A METHODOLOGY FOR INTEGRATING ROADWAY SAFETY HARDWARE MANAGEMENT INTO THE OVERALL HIGHWAY ASSET MANAGEMENT PROGRAM

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16. Abstract

Over the past two decades, state transportation agencies have developed management systems as analytical tools to support investment decision-making in Statewide Transportation Improvement Programs (STIP) and long-range plans. The most common management systems dealing with physical highway assets are those for pavements, bridges, and maintenance. In addition, there are management systems handling highway system operations, namely, congestion and safety. However, most state transportation agencies have not developed adequate management systems for roadway safety hardware assets such as roadway signs; signals; lighting; support and structure for signs, signals, and lighting; guardrails, barriers, and crash cushions; pavement markings; and traffic detecting devices. Cost-effective maintenance, rehabilitation, and upgrade/replacement of roadway safety hardware elements are vital to the safe and efficient operation of highways. The study began with review of literature on roadway safety hardware management. Questionnaire surveys were conducted to synthesize the current-state-of-practices for managing roadway safety hardware assets across the country. Subsequent to administering the questionnaire surveys, a structured outline of questions was prepared to help conduct case studies aimed to obtain in-depth information on safety hardware asset management programs in the 12 Midwest states defined by U.S. Census Bureau, as well as the state of Tennessee. Based on the findings of literature review, questionnaire surveys, and case studies, a methodology was proposed for roadway safety hardware data integration, primarily focusing on inventory process, data collection, and database management; and for estimating the benefits and costs of highway safety hardware projects proposed for implementation for highway segments and intersections. Finally, a new analytical framework was proposed for long-term and short-term roadway safety hardware investment programming and project selection. The analytical framework can also be adopted by state transportation agencies for integrating roadway safety hardware and general safety management, and integrating roadway safety hardware, general safety, as well as pavement, bridge, and maintenance management by simultaneously considering candidate projects associated with the corresponding types of highway assets in the optimization models for project selection.

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Final Report

A Methodology for Integrating Roadway Safety Hardware Management into the Overall Highway Asset Management Program

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EXECUTIVE SUMMARY

Over the past two decades, state transportation agencies have developed management systems as analytical tools to support investment decision-making in Statewide Transportation Improvement Programs (STIP) and long-range plans. The most common management systems dealing with physical highway assets are those for pavements, bridges, and maintenance. In addition, there are management systems handling highway system operations, namely, congestion and safety. However, most state transportation agencies have not developed adequate management systems for roadway safety hardware assets *such as roadway signs; signals; lighting; support and structure for signs, signals, and lighting; guardrails, barriers, and crash cushions; pavement markings; and traffic detecting devices*. Cost-effective maintenance, rehabilitation, and upgrade/replacement of roadway safety hardware elements are vital to the safe and efficient operation of highways.

The study began with review of literature on existing safety hardware management systems, other management systems dealing with one or more categories of roadway safety hardware assets, and safety hardware mainly pavement marking and guardrail investment decision-making and performance evaluation.

Questionnaire surveys were conducted in mid-July and August 2007 to synthesize the current-state-of-practices for managing roadway safety hardware assets across the country. In total, 130 experts on traffic safety and safety engineering from all state transportation agencies in the United States were contacted for participation. Forty four respondents from 28 states returned their completed surveys through the Website, by email, or by fax. It was found that many state transportation agencies manage several categories of safety hardware assets. Major tasks performed on safety hardware are concentrated on hardware inventories, routine inspections and condition assessments, and hardware project evaluation and selection. Maximizing safety hardware service life, minimizing vehicle crashes, and minimizing long-term costs are primary goals of roadway safety hardware assent management. Upper Management was reported in charge of overall budget negotiation, sub-allocation of budget to regions and counties, and negotiation of cost share with other agencies. Middle-level management is responsible for developing purchase specifications, determining maintenance cycles, and authorizing purchases. Front-line supervisors/ maintenance superintendents and field personnel are involved with the selection of specific item to replace or repair. The adoption rate of a software system was found to be very low. A major portion of responses indicated that the software systems for roadway safety hardware management cover entire states and are administered by the agency's central offices. The survey respondents emphasized the needs for refining data inventory processes and data collection standards, use of GIS-based systems and Web interfaces for data management, development of standardized and coordinated statewide management systems for systematic safety hardware replacements.

Subsequent to administering the questionnaire surveys, a structured outline of questions was prepared to help conduct case studies aimed to obtain in-depth information on safety hardware asset management programs in the 12 Midwest states defined by U.S. Census Bureau, as well as the state of Tennessee. The case studies were arranged in mid-August and September 2007 via telephone interviews. In total, 22 experts on traffic safety and safety engineering from the 13 state transportation agencies participated in one-on-one interviews. State transportation agencies were found to have developed performance measures to evaluate roadway safety hardware assets. There lacks consistency in the adopted performance measures among the states. No distinct performance targets are used to evaluate the efficiency and effectiveness of the roadway safety hardware asset management program. In general, roadway safety hardware data are collected by field staff using both manual and automatic collection methods and maintained by the central office. The data are not fully GIS-referenced. Many agencies have not differentiated data sampling for rural, urban Interstates and non-Interstates. Consistent data collection frequencies, data collection methods, and sampling procedures need to be developed. Efforts are needed to ensure the continuous update of the databases. Timely updating the data and interoperability of database management need to be

maintained. Most of the states allocate safety hardware management budgets according to expert opinion. There is a need to develop rigorous methods for safety hardware project evaluation. Ten of the thirteen states are definitely in favor of system integration. Technological requirements for integration appear not to be challenging. Major concerns of integration come from the agency culture for acceptance of integration that requires extensive inter-office information sharing, availability of funding resources, as well as sufficient, stable, and competent personnel that are crucial in maintaining data collection quality, timely updating database, and making sound investment decisions. Maintaining an intra-agency feedback process was found to be essential to ensure the success of a safety hardware asset management program.

A methodology was proposed for roadway safety hardware data integration, primarily focusing on inventory process, data collection, and database management. Under the inventory process, the data needs for maintaining roadway safety hardware asset program are listed. Presented are also various automatic data collection technologies, along with sampling methods and data collection frequencies. Data integration process is explained according to the FHWA initiatives. The nature, category, and type regarding the transformation of roadway safety hardware asset related data location referencing systems are described. The concepts of safety hardware database management are also explained.

A risk-based methodology was proposed for estimating the benefits and costs of highway safety hardware projects implemented for highway segments and intersections. For each type of highway segment-related or intersection-related crashes, the crash frequency is mainly affected by detailed safety issue items relevant to geometric design, consistency of design standards, pavement conditions, safety hardware conditions, and roadside features associated with the highway segments; while the crash severity is primarily influenced by roadside features. The safety index (SI) of a highway segment or an intersection by crash severity category- fatal, injury, and property damage only (PDO), measured by the crash frequency in number of crashes per year, can be estimated by considering total traffic exposure, probabilities of occurring different types of crashes, crash frequency for each type of crashes, and crash severity for each type of crashes. The difference in current-case safety index without safety hardware improvement and the base-case safety index with safety hardware improvement is regarded as the potential for safety improvements (PSIs) as a result of safety implementation. The annual potential for safety improvement is computed using the concept of consumer surplus. It is subsequently converted into dollar values to reflect crash cost savings as safety benefits generated by the safety hardware project. The annual safety benefits are expanded to life-cycle safety benefits using extrapolation. Correspondingly, life-cycle project costs are computed. Both life-cycle safety benefits and project costs are expressed in present worth and equivalent uniform annual values. Net present worth method and benefit-to-cost ratio method can be used as the basis for project tradeoff analysis. Statistical tests are introduced to compare the Empirical Bayesian crash estimates and PSIs for methodology validation.

Finally, a new analytical framework was proposed for long-term and short-term roadway safety hardware investment programming and project selection. This framework uses the risk-based methodology for safety hardware project evaluation to compute Safety Indices of highway segments or intersections. The associated Safety Indices are compared with the target crash level predefined by the transportation agency to identify highway segment or intersection safety hardware deficiencies. Safety hardware improvement countermeasures applicable to deficient roadway segments or intersections are then recommended. Further, the impacts of different countermeasure projects are assessed. Finally, the countermeasure projects are prioritized using optimization models on the basis of project impacts. The analytical framework can also be implemented for integrating roadway safety hardware and general safety management, and integrating roadway safety hardware, general safety, as well as pavement, bridge, and maintenance management by simultaneously considering candidate projects associated with the corresponding types of highway assets in the optimization models for project selection.

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
3R	Resurfacing, Rehabilitation, and Reconstruction
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AFMS	Automated Facilities Management System
AMF	Accident Modification Factor
ASTM	American Society for Testing Materials
BBF	Brightness Benefit Factor
BMS	Bridge Management System
BPR	Business Process Reengineering
CF	Crash Frequency
CFF	Crash Frequency Factor
COTS	Commercial Off-the-Shelf
CS	Crash Severity
CSF	Crash Severity Factor
DOT	Department of Transportation
DOR	Department of Roads
EB	Empirical Bayesian
ERP	Enterprise Resource Planning
EUA	Equivalent Uniform Annual
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic Information System
GIS-T	Geographic Information System for Transportation
GPS	Global Positioning System
GRAIL	Geographic Roadway Application for Information Location
HMIS	Highway Management Information System
HMMS	Highway Maintenance Management System

HPMS	Highway Performance Monitoring System
HSMS	Highway Sign Management System
ICAS	Inventory and Condition Assessment System
IDOT	Illinois Department of Transportation
IMIT	Italian Ministry of Infrastructures and Transports
IMMS	Inventory Maintenance Management System
IT	Information Technology
ITD	Idaho Transportation Department
ITS	Intelligent Transportation System
LOS	Level of Service
LRM	Linear Referencing Method
LTAP	Local Technical Assistance Program
MMS	Maintenance Management System/ Marking Management System
MVMT	Million Vehicle Miles of Travel
NCDOT	North Carolina Department of Transportation
NCHRP	National Corporative Highway Research Program
OSIS	Ohio Signal Inventory System
PDO	Property Damage Only
PMMS	Pavement Marking Management System
PMS	Pavement Management System
PSI	Potential for Safety Improvement
QA	Quality Assurance
QC	Quality Control
RCI	Roadway Characteristics Inventory
RDMTD	Road Directorate Ministry of Transport Denmark
RFIS	Road Feature Inventory System
RSHAM	Roadway Safety Hardware Asset Management
SD	Scaled Deviance
SHA	State Highway Administration
SHTD	State Highway and Transportation Department

SI	Safety Index
SIMS	Safety Information Management System/ Sign Inventory Management System
SMARTS	Sign Management and Retroreflectivity Tracking System
SMS	Safety Management System
SQL	Structured Query Language
TAC	Transportation Association of Canada
TEF	Traffic Exposure Factor
TMC	Transportation Management Center
TRB	Transportation Research Board
TRIMS	Tennessee Road Information Management System
TSIS	Traffic Signal Information System
TSIIM	Traffic Structure Inventory Inspection and Maintenance
TSSI	Traffic Signal System Inventory
VMT	Vehicle Mile of Travel
WIM	Weigh-in-Motion
WSI	Winter Severity Index

CHAPTER 1:
INTRODUCTION

1.1 Project Statement

The U.S. Department of Transportation (DOT) has identified roadway safety as an over-arching goal. Adequate management of roadway safety hardware assets *such as roadway signs; signals; lighting; support and structure for signs, signals, and lighting; guardrails, barriers, and crash cushions; pavement markings; and traffic detecting devices* is a key part to achieve this goal. This study proposes to synthesize the current-state-of-practice techniques for managing roadway safety hardware assets across the country; and to develop a methodology for integrating roadway safety hardware asset management into the overall pavement, bridge, safety, and maintenance management program. The study results are expected to assist state transportation agencies in acquisition, maintenance, and upgrade/replacement of roadway safety hardware in the most cost-effective manner.

1.2 Research Objectives

1.2.1 Background

Over the past two decades, state transportation agencies have developed management systems as analytical tools to support investment decision-making in Statewide Transportation Improvement Programs (STIP) and long-range plans. The most common management systems dealing with physical highway assets are those for pavements, bridges, and maintenance. In addition, there are management systems handling highway system operations, namely, congestion and safety. In general, each management system assists the decision-maker in making cost-effective investment decisions by performing the following tasks: i) establishing system goals and performance measures, ii) monitoring system performance pertaining to physical asset conditions or system levels of service, iii) predicting future performance trends, iv) recommending candidate projects to sustain system performance, v) evaluating project costs and benefits, vi) conducting project selection, and vii) providing feedbacks after project implementation to refine the analysis in subsequent decision cycles. However, most state transportation agencies have not developed adequate management systems for roadway safety hardware assets. Cost-effective maintenance, rehabilitation, and upgrade/replacement of roadway safety hardware elements are vital to the safe and efficient operation of highways. Table 1.1 lists main components of different categories of roadway safety hardware assets.

Table 1.1. Main Components of Various Roadway Safety Hardware Assets

Hardware Category	Component	Material Example
Roadway Sign	Sign sheeting Sign post Sign bridge and support	ASTM type or grade, color, and product designation
Traffic Signal	Signal display Controller system Structural support	 Tubular: steel, aluminum Pole: wood, concrete, steel
Roadway Lighting	Lamp Structural support Other	Incandescent, mercury vapor, sodium, metal halide, fluorescent
Detector	Sensor/detector	Loop, infrared, microwave, ultrasonic, video camera, WIM scales, radar
Guardrail, Barrier, and Crash Cushion	Guardrail/barrier/crash cushion	Steel, concrete, plastic
Pavement Marking	Lane and edge striping Pavement marker Other	Paint: epoxy, non-epoxy; Thermoplastic: plastic, polyester, tape

1.2.2 Study Objectives

A general objective of this project is to advance transportation asset management and optimization analysis of roadway safety hardware for improved highway safety performance. The specific objectives are as follows:

- Developing a method for establishing goals and performance measures, inventory process, data collection, performance trend analyses, and needs assessment for the management of roadway safety hardware assets;
- Introducing a method for life-cycle cost analyses of acquiring, maintaining, rehabilitating, and upgrading/replacing roadway safety hardware assets; and
- Exploiting a method for integrating roadway safety hardware asset management into the overall pavement, bridge, maintenance, and safety management systems to achieve globally optimal, most cost-effective resource allocation decisions.

1.2.3 Delineation of Tasks

Task 1: Information Search

1-a: Literature Review

Literature review will be conducted on documents made available by the FHWA, AASHTO, and state transportation agencies regarding roadway safety hardware asset management systems as well as pavement, bridge, maintenance, and safety management systems that are also involved with roadway safety hardware asset management. Emphases will be given to safety hardware management system goals and performance measures; asset inventory; sampling techniques, coverage, and frequency for data collection; data quality assurance; performance trend analyses; needs assessment; budget and costs of acquisition, maintenance, and upgrade/replacement of safety hardware assets; and system integration for most cost-effective resource allocation decisions.

1-b: Questionnaire Survey

A survey questionnaire that is similar to the questionnaire of the 2000 AASHTO survey of state transportation agencies will be prepared and sent to all 50 states to collected updated information on the best practices of roadway safety hardware asset management in the country.

1-c: In-Depth Case Studies

In-depth case studies on roadway safety hardware asset management programs in Midwest states of Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin will be performed. Key documents (and information on management systems, if developed) in use will be collected and solicited. Interviews and/or field visits to senior managers, maintenance and traffic engineers, technical staff, and DOT contractors will be made to gather more information and resources. The current status of roadway safety hardware asset management programs in above states and existing gaps will be documented.

Task 2: Method for Inventory Process, Data Collection, Performance Trend Analyses, and Performance-Based Needs Assessment

Maintaining safety hardware inventory, collecting data for condition monitoring, and calibrating effective performance curves to assist in needs assessment are a major task to manage roadway safety hardware assets. A method will be developed assist in a cost-effective inventory process, data collection, and needs assessment for roadway safety hardware asset management.

Task 3: Method for Roadway Safety Hardware Life-Cycle Cost Analyses

Activity profiles that show amount, frequency, and timing (cash flow diagrams) of work activities during life-cycle of the following six categories of safety hardware assets will be established: i) roadway signs and supports; ii) traffic signals and supports; iii) roadway lighting and supports; iv) guardrails, barriers, and crash cushions; v) pavement markings and treatments; and vi) detecting devices. The benefits of a

project associated with each hardware asset category will be calculated as the reduction in life-cycle costs with respect to a base case scenario.

Task 4: Method for Integrating Safety Hardware Asset Management into Overall Management System
This aspect of the study will explore an effective approach to integrate roadway safety hardware asset management into existing analytical tools such as pavement, bridge, maintenance, and safety management systems. The following aspects will be thoroughly investigated: i) data integration; ii) consistency of evaluating safety hardware projects with projects associated with major infrastructural assets using the life-cycle cost analysis approach; and iii) integrated selection of projects within roadway safety hardware assets and projects between roadway safety hardware and pavement, bridge, maintenance, and safety using optimization models. Tradeoff analyses may consider following options: joint project selection with major infrastructure assets; shifting budgets from and to major infrastructure assets; and deferring the implementation of some safety hardware asset projects.

For agencies that use separate and individual safety hardware asset management systems, the refined methodology to be accomplished in Tasks 2, 3, and 4 will enhance agency tasks of project evaluation and selection, and eventually help globally optimal, most cost-effective investment decisions.

Task 5: Report Preparation, Submission, and Implementation Plan
Interim reports documenting information search and inventory, data collection, performance trend analyses, and needs assessment will be submitted within 7 and 9 months of approval of this proposal, respectively. A final report on findings of Tasks 1-4 and an implementation plan will be submitted in the 16th month after approval of this proposal.

1.3 Report Organization

The report is comprised of six chapters. Chapter 1 discusses the increasing need for a new methodology for integrating roadway safety hardware into the overall highway asset management program, as well as research objectives and tasks. Chapter 2 documents the findings of literature review on roadway safety hardware asset management in the United States. Chapter 3 synthesizes the findings of questionnaire surveys on the current-state-of-practices for managing roadway safety hardware assets across the country. Chapter 4 summarizes the findings of case studies aimed to obtain in-depth information on safety hardware asset management programs in the 12 Midwest states as defined by the U.S. Census Bureau, as well as the state of Tennessee. Chapter 5 discusses inventory process, performance measures, data integration, and database management for roadway safety hardware management. Chapter 6 introduces a methodology for roadway safety hardware project evaluation. Finally, Chapter 7 proposes a new analytical framework for long-term and short-term roadway safety hardware investment programming and project selection.

In preparing this report we have attempted to provide both technical and non-technical information; some readers may wish to skip over the mathematics and focus on the broader concepts of the analysis strategy.

CHAPTER 2:
LITERATURE REVIEW

The literature review primarily concentrated on the review of existing safety hardware management systems, other management systems dealing with one or more categories of roadway safety hardware assets, and safety hardware mainly pavement marking and guardrail investment decision-making and performance evaluation, respectively. The findings are summarized in the subsequent sections.

2.1 Roadway Safety Hardware Management Systems

The American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) conducted surveys of state transportation agencies in 2000 and 2002, respectively, to evaluate the practices of roadway safety hardware asset management systems in the United States. The surveys well documented various management systems developed in eleven states dealing with one or more categories of safety hardware assets. This section briefly discusses roadway sign, traffic signal and lighting, pavement marking, and guardrail management systems.

2.1.1 Roadway Sign Management Systems

2.1.1.1 FHWA Sign Management and Retroreflectivity Tracking System

The FHWA Sign Management and Retroreflectivity Tracking System (SMARTS) is a mobile system used to measure the retroreflectivity of traffic signs (FTC, 2007). It tracks roadway signs at 200 feet apart and by illuminate the sign with a powerful flash tube it measures sign retroreflectivity. A small picture of each sign is captured by a camera. The image of the sign is stored in the systems database, along with Global Positioning System (GPS) coordinates and other data associated with that particular sign. This data will be used to evaluate the quality of the sign, and develop a sign inventory database. The SMARTS system has the capability to measure retroreflectivity at highway speeds and does not need traffic control to make the measurements. It provides highway agencies the data necessary to schedule timely maintenance of roadway signs on a system-wide basis.

2.1.1.2 Georgia Highway Sign Management System

The Georgia Highway Sign Management System (HSMS) is fully developed as a comprehensive database which is capable for storing all detailed information on highway signs in the state, but the system is still not populated with data (Roberts, 2002). The HSMS includes features such as bar-coding, stock inventory, and roadside inventory options. The database includes location of sign, GPS, milepost, location on left or right side of the road, type of sign, height, lateral offset to the bottom, fabrication, and installation date. The State is moving to a digital photo log system so that the system could be tied to a Geographic Information System (GIS) if funding permits.

