A and B CVEF locations. Bridge structures not found within this 10-mile radius were removed from the spatial layer.
ii. Removal of bridge structures from unaffiliated routes: Next, bridges from routes not associated with the CVEF were removed, leaving only bridges on the same route as a CVEF.
iii. Removal of under crossings, culverts, freeway overcrossings, and all downstream structures: From the subset of bridge structures on the route of each CVEF within a 10-mile proximity, each bridge was inspected using satellite imagery to verify the crossing type. Under crossings, culverts, freeway overcrossings, and all downstream structures were then manually removed from the spatial data. This resulted in only non-freeway overcrossing structures found within 10 miles (16093 m) upstream of a CVEF. Overcrossings were also removed from consideration wherever a significant detour between overcrossings and CVEFs existed.
iv. Location correction: Once the final set of overcrossing structures was obtained, the structures were repositioned to accurately reflect their location to address significant location deviations observed in the data.

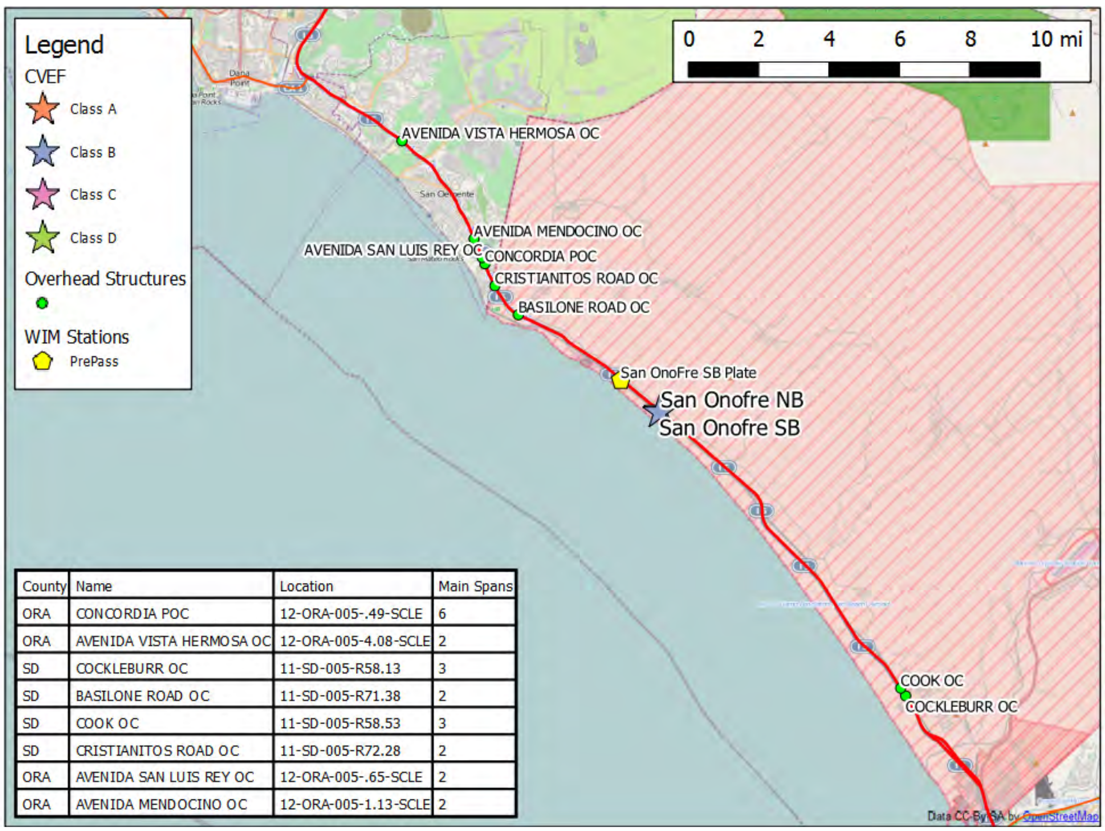
Figure 5.7 shows an example of an overhead structure found in the final set of candidate overcrossings, where test and validation equipment could be potentially secured above passing trucks.

Figure 5.8 shows the locations of overhead structures identified within 10 miles (16093 m) upstream of the north- and southbound San Onofre CVEFs along the I-5 freeway. A total of 73

[26] http://earth.dot.ca.gov/

overhead structures with a classification of B and above were identified within 10 miles (16093 m) upstream of CVEFs.

Figure 5.7 Basilone Rd. overhead bridge on I-5 freeway close to San Onofre CVEF



County	Name	Location	Main Spans
ORA	CONCORDIA POC	12-ORA-005-.49-SCLE	6
ORA	AVENIDA VISTA HERMOSA OC	12-ORA-005-4.08-SCLE	2
SD	COCKLEBURR OC	11-SD-005-R58.13	3
SD	BASILONE ROAD OC	11-SD-005-R71.38	2
SD	COOK OC	11-SD-005-R58.53	3
SD	CRISTIANITOS ROAD OC	11-SD-005-R72.28	2
ORA	AVENIDA SAN LUIS REY OC	12-ORA-005-.65-SCLE	2
ORA	AVENIDA MENDOCINO OC	12-ORA-005-1.13-SCLE	2

Figure 5.8 Location of overhead structures within 10 miles (16093 m) upstream of north- and southbound San Onofre CVEFs

5.2.2 Existing WIM Data Sites

WIM data sites are located on major truck routes for the purpose of collecting continuous truck-axle weight data with vehicles classified into one of 14 pre-defined classes, based on the FHWA vehicle classification scheme.

Existing WIM Data sites were considered.. Their general fulfillment of site condition requirements specified for WIM sensors in ASTM E1318-09 relate to the geometric alignment and profile of the pavement. Figure 5.9 shows an example of a WIM data site on the SR-99 freeway in Fresno, with locations of the WIM sensors and safety pullout areas indicated.

Figure 5.10 shows the hardware layout in a WIM Data cabinet. This site is equipped with a DOS-based 1060-series WIM controller that is currently the most prevalent WIM controller in California. The location of WIM Data sites compared with CVEFs is shown in Figure 5.11.

For this analysis, WIM Data sites are defined as sites that only serve the purpose of providing WIM census data. Sites that provide census data, which are also equipped with PrePass™, are considered as PrePass™ WIM sites.

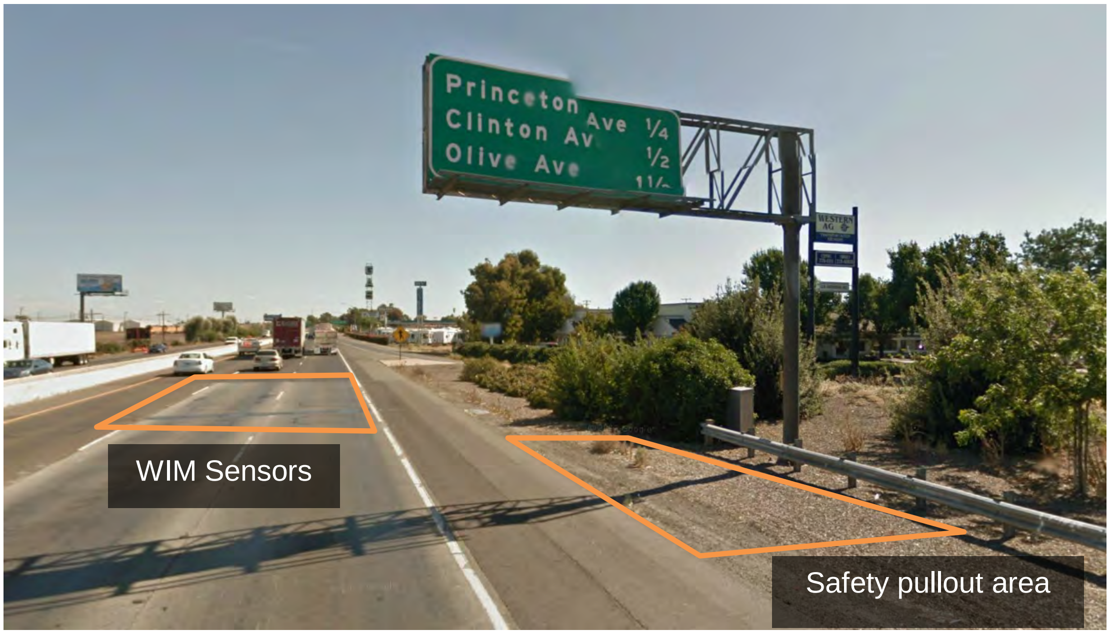


Figure 5.9 Example of WIM Data site on SR-99 in Fresno

Figure 5.10 WIM Data cabinet and controller at NB Saigon along the I-405 freeway

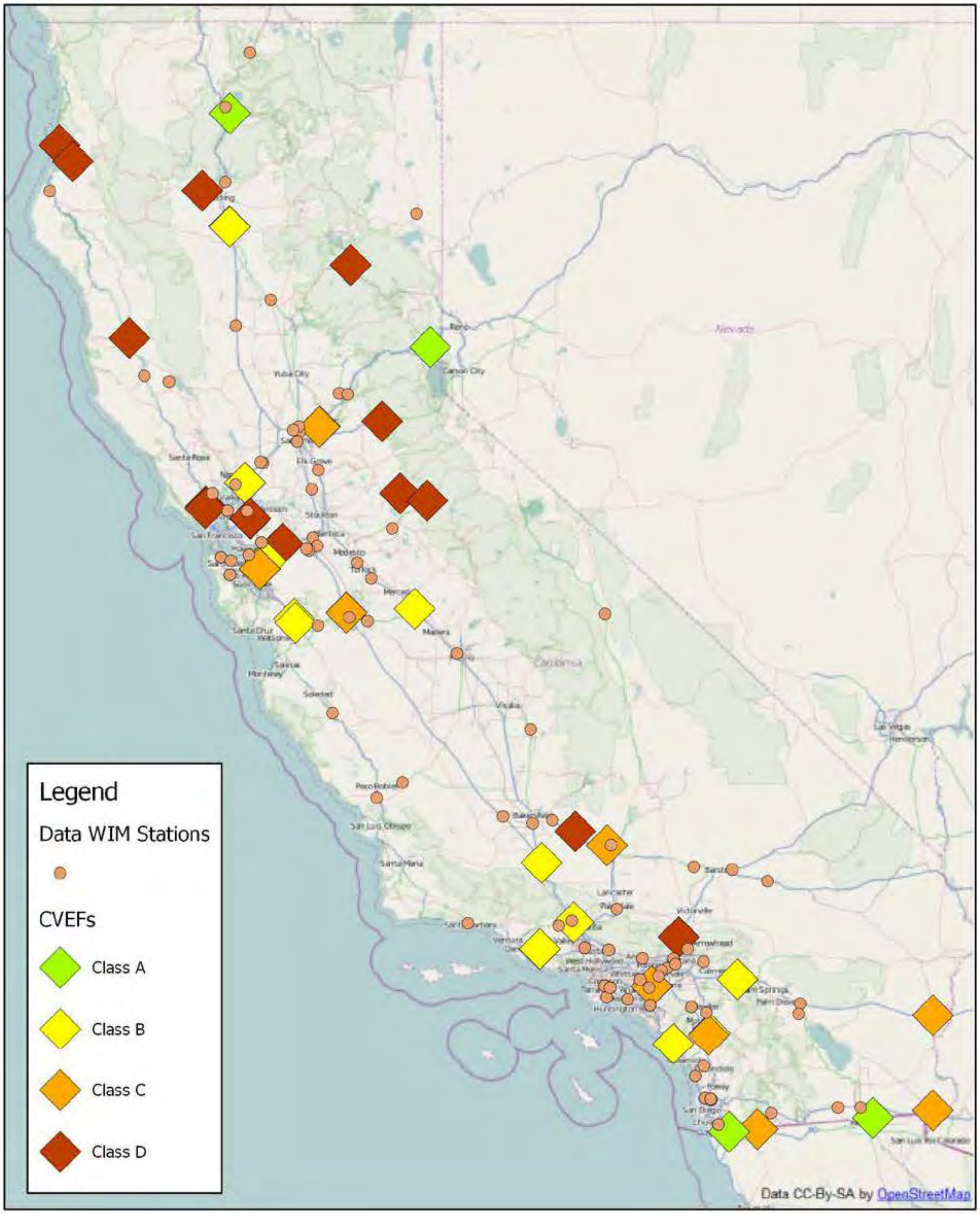


Figure 5.11 Location of WIM Data sites and CVEFs in California

5.2.3 Existing PrePass™ WIM Sites

PrePass™ WIM sites meet most geometric requirements specified in ASTM E1318-09 for the WIMTF. In addition, since all PrePass™ WIM stations are located in close proximity to CVEFs, they are ideally located for matching trucks traveling from the WIMTF to its associated CVEF. Communications and power infrastructure requirements are also attained at these sites to support the operation of WIM equipment and data transfer to the CVEF. Figure 5.12 shows an example of a PrePass™ WIM site with locations of the WIM sensors, safety pullout, and controller cabinet areas, as indicated. Figure 5.13 shows the location of a PrePass™ WIM station approximately one mile upstream of its associated class C CVEF.

The locations of PrePass™ sites in southern and northern California are presented in Figure 5.14 andFigure 5.15, respectively, represented as labeled cyan circles. The CVEF facilities are also shown in these figures, represented by square symbols, with colors denoting the class of the CVEF facility.