2.1.1.3 North Dakota Roadway Sign Asset Management System

The North Dakota Roadway Sign Asset Management System, which is not integrated with other asset management system, generates a database of list of signs to be replaced or reviewed by creating an inventory with a time stamp to reduce the data collection time (Kruse and Simmer, 2003). The data is collected using handheld computer and GPS technology to capture roadway sign location.

2.1.1.4 Oregon Sign Management System

In 1994, Oregon DOT's Region 2 initiated and developed a Sign Management System (R2Sign), a PC-based Microsoft Access database system database, to track signs in Oregon (FHWA, 2005).The primary use of the R2Sign database is to inventory and track maintenance of highway signs with an additional benefit of tracking to support the defense of liability actions brought against the State. However, the main purpose is to provide planning, scheduling, executing, and management of individual maintenance programs and also to determine maintenance budget and expected service life. The full scale R2Sign management system is implemented only in few states which indicate lack of integration across the entire

state in deploying the system. Oregon DOT district sign crews are the primary users and the system is not on network-connected computers. Data population varies within regions and districts.

2.1.1.5 Wisconsin Sign Inventory Management System

The Wisconsin Sign Inventory Management System (SIMS) allows for better planning for the replacement of signs using a system that records the service life span of signs (Wisconsin DOT, 2003). It also ensures that the signs are neither prematurely replaced nor remained in the field in poor condition. For cost efficiency, the SIMS is expected to provide a useful tool for contractor signing projects. The system provides an accurate listing of signs that need to be replaced, enabling the contractor to provide a realistic bid. The system will also facilitate the development of program funding needs annually.

The database of the system includes information on location, county, route, milepost, position on the roadway, sign direction, post type and length, sign code, size, base material, face material, age of sign, manufacturer's date and installation date, sign description (important for special signs), installation project identification, fleet number, sign number and condition (good, fair, or poor). The database covered approximately 70 percent of the Signs across the state.

2.1.1.6 Virginia Sign Inventory Management System

The new Virginia Sign Inventory Management System, which is entirely a Web-based application and requires only a standard web browser, has six key components: Random Condition Assessment, Needs-Based Budget Request Module, Planning and Scheduling Module, Work Order and Accomplishment Module, Inventory Module and Analysis Tools Module (Larson and Skrypczuk, 2004). The decision-support tools will provide resource management capabilities such as allocating financial, equipment, and human resource investments to specific groups of assets. Most of the decisions are based on the results of cost-benefit analysis. It will enable Virginia DOT to more efficiently and effectively manage roadway sign assets. The system will store location, position and direction, post length type, sign code that will facilitate better planning for the replacement of signs and the development of program funding needs on an annual basis. It is not integrated with other asset management systems.

2.1.2 Traffic Signal and Lighting Management Systems

2.1.2.1 Minnesota Automated Facilities Management System for Signal and Lighting Management

The Minnesota DOT uses Automated Facilities Management System (AFMS) tracks the electrical services section's maintenance activities, and coordinates requests for materials and work produced by the Minnesota DOT Metro Division and the eight districts traffic offices overseen by Minnesota DOT (FHWA, 2004). The AFMS is limited to traffic signals and other electric/electronic facilities that Minnesota DOT owns, operates, or maintains. The AFMS is used by the districts to order equipment, maintain the history of maintenance calls, summarize work orders, and keep track of the maintenance activities at each intersection. The AFMS was developed by Minnesota DOT with the goal of cost effectively and efficiently managing the asset classes covered by the system. The database covers all signals and lighting systems on state owned highways, but the AFMS is not integrated with the other Minnesota DOT asset management systems. The AFMS is fully populated, and new data entry is performed manually. No major enhancements are planned.

2.1.2.2 Oregon Traffic Signal Information System

The Oregon ODOT developed the Traffic Signal Information System (TSIS) to improve maintenance and inventory tracking. One of the stated uses of the tracking capability is to support liability actions brought against the State, potentially producing large savings in legal fees (FHWA, 2004). Oregon DOT anticipates additional benefits to include more effective planning, scheduling, executing, and managing individual maintenance programs. It will also allow the State to create an inventory of assets, determine maintenance budgets, facilitate accounting processes, and enhance the expected service life of the asset categories included. It will include data such as highway location and name, street name, direction of traffic flow, intersecting street name, nearest city, name of county, name of district, region number, name

of company supplying power, meter number for location, mile point, date of activation, recent date of repair, months of inspection and maintenance, comments, and signal priority. The TSIS is 65 percent to 75 percent populated with accurate data. The system is fully integrated throughout the DOT's intranet.

2.1.2.3 Virginia Traffic Signal System Inventory System

The Virginia Traffic Signal System Inventory (TSSI) system serves three groups of electrical staff for knockdowns, service reports and queries information (Larson and Skrypczuk, 2004). It tracks and manages the signal infrastructure. The TSSI is a PC-based system run on CartêGraph SIGNALview™ software. User groups, including electrical service personnel, engineers, and senior management, are developing data fields and forms. The database will eventually be integrated statewide. One district has begun to gather data on markings. An existing yard inventory will be integrated with the field inventory.

2.1.3 Traffic Structure Management System

2.1.3.1 Maryland Traffic Structure Inventory Inspection and Maintenance System

Known as Traffic Structure Inventory Inspection and Maintenance (TSIIM) system, Maryland State Highway Administration (SHA) developed an automated tool that could track maintenance and inspection activities (FHWA, 2005). The TSIIM comprises of three components: TSIIM Inspector, TSIIM Manager, and TSIIM Online. The TSIIM runs on Intel® processor-based PCs using a Microsoft Windows NT/2000/XP platform with a Crystal Reports® Runtime engine and Visual Basic Runtime libraries. At present, inspectors input their own data sets into the system. The data reviewer at Maryland SHA calls up those data sets by double-clicking on them. The Structures Team reviews the TSIIM data before a data set is populated. Future development includes upgrade to an extensible generic asset inventory, inspection, and maintenance data management program. The development will integrate data from all inspection teams, allow for the check-in and check-out of this data for repeat inspections and provide historical data review and optimal fund allocation analyses.

2.1.4 Pavement Marking Management Systems

2.1.4.1 Arizona Pavement Marking Management System

The Arizona DOT is currently developing a pavement marking management system which will include a database of all signs and pavement markings, a method for tracking lifetime product performance, and procedures and processes for monitoring, maintaining, and replacing these products (Arizona DOT, 2002).

2.1.4.2 Iowa Pavement Marking Management System

With an annual pavement marking program of approximately two million dollars and another three-fourth million dollars invested in maintenance of durable markings each year, the Iowa DOT is seeking every opportunity to provide all-year markings staying in acceptable condition under all weather conditions. A prototype Pavement Marking Management System (PMMS) was developed and it consists of two primary components: performance/life cycle curves for pavement marking products, and an application matrix tailored to the pavement marking products and roadway and environmental conditions faced by the Iowa DOT (Hawkins et al., 2006). Both components will continue to be refined and tailored to Iowa materials and conditions as more performance data becomes available. The system aims at managing the marking performances on basis of the retroreflectivity data being collected. The system is integrated into pavement and safety management systems.

2.1.4.3 Missouri Pavement Marking Management System

The Missouri DOT has developed a PMMS that provides an automated system not only to inventory pavement markings but also to manage them. Tailored for Missouri conditions, one of the major components of the system is to measure quality and durability (Davidson, 2003).

2.1.4.4 Virginia Marking Management System

The Virginia Marking Management System (MMS) was designed to develop quantity needs for contract plans and facilitate annual budget estimates for users, including engineers, financial analysts, and senior

management (Cottrell and Hanson, 2001). The data items to be collected by the system will include color, type, product manufacturer, reflectivity, spotting distance, and roadway surface type. The pavement marking database is planned to be integrated with various existing statewide databases such as materials, pavements, and bridges.

2.1.5 Guardrail and Crash Cushion Management Systems

2.1.5.1 TRB Roadside Safety Analysis Program

The Transportation Research Board (TRB)'s Roadside Safety Analysis Program (RSAP) deals cost effectiveness analysis procedure for assessing roadside safety improvements (NCHRP, 2003[1]). The RSAP software is based on the encroachment probability approach and has two integrated programs: the Main Analysis Program that deals the cost-effectiveness procedure and algorithms, and the User Interface Program provides a user-friendly environment for data input and review of program results. The cost effectiveness procedure is based on the concept of incremental benefit-to-cost analysis. Incremental benefit-to-cost analysis is accepted widely as the most appropriate method for evaluating safety alternatives. Benefits are measured in terms of the reduction in crash or societal costs associated with a safety improvement while costs are increase in direct to highway agency expenditures associated with the improvement. The software has Encroachment Module, Crash Prediction Module, Crash Severity Prediction module and Benefit/Cost Analysis Module. The encroachment model uses roadway and traffic information to estimate the expected encroachment frequency along a highway segment.

2.1.5.2 Idaho Grail System

The Idaho Transportation Department (ITD) Geographic Roadway Application for Information Location (GRAIL) System uses roadway video logging survey system to collect high quality digital images along with the GPS location data, curvature data and measuring distance traveled for maintenance of the guardrails in the state (ITD, 2002). It is integrated into the central system.

The Microsoft Windows 95/98/NT/2000 application system is designed to access ITD's database across the network, but also works on copies of flat files located on the user's hard drive, network drive, or CD-ROM. The software allows the user to view data elements along state highways. In addition, it provides a map (with optional hydrographs, minor road, and elevation layers). The system can also produce simple text-based output of user-selectable data items. It is not a GIS application, and is not designed to calculate land areas or identify impact zones or relate road attributes based on their distances from other facilities. The map is strictly to provide the user some visual context for the road of interest.

2.2 Other Management Systems Dealing with Roadway Safety Hardware

2.2.1 California Inventory Maintenance Management System

The California DOT (Caltrans) Inventory Maintenance Management System (IMMS) is a COTS software that uses Oracle and is Oracle-compatible so that different systems can interchange data (CALTRANS, 2006). The Caltrans IMMS is designed to track time, materials, and equipment. One feature of the system captures how much time the crew worked on each job. Work performance items listed in IMMS include day labor work order, input/output, and inventory order. IMMS is designed to give supervisors access to detailed information about each highway asset, where it is located on the roadway, and work being performed on the asset. All electric power systems are in IMMS, including luminaries, signals, ramp meters, flashers, cameras, message signs, all lighting, tunnel lighting, and loop detectors.

A key feature of the IMMS is the Roadway Feature Viewer. The IMMS Roadway Feature Viewer provides a convenient way for supervisors to scrutinize information about a roadway. For example, supervisors can easily see the locations of assets along the roadway and either view information about work being performed on an asset or create a work order for the asset. In addition, they can view the location of work being performed on a portion of the roadway and have access to information about the roadway itself, such as the number of lanes or speed limit. The system is not integrated with other asset management systems.

2.2.2 Florida Roadway Characteristics Inventory System

The Florida Roadway Characteristics Inventory (RCI) System is a computerized database of physical and administrative data related to the roadway networks that are either maintained by or are of special interest to the Florida DOT (Florida DOT, 2005). The system also contains other data as required for special Federal and state reporting obligations. Some of the specific items that the RCI database includes are roadway signs, traffic signals, pavement markings and treatments, guardrails, and barriers. The system currently tracks assets in the Department of Maintenance and Traffic Operations Control, including roadway lighting, structural supports, and detectors. The system is integrated into the central system. FDOT has populated the database with all available data for the RCI system. The database is updated daily when the department obtains new or modified information. The RCI database resides on the department mainframe computer system, and it is maintained by department computer personnel from the district and central offices.

2.2.3 Maryland Highway Management Information System

The Maryland SHA manages a number of databases operated by various divisions to inventory and report on the assets under their jurisdiction rather than maintaining a single, integrated, computerized database for all roadway characteristics. These databases are integrated as necessary through a shared route system based on the roadway inventory used for internal and Federal reporting requirements. The route system uses a standard key and mile points relating each of the ancillary systems to it and to one another.

The Highway Management Information System (HMIS) maintained by the database management section of the Highway Information Services Division is the main data source for roadway information (FHWA, 2005). Data are collected by inventory crews and integrated with data supplied by local county governments. The information gathered and maintained by the system is used for reporting and mapping within and outside Maryland SHA and for developing and maintaining GIS Roadway Route System that runs an Oracle database. By facilitating the reporting and map display of their data on a graphical roadway map, the GIS Roadway Route System serves as an integrating function for databases maintained by the agency's Bridge, Pavement, Signal Operations, Accident Reporting, and Project Planning Divisions.

The HMIS master file contains records to store each intersecting feature by route number and mile point. Features include, but are not limited to, intersecting routes, municipal and county boundaries, bridges, cultural features, some private roads, and road ends and cul-de-sacs. The Universe file contains roadway section data designated by route number, beginning mile point, and section length to support internal reporting and Highway Performance Monitoring System (HPMS) requirements. Data such as median width and type, number of lanes, shoulder type and width, pavement type, annual average daily traffic (AADT) and other characteristics are maintained.

2.2.4 North Carolina Maintenance Management System

The North Carolina DOT maintenance management system was developed to help plan, schedule, execute and manage individual maintenance programs (North Carolina DOT, 2003). It describes the condition of assets based on extrapolations from random sampling. It develops an annual plan both ideal and constrained and it also creates an inventory of assets, facilitates the accounting processes and schedules daily maintenance work. The system is a PC-based, three-tiered system with workstation access, an application server, and a mainframe Oracle server. The vision is to tie together the pavement maintenance, bridge management, and maintenance management systems and eventually add traffic signal management to allow a comprehensive assessment of needs down to the project level.

2.2.5 New Mexico Road Feature Inventory and Highway Maintenance Management Systems

The New Mexico Road Feature Inventory System (RFIS) maintains a video based system wherein each lane is recorded at 50-ft intervals with a video image width of 120-ft and all the asset data is imported to an Oracle database along with the video to create an extensive database on the entire New Mexico

roadway system to ease maintenance and limit legal liability by documenting safety assets (FHWA, 2005). Of the seven safety hardware asset categories, only lighting and traffic detectors are not included in the RFIS system. This is because lighting in New Mexico is maintained by local governments, not the State Highway and Transportation Department (SHTD). Nonetheless, the video can easily pick up the roadway lighting information as well. The State is eliminating the use of magnetic detectors and making a transition to the use of video technology. The quality control is achieved at 95 percent accuracy and the system is integrated into the central system.

The New Mexico Highway Maintenance Management System (HMMS) is a proprietary database which is separate from the RFIS system and it is a collection of highway information on labor, equipment, commodities, and maintenance management processes (FHWA, 2005). The HMMS is not integrated with any other highway asset management systems. One purpose of the HMMS is to help New Mexico SHTD use its resources in the most efficient manner to maintain the roadways in the best possible condition by guiding the field personnel in managing maintenance operations effectively. New Mexico is one of the few States that owns the source code for its HMMS, which allows the State to maintain the software internally without licensing or other maintenance fees. Following the demonstrated success in New Mexico, a number of other States including Georgia, South Carolina, and Tennessee have implemented an HMMS. The future plans for the New Mexico SHTD included merging of the two databases. The New Mexico SHTD recognizes the importance of coordinating, integration, planning with the Information Technology (IT) Department and it plans for central coordination for applications and development of any future software.

2.2.6 Tennessee Road Information Management System

The Tennessee Road Information Management System (TRIMS) is developed to improve cost-effective and efficient asset management (Tennessee, 2002). The TRIMS Oracle database contains information on each public road in Tennessee. The PowerBuilder® interface allows users to query inventory data, digital photographs, road mileage, documents, digital plans, and scanned documents. The TRIMS also has a graphic interface, which offers map-based queries and displays information on maps, providing a more effective tool for planners and engineers. The system is in use by field staff to plan and execute work and by office staff to manage needed maintenance and develop analyses in support of budget requests. The Tennessee DOT has developed an internal guide to the TRIMS system to familiarize users with the TRIMS hardware, network, operating systems, database, and intranet/Internet connections.

The TRIMS features information pertaining to accidents, city boundaries, county boundaries, elevation alignments, geometrics, horizontal alignment, maintenance features, maintenance inventory, railroad crossings, rivers, road history, road segments, road descriptions, route features, state boundaries, structures, surface conditions, traffic, urban boundaries and vertical alignments. The TRIMS is a fully functional database. In the future, Tennessee DOT wants additional support functions to improve access to the TRIMS through the Web and requires DOT regions to be able to contact the TRIMS through the intranet concerning upgrades on route openings, route realignments, and data issues.

2.2.7 Virginia Inventory and Condition Assessment System

To make the best possible maintenance investment decisions, the Virginia DOT initiated a comprehensive maintenance and operations business process reengineering (BPR) effort in 1995. The Virginia DOT initiated the development of an infrastructure decision-support systems and a large data collection program based on the recommendations from the BPR effort, referred to as the Inventory and Condition Assessment System (ICAS) (Larson and Skrypczuk, 2004). It is a PC-based client-server system based in Exor, a proprietary software system from the United Kingdom. The Oracle spatial database is being built by in-house staff.

The ICAS captures a GPS-referenced digital video log along every segment of highway at every 52.8-ft which helped develop centerline coordinates of the roadway network and are available in the DOT's GIS

data base and can be accessed through the Virginia DOT intranet. All the video images of the inventory and condition data for all roadway assets and roadway safety hardware elements within the DOT jurisdiction are collected using video logging, GPS and digital satellite imagery integrated with GIS with 95 percent confidence level of data accuracy. This system is fully integrated into the central system.

2.3 Roadway Safety Hardware Investment Decision –Making Practices

2.3.1 Pavement Marking Investment Decision-Making

2.3.1.1 Kansas Pavement Marking Investment Decision-Making Process

In recent years, the Kansas DOT has developed a sophisticated methodology to determine the most economical type of pavement marking to be used under various circumstances. From their analysis, a Brightness Benefit Factor (BBF) is determined, which is described as a benefit-to-cost ratio based on the material's retroreflectivity, durability, and installed cost. The analysis also includes variables such as traffic, expected life of the pavement, and motorists delay. Typical costs of products used by Kansas DOT are provided as well (McGinnis 2001).

Kansas DOT has an integrated preventive maintenance program that tracks all pavement markings by the year applied, expected life of pavement, type of material used, and performance guarantees of the pavement markings. Using this information, a prediction of pavement marking life may be made. In the spring, maintenance crews are sent out to visually inspect specific pavement markings at night for retroreflectivity compliance. Information from the inspections is sent to the engineering department to update the list of roads that require new markings and/or warranty repairs. In addition, the list takes into consideration all planned maintenance activities, so that in selecting the optimal marking material to be used, the service life of the marking can be evaluated relative to the interval until the next pavement maintenance activity (Kansas DOT, 1999).

2.3.1.2 North Dakota Pavement Marking Investment Decision-Making Process

The North Dakota DOT bases its selection of pavement markings on several criteria including type and condition of road surface, the anticipated level of traffic, and based on the location of the road the delineation will be used (e.g., center or edge) (Kruse and Simmer, 2003). The materials it considers for use include conventional paint; inlaid, patterned, and preformed plastic; and grooved, patterned, and preformed plastic. A guide was developed to determine best pavement marking practices in any given situation.

2.3.2 Guardrail Performance Evaluation

2.3.2.1 Arizona In-Service Highway Safety Feature Performance Evaluation Program

The Arizona In-service Highway Safety Feature Performance Evaluation Program includes four sub systems, which are complement to each other (Arizona DOT, 2002). They are Continuous Monitoring Subsystem, Supplemental Data Collection Subsystem, In-Depth Investigation Subsystem, and New Product Evaluation Subsystem.

Continuous Monitoring Subsystem is the backbone for the proposed program. A computer database will be created by merging various data files, like highway and traffic data file, accident data file, maintenance data file, and roadside feature inventory file into a single database for analysis. No supplemental or field data collection is required for this subsystem. The database is analyzed periodically to produce standard reports for general trend analysis and problem identification. The database could also be used to conduct comparative analyses on an ad hoc basis for selected roadside safety features and highway sections.

To supplement the first subsystem data for enabling a detailed analysis, on site inspection will be conducted to collect additional data on the roadway, roadside and selected safety feature. In-depth investigation to collect sufficiently detailed data is required by the In-Depth Investigation Subsystem. New product evaluation is an integral part of in-service evaluation, but it is different from the other three subsystems. The evaluation will be targeted at problems encountered with the construction/installation of

the roadside safety devices. A field trail is planned to work out any potential problems that might be encountered in the actual implementation of the proposed program. The devices, guardrail terminal, crash cushion, cable median barrier, breakaway sign, and breakaway luminaries, are selected for field trial. A conceptual framework for a national database with the mission of in-service performance evaluation of roadside safety features is also developed.

2.3.2.2 NCHRP Recommended Procedure for Guardrail Performance Evaluation

This National Cooperative Highway Research Program (NCHRP) report recommended some procedures for evaluating the safety performance of highway safety features (NCHRP, 2003[2]). Procedures are developed for the following features: longitudinal barriers: bridge rails, guardrails, median barriers, transitions, and terminals; crash cushions; breakaway or yielding supports for signs and luminaries; breakaway utility poles; truck-mounted attenuators; and work zone traffic control devices. Five evaluation criteria are recommended and three dynamic performance evaluation factors, including structural adequacy, occupant risk, post impact vehicular response, are used. Evaluation methods proposed include engineering assessment, simulation, full-scale crash testing, pendulum testing, and component testing.

2.4 Chapter Summary

The review focused on three aspects: existing safety hardware management systems, other management systems dealing with one or more categories of roadway safety hardware assets, and safety hardware mainly pavement marking and guardrail investment decision-making and performance evaluation, respectively. Emphases were given to safety hardware management system goals and performance measures; asset inventory and data collection; performance evaluation and needs assessment; as well as system integration for most cost-effective resource allocation decisions.

CHAPTER 3:
SURVEYS OF CURRENT SAFETY HARDWARE MANAGEMENT SYSTEMS

3.1 Introduction

A questionnaire survey was administered in mid-July and August 2007 to synthesize the current-state-of-practices for managing roadway safety hardware assets, such as roadway signs; signals; lighting; support and structure for signs, signals, and lighting; guardrails, barriers, and crash cushions; pavement markings and treatments; and deployed detecting devices across the country.

The survey questionnaire is attached in the Appendix A of this report, which consists of eight questions. Question one seeks information on major roadway safety hardware management tasks performed. Question two checks general goals of roadway safety hardware management. Question three verifies the usage of performance measures to manage roadway safety hardware assets. Question four deals with the level(s) of an organization where decisions about roadway safety hardware expenditures are made. Question five inquires current status of adoption phases of software systems for roadway safety hardware asset management. Questions six and seven solicit information on geographical coverage and administration of software systems for roadway hardware asset management, respectively. Question eight investigates the influence of these software systems on safety hardware maintenance, repair, and replacement/upgrade decisions. In the end, space was provided for respondents to supply with additional comments.

In total, 130 experts on traffic safety and safety engineering from all state transportation agencies in the United States were identified and contacted via a mass email. The email contained a link to the online survey Website. An electronic copy of the questionnaire in fillable PDF format was also attached to the email to allow more options to participate in the survey. A respondent may choose to submit the completed survey online, via email, or by fax.

The survey period lasted for five weeks and 44 respondents from 28 states returned their completed surveys. Of which, 35 completed the survey through the Website, 5 responded by email, and 4 responded their responses by fax. The following sections discuss the survey results.

3.2 Survey Results

3.2.1 Major Roadway Safety Hardware Asset Management Tasks Performed

Table 3-1 summarizes the responses of major roadway safety hardware asset management tasks performed by state transportation agencies. For safety and warning signs, the primary tasks performed were performing sign routine inspections (45 percent); proposing, evaluating, selecting, and implementing sign projects (45 percent); and maintaining sign inventory (39 percent). In addition, assessing sign condition by sampling (27 percent) was reported as a major task performed. Only 16 percent of responses indicated providing feedbacks as a major task.

For the management of information-related signs, performing sign routine inspections (41 percent); proposing, evaluating, selecting, and implementing sign projects (39 percent); and maintaining sign inventory (34 percent) were reported as primary tasks. Twenty three percent of the responses mentioned assessing sign condition by sampling and 11 percent of responses indicated providing feedbacks as major tasks.

For the management of signals, the primary tasks performed were maintaining signal inventory (52 percent), performing signal routine inspections (36 percent); and proposing, evaluating, selecting, and implementing signal projects (34 percent). Fourteen percent of responses indicated assessing signal condition by sampling and 11 percent mentioned providing feedbacks as major tasks.

For the management of lighting systems, the primary tasks performed were performing lighting routine inspections (32 percent); and proposing, evaluating, selecting, and implementing lighting projects (30

percent). Twenty-five percent responded maintaining lighting inventory, 23 percent mentioned assessing lighting condition by sampling, and 11 percent of responses indicated providing feedbacks as major tasks.

For the management of detection devices, the primary tasks performed were proposing, evaluating, selecting, and implementing detection device projects (41 percent); maintaining detection device inventory (34 percent); and performing detection device routine inspections (34 percent). In addition, providing feedbacks (23 percent) and assessing hardware condition by sampling (16 percent) was reported as major tasks.

For pavement marking management, the primary tasks performed were assessing pavement marking condition by sampling (39 percent); proposing, evaluating, selecting, and implementing pavement marking projects (39 percent); and performing pavement marking routine inspections (36 percent). Twenty-five percent responded maintaining pavement marking inventory as a major task. Eighteen percent stated providing feedbacks as a major task.

For the management of guardrails, barriers, and crush cushions, the primary tasks performed were proposing, evaluating, selecting, and implementing guardrail projects (52 percent); performing guardrail routine inspections (36 percent); and assessing guardrail condition by sampling (30 percent). Maintaining guardrail inventory (20 percent) and providing feedbacks (14 percent) received relatively low responses.

Fairly low response rates were received for ramp metering management. The major task performed were proposing, evaluating, selecting, and implementing ramp metering projects (18 percent); maintaining ramp metering inventory (16 percent); performing ramp metering routine inspections (14 percent); providing feedbacks (7 percent); and assessing ramp metering condition by sampling (2 percent).

In general, no task received higher than 52 percent of response rate. The responses to maintenance of hardware inventories for various categories of safety hardware assets varied considerably, with highest for signals (52 percent) and lowest for ramp metering (16 percent).The responses to performing hardware routine inspections varied from 45 percent for safety and warning signs to 14 percent for ramp metering. The responses to assessing hardware conditions by sampling varied from 39 percent for pavement markings to 2 percent for ramp metering. The responses to proposing, evaluating, selecting, and implementing hardware projects varied from 52 percent for guardrails, barriers, and crash cushions to 18 percent for ramp metering. The responses to providing feedbacks varied from 23 percent for detection devices to 7 percent for ramp metering. Lowest responses were consistently obtained for ramp metering on all tasks performed. This might be due to lack of ramp meters in the respective states or exclusion of ramp meters as a category of roadway safety hardware assets.

Table 3-1. Major Roadway Safety Hardware Asset Management Tasks Performed

Roadway Safety Hardware Category (No. and % of Responses)	Maintaining an Hardware Asset Inventory		Performing Hardware Routine Inspection		Assessing Condition by Sampling		Proposing, Evaluating, Selecting, and Implementing Hardware Projects		Providing Feedbacks	
Signs- Safety and warning	17	39%	20	45%	12	27%	20	45%	7	16%
Signs- Information-related	15	34%	18	41%	10	23%	17	39%	5	11%
Signals	23	52%	16	36%	6	14%	15	34%	5	11%
Lighting	11	25%	14	32%	10	23%	13	30%	5	11%
Detection devices	15	34%	15	34%	7	16%	18	41%	10	23%
Pavement markings	11	25%	16	36%	17	39%	17	39%	8	18%
Guardrails, barriers, crash cushions	9	20%	16	36%	13	30%	23	52%	6	14%
Ramp metering	7	16%	6	14%	1	2%	8	18%	3	7%

3.3 General Goals of the Roadway Safety Hardware Asset Management Program

As shown in Table 3-2, maximizing safety hardware useful service life (84 percent) was indicated as a primary goal of roadway safety hardware asset management. Minimizing vehicle crashes (75 percent), minimize long-term costs over safety hardware service life (66 percent), and meeting annual budget targets (50 percent) were also given significant importance. Twenty-seven percent of the responses mentioned sharing costs equitably with other jurisdiction and 25 percent indicated minimizing energy consumption and emissions as the goals.

For the twenty-three percent of responses choosing the "others" category, some respondents reported liability, track maintenance time, and fund expenditures for trends and future needs as their hardware management goals. Others reported retroreflectivity of signs and pavement markings, as well as the structural integrity of hardware supports as their goals.

Table 3-2. General Goals of the Roadway Safety Hardware Asset Management Program

Safety Hardware Management Goal	Response	
	No.	%
Maximize safety hardware useful service life	37	84%
Minimize vehicle crashes	33	75%
Minimize long-term costs over hardware service life	29	66%
Meet annual budget targets	22	50%
Share costs equitably with other jurisdictions	12	27%
Minimize energy consumption and emissions	11	25%
Others	10	23%

3.4 Use of Performance Measures for Roadway Safety Hardware Asset Management

The use of performance measures for roadway safety hardware management was not found to be very popular. As shown in Table 3-3, thirty-nine percent of the respondents reported that the performance measures were occasionally used. Of the remaining responses, 27 percent usually use performance measures, 14 percent always use performance measures, 11 percent never used performance measures, and 9 percent seldom used performance measures.

Table 3-3. Use of Performance Measures for Roadway Safety Hardware Asset Management

Use of Performance Measures for Safety Hardware Management	Response	
	No.	%
Occasionally	17	39%
Usually	12	27%
Always	6	14%
Never	5	11%
Seldom	4	9%

3.5 Organizational Levels Making Decisions about Roadway Safety Hardware Expenditures

The extent of involvement in roadway safety hardware expenditure decisions was found to be significantly different among upper management, middle management, front-line supervisor, and field personnel, as Table 3-4. The upper management was mainly involved with determining/negotiating overall budget (77 percent), determining/negotiating sub-allocation of budget to regions/counties (48 percent), and negotiating cost share with other agencies (39 percent).

The middle management primarily deals with developing purchasing specifications (64 percent), authorizing purchases (55 percent), determining/ negotiating sub-allocation of budget to regions/counties (50 percent), determining maintenance cycles (50 percent), and negotiating cost share with other agencies (45 percent).

The front-line supervisor/maintenance superintendent mainly focuses on determining specific items to repair/replace (75 percent), determining maintenance cycles (61 percent), and authorizing purchases (57 percent). The maintenance field personnel largely determine specific items to repair/replace (41 percent).

Table 3-4. Organizational Levels Making Decisions about Roadway Safety Hardware Expenditures

Expenditure Decision Level (No. and % of Responses)	Upper Management (Department Head/ Agency Director)		Middle Management		Front-Line Supervisor/ Maintenance Superintendent		Maintenance Field Personnel	
Determine/ negotiate overall budget	34	77%	14	32%	3	7%	2	5%
Determine/ negotiate sub-allocation of budget to regions/counties	21	48%	22	50%	3	7%	0	0%
Negotiate cost share with other agencies	17	39%	20	45%	4	9%	0	0%
Develop purchasing specifications	8	18%	28	64%	16	36%	2	5%
Determine maintenance cycles	5	11%	22	50%	27	61%	4	9%
Determine specific items to repair/replace	2	5%	14	32%	33	75%	18	41%
Authorize purchases	11	25%	24	55%	25	57%	5	11%

3.6 Adoption Phases of Software Systems for Roadway Safety Hardware Asset Management

As shown in Table 3-5, the percent reported on software adoption phases appears to be relatively low. Forty-one percent of respondents indicated that the software systems for lighting management had not begun. The percent of lacking software systems for the remaining categories of safety hardware assets varied from 39 percent to 18 percent. The percent of responses to the use of software systems in the initialization phase varied from 20 percent for signals to 9 percent for guardrails, barriers, crash cushions; and ramp metering, respectively. The percent of responses to the use of software systems in the development phase varied from 18 percent for information-related signs to 7 percent for lighting; and detection devices, correspondingly. The percent of responses to the use of software systems in the execution phase varied from 20 percent respectively for safety and warning signs and signals to zero percent for ramp metering. The percent of responses to the use of software systems in the assessment phase varied from 9 percent respectively for signals and pavement markings; and zero percent for ramp metering. The percent of responses to the use of software systems in the integration phase varied from 16 percent for information-related signs to zero percent for ramp metering.

Table 3-5. Adoption Phases of Software Systems for Roadway Safety Hardware Asset Management

Software Adoption Phase (No. and % of Responses)	Not Started		Initiation		Development		Execution		Assessment		Integration	
Signs- Safety and warning	9	20%	7	16%	7	16%	9	20%	3	7%	6	14%
Signs- Information-related	11	25%	6	14%	8	18%	8	18%	3	7%	7	16%
Signals	12	27%	9	20%	5	11%	9	20%	4	9%	5	11%
Lighting	18	41%	6	14%	3	7%	7	16%	2	5%	3	7%
Detection devices	17	39%	6	14%	3	7%	5	11%	1	2%	4	9%
Pavement markings	14	32%	8	18%	5	11%	4	9%	4	9%	3	7%
Guardrails, barriers, crash cushions	15	34%	4	9%	7	16%	6	14%	2	5%	5	11%
Ramp metering	8	18%	4	9%	4	9%	0	0%	0	0%	0	0%

3.7 Geographical Coverage of Software Systems for Roadway Safety Hardware Management

Table 3-6 summarizes the responses on agencies practicing the centralized and decentralized software systems. Fifty-nine percent of respondents reported having coverage for the entire states. Forty-one percent stated that they have coverage over one or more regions of the state.

Table 3-6. Geographical Coverage of Software Systems for Roadway Safety Hardware Asset Management

Geographical Coverage of Software System	Response	
	No.	%
Entire State	26	59%
One or more regions of the State	18	41%

3.8 Administration of Software Systems for Roadway Safety Hardware Asset Management

As seen in Table 3-7, a major proportion of respondents (61 percent) reported that their software systems are administered by central offices. Twenty percent responded it was managed by district offices. Of the 18 percent of responses under "others" category, the software systems are mainly managed by consultants and the agency's specific units. For instance, some agencies assigned Transportation Management Center mangers for administration of their software systems for roadway safety hardware asset management.

Table 3-7. Administration of Software Systems for Roadway Safety Hardware Asset Management

Administration of Software System	Response	
	No.	%
By central office	27	61%
By district office	9	20%
Others	8	18%

3.9 Influence of Software Systems for Roadway Safety Hardware Asset Management on Investment Decisions

The responses on the influence of software systems for roadway safety hardware asset management on investment decisions are listed in Table 3-8. Thirty-two percent of the respondents reported the developed software systems were of minimal influence on investment decisions. Twenty-five percent reported the influence of the software systems as moderate or unknown. Nine percent reported either extensive impacts or no impact of the developed software systems.

Table 3-8. Influence of Software Systems for Roadway Safety Hardware Asset Management on Investment Decisions

Usefulness of Software System	Response	
	No.	%
Minimal	14	32%
Moderate	11	25%
Don't Know	11	25%
Extensive	4	9%
No Impact	4	9%

Appendix B provides graphic presentations of survey results.

3.10 Additional Comments

The survey respondents provided more insights into the roadway safety hardware management issues. In total, eleven respondents provided additional comments on issues concerning refinement of data inventory processes and data collection standards, use of GIS-based systems to track of assets and Web interfaces for data management, development of standardized and coordinated statewide systems such as automated facility management systems and maintenance management systems for roadway safety hardware management, and systematic safety hardware replacements. Details of the additional comments are presented in Table 3-9.

Table 3-9. Summary of Additional Comments on the Improvements Needed for Roadway Safety Hardware Asset Management

DOT	Comments
Arkansas	Needs to develop a statewide asset management system
Colorado	Has a GIS-based system to keep track of our roadways, signs, signals, and street lights
Illinois	Standardizes and coordinates management systems between districts statewide
Minnesota	Connection to the department level funding decisions needs to be stronger as funding for maintenance and replacement hardware parts is not keeping pace with expense rate
North Carolina	- The DOT is currently tracking a database on pavement markings and is doing a proof of concept on a signal management system which will track the performance of isolated signals and systems, and the scheduled preventive maintenance - The DOT is getting ready to implement performance measures - Most of the software systems for asset management are developed centrally. This does not, however, prevent the individual county maintenance offices or division offices from creating their own databases and information collecting software - The software systems will be used to develop maintenance work plans in the very near future. Until such time as the hardware systems and performance measures are put in place, fully implemented, and the information analyzed, it is hard to determine the impact on decision making - Needs a standardized statewide system maintained by the local maintenance units
Ohio	Refinement of data collection standards for field data collection, systematic Sign replacement, and integration with highway maintenance work order systems
Tennessee	- Most of the roadway safety hardware assets are included in the assets that are utilized in the planning, budgeting, and reporting within the maintenance management system. However, the progress has not reached the point where the specific detailed information is being used to drive the management of these assets. The maintenance management system is only two years old and it is still being fine-tuned at this point - Needs better inventory processes, which will define the geo-coded location, condition, and other important data for each of these roadway safety hardware assets before beginning system integration and truly manage these assets in the most efficient manner - Ramp metering is not utilized at this time in the state - Signals, loop detection devices, and roadway lighting are maintained by the local municipalities once they are constructed
Utah	One year away from having a new maintenance management system in place and this will make a big difference in safety hardware management
Virginia	- Has a continuing program for evaluating the structural integrity of all overhead sign structures and high mast lighting towers, camera poles, and other ancillary towers/poles. - Is in the process of its first statewide evaluation of all signal poles and conventional lighting poles for structural integrity - Will gain its first statewide asset inventory for signs and signals. A general evaluation of the signal display equipment is noted by the structural inspectors as is the conditions of conventional, high mast, and sign lighting fixtures - Is in the late stage of developing a Request for Proposals for services to include the inventory and assessment of all signs except for those that are classed as supplemental guide signs, along its Interstates and limited access freeways and expressways - Contracts its supplemental guide sign program. That contractor is charged with performance management of these signs - Continually evaluates both sign display and signal/detection operations using its nine planning districts and five operations regions. However, the routine of this and the inspection parameters vary from location to location
Washington	- Needs inventory and management systems for pavement markings - The inventory data for guardrail, barriers, and crash cushions recently began - Monitors automated traffic reporting sites and perform preventative maintenance on the selected sites at least once a year. Data on equipment at each site are maintained in a MS Access database and are used for planning purposes
Wisconsin	Needs GIS integration and Web interface for data management

3.11 Summary and Concluding Remarks

3.11.1 Survey Summary

The key findings of the survey are as follows:

- Many state transportation agencies manage several categories of safety hardware assets, mainly including signs, signals, detection devices, pavement markings, and guardrails.
- Major tasks performed on safety hardware are concentrated on hardware inventories, routine inspections and condition assessments, and hardware project evaluation and selection. However, at most one-half of the agencies that responded to the questionnaire performed such tasks systematically.
- Maximizing safety hardware service life, minimizing vehicle crashes, and minimizing long-term costs are primary goals of roadway safety hardware assent management.
- Lower than one-third of the respondents mentioned regularly using performance measures to manage the roadway safety hardware assets.
- Upper management was reported in charge of overall budget negotiation, sub-allocation of budget to regions and counties, and negotiation of cost share with other agencies. Middle-level management also participates in sub-allocation of budget to regions and counties, and negotiation of cost share with other agencies, and is responsible for developing purchase specifications, determining maintenance cycles, and authorizing purchases. Front-line supervisors/ maintenance superintendents and field personnel are involved with the selection of specific item to replace or repair.
- The responses to adoption phases of software systems for roadway safety hardware management varied considerably across hardware categories. Irrespective of the adoption phase and safety hardware category, the adoption rate of a software system was found at most 20 percent. No response was provided for the execution, assessment, and integration phases of software systems for ramp metering management.
- A major portion of responses indicated that the software systems for roadway safety hardware management covered entire states and are administered by the agency's central offices.
- The influence of the developed software systems on safety hardware maintenance, repair, and replacement decisions was reported not to be extensive and appeared to be minimal.

3.11.2 Concluding Remarks

Large differences were found among various state transportation agencies in aspect of types of roadway safety hardware managed, tasks performed, the use of goals and performance measures, organizational levels making investment decisions, adoption phases of software systems for automating safety hardware management, geographical coverage and administration of the software systems, as well as the usefulness of software systems for assisting in decision-making. Some state transportation agencies currently maintain customized software systems dealing with different safety hardware assets, some use automated facility management systems or maintenance management systems to manage safety hardware. In general, the extent of software usage and functional capacity of the software systems fall far behind the software systems for highway pavement, bridge, and safety management. There are imperative needs for the refinement of data inventory processes and data collection standards, use of GIS-based systems and Web interfaces for data management, development of standardized and coordinated statewide systems for managing the roadway safety hardware assets, and systematic safety hardware replacements.

CHAPTER 4:
CASE STUDIES

4.1 Introduction

Subsequent to administer the questionnaire surveys, a structured outline of questions was prepared to help conduct case studies aimed to obtain in-depth information on safety hardware asset management programs in the 12 Midwest states as defined by the U.S. Census Bureau, as well as the state of Tennessee, as shown in Figure 5.1.