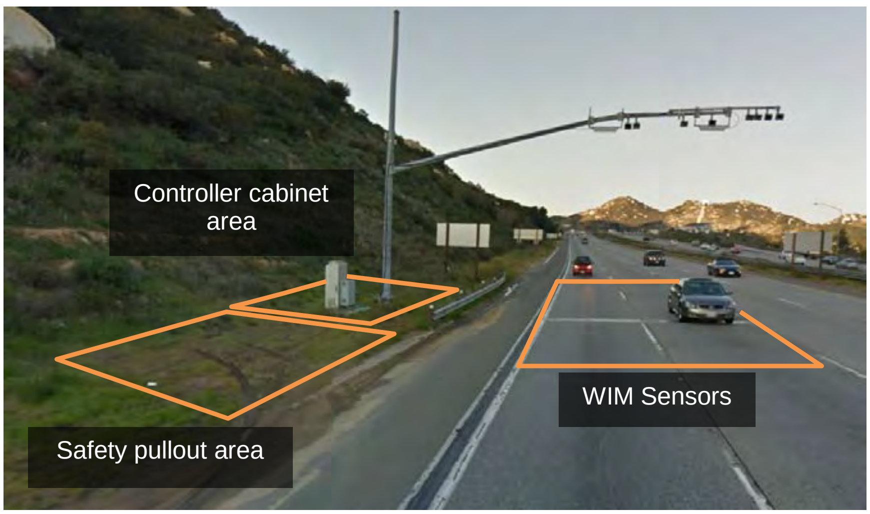


Figure 5.12 Example of PrePass™ WIM Site on SB I-15 at Rainbow

Figure 5.13 PrePass™ and class C CVEF locations on SB I-15 at Rainbow

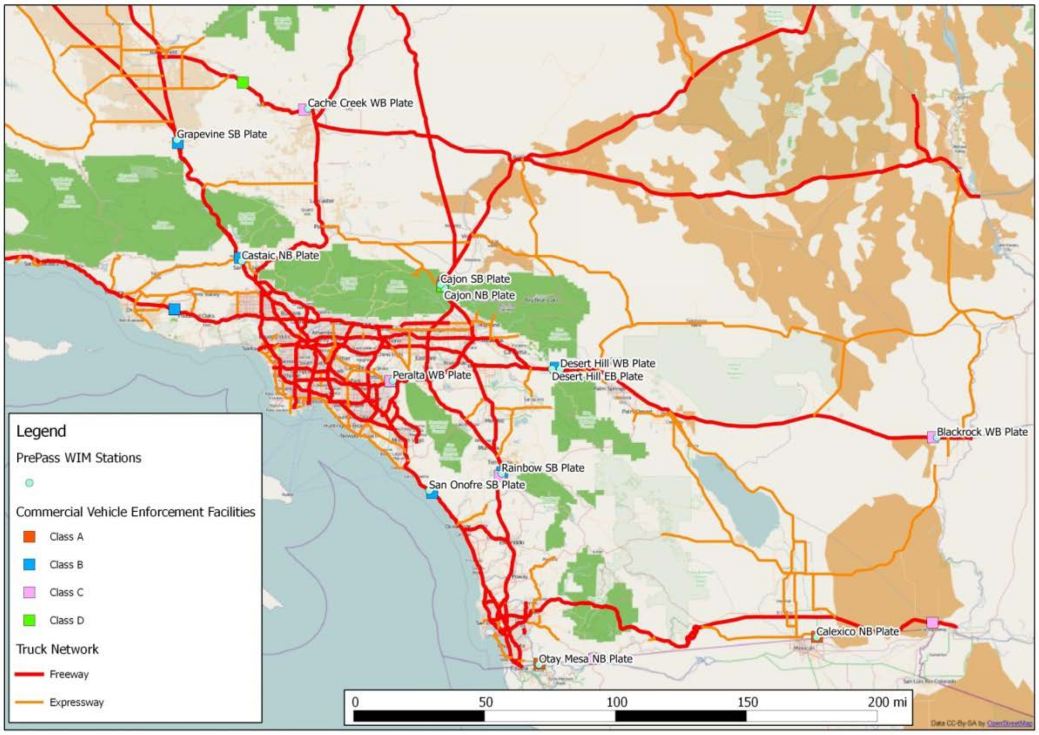


Figure 5.14 Southern California PrePass™ Sites

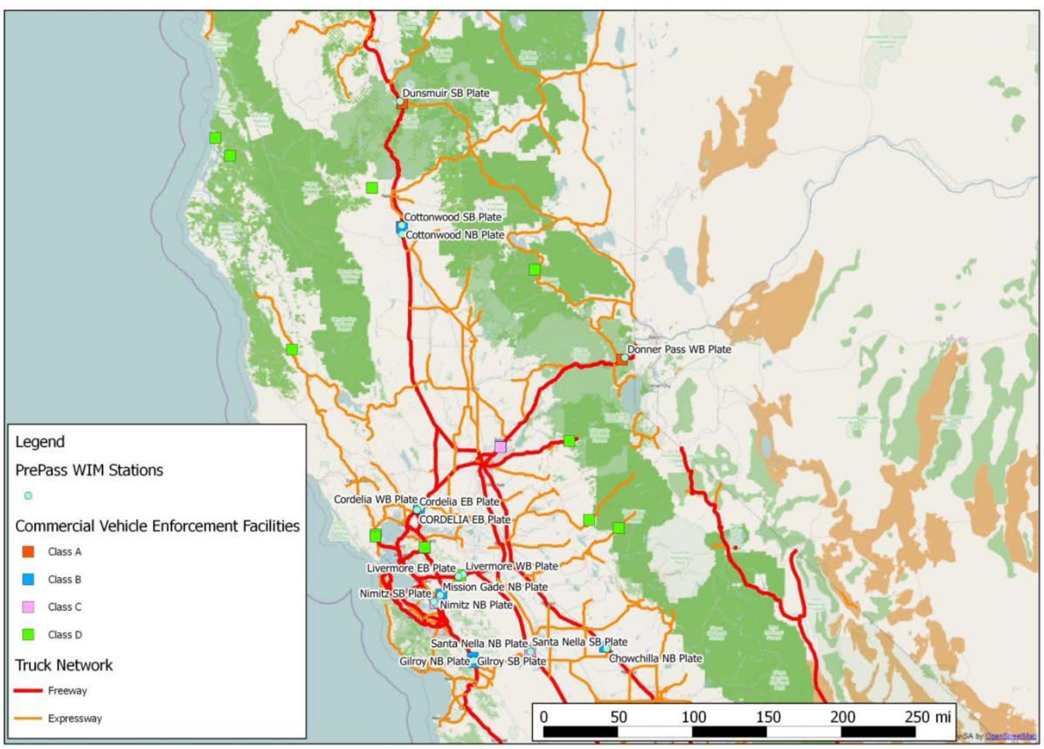


Figure 5.15 Northern California PrePass™ Sites

5.3 Comparison Criteria

Five criteria were used to evaluate the suitability of the site options:

- Overhead Equipment
- Geometric Alignment
- Proximity to CVEF
- Existing Power
- Existing Communication to CVEF

The overhead equipment criterion refers to the requirement for an existing overhead structure. A suitable overhead structure is necessary for mounting validation sensors and equipment for monitoring trucks traversing the WIMTF. In the absence of an overhead structure, additional costs will be factored in to construct a new structure.

The geometric alignment criterion refers to the site's fulfillment of the geometric requirements for WIM sites, as defined in ASTM E1318-09. This is a mandatory requirement, since existing geometry, such as the horizontal and vertical alignment, and cross slope of a potential site, cannot be changed.

Proximity to CVEF criterion refers to the requirement for CVEF to be located within close proximity, preferably downstream from the potential site. This is required for validating axle weight measures at the WIMTF, since the measures obtained at the static scales will be used as reference measures. The ability to effectively match trucks between the WIMTF and CVEF generally diminishes with greater distance between the pair.

The existing power criterion refers to the requirement for accessible power at the site without the need for extensive trench work. The presence of a conveniently accessible power source can significantly reduce the cost of deploying the WIMTF.

The existing communication to CVEF criterion refers to an existing communication infrastructure available at the site for data communication with the CVEF. Since data from the WIMTF is expected to be transmitted reliably to the CVEF in near real-time fashion, an existing communications infrastructure between the potential site and CVEF is desirable.

5.4 Comparison Results and Recommended Site Option

A comparison of the types of sites identified across five preliminary criteria is shown in Table 5.1. "X" indicates that the criterion is fully met by all candidates of the site type; "O" indicates that the criterion is partially met.

Table 5.1 Comparison of Site Types

No.	Criteria	Overhead Bridge	WIM Data Site	PrePass™ WIM Site
1	Overhead Equipment	X		O
2	Geometric Alignment		X	X
3	Proximity to CVEF	X		X
4	Existing Power	O	X	X
5	Existing Communications to CVEF			X

Comparing the site options presented in Table 5.1, it is clear that PrePass™ WIM sites fulfill the greatest number of requirements for the proposed WIMTF.

Although several overhead bridges can be found in close proximity to CVEFs, these sites were not specifically designed to meet ASTM E1318-09 requirements. This does not mean that none of the overhead bridge sites meet the geometric requirements. However, considerably more detailed geometric information of the highway is needed at each bridge location to assess if the criteria are met for individual sites. In addition to geometric concerns, significant work may be required to equip sites at these locations with power, as well as communication with CVEFs.

Existing WIM data sites fulfill the geometric requirements defined in ASTM E1318-09, which is a critical requirement of the WIMTF. In addition, these sites possess existing power infrastructure. However, most sites are located far from the nearest CVEF and therefore, are not ideally suited for verification of axle-weight measures.

In addition to the desirable attributes of WIM data sites, PrePass™ WIM sites also possess additional attributes, such as close proximity and existing communications with associated CVEFs. A potential limitation concerning PrePass™ WIM sites is the limited load capacity of the overhead structure needed for the installation of additional sensor equipment, currently used to mount PrePass™ DSRC equipment for communication with PrePass™ truck transponders. However, despite this shortcoming, the results show that PrePass™ WIM sites meet all the other criteria defined in this comparative analysis.

From this analysis, PrePass™ WIM sites are determined to be the ideal candidates for deploying a WIMTF. Further analysis will be performed to identify the final site recommendation for the WIMTF under Task 7.

6. Benefit and Cost Analysis

This chapter reports an in-depth study to quantitatively analyze the benefit and cost of the WIMTF. A benefit and cost analysis needs to be based on costs and benefits in monetary form. The team first analyzed the costs for initial installation and continuous operation and maintenance of the candidate site options. A range of benefits due to \WIM enhancements achieved through WIMTF, including prolonged pavement life, resource savings for maintenance, reduction of capital costs on roadway infrastructure through more cost effective planning, savings to freight operators, etc. were documented. Benefit-cost ratio is used to summarize the overall value of WIMTF.

6.1 The Baseline for the Benefit and Cost Analysis

To assess the benefits and costs for the WIMTF, several baseline factors must be established, including how a WIMTF can improve operational efficiency and effectiveness and how these improvements can be translated into economic factors.

6.1.1 Findings from California WIM Data

Caltrans currently operates 106 WIM stations. Thirty-five of these are used as PrePass™ CVEF Bypass to prescreen legally compliant trucks to bypass open CVEFs [9]. In 2010, data from all WIM stations recorded fewer than 65,000 overweight trucks, representing 0.083 percent of approximately 78 million trucks weighed by the WIM system.

According to the California Department of Motor Vehicles (DMV), a total of 5,464,926 registered commercial trucks and 2,035,007 commercial trailers were registered in California in 2012, including 450,886 Commercial Vehicle Registration Act- (CVRA)[27] registered trucks with gross vehicle weights more than 10,000 lbs (4535 kg) [10]. Additionally, 1,352,056 foreign based International Registration Plan- (IRP) trucks[28] [11] were registered in California in 2012. Note that the total number of registered trucks reported by the DMV in 2012 was lower than that reported by the DMV in 2010. We assume that each CVRA truck is operated 200 days a year, and each IRP truck is operated 50 days a year in California. We further assume that a truck is to be weighed twice on average during each trip, There would be approximately 316 million[29] truck weigh-data points to be collected in California annually. Therefore, the 78 million WIM weigh-data points collected by the California WIM system, in the best case scenario, represent less than 20 percent of truck trips that took place in California.

The extremely low percentage of overweight truck activities detected by WIM stations most likely does not represent the overall number of the truck overweight incidents in California.

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[27] Commercial vehicles paying fees based on GVW or CGW are hereafter referred to **as** *CVRA* vehicles.
[28] IRP facilitates commercial vehicle registration and operation among states and Canadian provinces. IRP member jurisdictions collect registration fees from their 'home based' interstate trucking companies on behalf of each member jurisdiction in which the companies operate and must register.
[29] [450,886 (CVRA trucks) x 200 (days/yr) + 1,352,056 (IRP Trucks) x 50(days/yr)] = 157,780,000 (truck trips/yr) x 2(times) = 315,560,000 (data points/yr)

Though the published estimates of the percentage of commercial vehicles that might exceed weight limits vary widely, studies to date have reported a much higher percentage of overweight trucks. The FHWA study estimated that 10 to 20 percent of trucks were operating illegally without a permit [12]. A report from the General Accounting Office estimated that 15 percent of trucks are overweight in the United States [13], while the Transportation Research Board provides a range of 10 to 25 percent. [14]. Additional studies on truck overweight activities at WIM stations suggest that overweight trucks could represent an even higher percentage. A study sponsored by Virginia DOT indicated that 38 percent of overweight trucks intentionally bypass CVEFs [15]; another study reports that 25 percent of trucks passing through the CVEFs in Connecticut are overweight [16]. It is common knowledge that estimates of the extent of illegal activities are prone to a wide margin of error. However, all estimates point to an overweight violation rate that is higher than 15 percent, which would represent about 65,000[30] overweight truck trips per day, or about 24 million overweight truck trips per year in California. The extremely low number of overweight trucks reported by the California WIM data collection system indicates that a much higher percentage of violation activities has not been detected and recorded.

6.1.2 Estimation of the Magnitude of the Overweight Problem in California

The research team further investigated potential sources for the large percentage of undetected overweight truck activity.

The 2010 California WIM data shows that, on an average, 15 to 20 percent of the WIM scales do not generate WIM data. Caltrans Division of Traffic Operations attributed the missing data to poor quality data or road construction. As a result of the bad data, a full month of data for the impacted WIM station was omitted. However, the missing data could affect the statistics of weighed trucks, as well as the total number of detected overweight trucks, but should not contribute to the low detection rate of overweight trucks.

It is possible for drivers with overweight trucks to select bypass routes and avoid WIM stations. Although the current 106 WIM stations being studied have been strategically located at highway segments with high truck volumes in order to form a Data WIM network, bypass routes are still available for many highway segments, due to the scarce nature of WIM stations. Aside from the fact that WIM stations are easily recognized by truck drivers, locations of WIM stations on California highways are well publicized along with the PrePass™ stations bypasses on the Caltrans website [9]. Drivers with overweight trucks frequently know when weigh stations are open, so they can postpone travel until the stations close or alternatively, select another route. This results in the number of overweight trucks being reduced when weigh stations are known to be in operation.

California WIM data notes higher incidents of overweight violations immediately following modifications in regular enforcement hours. [17]. It is believed that a certain percentage of truck drivers who know their vehicles are overweight go out of their way to avoid weigh stations.

[30] [157,780,000 (truck trips) x 15% (overweight trucks)] = 23,667,000 (overweight truck trips/year) / 365 = 64,841 (overweight truck trips/day)

Some truck drivers may not differentiate between WIM PrePass™ stations and DATA WIM stations, and simply avoid them all. While bypassing WIM stations may contribute to a reduction in the overweight detection rate, it is not possible that it accounts for more than 90 percent of overweight trucks bypassing the WIM stations in California.

Investigating missed detection of overweight trucks pinpoints the potential errors in WIM scales. It is likely that WIM scales are biased within a small percent toward heavier thresholds, the result of biased calibration settings or the specific type of WIM scale that has bias built in over time. The bias contributes to systematic errors that result in trucks appearing to weigh less than their actual weights. Consequently, a significantly high number of overweight trucks are sorted as having legal weights.

The study team verified with Caltrans WIM staff that, in practice, WIM scales are calibrated to be biased toward the heavier weight limit by approximately 3.5% points at PrePass™ WIM stations. This accounts for the margin of error and reduces the number of trucks within the legal weight limit being pulled over to CVEFs. Furthermore, a preliminary analysis of the sample calibration data for WIM data stations in California shows that the assumption of bias built-up over time is likely to be true, as prior calibration data has shown consistent bias toward a heavier weight limit. The biased calibration and bias built-up over time can be compounded resulting in even higher biases.

All WIM stations in California use bending strain scales, except for one location, which uses Piezoelectric. The standard deviations (1σ) for bending strain and Piezoelectric are 5 and 10 percent respectively. These percentages are larger than desired for weigh-in-motion purposes. Measurement accuracy is critical to the pre-screening decision. As explained in section 2.4, when a WIM scale is calibrated at 80,000 lbs (3628.7 kg), a truck weighing 80,000 lbs (3628.7 kg) has a 50% chance of being pulled in for inspection. A calibration bias is typically created to reduce the number of trucks within the weight limit from being pulled out for inspection. The bias is determined based on the standard deviation of the WIM scale. The larger the standard deviation, the larger the bias needs to be to ensure that a prescribed percentage of trucks not to be directed to the static scale. Consequently, pre-screening decisions made by the WIM system are correspondingly biased, resulting in a much higher chance for overweight trucks being undetected by the WIM.

The following example illustrates how biased calibrations would cause overweight trucks to go undetected. Based on typical WIM measurement errors distribution for Gross Vehicle Weight (GVW), as shown in Fig 2.1, Table 6.1, provides estimations of the probability of a static scale bypass of overweight trucks when CVEFs are calibrated at 2.5 and 5 percent respectively, with a bias toward the heavier overweight threshold.

Table 6.1 Probability of Static Scale Bypass based on GVW and WIM system type

	2.5% biased heavier		5% biased heavier	
% Over Legal Gross Vehicle Weight	Piezoelectric σ=10%	Bending Strain σ=5%	Piezoelectric σ=10%	Bending Strain σ=5%
0%	60%	70%	70%	90%
2.5%	50%	50%	60%	70%
5%	40%	31%	50%	50%
7.5%	30%	16%	40%	31%
10%	23%	7%	30%	16%
12.5%	16%	2%	23%	7%
15%	11%	0.6%	16%	2%

This example shows that if the expectation is that 90% of the trucks with a GVW of 80,000 lbs. (36287.4 kg) using a bending strain scale are not be directed to the static scales, the thresholds need to be re-calibrated about 5% heavier. The available overweight data quoted in the previous WIM studies indicated that the range of excess weight falls between 3,000 and 8,000 lbs. (1360.8 kg to 3628.7 kg) [7] or 3.7% to 10% overweight. With a calibration of 5% biased toward the heavier threshold, trucks that are 3,000 lbs. (1360.8 kg) in excess of the legal limit will have more than a 50% chance of bypassing the static weigh scales. Trucks that are more than 8,000 lbs. (3628.7 kg) overweight still have greater than a 15% chance of bypassing the WIMs.

The above example shows that when bending strain stations are set to use a threshold a few percentage points above weight limits, or as a result of bias built up, WIM stations would permit the largest number overweight trucks to bypass the static scales undetected. Because the distribution of overweight trucks is unknown, it is difficult to estimate the distribution of the percentage of overweight trucks by weight. However, this analysis shows that the number of overweight trucks is certainly higher than that captured by the weigh stations, and might even reach the 15 percent estimated national average of overweight trucks.

The characteristics and calibration of WIM scales determine the efficiency and effectiveness of weight enforcement [8]. The enforcement function of PrePass™ stations becomes largely diminished when WIM scales fail to detect a large percentage of overweight trucks. Consequently, truck overweight behaviors persist. Greater numbers of overweight trucks means substantially more damage to the California highway infrastructure.

6.1.3 Costs of California Highway Damages due to Overweight Trucks

WIMTF can facilitate the assessment of WIM systems and the development calibration methods to help reduce the standard deviation of WIM scales and therefore help reduce road damage. To evaluate the benefits of WIMTF, we need first to determine damage costs caused by overweight trucks. We have adopted the method used by Arizona DOT to derive cost estimates for damage caused by overweight trucks [7].

The California Transportation Commission released a needs assessment report estimating that a total of $536.2 billion will be needed over the next 10 years [18] and the projected revenue has a shortfall of $293.8 billion for filling the gap (the results are summarized in Table 6.2). As the most consequential element for the trucking industry, the needs study pointed out that $7.97 billion per year in revenues would be required just to maintain and operate existing highway systems. In FY 2012-2013, California trucking transportation revenue, collected from truck weight fees, fuel taxes and truck registrations, totaled $2.11 billion. Following this trend, revenue shortfall from the California trucking industry will be approximately $5.86 billion per year.

Table 6.2 Estimated funding needs, revenue, and revenue shortfalls [18]

Items	Funding
Funding needs for transportation system preservation, system management, and system expansion projects (10-year estimate)	$536.2 billion
Revenue (10-year estimate)	242.4 billion
Revenue shortfall (10-year estimate)	293.8 billion
Preservation costs for California highway (10-year estimate	$341.1 billion.
Revenues needed from trucking transportation (10-year estimate)	$79.7 billion
Revenue from California trucking transportation (FY 2012-2013)	$2.11 billion
Revenue shortfall from the California trucking industry (per year)	$5.86 billion

Previous studies show that legally loaded, heavy vehicles cause a relatively small amount of damage to road pavement structures, as opposed to overloaded, heavy vehicles, which are responsible for approximately 60 percent of the damage to the road network [19]. Based on data from the North Dakota Highway Patrol, the range of excess weight falls between 3,000 and 8,000 lbs. (1360.8 to 3628.7 kg). Since a tractor unit normally accounts for about 18,000 lbs. (8164.7 kg), this range implies that, on a total weight basis, overweight trucks are 5 to 13 percent over the legal load limit. However, axle weight is the most critical factor in pavement damage. The 3,000 to 8,000 lbs. (1360.8 to 3628.7 kg) must be distributed over the trailer's load-bearing axles. The range of excess weight would be about 4.5 to 12 percent per axle, if excess weight is distributed between two tandem axles [7]. Using this assumption, and based on AASHTO load equivalency equation[31], each overweight vehicle would pose about 19 to 45 percent more damage than a truck operating at the 80,000 lb. (36287 kg) legal limit. Thus, the overweight-vehicle share of the costs should be from 19 to 45 percent higher than if the vehicle was operating at the legal limit. This would generate an overweight truck share of between $1.134 billion and $2.637 billion[32] per year toward the uncompensated costs for California highway maintenance. If the total number of overweight trucks was reduced, the overall costs for highway maintenance would be reduced.

[31] A fourth power exponential approximation (1.0454 and 1.124)of the AASHTO load equivalency equation: for a 10% increase; this yields a ratio of (1.1/1.0)4 = 1.4631 or approximately 45%

[32] $5,860,000,000 x {4.5%, 12%} = {$1,134,000,000 $2,637,000,000}.

6.2 Estimated Benefits from the WIMTF

WIM systems reportedly generate substantial economic benefits in many respects, including pre-screening to invaluable traffic and weight data for better planning and maintenance management, as well as new construction activities. However, this analysis indicates that the benefits for existing WIM systems have been limited by weigh scale system errors.

A WIMTF can facilitate the advancement of WIM technologies by selecting technologies that produce measurement errors with smaller standard deviations, as well as developing continuous calibration methods to reduce calibration biases. WIM scales with inherently smaller standard deviations, or those that are calibratable to achieve a smaller standard deviation will yield significantly more accurate WIM results, maximizing violation detection, while minimizing unnecessary delays for the trucking industry. If the performance of WIM technologies is improved and Prepass™ WIM stations are widely adopted for enforcement pre-screening, truck overweight activities could be significantly discouraged. This, in turn, would reduce overall road infrastructure damage and maintenance costs. This analysis took into account the direct benefits of WIMTF achieved from savings in the operation of WIM stations, as well as indirect benefits attributed to the WIMTF improving WIM performance.

6.2.2 Savings in Operational Costs

The 106 WIM stations in California are operated by Caltrans Division of Traffic Operation with support from Caltrans Districts and three contractors. Three staff members at Caltrans Headquarters Division of Traffic Operations work full time to operate the WIM system and manage WIM data. The District technical staff provides assistance on the maintenance of phone and power services for WIM data stations. WIM ByPass, Data, and in-station maintenance are all managed by IRD, with a total contract value of approximately $1.4 million per year. Each WIM station is scheduled for calibration twice a year by running a standard weight truck through the WIM station. However, actual calibration intervals can be significantly longer. Some WIM stations go up to two years without calibration. Additional maintenance trips are necessary when system faults occur. Estimated per diem travel costs for Caltrans staff maintaining all WIM stations is close to $250,000 [26].

The WIMTF will facilitate the selection of superior WIM technologies and the development of significantly improved monitoring, calibration, and data processing tools. Monitoring and calibration tools will reduce the need for some calibration trips to the facility. A reduction of calibration trips by 50 percent would represent a saving of $125,000 per year in travel costs alone. Assuming that the data processing from all WIM stations can be automated without heavily relying on contractors, an additional $200,000-$300,000 per year savings could be achieved.

More substantially, a better calibrated WIM system, due to improved calibration tools will provide more reliable data for highway planning, design, and maintenance, and will more effectively support overweight enforcement. These economic benefits are covered in the analyses below.

Finally, it is envisioned that WIM will play an increasingly important role in highway infrastructure preservation, such that appropriate funding can be justified to establish PrePass™ stations for the remaining 20 CVEFs and to expand WIM data stations throughout California to enable collection of comprehensive truck operation data. The knowledge to be gained and the tools to be developed through the WIMTF will enable Caltrans to operate additional WIM stations without a substantial increase in staff, saving millions of dollars.

6.2.3 Savings from Reduced Overweight Truck Activities due to WIM Prescreening

WIM systems have been used as a part of the PrePass™ program to presort registered vehicles on the highway mainline when CVEFs are in operation. Vehicles equipped with PrePass™ transponders are queried when they pass over the PrePass™ station. PrePass™ trucks that are in compliance are signaled to bypass CVEF with no interruption. The WIM system directs only PrePass™-equipped vehicles suspected of non-compliance to report at static scales for further inspection, in addition to 15 percent randomly pulled in equipped trucks. All non-PrePass™ equipped vehicles are required to pull into the CFEF, if the facility is open and not full. Currently, only 15 to 18 percent of trucks in California participate in the PrePass™ program.

As discussed in section 6.1.2, the missing detection of overweight trucks has a significant impact on the role of WIM PrePass™ stations for prescreening overweight trucks for enforcement. When large numbers of overweight trucks can pass the PrePass™ stations undetected, overweight trucks are not enforced. Subsequently, road damages cannot be prevented or reduced. It is not clear the number of miles of the 15,159 mile state highway infrastructure are protected by the 35 CVEFs supported the PrePass™. However, if we assume that overweight truck activities going through the PrePass™ stations is reduced by 50% (from 11.7 million to 5.58 million), based on the estimated overweight truck share of between $1.134 billion and $2.637 billion per year toward the uncompensated costs for highway maintenance (see section 6.1.3), the cost reduction due to 50% fewer overweight trucks going through PrePass™ -protected roads would be between $111 million and $264 million per year[33].

The cost of maintenance and new road construction is an enormous burden for taxpayers, one which can be reduced with WIM as a data collection and enforcement tool. WIM Prescreening offers substantial benefits. Use of WIM prescreening at a CVEF enables current highway and enforcement facilities to accommodate higher truck volumes without expensive new construction. WIM Prescreening also helps protect the existing CVEF facility from unnecessary wear. Being able to target illegally overloaded trucks helps free up enforcement resources and makes enforcement operations more efficient, allowing more thorough inspections of potential violators. For taxpayers, more efficient enforcement operations, more efficient carriers and less damage to the infrastructure, means fewer tax dollars spent on this program, freeing up tax dollars for other important areas. These unsubstantiated cost savings are difficult to summarize at the statewide scale. Further evaluation can be done on a case-by-case basis.

[33] {$1,134,000,000, $2,637,000,000} x 50% = {$111,000,000, $263,000,000}

6.2.4 Savings through WIM for Infrastructure Planning, Design and Management

The data collected by WIM systems, combined with traffic data, such as truck volume, speed, classification, configurations, can be used to predict traffic patterns and loading requirements, in order to design their pavements accordingly. It therefore provides invaluable data for infrastructure planning, design, and maintenance.

Current traffic loading design procedures use a more 'conservative' pavement design when traffic-loading data is not available. Depending on pavement materials and type, this 'conservativeness' could be interpreted as a thicker pavement or a pavement where stabilizing agents are used to enhance its properties. In order to evaluate whether a design is adequate, it is necessary to know the actual loading conditions. Different pavement designs may have a similar life cycle, but one may have been subjected to much harsher loading conditions. Understanding loading conditions provides a better comparison between the actual functioning of the different pavements so that pavement designs are neither under- or over-designed, both of which are costly to remedy. Note that an overdesigned pavement does not necessarily last significantly longer than an adequately designed pavement, even though the cost could be substantially higher when it includes miles of infrastructure or bridges. Using accurate WIM data eliminates guesswork and enables Caltrans to plan and design new pavements based on actual and projected pavement loadings, as well as environmental and life cycle parameters to derive appropriate infrastructure pavement designs, as per recommendations developed by the Strategic Highways Research Program (SHRP).

Currently, the WIM scales have biased thresholds either by calibration or they have built up over time. The data collected by WIM data stations have significant system errors, to the extent that they do not represent the actual load factors of overweight trucks. A WIMTF will help improve calibration of the system, substantially improving the usability of WIM data.

The cost savings for correctly designing infrastructure based on improved WIM data would vary depending on the project, and it is difficult to quantify with an average value. Caltrans' statewide pavement performance goal for its 2011 Ten-Year Plan was to reduce the total distressed-lane miles for the system to 5,500 by FY 2021/22. Also in this plan, Caltrans included pavement rehabilitation needs of $2.9 billion per year. However, projected available funds are $406 million per year[34]. Conservatively, an annual 3 to 5 percent savings in rehabilitation costs in California due to accurate WIM data, could amount to $85 million to $145 million per year[35].

6.2.5 Savings by Applying WIM Data for Highway Maintenance

When highway maintenance activities are misestimated as a result of overloading or inaccurate traffic loading estimates, it can mean the degradation of a road. Accurate loading data provides Caltrans with an opportunity to adjust its maintenance activities and rehabilitative measures based on actual levels of deterioration. This ensures the prolonged integrity of a road, avoiding reconstruction and new construction wherever possible, particularly at locations where traffic volumes exceed design volumes. Adjusting maintenance schedules for earlier or more frequent

[34] Caltrans, 2011 State of the Pavement Report

[35] $2,900,000,000 x {3%, 5%} = {$85,000,000, $145,000,000}

maintenance would ensure that rehabilitative measures are correctly timed, rather than after the structural integrity of a road has been breached. Cost savings for earlier rehabilitative maintenance, as opposed to rehabilitating bad surfaces depends on many factors, including initial infrastructure design, and traffic volume. However, it is a general rule of thumb that maintaining a good road is five times less expensive than rehabilitating a poor one. [20]

As the current WIM data does not represent true truck overweight conditions in California, maintenance based on these WIM data, even if implemented, may not help gauge correct schedules. WIMTF's improved pavement loading data will support maintenance and scheduling decisions, which helps reduce maintenance costs. Based on the estimated $34 billion per year highway preservation costs (see section 6.1.3), if we assume that WIM data can contribute 1 to 3 percent reduction in highway preservation costs, that represents an annual savings of to $340 million to $1.02 billion[36].