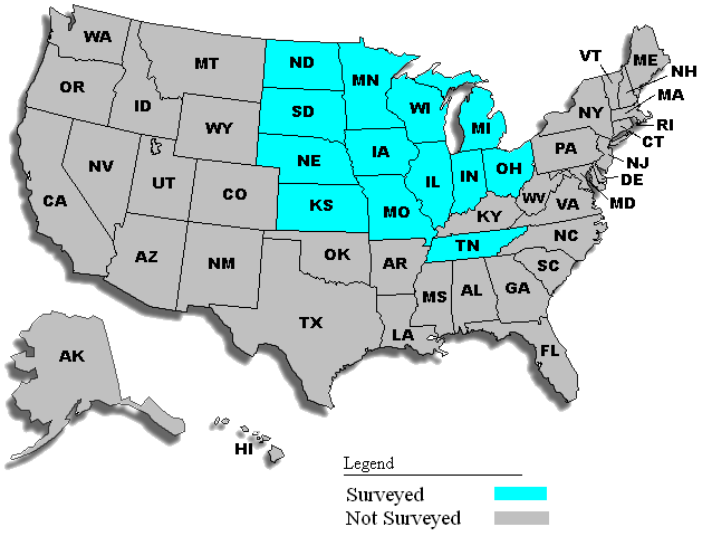

Figure 5.1. States Participated in the Case Studies

4.2 Case Study Methodology

The case study process began with contacting managers and engineers in-charge of roadway safety hardware management programs in the participating states. The research team was referred to individuals within these agencies that would assist us in answering the interview questions. All interviews were arranged by appointment and, at the time of appointments, the list of questions to be covered was briefly discussed to allow the participants to effectively prepare for the interviews. During the interviews, the structured outline of questions was asked and interviewees often discussed additional topics and issues that were considered to be important and unique to their home states.

The case studies were arranged in mid-August and September 2007 via telephone interviews on personnel responsible for the state safety hardware asset management programs. The interview questions are attached in the Appendix of this report, which consists of twelve questions. Question one seeks information on the types of roadway safety hardware assets managed by the agencies. Questions two and three solicit information on safety hardware performance measures and targets. Questions four and five inquire data collection frequency, coverage, and method; and database management. Questions six and seven investigate safety hardware budget allocation from the central office to regions/districts, and project evaluation and selection. Question eight examines the software systems developed for roadway safety hardware asset management. Question nine asks the opinion of the safety hardware program managers on the extent of success in their programs and on the need for integrating safety hardware management into pavement, bridge, maintenance, and safety management. Questions ten, eleven, and twelve investigate the existing and perceived challenges of system integration on agency's business process, data, and technology. In the end, space was provided for interviewees to supply with additional comments.

In total, 22 experts on traffic safety and safety engineering from the 13 selected states participated in one-on-one interviews. Each session lasted from 40 minutes to one and half hours. The following sections discuss the case study results.

4.3 Case Study Results

The following sections summarize the case study findings based on the interviews with various state transportation agency officials.

4.3.1 Illinois Department of Transportation[1]

The Illinois Department of Transportation (DOT) is maintaining all categories of roadway safety hardware assets on the 16,103 miles of state-maintained highways. The interviews mainly concentrated on various issues related to signs; pavement markings; and guardrails, barriers, and crush cushions.

For sign and pavement marking management, the hardware condition is used as the performance measure and no retroreflectivity readings are tested. In addition to useful service life of guardrails, percentage of corroded area is also used as a performance measure to assess guardrail condition. Generally, guardrails with more than fifty-percent of corroded area are replaced. There is no specific statewide performance targets set up for the management of different categories safety hardware assets.

Sampling has coverage throughout the states, no distinct bias between urban and rural areas, and between Interstate highways and non-Interstates. The data on signs are manually collected and entered in the Microsoft Access database. Currently, the Illinois DOT is in the process of updating sign inventory. For guardrail data collection, video vans are used. Milepost referencing system is currently in use. Individual district offices largely act independently in data collection; they occasionally share information with each other. The DOT central office manages the data collected by district offices in a centralized database.

As far as sign management is concerned, the DOT uses engineering judgment rather than retroreflectivity measurements to assess the performance. Likewise, pavement markings are assessed based on engineering judgment. The DOT conducts crash risk assessment by predicting crash risk as a function of exposure, probability of risk occurrences, and consequence, to evaluate safety performance of several categories of roadway safety hardware assets. The DOT has intension to develop safety performance models for guardrails as a function of guardrail condition and type.

At present, sufficient budget is available to fund safety hardware projects and annual budget appears to be stable. Some safety hardware projects are implemented along with 3R (resurfacing, rehabilitation, and reconstruction) projects. The upkeep of the safety hardware condition through maintenance treatments subsequent to major treatments is critical. There might be shortage of maintenance funds in the future. Once the budget is allocated to various districts, each district is given authority to decide which safety hardware projects need to take up, indicating a decentralized decision-making mechanism for budget allocation.

The DOT officials are in favor of integration of roadway safety hardware management into the overall asset management program. Maintaining compatible and reliable database is essential to the successful integration. However, the uncertainty of future budget and qualified staffing may complicate the

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[1] Respondents: Dave Piper, Bureau of Safety Engineering; and Aaron Weatherholt, Division of Traffic Operations, Illinois Department of Transportation, Springfield, Illinois

integration. Up to date inventory is also hindering the smooth integration process. The lack of communication between central office and districts, movement of staff due to promotion, transfer to different offices within the DOT, and retirement are the problems faced by the DOT in successfully implementing the roadway hardware asset management systems. The officials rate the state safety hardware management program as very successful.

4.3.2 Indiana Department of Transportation[2]

The Indiana DOT is maintaining 11,182 central lane miles of highways and also maintains all categories of roadway safety hardware assets. The maintenance of the assets is done as per the need. The signs are replaced for every ten to twelve years. Signals are replaced for every four years. Lighting is reported as with high maintenance costs and individual lighting systems are replaced entirely.

Safety hardware data are collected on the random sampling basis. The choice of a specific road and of a beginning milepost of the selected road is determined by random number generation. For sign data collection, the drive-through distance of the selected road is usually limited within twenty miles. The condition of every other sign along the road is inspected and the data collection continues until ten signs are encountered. If less than ten sign are found along one direction of the 20-mile road segment, the inspector would then drive on the reverse direction until hitting ten signs. Guardrails are inspected by local crews and the information on deficient guardrails is reported to the DOT central and district offices or to the state police department. The DOT has designated staff continuously driving through the state-maintained roads year-round to check for roadway and safety hardware deficiency.

Data collected by personnel at district and sub-district offices are entered in Microsoft access databases or Microsoft Excel files. The statewide database is maintained by the central office and is updated by district and sub-district offices.

Resource allocation is done by using operational performance indices which are updated continually. The official rated his program as a successful one and also mentioned that the extent of success would be rated higher when the updating of operational performance index system gets fully completed.

The DOT official favors integration. The technology needed for system integration is found not to be a difficult task in the present context. It was also mentioned that creating systems engineer positions to manage various aspects of system operations, especially Intelligent Transportation Systems (ITS)-related signs, signals, and detection devices, are necessary for monitoring and updating safety hardware asset inventory continuously.

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[2] Respondent: Carl Tuttle, Manager, Office of Traffic Engineering, Indiana Department of Transportation, Indianapolis, Indiana

4.3.3 Iowa Department of Transportation[3]

The Iowa DOT manages signs, lighting, pavement markings, and guardrails on the 8,894 miles of state-maintained highways. Signs are visually inspected and pavement markings are assessed by retroreflectivity level. Guardrails are assessed by the adequacy of structure and height as well as corrosion deficiency.

Data are collected each year over 6,000 segments for every one tenth of a mile through automatic collection techniques and the database is decentralized. The asset referencing is based on Geographical Information Systems (GIS). There is no priority given for rural, non-rural Interstate and non-Interstate for data coverage and sampling. The DOT has developed pavement marking management system and the sign management system is nearly ready to use. Some districts are facing difficulties in resource allocation due to lack of qualified personnel to use the software systems for decision-making.

The DOT is in the process of fully integrating safety hardware management into pavement, bridge, and maintenance management systems. The officials ranked their safety hardware asset management as a very successful one. Due to frequent staff position changes, the DOT is facing lack of personnel to carry the program forward continuously. The DOT upper level management is extremely supportive to the concept of asset management and system integration.

4.3.4 Kansas Department of Transportation[4]

The Kansas DOT is managing all categories of safety hardware assets except for ramp metering. The DOT maintains 10,369 miles of highways, a relatively rural state.

The ten-year state highway system program necessitates the replacement of all state-maintained signs for every ten years. Signals which come under the city jurisdictions are installed by city governments, but maintained by the DOT. Guardrails are procured, maintained, and replaced by district offices. Once the contract regarding the replacement of guardrails is awarded, the contractor would take the guardrails and assume the whole responsibility to disposal them.

The DOT uses durable but not extremely expensive epoxy as pavement marking materials. Retroreflectivity is used as a performance measure for pavement marking management, and a reading of 100 millicandelas per square meter per lux or less indicates the need for marking replacement.

The DOT engineer will not examine pavement markings for final acceptance until the pavement markings complete a 180 calendar-day observation period. The contractor is responsible for the performance of pavement markings during this period. The 180-day performance time begins with the day following the completion of the pavement markings. At the end of the 180-day period, the DOT engineer will examine the pavement markings and inform the contractor of all pavement markings required to be replaced. Before the project is accepted, replace all failed pavement markings, at own expense. The pavement markings are considered to be failed, when more than 10 percent of the substrate is exposed in a 2,000-ft section of longitudinal pavement marking line. The transverse lines and symbols will be evaluated separately for the exposure of 10 percent substrate. Abrasion of pavement markings at private entrances or intersections may be excluded from examination.

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[3] Respondents: Ron Beane and William Zitterich, Office of Maintenance, Iowa Department of Transportation, Ames, Iowa

[4] Respondents: Steven Buckley, Highway Safety Engineer; Bureau of Traffic Safety; and Brad Henry, Pavement Marking Specialist, Kansas Department of Transportation, Topeka, Kansas

If the contractor fails to complete the required replacement of pavement markings within 14 calendar days of the examination, during which the application of pavement markings is not precluded by adverse weather or road surface conditions, the DOT engineer, after giving the contractor written notice, will reinstate the assessment of working day charges or liquidated damages. Working day charges or liquidated damages will continue until the work is accepted. If more than 30 percent of pavement markings is required to be replaced, the replacement pavement markings will not be accepted until the completion of an additional 180-day observation period. The engineer will, upon satisfactory inspection of the pavement markings, accept the work and terminate the contractor's responsibilities.

Personnel at district offices will be given training on measuring retroreflectivity by using retroreflectivity readers, thereby contributing to the quality of the readings. The data are collected randomly by following every one tenth of mile irrespective of rural, urban Interstate and non-Interstate highways. In addition to random sampling, both central and district staff drive to any locations and collect readings for internal inspection.

The DOT officials mentioned budget allocated to safety hardware is sufficient. Liability issues from the DOT perspective are reduced by practicing performance-based contracting procedures. However, field engineers are not positively responded to trail new technologies and products. It was revealed that central and district offices often work together and this has helped make the safety hardware management program very successful. It was mentioned that pay-off of systematic hardware management is very high though upfront cost is relatively high and the officials are in favor of system integration. Performance-based contracting is helpful in transferring part of the risk of safety hardware management from the DOT to the contactor. Following good warranties will be helpful in achieving good quality of the work. Lack of qualified staff will hinder the practice of a successful safety hardware asset management program.

4.3.5 Michigan Department of Transportation[5]

Michigan DOT is maintaining all categories of roadway safety hardware assets on the 9,697 miles of state-maintained highways. The DOT has a three tier organizational structure, including the central office, thirty four regional offices, and transportation service centers. The DOT does not have explicitly expressed performance measures and targets. The hardware data are collected by transportation service centers, but maintained by the central office. Whenever there is a need to replace a hardware asset, it can be handed over to regional offices. Transportation service centers lack standards and guidelines, this to some extent has affected the quality of data collection. Sign inventory database is centralized, but has not been completely developed. Only lighting on freeways is state maintained. The DOT also manages ramp metering. The maintenance of guardrails is done by linear foot measurement. In 2006, Guardrail inventory, covering information on location, type, and length, was completed. The existing issues of database management are timely updating the data, and the lack of full automation for data collection. Some of the other challenges encountered are locating the hardware assets, improving data quality, and accurate information on maintenance activities.

The DOT currently uses both milepost and GIS-based referencing systems. There exists an interoperability issue for integration due to lack of a unique referencing system of the highway assets.

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[5] Respondent: Ron Vibbert, Manager, Asset Management Section, Bureau of Transportation Planning, Michigan Department of Transportation, Lansing, Michigan

Specifics of such issues may include making an integrated decision by combing all relevant data together, data sharing across various departments, and data errors.

The DOT is moving towards integration. The DOT official indicated that the technology needed for system integration is not an issue, but the problems are concerned with the agency culture in support of inter-office information sharing. The DOT's Local Technical Assistance Program (LTAP) Center works closely with regional offices and transportation service centers and is capable of developing the required software systems for integrated roadway safety hardware management. The DOT official further noted that implementation of asset management principles to roadway safety hardware asset management is paying rewards. For integration, inventory and data collection need to be improved. Safety implications after practicing roadway safety hardware asset management program are not known. The official commented on the issues of how to allocate resources between roadway safety hardware assets and other typical highway assets in a balanced manner. Developing a sound cross-asset tradeoff analysis methodology is essential to address this issue.

4.3.6 Minnesota Department of Transportation[6]

The Minnesota DOT is maintaining all categories of safety hardware assets on the 11,872 miles of state-maintained highways. The state manages approximately 400,000 signs and each piece is worth about two hundred dollars. Safety and warning signs and information signs are separately handled in the sign management system, with a higher priority given to safety-related signs. Signs are replaced every twelve years, and each year one twelfth of the signs on the state-maintained roads are replaced. A sign gets timely replaced if it is damaged by a vehicle crash, which does not need to follow the 12-year cycle. There is no rigid performance targets fixed for assessing different categories of safety hardware assets.

In urban areas, data on signs and detection devices are provided by a vendor. At the regional level, data are collected by in-house staff. Data are collected bi-annually and Interstate highways are given a higher priority. Sometimes, the quality of the data is one of the DOT's concerns.

The DOT central office allocates available budget to the regions. The database is both GIS- and GPS-referenced and maintained by the central office. At present, only some of the eight DOT regions are maintaining their own sign management systems. The DOT has decided to develop a pavement marking management system customized from the pavement marking management system developed in Iowa.

The DOT officials provided mixed responses to the idea of system integration. The upfront issues are agency-wide standardized processes for hardware replacement, use of common terminology, and update of system information. However, the main reason is that even though the idea of system integration appears to be sound, the cost involved would prohibit such effort, at least according to the current budget situation. The action oriented towards system integration is resource driven.

The DOT officials mentioned practicing a cautious approach in choosing software systems for hardware management. For instance, the DOT did not build the sign management system from scratch. The potential vendors were invited to show demos of software capabilities and the vendor was finally selected through fairly intensive competition. The DOT officials emphasized the importance of consistency among procedures and standards; organizational support in terms of communications and resources; and long-

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[6] Respondents: Ralph Adair, Metro Traffic Operations Engineer; and Susan Groth, Assistant State Traffic Engineer, Office of Traffic Safety and Operation, Minnesota Department of Transportation, St. Paul, Minnesota

term commitment of personnel to continuously monitor and update the safety hardware system. In addition, the issue of interoperability of the deployed system based on the current technologies and system upgrade using the new technologies must be thought through before developing any new software systems. The current safety hardware management program is rated as a very successful one. It was mentioned that ITS-related hardware installations should not be integrated.

4.3.7 Missouri Department of Transportation [7]

The Missouri DOT maintains all categories of safety hardware assets on the 32,465 miles of state-maintained highways except for ramp metering. No benchmarks or performance targets are set for the management of roadway safety hardware assets.

The data are collected yearly and data collection is carried out alternatively at day time and at night using random samples, respectively. The safety hardware data are collected purely by in-house staff and it is shared between the central and district offices. Data collection is administered by district offices. Sign retroreflectivity is measures at nighttime. The DOT just began to practice the replacement of sings for every ten years. The DOT has purchased a van for measuring retroreflectivity of pavement markings. The use of durable epoxy type materials or regular materials for pavement markings is largely dependent upon traffic volume. The DOT is the very first in the country to have adopted cable guardrails. As of today, 500 miles of cable guardrails have been installed. The guardrail inventory is well maintained, but the tracking of crash cushions and barriers are not as effective. In the current practice, the selection of safety hardware projects is mainly based on expert opinion.

The DOT has developed a software tool, called the *Tracker* system, to assess how well the DOT delivers services and products to its customers. The system uses eighteen performance goals that are expected by the DOT customers and are also fulfilled by the DOT: i) uninterrupted traffic flow; ii) smooth and unrestricted roads and bridges; iii) safe transportation system; iv) roadway visibility; v) personal, fast, courteous and understandable response to customer requests; vi) partner with others to deliver transportation services; vii) leverage transportation to advance economic development; viii) innovative transportation solutions; ix) fast projects that are of great value; x) environmentally responsible; xi) efficient movement of goods; xii) easily accessible modal choices; xiii) customer involvement in transportation decision-making; xiv) convenient, clean and safe roadside accommodations; xv) best value for every dollar spent; xvi) attractive roadsides; xvii) advocate for transportation issues; and xviii) accurate, timely, understandable and proactive transportation information. In each quarter, a *Tracker* report is published to allow the DOT customers to see the progress the DOT is making towards achieving those goals that they expect. According to the latest issue of the quarterly report, there is no issue concerned with budget allocation for sign management, but the timely update of data on signs is much more of a concern. Also, it is shown that there is a need to continuously monitor and replace the deficient portions of pavement markings. Sign and signal management are rated as successful.

The DOT has developed the GIS-based, fully integrated transportation management system that brings together information on all categories of highway assets, including pavements, bridges, crash records, safety hardware, and so forth. This has laid the foundation for system integration. It was recommended to refine the list of data collection items as we move toward system integration. Continuous update of the

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[7] Respondents: Brian E. Chandler, Traffic Safety Engineer, Traffic Division; Matt Myer, District Traffic Engineer, Central District, Missouri Department of Transportation, Jefferson City, Missouri.

inventory data, and consistency of data referencing, and data quality are some of the challenges mentioned.

4.3.8 Nebraska Department of Roads[8]

The research team received information only on guardrail management associated with 9,975 miles of state-maintained highways from the agency interview. Guardrails performance is assessed in complaisance of the National Cooperative Highway Research Program (NCHRP) Report 350. There are no distinct performance targets set up.

Five to six maintenance supervisors are exclusively designated and given responsibility to update the database covering statewide guardrail data. The data on guardrail type and location with GIS referencing are entered and maintained in Microsoft Excel files. The Nebraska Department of Roads (DOR) is practicing replacement of all guardrails for every twenty years and the replaced guard rails are salvaged at the DOR's maintenance yards. Currently, data are collected manually, and the DOR is in the process to complete the GIS-based database to facilitate automatic guardrail management. Guardrail maintenance and repair needs are largely determined by expert judgment. In addition, guardrails in the vicinity of a new construction or a 3R project are replaced.

The challenges being faced are having guardrails designed as per the NCHRP Report 350 requirements, timely inspection and replacement of guardrails, database update, and funding resources.

4.3.9 North Dakota Department of Transportation[9]

The North Dakota DOT is maintaining all safety hardware assets related to the 7,381 miles of state-maintained highways, excepting ramp metering. The conditions of the safety hardware assets are assessed in terms of the severity of wearing and traffic volume. The DOT does not have any rigid rules on performance targets. Signs are replaced after every 7 to 10 years. If signs are in the vicinity of road work they will be inspected and possibly replaced. Signals only on the Interstates are maintained by the state DOT. Signals on the Interstates are checked project by project, but treatments are made in bulk. The DOT staff regularly checks the lighting posts. Detection devices such as loop detectors and video detection devices are check as needed. Painting, epoxy, and plastic materials are used for pavement markings. Guardrails information is collected project by project, and they are assessed in compliance of NCHRP 350.

The data are generally collected manually and are maintained centrally. No systematic software system has been developed for signals and lighting. Investment decisions are based on engineering judgment and are taken year-by-year. District offices will send a priority list of projects which are proposed to be taken in the next three to five years to the central office. Then central office checks the computed project costs and types of projects proposed and, accordingly, budget is allocated. The overall rating of the roadway safety hardware asset management program is very successful. The DOT in-house staff provide technological support. The official expressed the intension of integrating safety hardware assets into the management of other categories of highway assets. The collection and updating safety hardware asset

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[8] Respondent: Phil Tenhulzen, Design Standards Engineer, Roadway Design Division, Nebraska Department of Roads, Lincoln, Nebraska.

[9] Respondent: Doug Schumaker, Traffic Safety Engineer, Design Division, North Dakota Department of Transportation, Bismarck, North Dakota.

data, vendors, human resources, and lack of specifications and guidelines are mentioned as some of the challenges for successful implementation of integrated roadway safety hardware asset management.