6.2.6 Weighing for Freight/Trade Planning and Regulation

It is difficult to put an economic value on WIM data in the context of freight/trade (Henny, 1995). Assumptions have been made to estimate the cost savings to the trucking industry. Motorists in California traveled 327.8 billion vehicle-miles over the 172,139 miles of public roads in 2011. Trucks account for approximately 7.5% of these vehicle-miles. Taking an average freight cost of $2.5 per mile [21], the annual cost of road freight in California is about $62 billion. If, through better data, road investment was better targeted to the needs of the road-freight industry, such that industry costs were reduced by only 0.1 - 0.2 percent, this would represent an annual benefit of $62 million to $124 million cost savings to the trucking industry[37].

6.2.7 Savings due to Reduced Truck Stops

Reducing the need for trucks to report to CVEFs has additional benefits in safety (from fewer truck-exits to, and merges from CVEFs), operating costs (less wear and tear on the static scales), more focused and thorough inspections (less traffic reporting to CVEFs), and fewer overloads from greater enforcement visibility and effectiveness.

Using the previously estimated 158 million truck trips per year in California, given the average two-minute delay at a CVEF for most trucks and assuming that CVEFs are open 12 hours per day, weighing each truck just once would take 1,200 years[38]. Based on the industry standard cost of one dollar per minute of delay at a CVEF, this equals $316 million for weighing each truck trip in California just once[39]. Assuming that long haul trips would involve, on average, two to three CVEF stops over the course of a year, CVEF stops could be nearly doubled. A Federal Motor Carrier Safety Administration (FMCSA) sponsored study estimated that PrePass™ provides higher savings to the trucking industry. This study showed cost savings for vehicle operation, including but not limited to, vehicle maintenance, driver's wages, administrative costs,

[36] $34,000,000,000 x {1%, 5%} = {$340,000,000, $1,020,000,000}
[37] $62,000,000,000 62 x {0.1%, 0.2%} = {$62,000,000, $124,000,000}
[38] 158,000,000 (vehicles) x 2 (min)/[60 (min/hour) x 12 (hour/day) x 365 (day/year) = 1200 years
[39] 158,000,000 (vehicles) x $2 = $326,000,000

and insurance, to be approximately $8.68 per bypass[40] [24]. The total for PrePass™ savings can be hundreds of millions to billions dollars in savings for the California truck industry.

As the CVEF can realistically only inspect 200 trucks per day, and due to the fact that California PrePass™ stations only capture a small percentage of overweight trucks, the economic gain to the trucking industry with PrePass™ deployment may not be substantial. In the future, when WIM accuracy is improved via the tools generated by the WIMTF, the total number of truck delays may increase, as more overweight trucks will be pulled in for inspection. However, current delays due to enforcement are justifiable and will reduce infrastructure damage.

6.2.8 Summary of Estimated Benefits from WIMTF

As summarized Table 6.3, the benefits are grouped into three categories, including (1) the savings realized when a WIMTF is established, and (2) savings to the trucking industry. Average savings are derived for each category of benefits, which are to be used for a cost-benefit analysis.

Table 6.3 Benefits from WIMTF

Items	Savings Generation (per year)
Savings from existing operation	
Savings in operation costs	$325k to $425k
Savings from Reduced Overweight Truck Activities due to WIM Prescreening	$111 million to $264 million
Savings through WIM for Infrastructure Planning, Design and Management	$85 million to $145 million
Savings by Applying WIM Data for Highway Maintenance	$340 million to $1.02 billion
Estimated Range of Savings	**~$861 million and ~$1.85 billion**
Savings to trucking industry	
Weighing for Freight/Trade Planning and Regulation	$64 million to 124 million
Estimated Savings to Trucking Industry	**$64 million to $124 million**

Please note that because this analysis is based on assumptions, the results presented in Table 6.3 and the analysis in the remaining of this chapter are estimates of the magnitude of savings.

6.3 Estimated Costs for Deployment of a WIMTF

The cost estimates presented in this section were developed using data provided by a previous National Cooperative Highway Research Program (NCHRP) study [25], WIM installation examples, and cost estimates for labor obtained from Siemens for the WIMTF. This study used extensive data from a majority of Caltrans' WIM facilities at the time, and so these cost data still reflect California conditions. In comparison with cost estimates from a more recent NCHRP study which synthesized cost data from a variety of sources, WIM-related equipment and

[40] Value is based on an FMCSA study: Economic Analysis and Business Case for Motor Carrier Industry Support of CVISN, Oct. 2007

installation costs have not changed significantly. Estimating costs for the WIMTF, we also made adjustments based on our best professional judgment.

6.3.1 Estimated Costs for Options Required by the Caltrans RFP

Caltrans has specified seven options for WIMTF. It was brought to the attention of the research team that the new Mountain Pass PrePass™ WIM site was planned for construction along southbound I-15 near the California-Nevada state border in conjunction with a new CVEF. Under task 5, the project team carefully reviewed these options, comparing the site options with WIMTF needs and requirements (see section 5.1 for the analysis). The result of the analysis of the Caltrans-recommended options is summarized in Table 6.4.

Table 6.4 Assessment of the Options Required by Caltrans

#	Options required by Caltrans	Estimated Costs
(a)	No need for a newly established test facility	No cost or benefit is associated with this option.
(b)	Upgrade the Berkeley Highway Lab	Because there is no safe place near the Berkeley Highway Lab to build a WIMTF, the BHL is not a viable option.
(c)	Upgrade the I-405 facility	A WIMTF would need to be built from scratch to include both WIM and CVEF.
(d)	Upgrade an existing Commercial Vehicle Enforcement Facility	This option is not considered because CVEF at a Commercial Vehicle Enforcement facility can not support testing of sensors at mainline highway speeds. This is not a viable option.
(e)	Offer a Pooled Fund Option	This is not a site option.
(f)	Use a National Laboratory in California	None of the National Laboratories have facilities with CVEFs that would support testing of sensors at mainline highway speeds. Therefore, this is not an option for WIMTF.
(g)	A site in California that is not currently part of the above	Various existing WIM sites have been evaluated; options are analyzed in the next section.
(h)	Mountain Pass PrePass™ WIM site along southbound I-15	Remote site; may not support testing WIM at a range of speeds and construction activity associated with in-pavement WIM sensor installation; requires full freeway closure; not a viable site.

The analysis concluded that options (b), (d), (f) and (h) do not meet the WIMTF requirements and therefore are not viable options. No further cost-benefit analysis was necessary on these options.

Option (a) does not have a cost or benefit, but will be addressed in the cost-benefit section. Option (c) requires significant new infrastructure to meet the WIMTF requirements. According to the data released by Caltrans, the recent reconstruction and modernization of the Cordelia Truck Scales facility, which includes a static weight scale and a WIM PrePass station, cost $100M. In addition to the basic infrastructure, instrumentation costs for a WIMTF will need to be included. Option (e) is a not a site option, but should be considered as a project funding approach.

Further investigation under option (g) has concluded that WIM PrePass^{TM} stations meet the CVEF requirements and have the necessary overhead equipment, communication and power infrastructures, and are therefore logical options. As the WIM Prepass^{TM} facilities have very similar instrumentations, the following analysis provides the cost for upgrading a typical WIM PrePass^{TM} station to become a WIMTF.

6.3.2 Estimated Costs for Candidate WIM Sites Recommended in This Study

In assessing the costs for deployment of the WIMTF, we use the following basic assumptions: two lanes will be instrumented with the reference WIM scales and additional equipment necessary for verifying the WIM systems and devices; WIM scales will be installed in proximity to the existing CVEF. Table 6.6 provides a summary of the cost estimate. Each line item is further explained below.

(a) Site Preparation Costs

Accurate operation of a WIM system requires that it be placed in strong pavement that is in good condition. Consequently, pavement rehabilitation is often necessary before sensors can be installed.

As per Long Term Pavement Performance (LTPP) Studies Traffic Data Collection Protocol for LTPP's recommended pavement specifications for WIM sites, the 200 to 500 feet of pavement immediately surrounding the axle sensors should be in excellent condition (no cracking, no visible rutting). A ¼-mile pavement rehabilitation effort is budgeted using a range of cost values for work, including anything from grinding the surface of an existing Portland Cement Concrete (PCC) pavement to completely rebuilding it. Additional costs for pavement rehabilitation during the first 10 years of the WIMTF have also been considered.

(b) Hardware System Costs

The hardware systems/components for a WIMTF include the instrumentation used to test and evaluate WIM technologies listed in Table 6.5. Estimated costs are included in Table 6.6. They are approximate values developed from available cost information and telephone conversations with vendors. The estimated costs of installed WIM systems (excluding pavement rehabilitation) do not vary significantly based on the specific WIMTF site, the detailed requirement specifications, or any special conditions placed by vendors. The costs for installing WIM systems and sensors, power, communications, and other site necessities are developed based on an estimate from Siemens, and are listed under installation costs. In addition to the hardware for instrumentation, we have listed the hardware to be tested on the right column in Table 6.5. That hardware will be provided by manufacturers at no cost to Caltrans.

Table 6.5 Hardware for WIMTF

Items	Quantity (WIMTF instrumentation)	Quantity (components to be tested)
WIM scale	2	4
Vision-based and microwave-based speed detection sensors	2	4 or more
In-pavement inductive loops	4	
License plate readers	2	4 or more
Vehicle identification sensor	2	4 or more
Bluetooth readers	2	
Brake temperature sensors	1	4 or more
Safety barriers	1/4 mile	
332 cabinets for hosting test equipment	9	

Table 6.6 Estimated Initial Costs of the WIMTF

Item	Units	Unit Cost	Subtotal	Notes
Initial pavement rehabilitation costs		$50,000	**$50,000**	
Dep Pit Load Cell scale	2	$52,000	$104,000	
One additional WIM scale	2	$50,000	$100,000	
Vehicle speed detection sensors	2	$4,000	$8,000	
License Plate Identification readers	2	$4,000	$8,000	
Wayside brake temperature sensors	2	$8,000	$16,000	
Inductive loops	8	$1500	$12,000	
Communication modem and devices	1	$500	$500	
332 Cabinets	9	$5,000	$45,000	
Data processing computer	1	$8,000	$8,000	
Data storage (Raid)	1	$2,000	$2,000	
Software	Various	$15,000	$15,000	
Safety barriers (material only)	¼ mile	$24,000	$24,000	
Installation Costs	Various	**$100,000**	**$100,000**	
Total Initial Costs			**$492,500**	

(c) Sensor Failure Rates, Costs Per Sensor, and Sensors Per Lane

Axle sensors fail for a variety of reasons, including poor installation, pavement failure, sensor fatigue, and faulty sensor design and construction. These failures occur due to increased fatigue, and because pavements tend to deteriorate more quickly under overweight conditions. The failure rate may vary depending on the condition of the installation and pavement. Also note that the failure rate is not linear and can be expected to increase as sensors age. The rate given in this spreadsheet reflects conditions two or more years after installation.

(d) Central Computer Hardware and Software

Two computer systems will be needed, including a local computer system in the field to collect, store, process, and communicate WIM data to remote terminals through the Internet and a central computer that synthesizes data from all sources and conducts various processes to support WIMTF research. In addition to basic hardware requirements, various processing software supplied by the WIM system vendor may be needed. We expect that Caltrans already has a license for processing WIM data and the vendor will supply their software to support the processing of their system/devices. Moreover, integrated data processing software will be needed, which is listed under the tools development section.

(e) Operating Costs

Operating costs are divided into four categories: utilities, calibration, maintenance, and office processing. Because a WIMTF has significantly more equipment than a typical WIM station, continuous performance monitoring and periodic calibration tests are needed to ensure the integrity of the collected data and to guarantee that it provides usable information and supports research. Most WIM systems come with an "auto-calibration" capability. Though previous accuracy analysis data submitted to LTPP showed that these calibration tools do not always work reliably, we will need to apply these tools until new calibration tools are developed.

(f) Pavement Rehabilitation Costs

Pavement deteriorates as it ages, and WIM sensor performance deteriorates, just as sensor life expectancy decreases. In many cases, sensor failure is caused not by the failure of the sensor itself but by the failure of the pavement around the sensor, which causes the sensor to quit operating correctly, or results in sensor damage that would not otherwise have occurred [26]. Therefore, the pavement that contains WIM system sensors must be rehabilitated periodically. When the pavement is repaired or replaced, WIM sensors almost always have to be replaced. This repair/replacement is budgeted for, as well.

(g) Other Potential Costs

Additional "one-time" costs will be needed to equip the WIMTF. The items required vary by technology, but can include test equipment and specialized electronic diagnostic tools.

(h) WIMTF Operation, Research and Development

The operation of the WIMTF will be conducted in conjunction with research and development activities. The WIMTF will need to include a number of software tools, including: (a) data acquisition tools for collecting and integrating all data sources into a single database; (b) data processing tools that will synthesize and preprocess the data from all sensors and monitor their condition; (c) truck re-identification methods; and (d) advanced calibration methods. Some of these tools, such as calibration methods, will be subject to new research, and additional methods and tools will need to be identified. This work will be conducted by a contractor. The costs for WIM operation, research and development are identified in Table 6.7and Table 6.6.

Table 6.7 Estimated Annual Costs for the WIMTF Maintenance, Operation, and Research

Annual Site Maintenance				
Annual pavement rehab		$10,000	$10,000	
Cost for field electronic replacement	Various	$20,000	$20,000	Incl. WIM scales replacement
Annual non-rehab maintenance		$5,000	$5,000	
Cost per alternative calibration session	4	$5,000	$20,000	
Subtotal for maintenance			**$55,000**	
Labor				
Caltrans staff				No change from the current level
WIMTF operation, research and development of new approaches (contract)		$500,000-$1,000,000	$750,000	Average costs $750,000 per year
Subtotal for Labor			**$750,000**	
Travel and per diem costs	20	500	**$10,000**	
Total Annual Costs			**$815,000**	

6.5 Benefit and Cost Analyses

The benefit and cost analysis has concluded that when WIM scales have smaller system errors and are calibrated to reduce biases, substantial cost savings can be generated, as summarized in Table 6.3. The cost analysis provides an estimate for initial and operation costs of WIMTF. Based on these analyses, a Benefit and Cost Analysis (BCA) analysis using the benefit-cost ratio (BCR) was conducted. The BCR is calculated by the net present value (NPV) of benefits divided by the NPV of costs. The NPV is the current estimated value of all net benefits, which are the sum of benefits minus costs.

$$\text{BCR } A = \frac{B_{PNV}}{C_{PNV}}$$

We follow a common practice that if the BCR exceeds one, then the proposed WIMTF would be a good candidate for a positive recommendation.

The benefit-cost analysis uses the benefits attainable from the analysis on savings from the existing operation as the baseline. Costs for two types of candidate sites are evaluated, including a site near the I-405 facility recommended by Caltrans, and a typical PrePass^{TM} station (because their conditions and instrumentations are similar). The I-405 facility requires $100 million for building WIM and CVEF from scratch, plus any necessary instrumentation for WIMTF. A brand new WIM facility may be better designed to meet WIMTF needs. However, it is difficult to justify the $100M new construction costs while 35 PrePass™ stations are also available as candidates. Any of these stations can be upgraded with a fraction of the cost for this new construction to meet the requirements for WIMTF. Therefore, we will focus the cost-benefit analysis on the PrePass™ candidates, followed by a comparative analysis with the I-405 facility.