4.3.10 Ohio Department of Transportation[10]

The Ohio DOT is maintaining all categories of roadway safety hardware assets on the 19,291 miles of state-maintained highways. Inventory and data update are mainly carried out by in-house staff. Data are sampled randomly over eighty-eight counties. Signs are replaced for every fifteen years and the information on sign installation and maintenance history can be identified by the back side sticker of each sign. Signs have inventory database and are inspected yearly.

Signals are inspected yearly and repaired or replaced as needed. The DOT uses conflict monitor grade scale from one to six to assess the performance of signals. The performance target mentioned was a scale of four. The DOT in-house staff developed Ohio Signal Inventory System (OSIS) in Java for signal management. The system stores information on location, devices, signal heads installed, coordinated systems, detectors, pedestrian operations, and agencies that own, maintain, and pay for the signal system. The system also stores information on the electric, telephone (if a modem is installed), and railroad (if the signal system is less than 200-ft from a railroad crossing) companies. Photos, project plans, and maintenance history of the intersection are also stored in the system. The entire OSIS application is comprised of three modules: i) the OSIS main application where the user can enter all the information about the traffic signal; ii) the laptop inspection module to enter inspection detail at the signal site without connection to the DOT Intranet; and iii) a web site dedicated to the system where the users can get the most recent information, download the new version, and access to some system features.

Lighting inventory is updated for every quarter period. Only the detection devices on freeways are maintained. Pavement markings are inspected yearly by driving through a road segment; no retroreflectivity readings are measured. Ramp meters on freeways are maintained as a part of freeway management system.

There is no agency-level guideline for resource allocation, which is usually done by engineering judgment. All twelve districts maintain their own autonomous resource allocation procedures. The DOT officials are not in favor of integration due to raising speculations of attributing more responsibilities on staff by integrating various management systems. Continuous updating inventories and lack of staff are some of the challenges mentioned. There appears to be not many benefits by considering roadway safety hardware assets in the 3R process. Overall rating given by one interviewer is very successful and other is neutral. The DOT officials mentioned the existing software systems are sufficient but a lot of improvements are still needed. Other comments provided include organizational structure, consistency in data, participation of local agencies to update inventory, lack of information on some aspects of the safety hardware management, and willingness to adopt for new technologies and products.

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[10] Respondents: Kevin Duemmel, State Traffic Engineer, Office of Traffic Engineering; Homer Suter, Assistant Office Administrator, Office of Traffic Engineering, Ohio Department of Transportation, Columbus, Ohio.

4.3.11 South Dakota Department of Transportation[11]

The South Dakota DOT is maintaining all categories of roadway safety hardware assets on the 7,871 miles of state-maintained highways, excepting ramp metering. Inventories of signs and signals exist and the rest does not have a comprehensive inventory, but the DOT is seeking to develop a statewide inventory for pavement markings and guardrails, respectively.

The age of signs is used as a performance measure for assessing sign condition. Sign inventory data are collected by local offices, but maintained by the central office. Data are collected manually and updated annually. The DOT is treating rural, urban Interstate and non-Interstate highways equally for data coverage. Signs are inspected visually during night times. Currently, signs are referenced by milepost, and the DOT is seeking upgrading the referencing to GIS-based system. The sign and signal inventories are new and contain a lot of data information. The DOT official mentioned the need to integrate sign and signal inventory data with their historic maintenance data. The problem with data is timely update the inventory.

The budget is allocated to the projects based on the "worst first" approach. Budget for roadway safety hardware assets is specified in maintenance budget category. Each year at least ten percent of the signs are replaced, until all signs are maintaining at or above the minimum acceptable standard. Moreover, the replacement of signs is on the case by case basis. Within the signs, STOP and YIELD signs are given the highest priority than other signs. Still, no rigid rule exists for allocating budget.

The rating given for both sign and signal management system is neutral. There exists inconsistency among installation, design, and operating procedures of a safety hardware asset management system. Trade-off decision like, spending a lot of money on high quality pavement marking materials which will yield moderate increase in the service life, making a decision process very complex.

The DOT is in the favor of integration. Some of the challenges mentioned are: data accuracy and updating, balancing resources among other highway asset categories, and lack of qualified personnel. Continuous change of positions among staff will hinder the progress of the work and will affect the quality of the end product. The DOT mentioned that they are not facing any institutional related problems. The DOT is cautious about warranty based contracting by mentioning the problems like, contractors are quoting higher rates and unknown about the implications of warranty contracts.

4.3.12 Tennessee Department of Transportation[12]

The Tennessee DOT maintains signs, pavement markings, and guardrails on 13,818 miles of state-maintained highways. The sign inventory data are updated for every year. The DOT is practicing replacing the defective parts of the signs not entirely signs. Signs and pavement markings are assessed mostly by retroreflectivity measures in compliance with Federal requirements.

Data collection is done by both vendor and in-house staff. The Tennessee DOT is using NABSTAR software developed in Austin, Texas to facilitate automatic data collection. This software not only allows entering the feature descriptions and present condition of the hardware assets, but also voice data about a

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[11] Respondents: John Adler, Traffic Safety Engineering Specialist, Operations Support Office, South Dakota Department of Transportation, Pierre, South Dakota

[12] Respondent: Christopher Harris, Civil Engineering Manager, Maintenance Division, Tennessee Department of Transportation, Nashville, Tennessee

particular feature. Data are milepost referenced and the DOT is planning for GIS-based database management systems. The DOT is trying to develop a comprehensive sign, pavement marking, and guardrail management system at a full scale. The DOT expressed the possibility of expanding existing software system and insisted the compatibility of the software with the updated technologies. Though Interstates are being given a higher priority, there are no distinct rules developed for data sampling among rural, urban Interstates and non-Interstate highways.

Tennessee had a good maintenance management system (MMS) that uses maintenance rating index as a performance measure. The budget for signs, pavement markings, and guardrails is mentioned as a line item in maintenance management. Maintenance and repair needs for signs, pavement markings, and guardrails are reported by field staff. Funds for upgrading guardrails come form safety management fund. The DOT is practicing replacing all the sings for every twelve years. Sign management on the Interstate highways has been given a higher priority. Four regions of the DOT prepare a list of projects submitted to the central office for possible implementation. It was mentioned that projects are not evaluated based on engineering economic analysis, but they are prioritized by the extent of damage done to safety hardware assets. Based on prioritization and the need, the budget is allocated to different safety hardware projects. Each year customer satisfaction survey is conducted to get the feedback from the road users on the functioning of the transportation system.

The Tennessee DOT is in favor of integration. The maintenance and repair related work is done by both in-house and sub-contractors. Some issues of quality of products obtained from both type of personnel are identified. The DOT is trying hard to integrate man power, equipment, and material management as part of maintenance management. Maintenance inventory of all features is challenging after integration and database update is a daunting task. Funding and lack of qualified and experienced staff are hindering the smooth progression of the safety hardware asset management.

4.3.13 Wisconsin Department of Transportation[13]

The Wisconsin DOT is maintaining signs, pavement markings, and guardrails on the 11,781 miles of state-maintained highways. The Compass program is the DOT's quality assurance and asset management program that allows for sound communication, accountability, and decision-making. Through this program the performance of traveled way, traffic management and signs, safety devices, shoulders, drainage and roadsides, winter operations, bridges, and customer satisfaction are gauged each year and they are compared with the set targets. The quality assurance phase of Compass program was launched in Fall 2002. This phase provides a quantitative measure of asset performance and also specifies how close the performance is with the set targets. The program helps in communicating with customers and legislators about service options, in prioritizing maintenance activities, in focusing on the resources most needed, and in illustrating the costs and benefits of different choices constrained by limited resources.

Data on signs consist of age, condition, type of material, and winter operation information. The DOT maintains both pavement marking and guardrail data. To ensure data quality, the personnel involved with data collection are trained and certificated every year. Districts and counties jointly manage data. Data are collected manually, maintained in electronic files, and updated every two years. The DOT has five

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[13] Respondents: Mike Adams- Road Weather Information System Program Manager, Scott Bush- Compass Program Manager, Mike Sproul, and Cheryl A. Sulzer- Level of Service Program Manager, Bureau of Highway Operations, Wisconsin Department of Transportation, Madison, Wisconsin

regions and data on approximately 240 one-tenth-mile segments are collected per region per year, which gives data information on approximately 1,200 one-tenth-mile roadway segments.

The DOT developed a level of service (LOS) model for allocating budget to counties on more equitable basis and give rational output based on system size and needs. Safety, riding comfort, preservation of investment, aesthetics, user costs, user convenience, stewardship, and emergency response due to severe weather conditions are the factors considered in the LOS model.

As one required input of the LOS model, the DOT also developed Winter Severity Index (WSI) that could be applied to all counties, as a part of maintenance management. This index would help the maintenance authorities to prepare well for winter maintenance operation throughout the state. This index uses the following information: winds, pavement temperatures, snow amount, number of snow events, number of freezing rain events, and total storm duration. The first step is to determine which factors need to consider for a given situation in developing an index. Then correlation coefficients are developed between each of the identified weather factors and the cost factors, as well as a total cost factor. Based on the correlation coefficients between the weather factors and total cost, weights of importance are assigned to the weather categories. These weights are calculated by assigning the highest correlated criteria a value of 10 and then assigning a weight to the others based on the ratio of the respective correlation coefficients. In each of these weather categories, each county's value is compared to that of the county with the maximum value in the category during the analysis period. Then, each county's value in a particular category is normalized by dividing the maximum value. The percentages are multiplied by the weighting factors for each category, then these numbers are added together to get a total. These numbers are normalized to a 30-point scale in order to come up with numbers that can easily be compared to the 30-storm average now being used in the LOS model.

The DOT official mentioned the existing safety hardware management program is very successful. The DOT is in favor of partially integrating the safety hardware asset management into the overall pavement, bridge, and safety management program. The current Compass program and the LOS model offer opportunities for system integration. The DOT officials mentioned the need for developing optimal maintenance options with minimum political influence. In particular, the DOT is interested in assessing the impact of varying budget levels on the preservation of statewide roadway safety hardware assets.

4.4 Summary and Concluding Remarks

4.4.1 Case Study Summary

Case studies examined roadway safety hardware asset management programs at the state transportation agencies in the Midwest region and state of Tennessee. The major findings are summarized as follows:

- State transportation agencies have developed performance measures to evaluate some roadway safety hardware assets. Safety hardware condition and useful service life (or age) are commonly used as the performance measures for signs and signals. Retroreflectivity is used as a performance measure for signs and pavement markings. Some agencies have adopted percent of loss of painting as a performance measure for pavement markings. Structural height, lateral deviation, and percent of corroded area are used as performance measures for guardrails. However, no distinct measures are used for detection devices and lighting. Few states are managing ramp meters.
- No distinct performance targets are used to evaluate the efficiency and effectiveness of the roadway safety hardware asset management program.
- In general, roadway safety hardware data are collected by field staff using both manual and automatic collection methods and maintained by the central office. The data are not fully GIS-referenced. Many agencies have not differentiated data sampling for rural, urban Interstates and non-Interstates. Wisconsin DOT has implemented a training program to train data collection personnel to ensure data quality. Certificates are issued to the trainees. Only certified personnel are allowed for data collection and certification is required to be renewed every year.

- Most of the states allocate safety hardware management program budgets according to expert opinion. There are a few exceptions. For instance, the Wisconsin DOT uses a LOS model for allocating budget to counties in an equity manner. The Illinois DOT has developed risk assessment scales by predicting crash risk as a function of exposure, probability of crash occurrences, and consequence to evaluate safety performance of several categories of safety hardware assets. In some states, safety hardware projects are implemented along with 3R or maintenance projects, indicating integrated resource allocation. These approaches offer new opportunities to develop more sophisticated methods for evaluating and selecting safety hardware projects jointly with other types of highway projects.
- Many states have developed individualized software systems to manage one or more categories of safety hardware assets. None of these software systems has been integrated. In most cases, the software systems were developed by vendors.
- A majority portion of the states rated their current roadway safety hardware management programs as being successful.
- Based on the case study findings, ten of the thirteen states are definitely in favor of system integration. A few states have developed integrated database management systems that have laid the foundation towards the integration of roadway safety hardware management into the overall asset management program. For instance, the Iowa DOT is in the process of fully integrating the safety hardware management into the overall pavement, bridge, and maintenance management program. The Missouri DOT has a comprehensive GIS-based transportation management system that contains information on all categories of highway assets.
- Technological requirements for integration appear not to be challenging. Major concerns of integration come from the agency culture for acceptance of integration that requires extensive inter-office information sharing, availability of funding resources, as well as sufficient, stable, and competent personnel that are crucial in maintaining data collection quality, timely updating database, and making sound investment decisions.

4.4.2 Recommendations for Future Work

Based upon the case study findings, the following conclusions are drawn:

- Even though performance measures are being adopted by state agencies for assessing various categories of roadway safety hardware assets, there is a lack of consistency in those performance measures. IN addition, the case study findings reveal that performance targets need to be established to assess the efficiency and effectiveness of the roadway safety hardware asset management.
- The quality of data collection needs to be maintained by adopting automated data collection techniques and using adequately trained field staff.
- The scattered data sampling covering the entire region or the state is essential to nullify the spatial variations in the data coverage. The continuous update of data will ease the gaps in the historical time series data. Consistent data collection frequencies, data collection methods, and sampling procedures need to be developed.
- Many state transportation agencies are maintaining centralized databases, but timely update of the databases is hindering the successful and continuous implementation of the safety hardware asset management systems. Efforts are needed, probably at the regional or district level, to ensure the continuous update of the databases. The interoperability of database management by various DOT offices needs to be maintained. The database management system shall be upgradeable to benefit from technological advances.
- The maintenance, repair, and replacement of safety hardware assets are being conducted mostly by engineering judgment. There is a lack of consistent methods for safety hardware project evaluation. These methods shall be able to support tradeoff analysis of safety hardware projects with other types of highway projects. Risk- and uncertainty-based project evaluation procedures are gaining popularity to realistically capture the changes in the input parameters of the project evaluation. Budget uncertainty

over the project selection period is often encountered. The new methods shall also handle risk and uncertainty cases in a consistent manner.

- The agencies need to recruit competent staff to continuously monitor and manage the roadway safety hardware assets. If staff changes are unavoidable, guidelines and manuals need to be developed to help new staff quickly follow the program management.
- As experienced by some of the states, performance-based contracting could help achieve the safety hardware management goals more cost-effectively.
- States are generally in favor of integration. Issues of organizational culture, funding resources, and staffing must be adequately addressed.
- Integrated resource allocation of the roadway safety hardware projects along with maintenance projects has been made using maintenance management systems. Such integration needs to be expanded to facilitate integrated investment decision-making involving all other categories of highway assets. This involves expanding the maintenance management systems to an overall highway asset management system that uses an integrated database, maintains consistent evaluation of various types of highway projects, and enables tradeoff analysis of different types of highway projects in resource allocation.
- Like the existing asset management programs dealing with pavements, bridges, maintenance, and safety, maintaining an intra-agency feedback process is essential to ensure the success of a roadway safety hardware asset management program.

CHAPTER 5:
INVENTORY PROCESS, PERFORMANCE MEASURES, DATA INTEGRATION, AND DATABASE MANAGEMENT

5.1 Inventory process

The implementation of a roadway safety hardware asset management program needs a comprehensive inventory of the roadway safety hardware assets. The inventory process must be developed with a well-defined plan for the use of each data element collected. To provide the agency with the support needed in the decision-making process, it is important to determine what data need to be collected, how the data will be used, and how and when the data collection will be done. This ensures that the types of data collected can be used in the decision-making process, and eliminates the collection of needless data that is costly in both dollars and time. Several factors should be included when deciding what data to collect are:

- What decisions are going to be made?
- What data is necessary to make those decisions?
- Size of the system,
- Type and characteristics of the agency,
- Type and cost of data acquisition and processing,
- Required data accuracy,
- Required frequency of data collection,
- Database capabilities.

5.1.1 Data Needs

The data items to be collected and included in the database will depend on the management analysis needs of the agency, which in turn will depend on the types of infrastructure, available resources, and organizational units that will use the data. Data needs of a typical RSHAM program can be classified as:

5.1.1.1 Roadway Inventory Data

Road classification data include data items such as functional class of road, identification codes, location, history of construction and rehabilitation, and geometrical characteristics such as divided/undivided roadway, number of lanes, lane widths, shoulder widths, radius of curves, and degree of curvatures. Pavement data items include pavement type, layer thickness and materials, overlays, and drainage.

5.1.1.2 Traffic-Related Data

Traffic volume and composition data are obtained from traffic counts and surveys. Included are data on Annual Average Daily Traffic (AADT), traffic composition of different vehicle types, lane distribution, and directional distribution of different vehicle types. Where available from Weigh-in-Motion (WIM) stations or surveys, data on the axle load distributions of the axle groups of different vehicle types should be included in the database.

5.1.1.3 Accident Data

Traffic accident data can be useful to identify the causes of accidents, to improve geometric designs, and to estimate accident cost impacts of different alternatives.

5.1.1.4 Pavement Condition Data

Pavement serviceability data are usually measured in terms of pavement roughness. Rougher pavements have consequences for excessive vehicle operating costs, such as tire wear and vehicle maintenance, as well as for passenger riding comfort. These effects also depend on the pavement type. Skid resistance is an important pavement characteristic influencing safety. Skid resistance is measured by a coefficient of friction or a skid number, which depends on the amount of water on the pavements. Pavement

serviceability measures the acceptability of rid quality of a road to the users. As roads are provided to serve the users, pavement performance represented by its serviceability history is a useful and meaningful indicator to engineers concerning the state of health of pavements. Pavement serviceability is highly correlated to pavement surface roughness. It can either be measured directly from users rating surveys or be computed from measurements of pavement surface roughness.

5.1.1.5 Climatic and Environmental Data

Data on climatic conditions, such as precipitation, temperature variation, and freeze-thaw cycles are useful to develop models to predict pavement deterioration. Pavement and subgrade characteristics such as drainage coefficients, modulus of resilience should also be taken into account.

5.1.1.6 Productivity Data

Data on the resource requirements of standard activities are used to estimate the resource needs and costs of alternatives. Resource needs of activities include manpower requirement by size and profession, material requirement by type and quantity, equipment requirement by type and number, time requirement, and money requirement.

5.1.1.7 Other Data Needs

In addition to the above-mentioned data needs, data items listed in Table 5.1 are needed for inventory of roadway safety hardware assets.

TABLE 5.1. Data Needs of a Roadway Safety Hardware Asset Management System

Safety Hardware Asset	Data Requirement
Signals	Type and service life of the structural support, service life of signal heads, bulbs, and signal controller, maintenance history, condition of the signal
Signs	Type and service life of sheeting and painting material, font size, visibility, retro reflectivity of signs, and maintenance history
Lighting	Type and service life of structural support and lighting bulbs, level of illumination of the bulbs, maintenance history, spacing between lighting poles
Detection devices	False alarm rate, life of the detector components

5.1.2 Data Collection

Data collection should be separated into two levels. The network-level data should answer the general planning, programming, and policy decisions supported by the network-level asset management. The project-level data should support decisions applicable to a selected section of the network. As data are collected, selected elements can be stored to create a more complete database over time. However, a plan must be developed to keep that data current.

Typically, when an agency decides to implement a RSHAM program, the first issue to be addressed is what kind of data should be collected. Usually, this is done through a committee composed of various personnel who will sit down and develop a wish list of data they would like to collect. Another common approach is to try to use data that already exists to build a RSHAM program. Data collection is time-consuming, expensive to store, and expensive to analyze.

Infrastructure data collection has been an ongoing process since the 1960s. Collecting condition information is generally the most costly part of the initial implementation of a roadway safety hardware asset management program and of continued operation. In general, the detail and accuracy of data collection varies from very detailed for research activities to very gross for some network-level management systems. It is not necessary to collect all of the data at each level.

Many different methods are available to collect each of these condition measures. Some methods are also usually more accurate, more precise, and have the greatest resolution. Accuracy is the degree to which the method provides a true value. Precision is the repeatability among multiple measurements. Resolution is the smallest increment that can be measured. The precision, accuracy, and resolution needed depend on

the goals of a particular asset management system and the budget availability. Some methods are more subjective than others.

5.1.2.1 Data Collection Methods

In the last decades, various methods and technologies used have shown a trend towards automation and computerization. Methods used for the collection of asset management data include: i) manual, ii) automated, iii) semi-automated, and iv) remote collection. Regardless of the method used, the existence of an effective Quality Control/Quality Assurance (QC/QA) program is vital for the success and reliability of the collection. A brief description of each method is presented in the following sections.