Based on the cost analysis, an estimated of $442,500 is needed for the initial instrumentation of WIMTF. We assume the life of a WIMTF to be 10 years. This initial cost is amortized for 10 years; $815K annual budget is added for operation and research purposes.

The project team is unclear about the costs for upgrading current PrePass™ stations to achieve the desirable error characteristics. These upgrades will need to be determined based on results and recommendations produced by the research using WIMTF. It is envisioned that these recommendations could range from the need for new software developed by the WIMTF to a combination of new WIM scales and infrastructure improvements. The costs of these anticipated updates would vary widely, possibly between tens of thousand dollars to hundreds of thousand dollars per WIM station. We therefore have to make some assumptions in order to make the cost-benefit analysis realistic. The assumed values for the upgrades are between $40K (average $10K per scale for a four lane highway) and $200K (average $50K per scale for a four lane highway). The total assumed costs for 106 stations would be $4.24M and $33.92M. This cost is amortized over 10 years.

Table 6.8 Benefit Cost Ratio

	a typical WIM PrePass™
Minimum benefits from the current operation	$861 million
Minimum benefits for trucking industry	64 million
Costs for instrumentation (amortized for 10 years)	$44,250
Costs for operation and maintenance	$815,000
Costs for upgrading PrePass™ stations	$424,000 to $2,120,000
BCR on savings from existing highway operation	290 to 670
Additional BCR for trucking industry	20 to 75

A BCR much greater than 1 indicates that positive economic benefits of the WIMTF far outweigh the costs. This large magnitude of BCR should tolerate any uncertainty or margin of error introduced by the estimation nature of the cost and benefit values. Therefore, the investment in a WIMTF will have a tremendous impact on preserving thousands of miles of interstate from premature wear and reducing maintenance costs. The cost-benefit analyses lead to a positive recommendation for establishing a WIMTF in California.

The team investigated Caltrans recommended site options and determined them not to be feasible. The benefits and costs for instrumentation and operating/maintaining a WIMTF at the I-405 facility and a PrePass station are about the same. However, when replacing the costs for upgrading PrePass™ stations with the $100M costs for establishing a new facility, the BCR for the I-405 facility is reduced by a factor between 4 and 9. Though the BCR is still positive, it is hard to justify a facility to offer the same benefits with a significantly lower BCR. The team therefore determined to omit the planned I-405 facility as a WIMTF candidate.

The team assessed two other no-site related options provided by Caltrans. No benefits discussed in this report will be achieved through 'No need for a newly established WIMTF' option. We recommend against this option. The project team recommends pursuing the pooled fund option offered by Caltrans, as it will reduce overall costs for establishing and operating WIMTF, and the results from the WIMTF can be shared among the pooled-fund participating states.

6.4 Potential Future Benefits from the WIMTF

WIM systems can potentially generate revenues through enforcement. This fund is currently distributed only to local governments under existing legislative provisions. This study looked into the need for future investigation on possible means to reinvest a portion of fine revenues into highway preservation funds from overweight truck enforcement.

6.4.1 Revenue from WIM Pre-screening for WIM Enforcement

In addition to savings from a likely reduction in overweight trucks, improved WIM with smaller variance and accurate calibration will improve pre-screening, preventing overweight trucks from bypassing.

The WIMTF will create tools that enable the WIM pre-screening facility to function more effectively with a much lower number of overweight trucks to bypassing undetected. In Section 6.2.2, we have assumed a 50 percent reduction in overweight trucks from today with the addition of more effective PrePass™ screening. We further assume that 80 percent of the remaining overweight trucks, or 4.68 million overweight trucks annually, will be detected and fines enforced. Assuming that the number of overweight trucks at different overweight categories is uniformly reduced, Table 6.8 shows the corresponding fine revenue collected from the 35 WIM PrePass™ stations would be approximately $940 million (see Table 6.8 for details). This analysis shows that the biased WIM calibration substantially compromised potential revenue generation by PrePass™-supported CVEFs.

Table 6.8 Estimation of revenue collected by Enhanced PrePass™ stations

Overweight (lbs)	10000	8000	6000	4000	2000	
# of violation trucks	45627	259793	703955	1156498	2514127	4,680,000.00
fine value	$1,500	$1,200	$360	$145	$55	
Total revenue	$68,440,111	$311,751,691	$253,423,955	$167,692,240	$138,276,960	$939,584,958

6.4.2 Potential Revenues from WIM for Direct Enforcement

Using the previously estimated 158 million truck trips per year in California, given that the capacity of current weigh stations process an average of 240 trucks per day per CVEF for most trucks, weighing each truck just once per trip would require a total of approximately 1800 static weigh scales to complete[41]. The costs for establishing new CVEFs are prohibitive for widespread deployment, as required to increase the overweight enforcement capabilities in California.

Direct enforcement using WIM is the most cost effective way of protecting the infrastructure. To date, WIM for direct enforcement has not been implemented, the result of technological uncertainties. However, as WIM technologies advance and the knowledge about WIM progresses, WIM systems will evolve from a pre-screening tool to a more direct and primary enforcement means. Some WIM technologies have advanced to a level that meet the requirements for WIM Level IV enforcement application. For example, Single Load Cell technology has reportedly produced an accuracy level such that that 95 percent of the WIM measurement data are within less than ±1.5 percent of the actual vehicle weights. If WIM scales have a 1.5 percent standard deviation, enforcing overweight trucks will result in only a 5 percent error detection rate for trucks that are overweight by, at most, 2.5 percent, and a 0 percent detection error for trucks that are overweight by more than 2.5 percent. This error rate is comparable to a well-calibrated static weigh scale.

WIM for direct enforcement can produce increased direct and significant benefits by discouraging and reducing the number of overweight trucks on the road, and by collecting previously uncollectable fines. Assuming that a network of WIM systems is established in California covering the entire highway network, all overweight vehicles would be identified, thus achieving very high enforcement rates. Consequently, the number of overweight vehicles would be substantially reduced. Assuming that a networked WIM enforcement system is established that captures 80 percent of 7.5 percent of the overweight trucks activities (50 percent reduction in overweight activities) in California, using the method discussed in section 6.4.1, a total of $3.8 billion in fine revenues would be collected.

Efforts for applying WIM as a direct enforcement tool have progressed. The European Union has sponsored projects to investigate WIM for direct enforcement. The REMOVE project has developed a set of technical specifications for High Speed (HS-) WIM systems to be used for direct enforcement of overloading. Another project, ‘Overloading’, has built a Mid-Speed (MS-) WIM system for direct enforcement near the city of Arnhem in The Netherlands. The system includes 32 WIM sensors and a special calibration vehicle for dynamic calibration. A total of five operational tests have been performed there [22].

Using elements of FHWA’s Truck Size and Weight Program combined with the FMCSA’s Commercial Vehicle Information Systems and Networks (CVISN) Program, various aspects of WIM have been studied. The studies produced the “American Lego diagram” to form the Smart Roadside Initiative. This initiative lays out the building blocks for the implementation of advanced technologies for a truck-weight enforcement program for greater enforcement using fewer human resources. The “American Lego diagram” gives provisions for intervention and

[41] 158,000,000 trucks /[240 (trucks) x 365 (days/year)] = 1800 years

direct enforcement. In a separate effort, the state of Oregon has conducted field testing to investigate the potential of WIM being used as a direct enforcement tool under low-speed conditions [23].

The tests of level 4 applications in Europe and in the United States represent the initial efforts; the results show that WIM enforcement is not yet ready for highway mainline applications. The WIMTF will be an effective tool to support the development of specifications for WIM systems for direct enforcement, for validating available WIM technologies, for the development of continuous calibration methods, and to generate knowledge and experience, raising stakeholder confidence in the accuracy and robustness of WIM for enforcement purposes.

Additionally, the cost-benefit analyses also lead to recommendations for investigating the potential approaches to changing existing policies and practices on the distribution of revenues from overweight truck enforcement. These changes could generate new revenue from improved WIM PrePass™ to offset the funding shortfall for preserving highway infrastructure.

A feasibility study of a networked WIM system in California is also recommended. We have concluded that the data collected by existing WIM stations are not sufficient statistically or qualitatively to support highway planning and maintenance decisions. A comprehensive Data WIM network should be initially established in regions of the state with the largest number of truck vehicle miles, including Southern California, the Central Valley, the Bay Area, and the Border Region, to cover all highway segments maximally disallowing trucks to bypass the WIM station.

6.4.3 Policy Issues on Revenue Distribution from Overweight Enforcement

Analysis of the potential future benefits shows that significant revenues can be generated, as seen in Table 6.9.

Table 6.9 Benefits from WIMTF

Items	Savings or Revenue Generation (per year)
Estimated Range of Revenues	
Future savings and revenues for WIM direct enforcement	
Revenue from WIM Pre-screening for WIM Enforcement	$940 million
Revenue from WIM for Direct Enforcement	3.8 billion
Total estimated future revenues	**~$4.74 billion**

Ideally, the combination of cost reduction for pavement maintenance, due to reduced levels of damage caused by overweight trucks, and the fine revenues would cover a significant portion of the $5.86 billion shortfall estimated by the California Transportation Commission for maintenance and operation of the State Highway System. However, under current state provisions, revenues from overweight truck enforcement are distributed to local agencies with zero dollars dedicated to California state highway preservation. This practice is inherited from policy regulations governing the distribution of traffic violation revenue, which, in turn, is determined by (1) the law enforcement agency issuing the citation, (2) location of the violation, (3) population of the counties, and (4) the nature of the violation, such as Vehicle Code, Health and Safety Code, Penal Code, or Fish and Game Code.

Overweight truck violations are significantly different from other violations, and are directly responsible for infrastructure damage, particularly within the state highway system, though it only accounts for 10 percent of the road infrastructure, carries 60 percent of annual vehicle miles traveled in California, and the majority of overweight truck miles, which occur on the state highway. There is a need to look into ways to reinvest the money collected from overweight truck violations into the highway infrastructure preservation, with reasonable redistributions among all types of roadway infrastructure. To achieve this redistribution, existing policies and provisions must be updated. This study recommends that Caltrans commission a study to investigate the feasibility for updating policies and provisions governing infrastructure-preservation financing to include enforcement revenues collected from overweigh truck fines in California.

7. Site Selection Recommendations

This section describes the analysis performed to further reduce candidate sites to derive the final set of WIMTF sites.

7.1 Preliminary Selection Criteria

The preliminary criteria used in this analysis for identifying the reduced set of WIMTF candidate sites are as follows:

<u>Minimum Disruption:</u>
The WIMTF will have at least one non-adjacent, non-instrumented lane that can be open to traffic during installation of pavement-based sensors at the WIMTF.

<u>Safe Access:</u>
The WIMTF shall have a safety pull-out within 100 ft. (30.48 m) of the WIM-system sensors that accommodates at least two vehicles.

<u>Multiple Test Pass:</u>
The WIMTF and CVEF shall be located within 10 miles (16093 m) of freeway exits to permit safe turnaround of FHWA Class 9 trucks for making multiple passes.

<u>Speed Range:</u>
The WIMTF shall contain at least two instrumented lanes with range of speeds between 10 and 80 mph (16 to 130 km/h).

For this set of criteria, sites are analyzed to determine the number of lanes accessible to general traffic. Since two instrumented lanes are desirable for the WIMTF, and installation of sensors may require the closure of lanes immediately adjacent to instrumented lanes, a minimum of four lanes would be desirable to ensure that at least one lane is still open and passable to general traffic during test-sensor installation, as shown in Figure 7.1. The lanes included in this analysis only include general purpose mainline lanes. Hence special-use lanes, such as HOV lanes, were not considered.

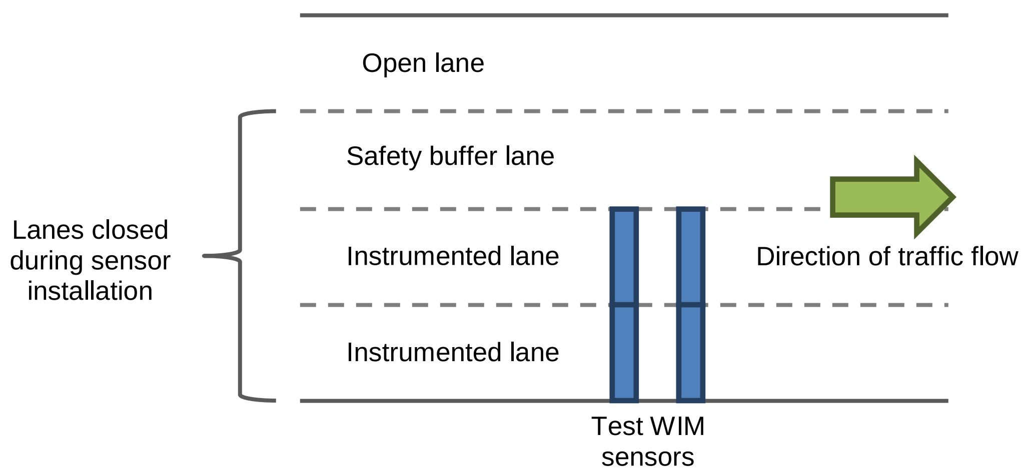
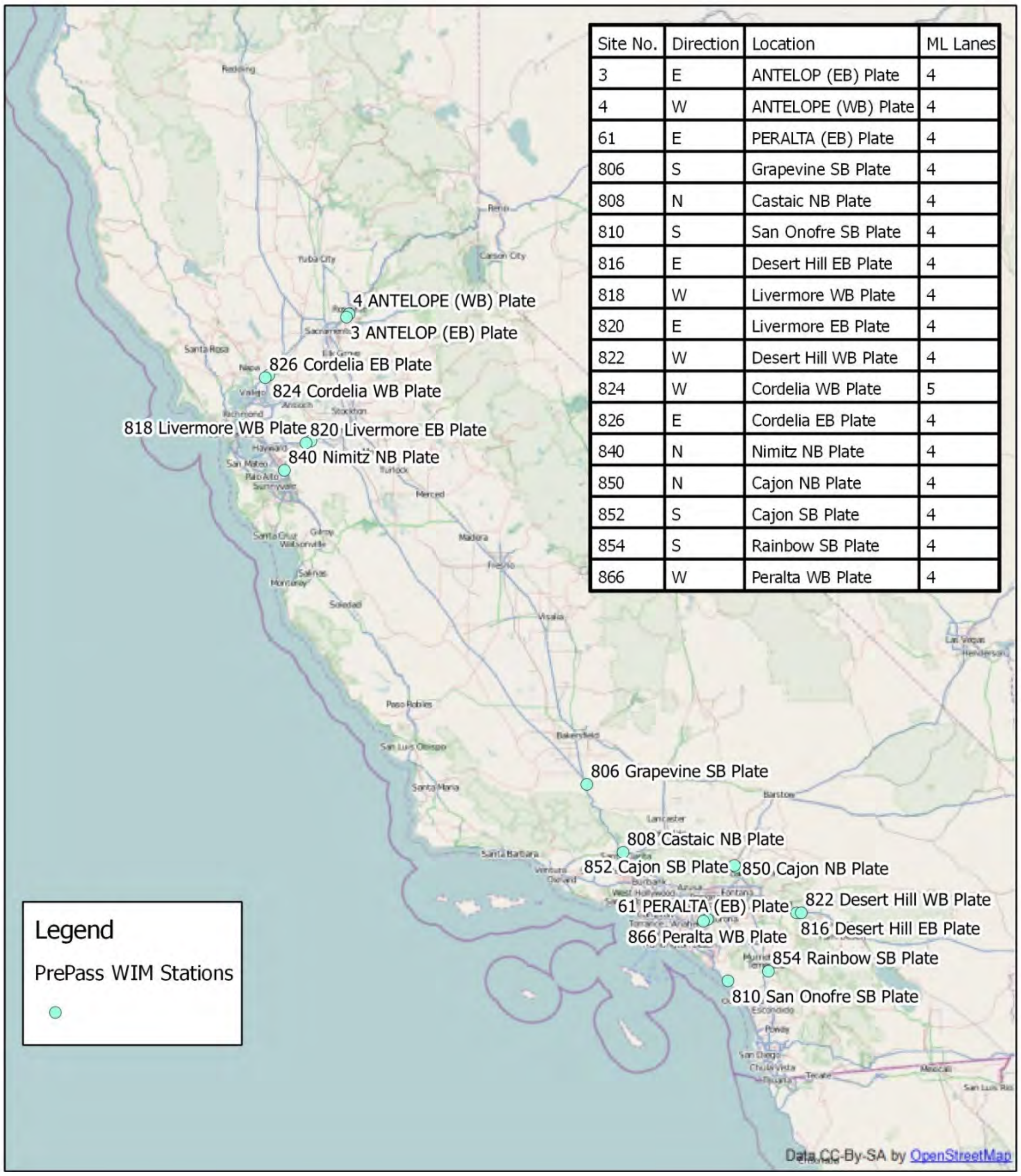