5.1.2.1.1 Manual Collection

The method employs two or more data collectors and a distance-measuring device. The collected data are documented either with pen and paper or in most recent cases with hand-held computers equipped with Global Positioning Systems (GPS) (Czerniak and Reilly, 1998). The data collectors walk from one site to the other, and inspect and record the condition of the considered assets. A variation of this method, the windshield survey, uses a vehicle to perform the inspection while driving along the travel line; the recording is still done manually. Manual surveys allow for very detailed data collection but are very labor intensive and require more time per asset than automated or semi-automated methods.

5.1.2.1.2 Automated Collection

The method involves the use of a multi-purpose vehicle that is equipped with a distance-measuring device, digital video cameras (downward and/or forward looking), a gyroscope, laser sensors, computer hardware and potentially GPS antennas in order to capture, store, and process the collected data. The gyroscope and GPS are used to capture location data. The laser sensors are used to acquire pavement surface properties and the downward looking cameras are used to assess pavement surface properties (usually distresses). The forward-looking cameras are used to determine the location of roadside assets and assess performance measures. Specifically developed software is generally used in order to visualize in three dimensions the location of the transportation assets from the digital two-dimension frames. The newest data collection equipments have achieved high automation and accuracy and are capable of very fast and comprehensive data collection. In most cases, however, even with the use of automated methods, some post-processing of the data is required.

5.1.2.1.3 Semi-Automated Collection

This method involves similar equipment as the completely automated method but with a lesser degree of automation. It is very popular within transportation agencies and yields comprehensive and accurate data collection when properly implemented.

5.1.2.1.4 Remote Collection

This last method pertains to the use of satellite imagery and remote sensing applications. These methods involve high resolution images acquired through satellites or other types of images and scans obtained by remote sensing technologies (lasers, aerial photos, etc.). The images are used in conjunction with ground information in order to reference the location of the transportation assets and to assess asset condition or capture various asset attributes and characteristics.

5.1.2.2 Automated Data Collection of Roadway Signs and Markers

Various kinds of reflective sheeting are used on road signs and markers to enhance the readability and perception of information displayed during low light and nighttime conditions. Unfortunately, the effectiveness of these reflective materials tends to deteriorate over time. Retroreflectivity (defined as the ability of a material to reflect incident light back towards its source), specified in candelas per lux per square meter (cd/lux/m^2), is an important characteristic utilized by transportation agencies to assess the nighttime visibility of road signs.

5.1.2.2.1 RetroView

Mandli Communications (http://www.mandli.com/systems/retro.php) has developed RetroView™ and RetroCurve™, an automated system that provides a safe, cost-effective method to measure the Retroreflectivity of the signs and markers. Accurate reflectivity data can be collected from a moving vehicle, called as Digilog VX data collection system, traveling at posted road speeds. Luminance values are determined on the- fly using an active infrared light sensor triggered at periodic intervals along a route along with a high-intensity black and white digital image.

5.1.2.2.2 Digital Imaging

The camera is attached to an adjustable mount inside the vehicle on the front windshield for easy access and protection from outside elements. The camera is positioned at driver's eye level with a right-of-way view. This field of view includes the lane of travel, street signs, guide signs, mile markers, pavement markings, and overhead signs. When the system has a second camera installed, this camera is also mounted at driver's eye level, but angled to the right approximately 55 degrees (http://www.mandli.com/systems/retro.php). The dual camera extended field of view includes guide signs, roadside features, billboards, vegetation, and terrain. The camera positions are fully adjustable and can be locked once the desired position is acquired. The data collection software, DVX, is designed to handle up to four cameras simultaneously.

5.1.2.2.3 RetroChecker RC 2000

The RetroChecker RC 2000 (http://www.mechatronic.de/01firma/en/index_firma_en.html) is a convenient rechargeable measuring instrument for the determination of the coefficient of retroreflection of retroreflective materials (nighttime visibility). Additional equipment like data storage, GPS, barcode reader and corresponding software are embedded with the RC 2000 to build up a comprehensive traffic sign inventory. To carry out a measurement the RC 2000 is positioned directly on the traffic sign under examination and it immediately delivers results with laboratory precision. GPS data for localization and bar codes for identification of traffic signs are recorded and stored automatically and can be transferred to a PC via a serial interface. The RetroChecker RC 2000 can be used for all types and colors of retroreflective sheeting.

5.1.2.2.4 Line-Inspector

The Line-Inspector (Vonderohe et al., 1993) combines precision measurement of the nighttime visibility (R_L) and the daytime visibility (Q_d) in one compact instrument. It is suitable for all types of road markings - smooth, textured, profiled colored or white, with or without aggregates and reflective beads, for wet and dry measurement.

5.1.2.2.5 RoadVista Model 922

The RoadVista Model 922 (http://www.roadvista.com/products/model922.shtml) is a handheld sign retroreflectometer designed for use in the field. It is designed to measure the retroreflection (R_A) of road signs and other materials. Utilizing the ASTM standard annular geometry, the 922 measures observation angles of 0.2 degree and 0.5 degree simultaneously, with an entrance angle of -4 degrees.

5.1.2.2.6 RoadVista Model 1200F

The new RoadVista model 1200F (http://www.roadvista.com/products/model922.shtml) is the retroreflectometer designed for use in field measurements of Raised Retroreflective Pavement Markers (RPMs). It is designed to measure the retroreflection (R_I) of all RPMs. An internal GPS and printer come standard allow the field user to quickly verify the data. The internal memory will store up to 10,000 measurements before downloading to a computer. The 1200F connects to any standard computer using an RS-232C interface. Our mapping software allows the user to plot the data on a clickable and printable map to quickly identify problematic areas that need attention.

5.1.2.2.7 StripeMaster II

The StripeMaster II (http://www.roadvista.com/products/model922.shtml) measures retroreflectivity of pavement markings accurately on wet or dry surfaces and it has an RS-232C interface that allows data to be downloaded into any traffic inventory system. The StripeMaster II is designed for quick and easy measurements with the touch of a button. An internal GPS and printer come standard, allowing the field user to quickly verify the data. The internal memory will store up to 10,000 measurements before downloading to a computer.

5.1.2.2.8 Model 930C

The Model 930C Laboratory/Field Retroreflectometer (http://www.roadvista.com/products/model922.shtml) provides a convenient, handheld way to inspect new retroreflective materials and signs as well as determine degradation resulting from weathering at many different observation and entrance angles. Its accuracy is more than adequate for over 90 percent of all field inspections. The system includes three ranges of sensitivity, an entrance angle attachment and two sets of standards of all colors in engineering and high intensity types. The optical head observation angle is continuously adjustable from 0.2 degree to 2.0 degrees. The light sensor meets the requirements of a match to the CIE standard human eye. A photometric filter fit allows accurate measurements of other colors when the 930C is standardized using the white calibration reference. Power the system via the standard 110/220 VAC supply or the included DC battery pack. If field measurement is needed for high-mounted traffic signs, the Model 907-30 extension pole kit is recommended.

5.1.2.2.9 Laserlux® CEN 30 Mobile Retroreflectometer

The Laserlux® CEN 30 mobile retroreflectometer (http://www.roadvista.com/products/model922.shtml) is the sophisticated mobile highway retroreflectometer system with proven optical head technology and the system objectively measures the retroreflectivity of pavement markings using a scanning laser source. The system ensures that measurements are collected quickly and accurately by incorporating new high-speed data acquisition electronics and software, and precise angular settings of illumination and angle of observation. The system provides real-time pavement marking reflectivity and can be used either day or night at variable traffic speeds. Designed with CEN 30-meter geometry, the system has a scan width of 1.1 meters, giving the user both contrast and retroreflectivity measurements anywhere within the scan width. Features include Windows 98/ME/NT/2000/XP-based graphical data logging software with a GPS for location data logging, mounting brackets for left- or right-side vehicle measurements, a forward-looking video camera with cab-mounted monitor for driver guidance and cab-mounted video recording camera with data overlay.

5.1.2.2.10 Impulse RM for Signs

Impulse RM (http://www.lasertech.com/) is a handheld device are manually directed toward, or precisely at, a target object and then manually fired. Once fired, the handheld device bounces a laser beam off the target object and measures the reflected laser energy that is then used to determine a retroreflectivity value. Sign retroreflectivity (R_A) is usually measured with an Impulse RM that is pointed at the face of a sign at a distance of about 100 feet. The resulting RA value correlates roughly to a geometry of 0.2/-4 (observation angle and entrance angle), which has become a generally accepted standard geometry in the industry for signs. The handheld device can measure a single R_A value for a single sign, and can only measure either foreground or background R_A with a single measurement.

The user of the handheld device must be stationary – either standing along the side of the road, sitting on top of an all-terrain vehicle that is stopped along the side of the road, or leaning out of a car or truck that is parked on the side of the road. Operators will typically make several measurements for a given sign and will report the average value, the most frequently occurring value. Since operators must hold the device very steady while a measurement is made, there are considerable opportunities to obtain values for objects other than the intended sign. The net result is that R_A measurements made with handheld devices have considerable exposure to error-inducing procedures.

5.1.2.2.11 SMARTS

Another technique for determining the nighttime visibility of signs has been introduced by the Federal Highway Administration (FHWA, 2001[1]). The Sign Management and Retroreflectivity Tracking System (SMARTS) is a vehicle that contains: One high intensity flash source, one color camera, two black and white cameras, one range-sensing device, and a GPS positioning system

The SMARTS vehicle requires two people- a driver and a system operator - for proper operation. As the SMARTS vehicle travels down the road, the system operator locks on to a sign up ahead by rotating the camera and light assembly to point at the sign. At a distance of 60 meters, the system triggers the flash source to illuminate the sign surface, an image of which is captured by one of the black and white cameras. A histogram is produced of the sign's legend and background that is then used to calculate retroreflectivity. A GPS system stores the location of the vehicle along with the calculated retroreflectivity in a computer database.

5.1.2.3 Level of Illumination

Quantity of light or the light output and light levels are measured in lumens, lux and footcandles. Initial Lumens/ Footcandles reflect the amount of light produced by a lamp when it is installed. Supply voltage variations, lamp's interaction with the ballast and dirt build up reduce the produced amount of light. Light level standards are affected by light quantity and quality desired fixture efficiency and other applicable factors. The following sections describe some of the technologies applicable to measure the level of illuminations emitted from a light source.

5.1.2.3.1 HISLAT®

The Odyssey Energy Limited, New Zealand developed equipment and methods for assessing contractor performance based contracts, using HISLAT® nighttime lighting performance surveys (http://www.odyssey.co.nz/). The HISLAT® unit is a very portable, laptop computer based, unit for mobile streetlight assessment. It is designed to be used at normal driving speeds (up to 62mph) thus eliminating the need for road closures or other expensive traffic management plans.

The data is collected automatically from a moving survey vehicle by using specialist sensors and equipment that can be easily installed on that vehicle. Although the survey equipment has been designed for simple operation and automatic data collection, two operatives are required to carry out the survey. This allows the driver to concentrate purely on safe driving.

The transducer is the only item of equipment that is permanently installed in the survey vehicle. The transducer sends a series of pulses to the displacement meter, which is programmed to display to the nearest meter. The displacement meter then sends a suitable signal to the data sampler. An initial displacement calibration is required for each survey vehicle. The photodiode is located on the roof of the car in the appropriate location. The photodiode is powered from the light adaptor inside the car. The luminance figures are sent to the data logger on a continuous basis. The photodiode needs to be checked for calibration on a regular basis. The data logger then sends both figures to the laptop for recording in a database. This allows the light level to be recorded for each displacement pulse along the road. The data sampler software allows recording and displaying of the luminance values in the graph or spreadsheet format and transfer into MS Excel.

On two-lane roads, the driver is required to position the vehicle close to the centerline of the road to ensure the recording photodiode is located approximately 0.5 meter from the centerline of the carriageway. The operator needs to identify the start location and start the data acquisition at the RAMM start point on the road. All data collection and recording are performed automatically until the end of the run, leaving the operator free to make notes of factors that could affect the graphical output.

The results can be represented graphically as a lux level / displacement plot. The KPM is defined as the average lux per sub-group function which is the calculated area beneath the plot line divided by the length (m) over which the survey is completed.

5.1.2.3.2 Spectroradiometer

OL 754 Spectroradiometer from Optronic Laboratories, Inc. (http://www.lightinglab.fi/facilities/Spectroradiometer/index.html) is able to measure the spectrum of different light sources from 250 to 800 nm or from 200 to 400 nm depending on the calibration and luminous intensity. The system saves the measured values in an ASCII-file on a laptop computer from where it is easy to calculate various lighting quantities directly after the measurement or on a later stage.

5.1.2.3.3 ProMetric 1400 Luminancephotometer

The ProMetric 1400 Luminancephotometer (http://www.lightinglab.fi/facilities/Spectroradiometer/index.html) is used for luminance measurements and analysis in indoor and outdoor lighting. The photometer consists of a peltier cooled CCD based still frame camera and a computer. Simultaneous luminance values of the whole scene are captured in a few seconds. The image consists of 250,000 pixels. The results can be saved as numerical values for later analysis. The luminance range that can be measured with the ProMetric 1400 is from 0.005 cd/m^2 to 1010 cd/m^2. For road lighting measurements a program has been developed at the Lighting Laboratory, which calculates the CIE road lighting parameters from the ProMetric measurement results.

5.1.2.4 Detector Diagnostics Tests

The proper functioning of a detector can be found by using its false alarm rate (http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1618&context=its/path). The following section will describe the tests to be performed to know the detector diagnostics. These diagnostic tests are grouped into two levels: critical functioning tests and qualitative tests. For each detector in each lane at a directional station, nine specific diagnostics are applied to the stream of detector signals it receives. The nine specific diagnostics that have been implemented, first three at the upper level (critical functioning tests) and six at the lower level (qualitative tests), and each test and its criteria for failing the test are described below:

5.1.2.4.1 Activity Test

If the detector signal has not changed state in the last 15 minutes, the test fails. The intent of this upper level diagnostic is to insure that the detector meets its minimum critical functioning level. If it does not, it is reported as failed.

5.1.2.4.2 Minimum On-Time

If 5 percent or more of the on-times in a sample of 100 vehicles are less than 8/60 seconds, the test fails. The only possible problem recognized would be the situation when a relative large platoon of short-length vehicles (i.e., motorcycles) at high speeds would pass over the detector. The intent of this upper level diagnostic is to insure that the detector meets the minimum critical functioning level. If it does not, it is reported as failed.

5.1.2.4.3 Maximum On-Time

If 5 percent or more of the on-times in a sample of 100 vehicles are greater than 600/60 seconds, the test fails. The only possible problem recognized would be the situation when a relative large cluster of long-length vehicles (i.e., long trucks) at low speed would pass over the detector. The intent of this upper level diagnostic is to insure that the detector meets the minimum critical functioning level. If it does not, it is reported as failed.

5.1.2.4.4 Mode On-Time

If mode on-times of 1000 vehicles are less than 10/60 seconds or greater that 16/60 seconds, the test fails. This test is a longer-term test that compares the measured on-times of individual vehicles against the on-times of typical length vehicles. The test is only valid when applied under free-flow conditions.

5.1.2.4.5 Dynamic Minimum On-Time

This diagnostic is one of the new diagnostics and is the same as the minimum on-time diagnostic described earlier except the threshold value is a variable depending on on-line calculated speed. The test fails if 5 percent or more of the on-times in a sample of 100 vehicles are less than the calculated minimum acceptable on-time threshold value. The equation for the minimum acceptable on-time is

$$\text{Min on-time (1/60 seconds)} = ((v_l + d_l)/(sp))(3{,}600/88) \quad (5\text{-}1)$$

where

vl = Average vehicle length, assumed 20 feet,

dl = Detector zone length, assumed 6 feet,

sp = Calculated average speed, mph.

The intent of this lower level diagnostic test is to provide a warning when a detector is suspected of poor performance.

5.1.2.4.6 Dynamic Maximum On-Time

This diagnostic is one of the new diagnostics and is the same as the maximum on-time diagnostic described earlier except the threshold value is a variable depending on on-line calculated speed and whether it is designated as a truck-use lane or not. The test fails if 10 percent or more of the on-times in a sample of 100 vehicles are less than the calculated minimum acceptable on-time threshold value. The equation for the maximum acceptable on-time is

$$\text{Max on-time (1/60 seconds)} = ((v_l + d_l)/(sp))(3{,}600/88) \quad (5\text{-}2)$$

where

$v_l + d_l$ = 30 feet for predominant passenger vehicle lanes and 66 feet for other lanes

v_l = Vehicle length, assumed to be 24 feet for predominant passenger vehicle lanes and 60 feet for truck use lanes

d_l = Detector zone length, assumed 6 feet

sp = Calculated average speed, mph.

Experience with this diagnostic test resulted in changing the original 5 percent value to 10 percent to reduce the number of false calls. The intent of this lower level diagnostic test is to provide a warning when a detector is suspected of poor performance.

5.1.2.4.7 Minimum Off-Time

If 5 percent or more of the off-times in a sample of 100 vehicles are less than 25/60 seconds, the test fails. Car-following rules under capacity conditions were first modeled to select this threshold value. It was found that the threshold value was essentially independent of speed and primarily limited to maintaining a minimum safe headway. Initially a threshold value closer to 60/60 seconds was used. However, field experimentation indicated that a much lower threshold value of 25/60ths of a second was a more appropriate threshold value that is currently implemented. The intent of this lower level diagnostic test is to provide a warning when a detector is suspected of poor performance.

5.1.2.4.8 Dynamic Maximum Off-Time

This is one of the new diagnostics. If 5 percent or more of the off times in a sample of 100 vehicles are greater than a threshold value that is a variable depending on the calculated average time headway, the test fails. The equation for maximum acceptable off-time is

$$\text{Max off-time (1/60 seconds)} = (t)(\overline{T})(60) \quad (5\text{-}3)$$

where

T = 3, representing 3 standard deviations

$\overline{T}$ = Average time headway, seconds per vehicle

60 = Conversion from seconds to 1/60 seconds.

The intent of this lower level diagnostic test is to provide a warning when a detector is suspected of poor performance.

5.1.2.4.9 Dual Detector On-Time Difference

This test compares the on-times of the upstream detector with the on-times of the immediate downstream detector for each pair of detectors system. If 5 percent of the on-time difference of 1,000 vehicles is not between +/- 3.5/60 seconds, the test fails. Under congested conditions, normal traffic can result in very large differences in on-times between detectors so this test is restricted to free-flow conditions. The version developed under the previous project used an overly simplistic method of determining free-flow conditions that resulted in unpredictable results and large numbers of false failures. The free-flow determination method was revised and the new test is much improved. The intent of this lower level diagnostic test is to provide a warning when a detector is suspected of poor performance. The only changes in this diagnostic have been to increase the percentage of failures from 3.5 percent to 5 percent and to improve the determination of free-flow conditions.

5.1.2.5 Safety Performance Evaluation of Longitudinal Barriers, Terminals, and Crash Cushions

The National Cooperative Highway Research Program (NCHRP) Report 350 presented uniform guidelines for the crash testing of both permanent and temporary highway safety features and recommended evaluation criteria to assess test results (Michie, 1993). Guidelines are also presented for the in-service evaluation of safety features.

Procedures presented involve vehicular tests to evaluate the impact performance of permanent and temporary highway safety features. Performance is evaluated in terms of the degree of hazard to which occupants of the impacting vehicle would be exposed, the structural adequacy of the safety feature, the hazard to workers and pedestrians that may be behind a barrier or in the path of debris resulting from impact with a safety feature, and the post-impact behavior of the test vehicle. Individual tests are designed to evaluate one or more of the principal performance factors: structural adequacy, occupant risk, and post-impact behavior of vehicle. In this report, evaluation criteria and applicable tests are explained and presented in a table.

5.1.3 Data Sampling

Data collection process is very much time consuming and cost-intensive exercise. It is often not possible to collect the data from all the geographic area. It is a common practice to collect only a portion of a data, called as a representative sample, to meet the data demands. Sampling techniques represents an effective method by which one may carry out data collection. The use of sampling can contribute significantly to the overall goals of maximizing data coverage and encouraging proper reporting practices.

5.1.3.1 The Sampling Process

Each step in the sampling process involves a choice of several alternatives. As the sampling plan is being developed, it is important to keep the following steps in mind.

- Define the populations to be sampled in a manner which will provide the most homogeneous subpopulations,
- Determine applicable stratifications within subpopulations,
- Choose the type of sampling unit,
- Determine the sample size,
- Establish correspondence,
- Select the sample units,
- Perform a preliminary sample and make a stop-or-go decision,
- Complete the sample examination,
- Project the results to the population,
- Evaluate the sample results.

In order to successfully complete the steps in the sampling process, relevant information about the roadside safety hardware asset system should be obtained.

5.1.3.2 Sampling Methods

The following section describes various available methods for sampling the data.