Figure 7.1 Required lane closures for sensor installation at the WIMTF

In this analysis, the number of mainline lanes at each PrePass™ WIM site was verified using satellite imagery. Figure 7.2 shows the locations of 17 PrePass™ WIM sites that meet this criterion with at least four mainline lanes. It can be observed that most of the sites are located in urban areas near or within the Los Angeles area, the San Francisco Bay area, and Sacramento metropolitan areas with multi-lane freeway facilities.



Site No.	Direction	Location	ML Lanes
3	E	ANTELOP (EB) Plate	4
4	W	ANTELOPE (WB) Plate	4
61	E	PERALTA (EB) Plate	4
806	S	Grapevine SB Plate	4
808	N	Castaic NB Plate	4
810	S	San Onofre SB Plate	4
816	E	Desert Hill EB Plate	4
818	W	Livermore WB Plate	4
820	E	Livermore EB Plate	4
822	W	Desert Hill WB Plate	4
824	W	Cordelia WB Plate	5
826	E	Cordelia EB Plate	4
840	N	Nimitz NB Plate	4
850	N	Cajon NB Plate	4
852	S	Cajon SB Plate	4
854	S	Rainbow SB Plate	4
866	W	Peralta WB Plate	4

Figure 7.2 Location of sites which meet the minimum disruption criteria

7.2.2 Safe Access Analysis

The purpose of the safe access analysis is to identify sites that have a pull-out area located a safe distance away from freeway traffic that is within close proximity to the candidate site.

In this analysis, each site is assessed to determine if existing off-shoulder pull-out areas are located within 100 feet of the candidate site. The evaluation is performed using satellite imagery via the Quantum GIS software, as shown in Figure 7.3. First, a 100-foot perimeter is created around the candidate site. Next, it is determined if a safe pull-out area can be identified within the defined perimeter. From the analysis, it was found that all existing PrePass™ WIM sites meet the safe access criteria.

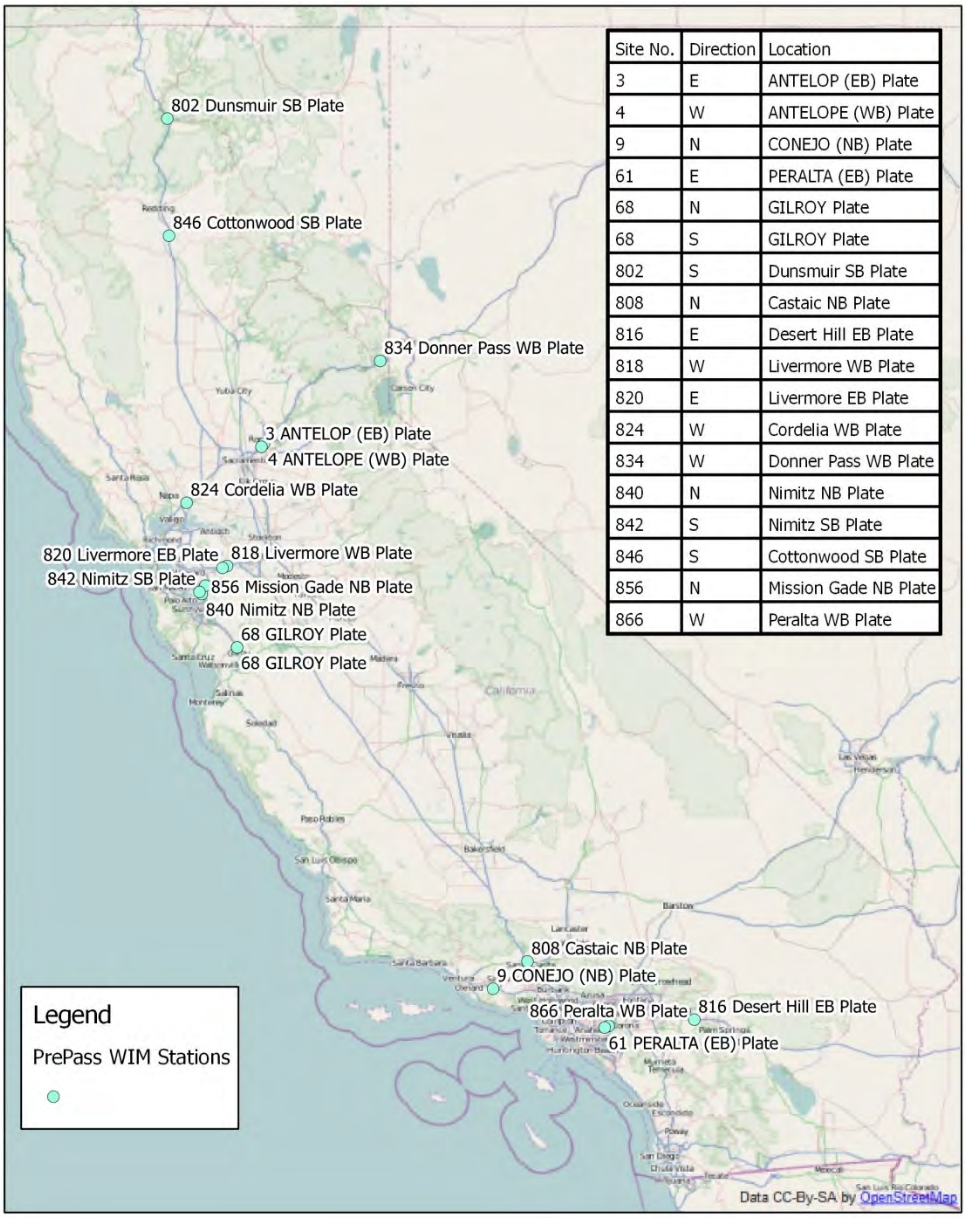
Figure 7.3 Evaluation of safe access proximity

7.2.3 Multiple Test Pass Analysis

The multiple test pass analysis identifies sites where a FHWA Class 9 (5-Axle Single Trailer) test truck can perform multiple test runs without being subjected to an extensive round-trip travel distance and time. The distance criterion in this analysis is a maximum of 10 miles (16093 m) roundtrip. In addition, the candidate site must also be located at least one mile from the freeway entrance ramp to ensure that the test vehicle has sufficient distance to accelerate to the desired operating speed.

Figure 7.4 shows the identified freeway entrance and exit ramps for test runs associated with the candidate site corresponding to the Peralta PrePass™ WIM site. Distances were measured using maps and satellite imagery via the Quantum GIS software. A total of 18 PrePass™ WIM sites met the multiple test pass criteria. The locations of these sites are shown in Figure 7.5.

Figure 7.4 Identification of entrance and exit ramps for test runs



Site No.	Direction	Location
3	E	ANTELOP (EB) Plate
4	W	ANTELOPE (WB) Plate
9	N	CONEJO (NB) Plate
61	E	PERALTA (EB) Plate
68	N	GILROY Plate
68	S	GILROY Plate
802	S	Dunsmuir SB Plate
808	N	Castaic NB Plate
816	E	Desert Hill EB Plate
818	W	Livermore WB Plate
820	E	Livermore EB Plate
824	W	Cordelia WB Plate
834	W	Donner Pass WB Plate
840	N	Nimitz NB Plate
842	S	Nimitz SB Plate
846	S	Cottonwood SB Plate
856	N	Mission Gade NB Plate
866	W	Peralta WB Plate

Figure 7.5 Location of sites which meet the multiple pass criteria

7.2.4 Speed Range Analysis

The purpose of the speed-range analysis is to identify sites that provide a wide range of truck traffic speeds, which is essential to determine if prototype WIM sensors are able to provide accurate axle- weight measures throughout the required speed range. The speed range analysis evaluates the range of traffic speeds in proximity to candidate sites. Two data sources were used in this analysis: the American Transportation Research Institute (ATRI) truck GPS data reports from the development of the California Statewide Freight Forecasting Model (CSFFM), and Caltrans' Performance Measurement System (PeMS).

The ATRI truck GPS data set was considered because its samples are comprised exclusively of individual truck-speed data. However, both the sampling period and sampling frame are limited. The samples were obtained from four two-week periods from the months of February, May, August, and November, 2010, and were limited to trucks that subscribe to the program. Although the type of truck found in the ATRI dataset may be biased, most of the samples were obtained from tractor trailers, the truck configuration of interest in this study.

The PeMS dataset is obtained via inductive loop estimates of vehicle speeds. It is useful for providing general traffic speed conditions at an aggregate level where vehicle composition is known or can be reasonably assumed. However, it cannot be used to estimate the speed of individual trucks within the traffic stream. The assumption in this analysis is that the overall speed estimated from single loop detectors is an adequate representation of trucks speeds. Although trucks travel slower than general traffic at free flow conditions, their speeds are not expected to be significantly different in congested flow, which is the focus of this analysis. Figure 7.6 shows two PeMS stations used to estimate truck speeds at their corresponding PrePass™ locations.

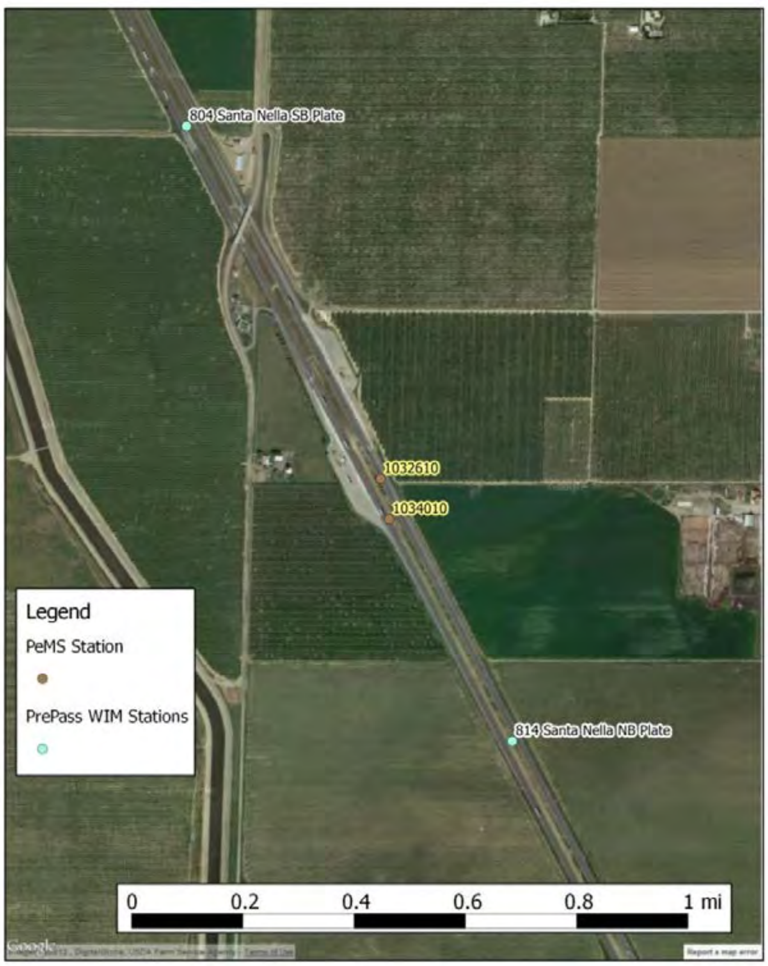


Figure 7.6 Locations of PrePass™ WIM and corresponding PeMS stations along I-5 freeway at Santa Nella

For truck GPS analysis, GPS truck pings along a quarter-mile stretch adjacent to each candidate site analyzed. Only trucks traveling in the direction of the candidate site were considered, as shown in Figure 7.7.

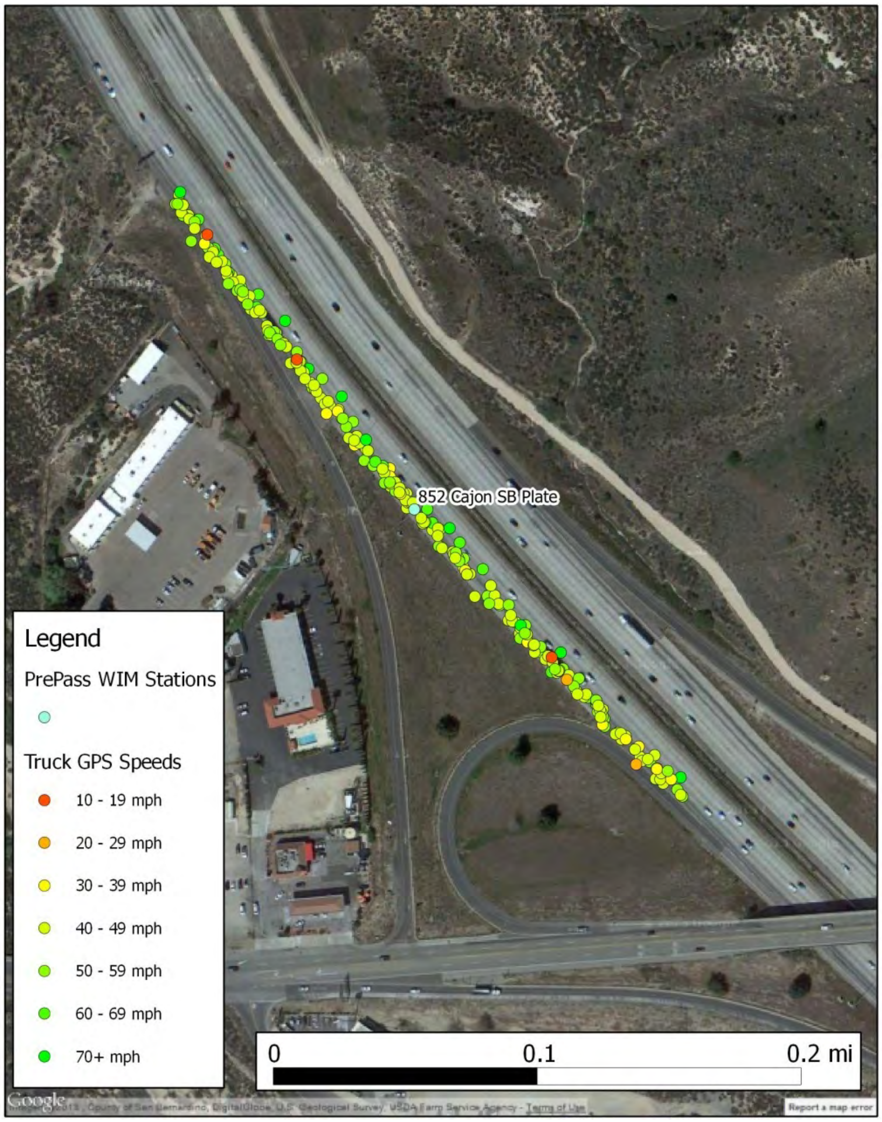


Figure 7.7 GPS truck speeds on SB I-15 at SB Cajon PrePass™ WIM site

For the PeMS analysis, five-minute weekday speed data was obtained for the entire month of March 2013, yielding 20, 24-hr. days for each site analyzed. The PeMS location closest to each candidate site was assumed to possess similar traffic speed characteristics, and therefore selected for analysis.

In both analyses, observation frequencies were grouped in 10 mile-per-hour bins. The sites which meet the speed range criteria through either the PeMS or truck GPS analysis are shown in Figure 7.7. It can be observed that the sites that meet this criteria are generally located within metropolitan areas that may be subject to recurrent traffic congestion, hence contributing to the variation in observed speeds.

Site No.	Direction	Location
4	W	ANTELOPE (WB) Plate
61	E	PERALTA (EB) Plate
818	W	Livermore WB Plate
826	E	Cordelia EB Plate
840	N	Nimitz NB Plate
842	S	Nimitz SB Plate
852	S	Cajon SB Plate
854	S	Rainbow SB Plate
856	N	Mission Gade NB Plate
866	W	Peralta WB Plate

Figure 7.8 PrePass™ WIM sites that meet the speed range requirement

7.3 Final Candidate WIMTF Sites and Recommendation

From the analysis in the previous section, the location of the final candidate sites that meet all four criteria described are shown in Figure 7.8. The CVEFs associated with each candidate WIMTF site were considered in the final recommendation (see Table 7.1 and Figure 7.9). While the facility class may not appear critical, a better equipped CVEF is expected to provide superior infrastructure for installation of equipment required for matching trucks and validation of axle weights. Hence, given these considerations, the NB Nimitz PrePass™ WIM site on the I-880 freeway (shown in Figure 7.10) is our final recommended WIMF site. Figure 7.11 shows a larger satellite overview showing the location of the NB Nimitz PrePass™ WIM site relative to the CVEF location.

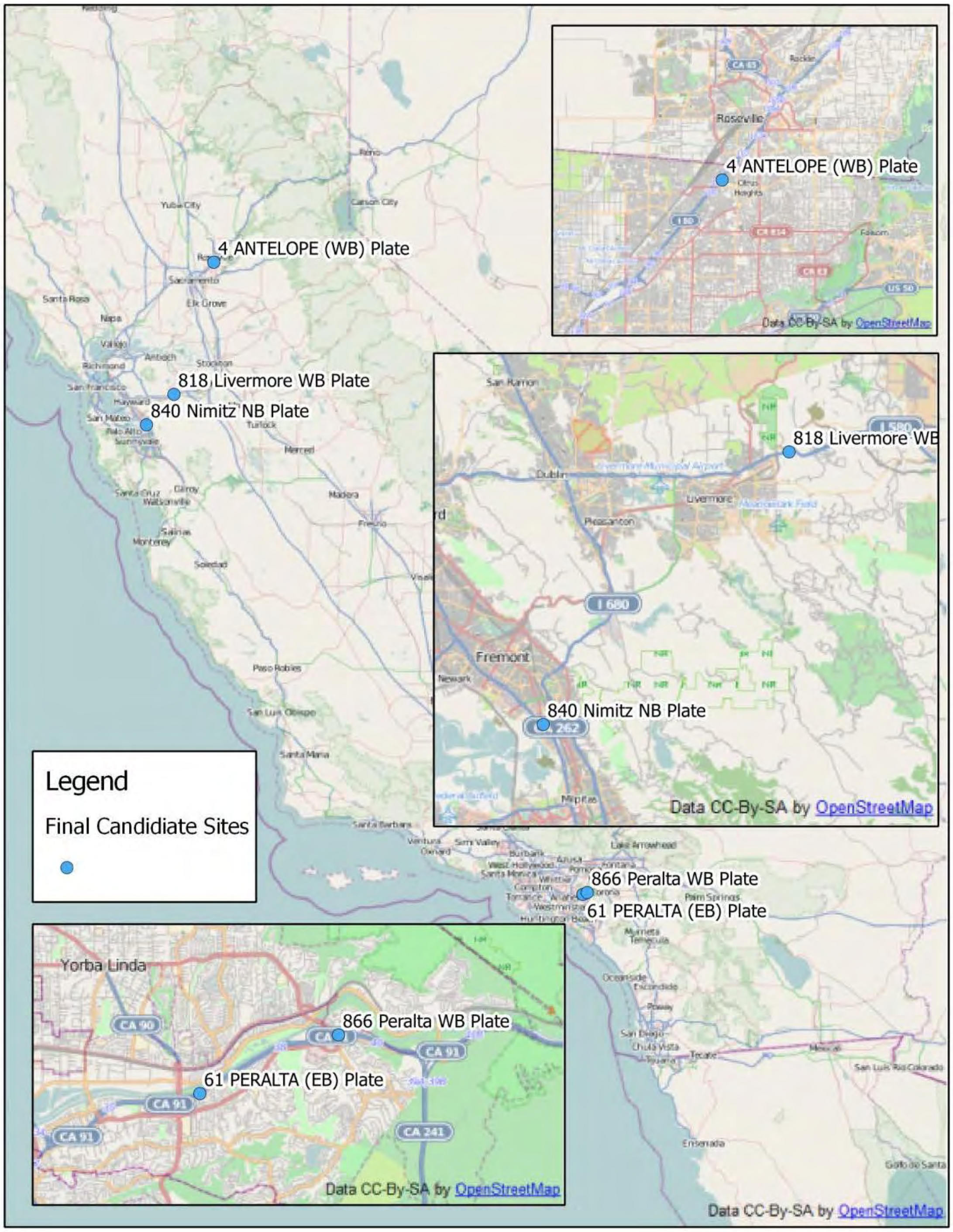


Figure 7.9 Final candidate WIMTF sites

Table 7.1 CVEF Class associated with candidate sites

Name	CVEF Class
NIMITZ COMMERCIAL VEHICLE ENFORCEMENT FACILITY (B) - NB	B
ANTELOPE COMMERCIAL VEHICLE ENFORCEMENT FACILITY (C)	C
PERALTA COMMERCIAL VEHICLE ENFORCEMENT FACILITY (C) - EB	C
PERALTA COMMERCIAL VEHICLE ENFORCEMENT FACILITY (C) - WB	C
LIVERMORE COMMERCIAL VEHICLE ENFORCEMENT FACILITY (D) - WB	D

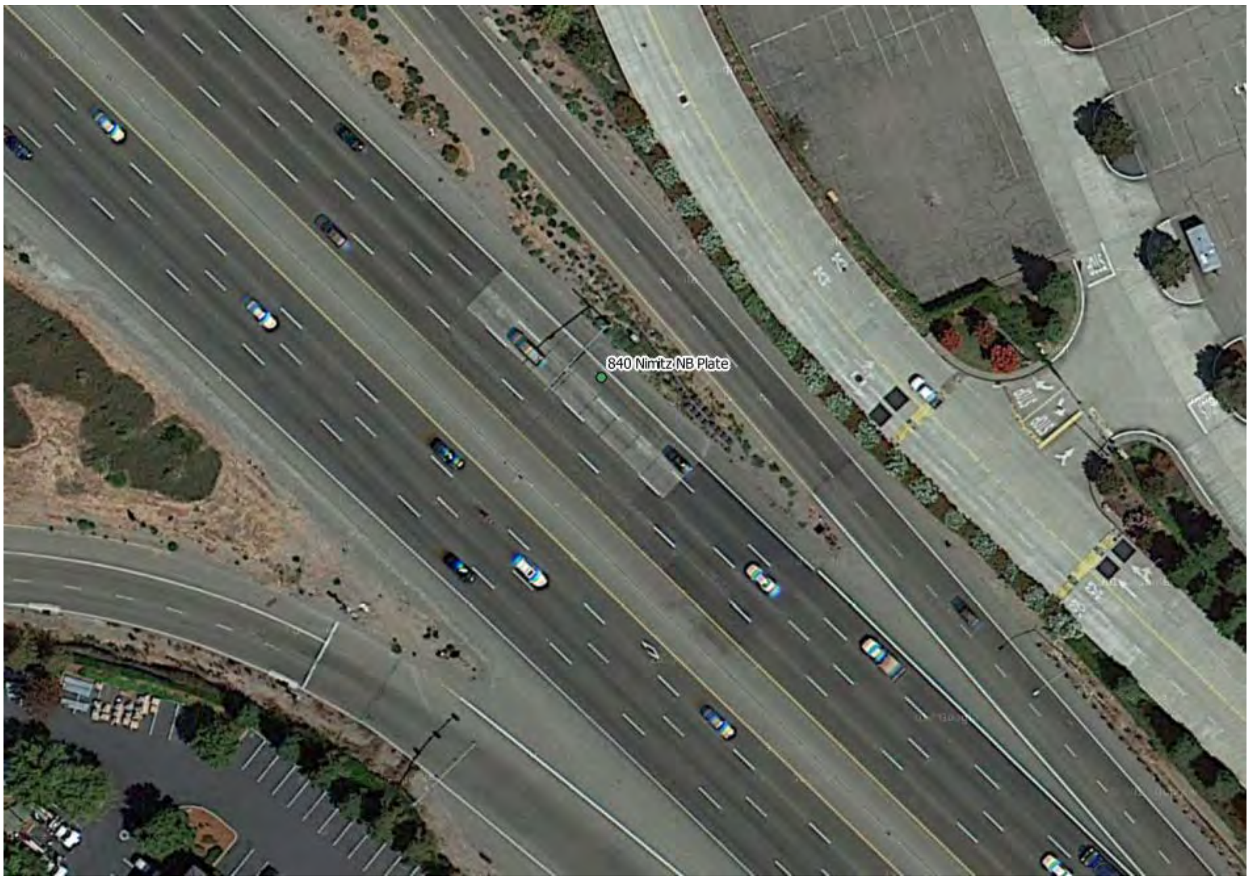


Figure 7.10 NB Nimitz PrePass™ WIM Station along the I-880 freeway

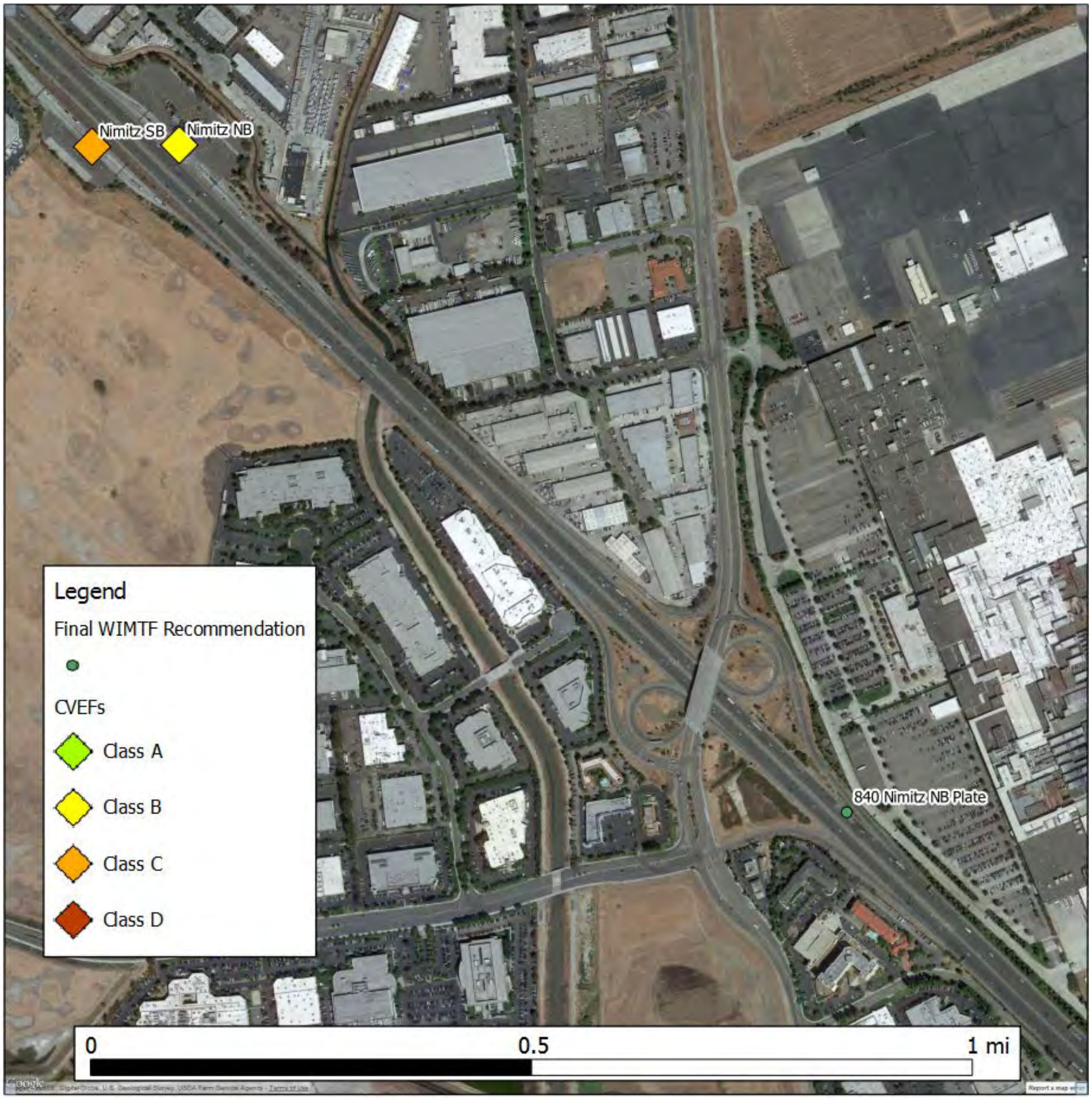


Figure 7.11 NB Nimitz PrePass™ and CVEF locations on I-880

8. Summary and Recommendations

The following summarize the findings obtained from all tasks conducted under this study.