5.1.3.2.1 Quota Sampling

In quota sampling, the population is first segmented into mutually exclusive sub-groups, just as in stratified sampling. Then judgment is used to select the subjects or units from each segment based on a specified proportion.

5.1.3.2.2 Simple Random Sampling

In a simple random sample of a given size, all such subsets of the population are given an equal probability. Each element of the population thus has an equal probability of selection: the population is not subdivided or partitioned.

5.1.3.2.3 Stratified Sampling

Where the population consists of a number of distinct categories, the population can be organized by these categories into separate strata. A sample is then selected from each stratum separately, producing a stratified sample. The two main reasons for using a stratified sampling design are to ensure that particular groups within a population are adequately represented in the sample, and to improve efficiency by gaining greater control on the composition of the sample. Higher efficiency can be achieved by varying the sampling fraction from stratum to stratum.

The sample size is usually proportional to the relative size of the strata. However, if variances differ significantly across strata, sample sizes should be made proportional to the stratum standard deviation. Disproportionate stratification can provide better precision than proportionate stratification. Typically, strata should be chosen to have means which differ substantially from one another and to minimize variance within strata and maximize variance between strata.

5.1.3.2.4 Cluster Sampling

Sometimes there is a need to cluster the sample in some way e.g. by selecting assets data from certain areas only, or certain time-periods only. Cluster sampling is an example of two-stage sampling or multi-stage sampling: at the first stage, a sample of areas is chosen; at the second stage, a sample of assets within those areas is selected.

This can reduce travel and other administrative costs. It also means that one does not need a sampling frame for the entire population, but only for the selected clusters. Cluster sampling generally increases the variability of sample estimates above that of simple random sampling, depending on how the clusters differ between themselves, as compared with the within-cluster variation.

5.1.3.2.5 Random Sampling

In random sampling, also known as probability sampling, every combination of data from the population, or stratum, has a known probability of occurring, but these probabilities are not necessarily equal. With any form of sampling, there is a risk that the sample may not adequately represent the population but with random sampling there is a large body of statistical theory that quantifies the risk and thus enables an appropriate sample size to be chosen. Furthermore, once the sample has been taken the sampling error associated with the measured results can be computed. With non-random sampling there is no measure of the associated sampling error.

5.1.3.2.6 Systematic Sampling

This method requires all sampling units of equal length or of uniform characteristics to be randomly ranked, and every r^{th} element of the ranked list is selected. The first sampling unit is sampled at random between 1 and r, say the mth unit. The final sample will therefore consist of sample unit number m, (r+m), (2r+m), (3r+m), and so on. The same limitations mentioned of the simple random sampling method also apply to this method.

5.1.3.3 <u>Sampling Size</u>

The determination of adequate sample size is a process that is unique for each study. Thus, no single formula can be provided to compute the correct sample size for a generic study. Sample size requirements for any individual field investigation are affected by the following factors.

First, the entire process of statistical modeling and hypothesis testing is data driven. Thus, statistics estimated from the data, such as the means and variances, will be the primary determinants of sample size for a particular study. Note that data varies across fields of discipline and across studies, as do measurement procedures, thus sample sizes must be estimated for each study that is unique. The type of statistical procedures to be employed will affect the sample size requirement. Thus, analysis of variance, regression, cross-classification, etc., all have varying requirements underlying their use, and are affected by decisions of the analyst along the way.

The level of confidence, 1-α that the engineer would like to employ in hypothesis testing will also affect sample size. Recall that this amounts to setting the alpha level in analyses- or the probability of rejecting the working hypothesis when it is true (a type I error). Similarly, the power, 1-β, required of an analysis will affect sample size requirements. The beta is the probability of failing to reject the working hypothesis when it is false (a type II error). The method of sampling employed in a study- random, stratified random, cluster, or some other method not mentioned here, will also affect sample size requirements.

$$c.v = \frac{\sigma}{\mu} \approx \frac{s}{\bar{x}} \tag{5-4}$$

where

σ = Population standard deviation,

μ = Population mean,

s = Sample standard deviation,

$\bar{x}$ = Sample mean.

$$n' = \frac{c.v^2 \times z^2}{e^2} \tag{5-5}$$

where
n' = Uncorrected sample size,
Z = z-statistic based on confidence level,
e = Relative permitted error.

$$n = \frac{n'}{1 + \frac{n'}{N}} \tag{5-6}$$

where
n = Sample size (corrected for finite population),
N = Population size.

5.1.4 Data Collection Frequency

The data on the physical condition and operations of roadways safety hardware assets need to upgraded at regular interval to assist the decision making process. Collection of asset data is cost and time intensive, which also consumes many resources. Data can be collected annually; semi-annually, quarterly, or monthly depends on the need, geographical coverage, and functional classification of the existing highway system.

5.2 Performance Measures

Many transportation agencies are using performance measurement to help track the impacts of program investments and provide accountability to the public. Performance measures are used to evaluate a range of solutions for addressing transportation needs, to make tradeoffs across different resource allocation options, to communicate the implications of different investment levels, and to establish targets for results to be achieved based on available resources. Some agencies use performance targets as an integral part of their performance management approach.

Some of the performance measures for managing roadway safety hardware assets are listed in Table 5.2 (Madadu and Li, 2007). Safety hardware condition and useful service life (or age) is commonly used as the performance measures for signs and signals in the decision-making process. Retroreflectivity is used as a performance measure for signs and pavement markings. Percent of loss of painting can also be used as a performance measure for pavement markings. Structural height, lateral deviation, and percent of corroded area are used as performance measures for guardrails. However, no distinct measures are used for detection devices and lighting. Very few states manage ramp meters and no specific performance measures are widely used for ramp meters. There lacks consistency in the adopted performance measures among the states. No distinct performance targets are used to evaluate the efficiency and effectiveness of the roadway safety hardware management program.

Table 5.2. Safety Hardware Performance Measures Adopted by the Selected States

Hardware Category	Performance Measure
Signs	Age of signs Retroreflectivity (candelas per lux per square meter) Maintenance rating index Percent of signs replaced every year Risk assessment scale
Signals	Age of the signals Conflict monitor grade scale
Detection devices	False detection rate
Lighting	Level of illumination (lumens per square meter)
Pavement markings	Retroreflectivity (candelas per lux per square meter) Percent of paint loss per one tenth of a mile Risk assessment scale
Guardrails	Age of guardrails Percent of deformed length Percent of corroded area Percent of change in structure height Risk assessment scale

5.3 Data Integration

Asset Management is a data intensive process that involves the gathering, retrieval, storage, analysis, and communication of enormous quantities of data. Often the data is collected by various methods, referenced by using different data referencing systems, and has different sampling sizes, frequencies and coverage. This heterogeneity and questionable accuracies inherited with in the data making them unable to use within and across agencies. Data integration is the process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization.

It is critical that the data be readily accessible and comparable. Data integration and data sharing, therefore, are vital components of Asset Management. Further, improvements in computer data processing and information management technologies have made it possible for organizations to electronically link or combine large data files.

This section describes the processes involved in data integration emphasizing the FHWA initiatives. Common Data integration techniques are explained. Common benefits and challenges are presented in the following sub-sections.

5.3.1 Need for Data Integration

Information management activities within transportation agencies involve tools and methodologies to collect, store, process, analyze, and present data elements required for a wide range of management analyses. The comprehensive information arising from these activities helps to create a holistic decision-making framework. Data integration and data sharing will help the agencies to better know their existing system and creates an environment for making optimal investment decisions under the shrinking resources and other constraints.

5.3.2 Data Integration Process

A data integration team consisting of database users, asset managers and decision makers, information technology and database management professionals, and other key stakeholders in the Asset Management process (FHWA, 2001[2]). The agency may also seek the services of an external group of data integration experts or consultants any or all stages of the process.

A generic framework for the key activities involved in data integration and the corresponding elements to consider for each activity are shown in Figure 5.1 (FHWA, 2001[2]). The process begins with a *requirements analysis*, which includes identification and analysis of the target data to be integrated. The next step, *data and process flow modeling*, uses the information obtained from the requirements analysis to build diagrams depicting the flow and use of data across the agency. *Alternative data integration strategies* can then be identified and evaluated on the basis of all the information assembled. A strategy can be chosen, and its detailed *database design specifications and plans* developed. The final step involves *development, testing, and implementation* of the integrated data strategy.

5.3.2.1 Requirements Analysis

A requirements analysis is the first and most important stage of data integration. At this stage, an agency will identify the requirements of the data integration system: the business processes that will be supported, the data that will be shared, the goals the agency is trying to achieve, and the constraints or challenges that are expected to influence the process. Depending upon the size and extent of integration, the analysis can be quite complex and time consuming.

5.3.2.2 Data and Process Flow Modeling

Data and process flow modeling follows the requirements analysis phase of data integration. Specifically, the information obtained from the user requirements analysis can be used to develop diagrams depicting the flow of data within and among the business processes. The objective of data and process flow modeling is to create a picture of the relationships between the data and the business functions that the data support. Data flow diagrams help database engineers and analysts determine the design specifications for the integrated data. Flow diagrams consist of data, business processes, and relationships, which are represented by arrows. The direction of the arrows indicates where the information is going or which process is dependent on another.

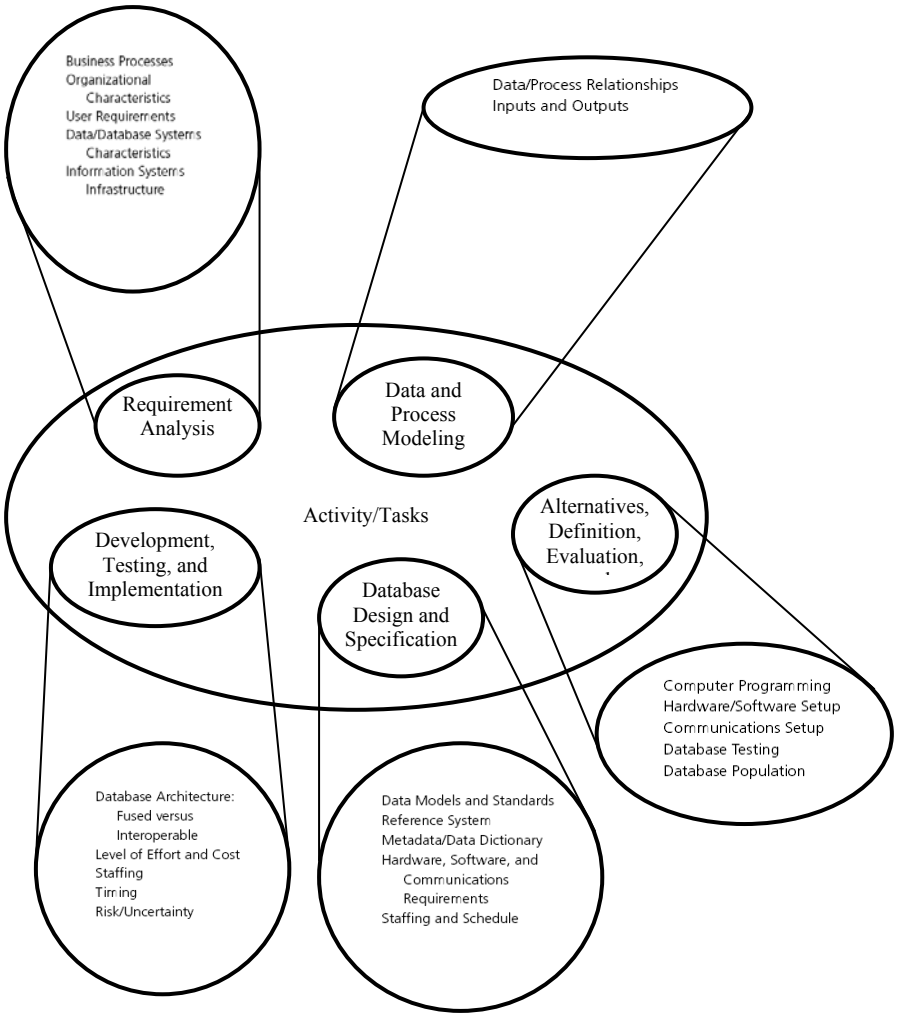


Figure 5.1. Illustration of data integration process.

5.3.2.3 Alternatives Definition, Evaluation, and Selection

The information obtained from the requirements analysis and flow diagrams provides the basis for the next step in data integration: identification of feasible integration alternatives. In general two alternative approaches exist: fused databases and interoperable databases. Data fusion, also referred to as data warehousing, pertains to one-time integration that combines information from multiple sources. These sources of fused data may be cast aside when data are migrated to the warehouse, or they may continue to exist to serve specific business processes. Alternatively, interoperable database systems—also referred to as federated or distributed systems, consist of databases that communicate among themselves via multi-database query. Interoperable databases involve an alternative interface through which a data source (e.g., an existing database) can be viewed and manipulated. The two database options are depicted in Figure 5.2.

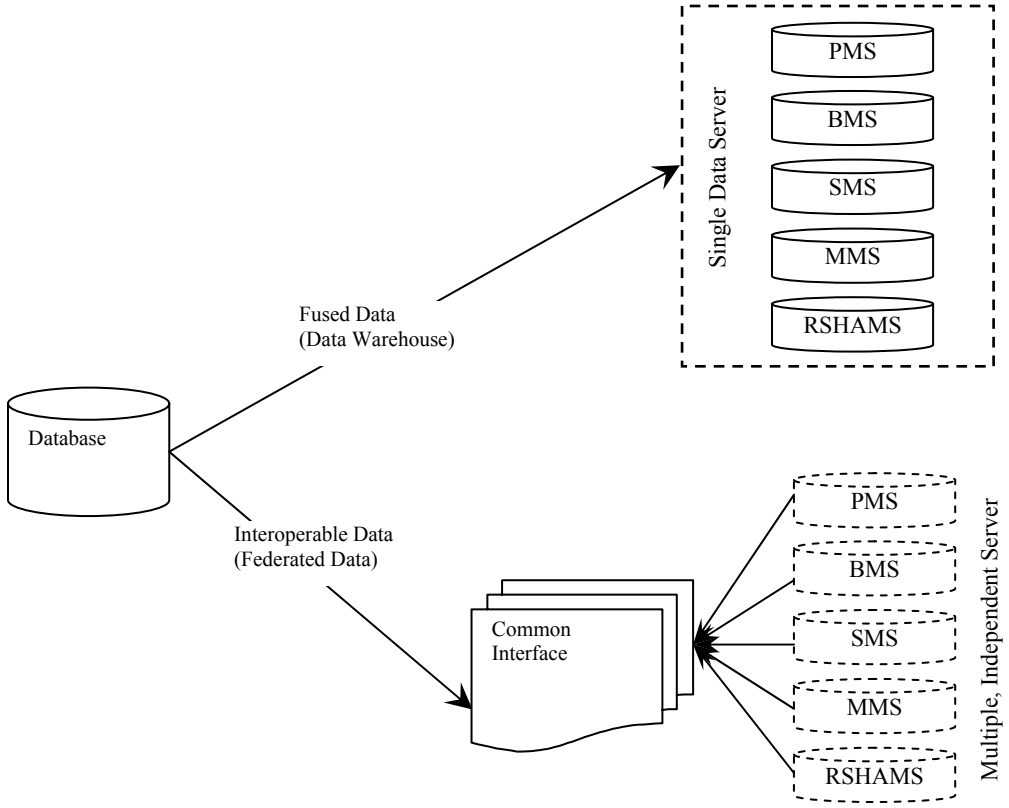


Figure 5.2. Database Alternatives

5.3.2.4 Database Design and Specifications

The database design and specifications can be used to generate the detailed plans and methods in implementing the selected data integration strategy. They also produce the overall approach to the database development effort. Whether a fused or interoperable database environment is selected, these elements are included in the integrated database design: data models, standards, and reference systems; metadata and data dictionary; computer communication requirements, software, hardware, staffing, and data management requirements. The two databases are compared in Table 5.3.

Table 5.3. Comparison of Fused and Interoperable Databases

Characteristic	Fused Database (Data Warehouse)	Interoperable Database
Number of Data Servers	One (central)	Multiple (distributed)
Location of Data Server(s)	Single site	Multiple sites
Data Replication	Yes	No
Advantages	Easy to manage and control the databases	Can keep data in independent locations and file servers (autonomy of sites)
	Maximum data processing power (quick access to the database)	No reliance on a single site that can become a point of failure. Changes made to data at one location can propagate quickly to become visible at other locations
	Able to handle large amounts of data and processing requests	Unified description of all data; no need to know database models
	Provides data security	Allows access to resources in the computer network
Disadvantages	Requires considerable time and resources to implement	Hard to support and maintain integrated (global) data model
	Data is generally in read-only format and cannot be updated online	Need to rebuild the database system every time data export protocols change
	Storage requirements can become a major problem	Requires rigorous procedures for database access and updates

5.3.2.5 Development, Testing, and Implementation

The last stage in data integration is software development and system implementation. These include prototyping and use case applications development, computer systems and network communications setup, and populating the database with data. Development activities include testing, evaluation, and modification of database models, data management applications, and communications interfaces. It is advisable that the development approach be as modular and incremental as possible in order to accommodate future additions or changes to the database or any component of the integrated environment.

5.3.3 Transformations

In order to make the diverse data sets as interoperable transformation of data is necessary. Most transportation agencies have large quantities of variable, heterogeneous data. Data heterogeneity usually results from the presence of internal legacy systems that use different data formats. Data in different formats from external systems continue to be added to legacy databases to enhance the value of the information. Thus, data integration often involves transforming one data format to others data formats. Many transportation agencies recognize a need to be able to translate location references between spatial referencing systems.

Transportation agencies are practicing numerous location referencing methods to meet diversified data needs of their asset management system. The agencies will need transformations between LRMs to support their business work flows (Baker and Blessing, 1974; White and Griffin, 1985; O'Neill, 1997; Vonderohe et al., 1997; Ries, 2000; Adams et al., 2001; ESRI, 2003). Transportation LRMs can be organized into three groups, like geodetic, geometric, and linear. These groups are depicted in Figure 5.3. Geodetic or geographic LRMs describe locations on the earth's surface. Geometric LRMs represent discrete features on the earth's surface. Linear LRMs describe locations along discrete features.

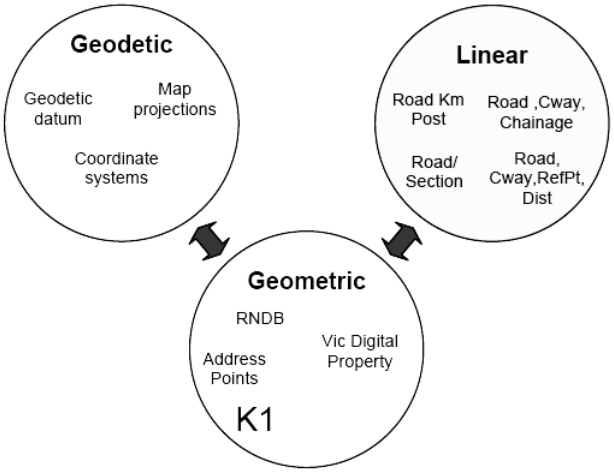


Figure 5.3. RM Groups and Their Relationships

Direct and indirect ways are the two approaches available for transforming the data between two interoperable data sets. The direct transformation of a linearly referenced location to a geodetic location is viable only through the intermediated transformation to geometric method. In the direct methods, data are transformed to any other required formats, with out changing the existing legacy system directly. No neutral location reference is required. In the indirect approach, a neutral location reference is managed to perform transformations. The two approaches are depicted in Figure 5.4, and 5.5.