Summary of WIM Calibration and Calibration Guidelines

To support the effective deployment of WIM/VWS, Caltrans is considering the development of a WIMTF for the evaluation of existing, new, and emerging hardware and software for WIM and VWIM systems. As a planning activity, this project was initiated to develop the requirements and recommendations for this WIMTF. One task of this project was to investigate various methods for calibration and evaluation of the weight measurements, and to provide guidelines and procedures for WIM calibration at the WIMTF. This report presents the results of this task.

As part of the background research, we first compared the common WIM scale technologies, which include piezoelectric sensors (quartz, polymer, and ceramic), load cells, and Bridge WIM. Four types of highway WIM systems were also reviewed based on the classification defined by ASTM E1318. With this background knowledge, we continued to investigate various WIM calibration methods.

The WIM calibration methods can be separated into three groups: on-site field calibration, continuous calibration using static measurements from enforcement activities, and emerging methods. On-site field calibration is the most commonly used WIM calibration method in place today. The ASTM E1318 Standard Specification requires each of two loaded, pre-weighed and measured test vehicles to make multiple runs over the WIM-system sensors in each lane at specified speeds. The recorded data is then used to determine the necessary changes to the WIM-system settings for calibration. Continuous calibration methods, on the other hand, use static axle weight records obtained by enforcement officials or the static measurements at nearby CVEFs to calibrate the WIM systems. Such methods require the association between the WIM measurements and the static weight records based on some kind of vehicle identification information. Emerging calibration methods include automatic calibration based on continuous, dynamic calibration using specially designed vehicles, as well as calibration methods that employ novel sensor configurations and smart estimation algorithms based on vehicle dynamic (suspension) models. In addition to the calibration methods, quality control methods for monitoring and evaluating WIM data were also investigated.

Based on our investigation of WIM calibration methods, we recommend that the primary guideline or principle for calibrating WIM/VWIM technologies at the WIMTF should still be the on-site field calibration, as defined in ASTM E1318. The continuous calibration and emerging calibration methods have great potential for becoming a primary calibration means, or for supplementing on-site field calibration methods for WIM systems. We recommend that continuous calibration methods be developed and verified under the WIMTF program in order to prepare such technologies for broader applications in California. The WIMTF should be able to obtain ground truth data (e.g., measurements from enforcement facilities or from a well-calibrated reference WIM system) to facilitate the evaluation of these calibration methods. Accordingly, the WIMTF should follow the test and calibration procedures defined in ASTM

E1318 for WIM system test, calibration, and recalibration. Due to the uniqueness of the WIMTF from a regular WIM system, a few considerations were also discussed.

Based on the review of the WIM calibration methods, as well as the recommended guidelines and procedures, we further identified the calibration needs and derived the corresponding tentative requirements. These needs and tentative requirements will be incorporated into the subsequent Task 4 to establish the requirements for the WIM/VWIM Test Facility.

Summary of Needs and Requirements

To support the effective deployment of WIM/VWS, Caltrans is considering the development of a WIMTF for the evaluation of existing, new, and emerging hardware and software for WIM and VWIM systems. As a planning activity, this project was initiated to develop the requirements and recommendations for this WIMTF. One task of this project was to define and develop needs and requirements for the WIMTF. This report presents the results of this task.

Based on the project goals, the objectives of the envisioned WIMTF were outlined to include the functions and capabilities that need to be present. We adopted a systems engineering process to formally develop WIM requirements based on (1) the customer needs from Caltrans and CHP and (2) technical needs for validating WIM/VWIM technologies. The research team first conducted a review of WIM activities, and then a thorough study of customer needs from Caltrans and CHP, as well as the technical needs for validating WIM/VWIM technologies. These needs are the basis for the development of the technical requirements and site requirements. By taking into account the constraints and concept of operations, we then identified (1) the interfaces between internal sub-systems or components, as well as the connections to external systems, (2) major system functions that should achieve the objectives of the test facility, and (3) other non-system functions or constraints needed to support the operation of the test facility. Based on these three categories of needs, we further investigated and developed the corresponding requirements.

The needs and requirements are categorized into the following sections:

- Non-Functional
- Site
- Functional
- Interface
- Data

The detailed descriptions of the needs and requirements are provided in the main body of this report.

Summary of Benefits and Costs Analyses

The characteristics and calibration of WIM scales determine the efficiency and effectiveness of weight enforcement. The quality of WIM data may also influence the outcomes of infrastructure planning, design, and maintenance. In the real world, PrePass™ WIM stations in California have been calibrated with bias to direct trucks with boarder line weight to CVEFs. This study has revealed that when WIM stations are set with biased threshold a few percentage heavier than weight limits, significant numbers of overweight trucks bypass the CVEFs. The analysis presented in this report indicates that a WIMTF can help to select WIM scales with smaller standard deviation and support continuous dynamic calibration to achieve significantly more accurate WIM results, which in turn maximizes the detection rate of violations, while minimizing unnecessary delays for the trucking industry.

The study estimated the costs for the WIMTF, as well as the cost savings from more effective overweight enforcement and more efficient planning, operation, and maintenance of the state highway system. A BCR analysis on savings was conducted, showing much greater than 1, indicating that the positive economic benefits of the WIMTF far outweigh the costs. The investment in a WIMTF will have a tremendous impact on preserving thousands of miles of interstate from premature wear, and reducing maintenance costs as well as generating significant savings for the freight industry.

The team assessed three Caltrans-recommended site options and determined: (1) the I-405 facility is much less cost effective than any of the PrePass™ stations because of the need for a $100 million new infrastructure, (2) 'No need for a newly established WIMTF' option does not offer any benefits described in this report; and is therefore not recommended, and (3) the pooled fund option will reduce the overall costs to California for establishing and operating a WIMTF, and the results from the WIMTF can be shared among the pooled-fund participating states.

The benefit-cost analyses lead to a positive recommendation for establishing the WIMTF in California.

The potential benefits of future application of WIM were also analyzed, indicating that WIM, with improved error characteristics, can generate substantial revenue that could contribute to highway preservation if the current policies and provisions for distribution of fine revenue collected from overweight trucks can be adjusted. This project lead to a recommendation for studies on policy issues related to the distribution revenues from overweight enforcement and the feasibility of a statewide network of WIM stations.

Summary of Site Selections

Site selection was conducted in two steps. Based on the requirements for a WIMTF, the research team identified several dozen sites and performed an initial screening of the potential test facility sites. Five criteria were used to evaluate the suitability of the site options, including:

- the availability of a suitable overhead structure necessary for mounting validation sensors and equipment for monitoring trucks traversing the WIMTF;
- fulfillment of the geometric requirements for WIM sites as defined in American Society for Testing and Materials (ASTM) E1318-09;
- proximity to Commercial Vehicle Enforcement Facility (CVEF) for validating the axle-weight measures at the WIMTF as reference measures;
- existing power requirement for accessible power at the site without the need for extensive trench work;

- existing communications to CVEF infrastructure available at the site for data communication with the CVEF.

It is clear that PrePass™ WIM sites fulfill the largest number of requirements for the proposed WIMTF. In addition to the desirable attributes of WIM data sites, PrePass™ WIM sites also possess additional attributes, such as close proximity and existing communications with associated CVEFs. The following sites are down-selected from this comparative analysis.

Further analysis was conducted to derive the final site recommendation. The following criteria are used for identifying the reduced candidate set of WIMTF sites, including:

- Minimum Disruption: The WIMTF will have at least one non-adjacent non-instrumented lane that can be open to traffic during installation of pavement-based sensors at the WIMTF.
- Safe Access: The WIMTF will have a safety pull-out within 100 ft. (30.48 m) of the WIM-system sensors that accommodates at least two vehicles.
- Multiple Test Pass: The WIMTF and CVEF will be located within 10 miles (16093 m) of freeway exits that permit safe turnaround of FHWA Class 9 trucks for making multiple passes.
- Speed Range: The WIMTF will contain at least two instrumented lanes with range of speeds between 10 and 80 mph (16 to 130 km/h).

While the facility class may not appear critical, a better equipped CVEF is expected to provide superior infrastructure for installation of equipment required for matching trucks and validation of axle weights. With this consideration, the NB Nimitz PrePass™ WIM site on the I-880 freeway is recommended for the California WIMTF site.

Recommendations

This study recommends that Caltrans establish a WIMTF in order to realize the full benefits described in this report. We further recommend the NB Nimitz PrePass™ WIM site on the I-880 freeway as candidate site for the WIMTF. A pooled-fund approach is recommended for funding this facility.

Based on the investigation of WIM calibration methods, we recommend that the primary guideline for calibrating WIM/VWIM technologies at the WIMTF should still be on-site field calibration, as defined in ASTM E1318. Continuous calibration and emerging calibration methods have great potential in the future for becoming a primary calibration means or for supplementing on-site field calibration methods for WIM systems. We recommend that continuous calibration methods be developed and verified under the WIMTF program in order to prepare such technologies for broader applications in California.

The study further recommends an investigation of the potential approaches to change the existing policies and practices on distribution of revenues from enforcement of overweight truck, which will enable the new revenues generated from improved WIM PrePass™ to offset funding shortfalls to be used for the preservation of the highway infrastructure.

A feasibility study of a networked WIM system in California is also recommended. We have concluded that the data collected by existing WIM stations are not sufficient statistically or qualitatively to support a decision for highway planning and maintenance purposes. A comprehensive Data WIM network should be first established in regions of the State with the largest number of truck-vehicle miles, including Southern California, the Central Valley, the Bay Area, and the Border Region, to cover all highway segments maximally disallowing trucks to bypass the WIM station.

The project team recommends pursuing the pooled-fund option for both research and planned development of WIMTF, as it will reduce the overall costs to California for establishing and operating WIMTF, and the results from the WIMTF can be shared among the pooled-fund participating states.

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[10] Commercial motor vehicles with a declared gross vehicle weight (GVW) or combined gross vehicle weight (CGW) of 10,001 lbs. or more and most trailers.

[11] Vehicles based in other states but pay registration in California, operating at a gross or combined gross weight (G/CGW) weight of 26,001 lbs. or more must have IRP registration

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10. Appendixes

Appendix A: WIM Data Description

#	Data Name	Data Description
1	Wheel Load	The sum of the tire loads on all tires included in the wheel assembly on one end of an axle; a wheel assembly may have a single tire or dual tires
2	Axle Load	The sum of all tire loads of the wheels on an axle; a portion of the gross-vehicle weight.
3	Axle-Group Load	The sum of all tire loads of the wheels on a defined group of adjacent axles; a portion of the gross-vehicle weight
4	Gross-Vehicle Weight	The total weight of the vehicle or the vehicle combination including all connected components; also, the sum of the tire loads of all wheels on the vehicle
5	Speed	Speed in miles per hour
6	Center-to-Center Spacing Between Axles	The distance between the centers of the adjacent axles on the vehicle
7	Vehicle Class (via axle arrangement)	The Federal Highway Administration (FHWA) Vehicle Types[42]
8	Site Identification Code	A 10-character alphanumeric site identification code for each data-taking session
9	Lane and Direction of Travel	A number beginning with 1 for the right-hand northbound or eastbound traffic lane and continuing until all the lanes in that direction of travel have been numbered; the next sequential number shall be assigned to the lanes in the opposite direction of travel beginning with the left-hand lane and continuing until all lanes have been numbered
10	Data and Time of Passage	The date[43] and time[44] a vehicle passed the WIM system
11	Sequential Vehicle Record Number	The WIM system shall provide sequential-numbering (user-adjustable) for each recorded vehicular data set
12	Wheelbase	The distance between the front-most and the rear-most axles on a vehicle or combination that has the tires on these axles in contact with the road surface at the time of weighing.
13	Equivalent Single-Axle	The cumulative number of applications of the chosen standard single-axle load that will have an equivalent effect on pavement serviceability

[42] See U.S. Department of Transportation Traffic Monitoring Guide for the complete description of FHWA Vehicle Type.
[43] In the United States, the MM/DD/YYYY format, where MM is the month, DD is the day, and YYYY is the year, is generally accepted.
[44] The time shall be in the following format: hh:mm:ss, where hh is the hour beginning with 00 at midnight and continuing through 23, mm is the minute, and ss is the second.

	Loads (ESALs)	as all applications of various axle loads and types by vehicles in a mixed-traffic stream. (The WIM systems shall compute ESALs using American Association of State Highway and Transportation Officials (AASHTO) axle load equivalence factors for single, tandem, and triple axles for flexible or for rigid pavements.)
14	Violation Code	A 2-character violation code used for each detected violation of all user-set parameters[45].

[45] Provision shall be made for the user to define up to 15 violation codes. Examples of the violation code are WL (for wheel load violations), AL (for axle load violations), AG (for axle-group load violations), and so on.

Appendix B: List of the sites evaluated

Site No.	Location Name	Lanes	Vendor	WIM Type	Cal PM
0	Antelope WB Plate	4	IRD	PrePass/Data	17.2
802	Dunsmuir SB Plate	2	IRD	PrePass	R9
804	Santa Nella SB Plate	2	IRD	PrePass	24
806	Grapevine SB Plate	2	IRD	PrePass	12
808	Castaic NB Plate	2	IRD	PrePass	R53.3
810	San OnoFre SB Plate	2	IRD	PrePass	R68.4
812	Cottonwood NB Plate	2	IRD	PrePass	41
814	Santa Nella NB Plate	2	IRD	PrePass	23
816	Desert Hill EB Plate	2	IRD	PrePass	14
818	Livermore WB Plate	2	IRD	PrePass	R9.0
820	Livermore EB Plate	2	IRD	PrePass	R9.0
822	Desert Hill WB Plate	2	IRD	PrePass	R16.0
824	Cordelia WB Plate	2	IRD	PrePass	14
826	Cordelia EB Plate	2	IRD	PrePass	14
828	Blackrock WB Plate	2	IRD	PrePass	R144.0
830	Cache Creek WB Plate	2	IRD	PrePass	105
832	Chowchilla NB Plate	2	IRD	PrePass	28
834	Donner Pass WB Plate	2	IRD	PrePass	19
840	Nimitz NB Plate	2	IRD	PrePass	4
842	Nimitz SB Plate	2	IRD	PrePass	4
844	Calexico NB Plate	2	IRD	PrePass	1
846	Cottonwood SB Plate	2	IRD	PrePass	41.5
848	Otay Mesa NB Plate	2	IRD	PrePass	11.8
850	Cajon NB Plate	2	IRD	PrePass	R21.0
852	Cajon SB Plate	2	IRD	PrePass	R21.0
854	Rainbow SB Plate	2	IRD	PrePass/SHRP/LTPP	R53
856	Mission Grade NB Plate	2	IRD	PrePass	R9.0
866	Peralta WB Plate	2	IRD	PrePass	R14L
870	Carson NB Plate	2	PAT	PrePass	10.8
872	Carson SB Plate	2	PAT	PrePass	13.1
874	CORDELIA EB Plate	2	IRD	PrePass	13