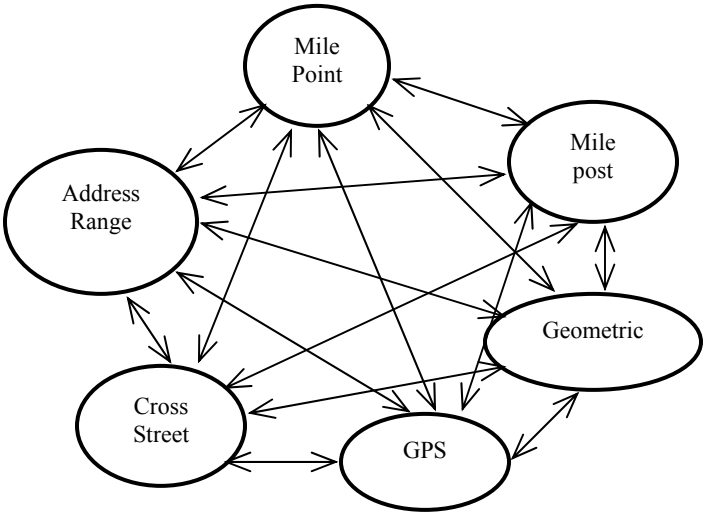


Figure 5.4. Direct Transformation Approach

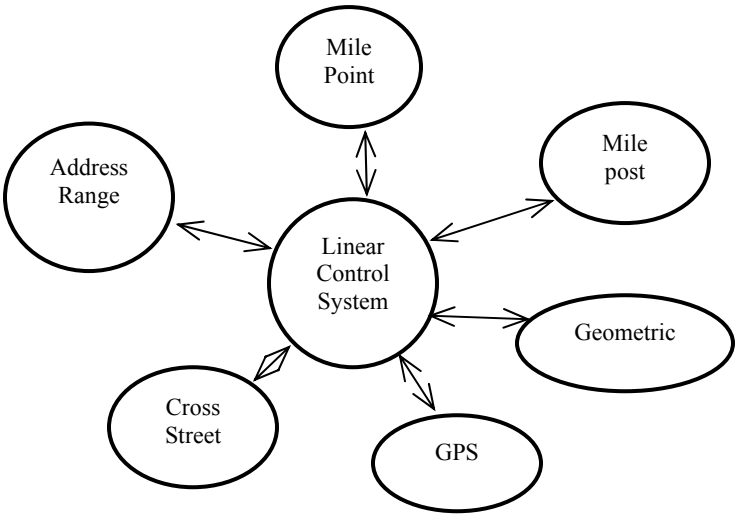


Figure 5.5. Indirect Transformation Approach

There are several advantages following the indirect approach. First, it requires maintaining significantly ewer transformations. Second, only two transformations are required if an additional LRM is introduced. Third, it makes the system interoperable. Primary advantage of the direct approach is no intermediate transformations are required.

5.3.3.1 Categories of the Transformation

There are several categories of the transformation of data sets. *The first category* is purely spatial transformation, with time being constant. This category includes the transformation from one linear method to another, from one linear method to two or three dimensional location referencing method and transformation among two or three dimensional location referencing methods. Transformation among two or three dimensional location referencing methods is performed through cartographic transformation methods, such as rubber-sheeting, conflation techniques or from one map projection to another. *Second category* of transformation involves converting a location referencing method address at a specific time to the equivalent location method address at a different time. This spatial temporal transformation supports historical analysis and data integration. *Third category* of transformation involves conversion of a linear(distance) location referencing method to a linear(temporal) location reference method, and theses transformations may be achieved through piecewise linear (possibly stochastic) functions.

5.3.3.2 Nature of the Transformations

The choices need to be made regarding the nature of the transformations. *Linear transformation* represents transformation from one linear location reference method to another linear location reference method. *Nonlinear transformation* is the transformations to or from a location reference method to a geometric or geodetic location reference method. Transformations among geometric and geodetic location reference methods are also falls under this category. *Temporal transformation* may support temporal conversions or converting a location reference to or from a temporal reference

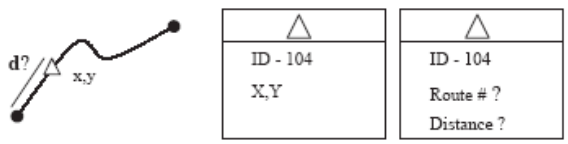
5.3.3.3 Types of Transformations

As shown in Figure 5.6, the main types of transformations for transportation applications involving linear reference systems are as follows (Fekpe et al., 2003):

- *Transformation Type 1*: Transformation of a 2D (or 3D) location to a linear location .For instance, data collected using GPS need to be converted to a linear referenced position.

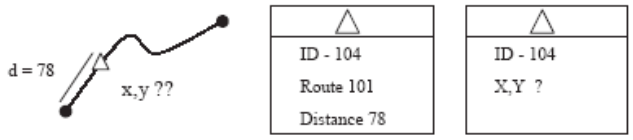
- *Transformation Type 2*: Transformation of a linear location expression to a 2D (or 3D) expression. This transformation may occur when linearly referenced data need to be converted to 2D (or 3D) coordinates for analytical purposes such as finding all regulatory signs within a mile of an intersection for all intersections in a jurisdiction.

- *Transformation Type 3*: Transformation of one linear location reference to another linear location reference. This might occur if transportation features referenced in a legacy linear system need to be updated to a new linear system or if more than one linear system exists within an organization and data need to be integrated across these systems.



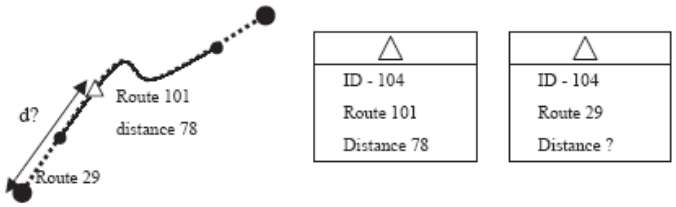
(a) Transformation Type 1

2D (x,y) coordinate is known, distance d is unknown and must be determined, route may or may not be known.



(b) Transformation Type 2

Route and distance are known, 2D coordinate is unknown and must be determined.



(c) Transformation Type 3

Route and distance are known in Linear System 1; route may be known but distance is unknown in Linear System 2.

Figure 5.6. Illustration of Transformation Types

5.3.4 Integration Methods

5.3.4.1 Transformation between GPS and LRS

As shown in Figure 5.7, coordinates of transportation features are captured using GPS and transformed to UTM or State Plane. The transformation can be accomplished through following steps (Fekpe et al., 2003):

- Compute the 3D (i.e., slope) distance of the road centerline, starting at the beginning of the road
- Compute the mileposts of all intersections (i.e., log points and anchor points). This road centerline, together with the distance references of the log points, serves as the network.
- Find the closest point on the centerline of the roadway assets inventoried, and then compute the milepost (i.e., distance from the start of the route) and the offset of the feature from the centerline

Two measures including distance and offset are the outputs of the transformation. This method also allows the positioning of linear features if the beginning and end points of the feature were measured. The methodology is depicted in Figure 5.8 (Fekpe et al., 2003).

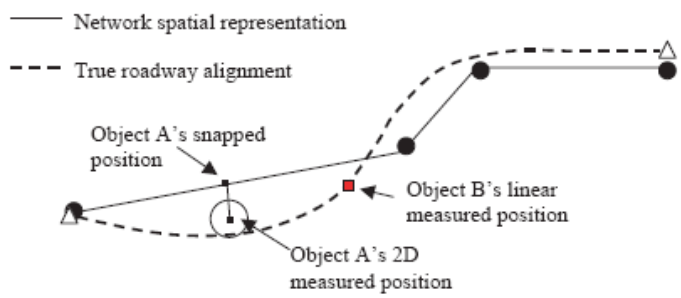


Figure 5.7. Transformation of 2D-Measured Position to LR Position

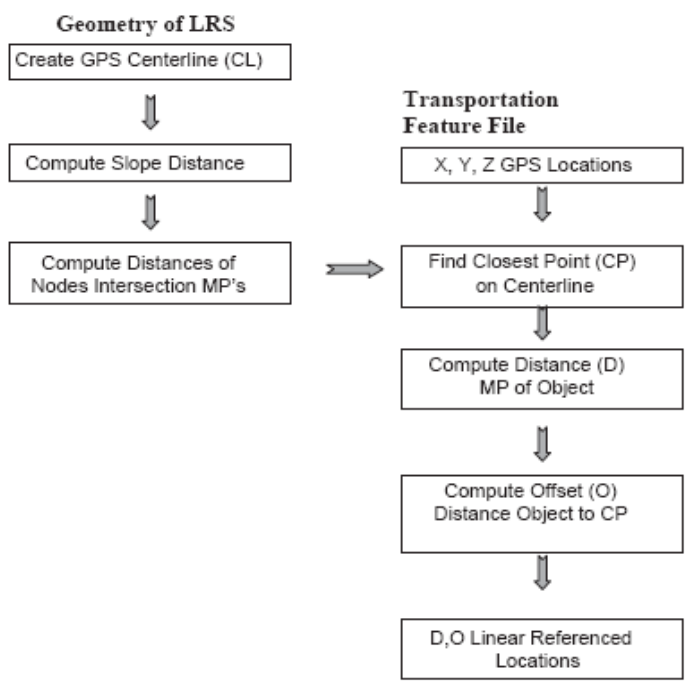


Figure 5.8. Steps in Transformation of Data for GPS to LRS

5.3.4.2 Transformation between Two Linear Reference Systems

State transportation agencies have legacy data that are positioned using a form of linear referencing system. Event data captured with GPS to a linear reference system (LRS-1) and then convert this system to the customer's legacy linear reference system (LRS-2). This can be accomplished with the following steps as illustrated in Figure 5.9 (Fekpe et al., 2003).

- Compute the distance to all intersections and the end point of LRS-1 relative to the origin or starting point of the legacy road centerline LRS-2.
- Take the transportation feature data referenced in LRS-1 and, using the anchor points (i.e., intersections) as reference objects, squeeze or stretch the distances to match the measured distances of the legacy system, LRS-2. The desired transformations can be accomplished with most standard GIS programs using dynamic segmentation routines.

The result is the new feature inventory referenced to the old centerline. This allows the user to combine new roadway features with legacy data without having to change the existing system completely. The opposite transformation also may occur where legacy data are transformed to a newer linear referencing system features referenced in the legacy system to a new linear system.

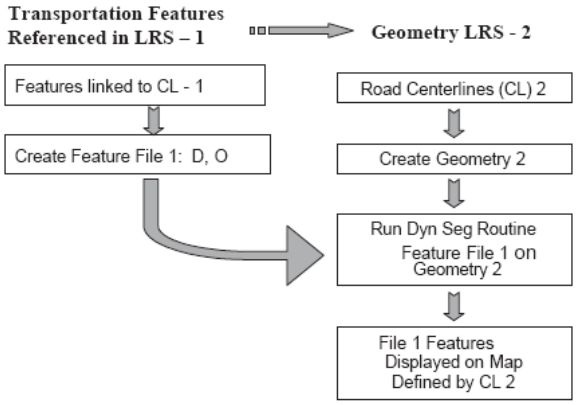


Figure 5.9. Steps in Transformation of Data from LRS-1 to LRS-2

5.3.4.3 Dynamic Segmentation

The definition of dynamic segmentation offered by ESRI (2001) is a process of transforming linearly referenced data (commonly called events) stored in a table into a feature that can be displayed on a map. This is accomplished by referencing non-spatial tabular data (events) to spatial linear features (routes) in ArcGIS.

Dynamic segmentation allows multiple sets of attributes to be associated with any portion of a linear feature. These attributes can be stored, displayed, queried, and analyzed without affecting the underlying linear data's x, y coordinates. The dynamic segmentation functionality was developed by ESRI and they have released numerous documents explaining the use and application of this method. The following are the steps involved in the dynamic segmentation process.

- Gather spatial data
- Process data for the study area
- Develop routes
- Apply dynamic segmentation technique.

Dynamic segmentation controls the attribute (i.e., holds the attribute value constant) and measures the locations where this attribute exhibits the specified value. In this case, we pre-specify the condition of interest and allow each segment to vary in length to encompass all contiguous locations that exhibit that value. Dynamic segmentation will i) compute the spatial locations or segments of events for highway assets stored and managed in an attribute table using a linear referencing measurement system; ii) allow merging multiple data events; iii) allow data queries and event analysis across multiple databases; and iv) support visualization of multiple asset data linked to a common LRS (ESRI, 2001; FHWA, 2007). An example of Data Segmentation is depicted in Figure 5.10.

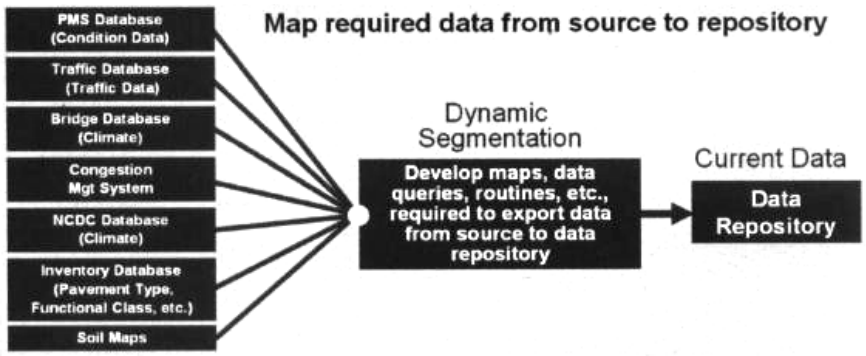


Figure 5.10. Dynamic Segmentation Process

5.3.4.4 Geo-Coding

The process of matching tabular data that contain location information such as street addresses with real-world coordinates. *Address matching* is a powerful method of integrating address-based data with other types of spatial data.

5.3.4.5 SQL Relationships

Structured Query Language (SQL) is based on set and relational operations with certain modifications and enhancements. A typical SQL query has the form: *Select* attributes (A_1, A_2, A_3, A_4… An) *From* relations (r1, r_2, r_3, r_4… r_n) . A typical relationship is shown in Figure 5.11 (FHWA, 2007).

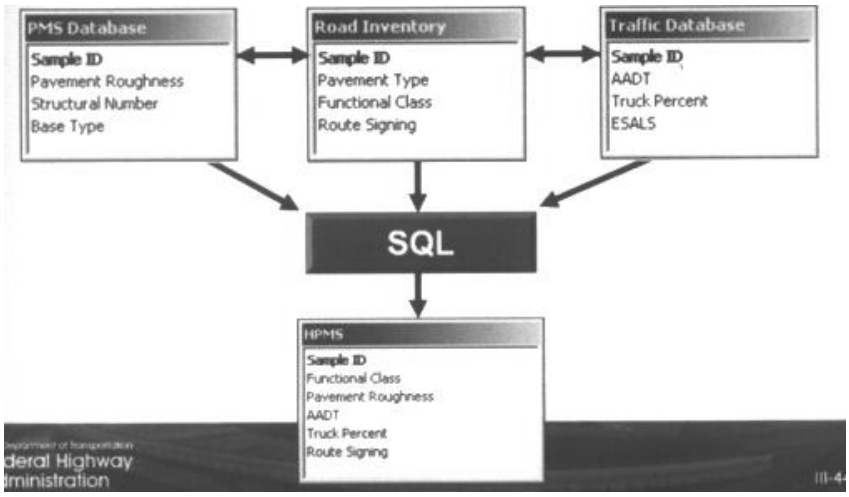


Figure 5.11. A Typical SQL Relationship

5.3.5 Challenges of Data Integration

Some of the challenges encountered while integrating the data are:

- Heterogeneous data,
- Bad data,
- Lack of storage capacity,
- Unanticipated cost,
- Inadequate cooperation from staff,
- Lack of data management expertise.

5.4 Database Management

Transportation agencies are collecting huge amount of data to make better informed decisions. The data storage and updating is a daunting task facing by many agencies. Often it is required to retrieve the historic data and perform some queries to get the required information. It would be better if all the required information is displayed in graphical way. Data base management system is a tool to perform all such activities. In the market, there are many commercial available data base management systems (such as ORACLE DBMS and MySQL). However, Geographical Information System (GIS) is proven to be very handy and effective tool for managing the data in an effective way (Poling et al., 1994; Harvey and Shaw, 2001). This section explains briefly the steps involved in developing a data base.

To begin with, a GIS consists of two broad categories of attribute data and spatial data. The GIS seamlessly integrates the two giving the user the capability of applying spatial analysis to the attribute data. Attribute data consists of descriptions attached to an object. Attribute data is the same as the data stored in a traditional database. For example, a road section might have attribute data such as AADT, minimum width and maintenance cost. Spatial data consists of geo-coded objects (points, lines and polygons) that have an orientation and relationship in a two or three-dimensional space. These objects have precise definitions and are related to one another with the rule of mathematical topology.

5.4.1 Database Planning, Design, and Construction

Each potential data source for the GIS database must be identified, reviewed, and evaluated for suitability to use in the GIS. Maps, photos, and remotely sensed data are the most likely sources and should be evaluated for

- Appropriate scale,
- Projection and coordinate system,
- Availability of geodetic control points,
- Aerial coverage,
- Completeness and consistency across entire area,
- Symbolization of entities (especially positional accuracy of symbol due either to size of symbol or off-set placement on map),
- Quality of line work and symbols,
- General readability and legibility for digitizing (labels),
- Quality and stability of source material,
- Amount of manual editing needed prior to conversion,
- Edge match between map sheets,
- Existence and type of unique identifiers for each entity,
- Positional and attribute accuracy.

All of the above information needs to be documented for each potential data source. *Database planning and design* involves defining how graphics will be symbolized (i.e., color, weight, size, symbols, etc.), how graphics files will be structured, how non-graphic attribute files will be structured, how file directories will be organized, how files will be named, how the project area will be subdivided geographically, how GIS products will be presented (e.g., map sheet layouts, report formats, etc.)., and what management and security restrictions will be imposed on file access. This is done by completing the following activities:

- Select a source (document, map, digital file, etc) for each entity and attribute in the E-R diagram,
- Set-up the actual database design (logical/physical design),
- Define the procedures for converting data from source media to the database,
- Define procedures for managing and maintaining the database.

Actual procedures and the physical database design cannot be completed before specific GIS hardware and software has been selected while at the same time GIS hardware and software selection cannot be finalized until the selected GIS can be shown to adequately perform the required functions on the data. Thus, these two activities (design and testing) need to be conducted concurrently and iteratively. The GIS software to be used dictates most of the physical database design. The structure and format of the data in a GIS, like ARC/INFO, Intergraph, MapInfo, etc. have already been determined by each vendor respectively. The completed physical database design must account for all entities and their attributes, the spatial object with topology and coordinates as needed, and all relationships to be contained in the database

Developing a GIS database is frequently thought of as simply replicating a map in a computer, but building a GIS database involves much more than replicating a map. While substantial portions of the GIS database will come from map source documents, many other sources may also be used, such as aerial photos, tabular files, other digital data, etc. Also, the map representation is only part of the GIS database. In addition to the map representation and relational tables, a GIS can hold scanned images (drawings, plans, photos), references to other objects, names and places, and derived views from the data. The collection of data from diverse sources and its organization into a useful database requires development of procedures to cover the following major activities:

- *Getting the data* that may include acquiring existing data from both internal and external sources, evaluating and checking the source materials for completeness and quality, and/or creating new data by planning and conducting aerial or field surveys.

- *Fixing any problems in the data source* often focused only on map source documents; this activity has been called map scrubbing.

- *Converting to digital data* the physical process of digitizing or scanning to produce digital files in the required format.

- *Change control*, most map series are not static but are updated on a periodic basis. Once a portion of the map has been sent to digitizing (or whatever process is used), a procedure must be in place to capture any updates to the map and enter these into the digital files.

- *Building the GIS Database* once digitizing has been completed. Several considerations required for this process are covered under GIS Data Database Construction, GIS System Integration and GIS maintenance and use. A database construction process is divided into two major activities: Creation of digital files from maps, aerial photos, tables and other source documents; Organization of the digital files into a GIS database.

5.4.2 Data Standards

Incorporating data standards in the database design and specifications helps facilitate the integration process by identifying or establishing acceptable rules for representing, accessing, manipulating, transferring, and reporting data. Some of these standards or rules may already exist in the agency and would be identified in the requirements analysis stage of the data integration process. The development of new standards requires evaluating both the data elements and the processes that draw information for specific applications.

The three most common data standards are data representation standards pertaining to how a specific data would be stored in the databases (e.g., content, format); data access and manipulation standards including conventions for requesting information from the database (e.g., database communications protocol and database query language); and data transfer and reporting standards that specify the format that will be used to export the data from the database to an external destination such as an application or another database.

5.4.3 Metadata and Data Dictionary

In addition to defining the data models, standards, and reference systems, a key component of database design is the creation of metadata and data dictionaries, which are basically detailed descriptions of the data. "Metadata" pertains to data about the data. One aspect of metadata includes the data's meaning: what it represents in the real world as well as its formal names, definitions, integrity, and accuracy. The other aspect of metadata describes the physical nature of data: how it is stored, the data types (e.g., text, image, numeric), and structure (e.g., relational, object-oriented), location, systems accessing it, and any other information to help the database analyst manage the data.

The data dictionary is a subset of the metadata containing an organized catalog of the data files about the definition, type, structure, and other properties of the data such as the number of records or fields. The data dictionary facilitates the integration of data by ensuring a consistent definition and correct usage of data in the databases and by making clear distinctions among various data items.

5.4.4 Requirements

5.4.4.1 Computer Communication Requirements

The process by which integrated data will be accessed by various users or clients from their computer terminals and workstations is also included in the database design and specifications. Access to the data by end users and application programs is normally carried out through a computer interface. Depending on whether a fused or interoperable database is selected, the user may access data directly from a warehouse in which the database resides or dial up to a computer network to access the data from other computers or database servers and use these data on a local machine.

A computer network is a system where multiple computers share the resources of all computers connected to the network via a high-speed communications link. The computer network allows the databases stored in one location to be accessed by various users working on separate computers in different places. These users can communicate with each other or exchange information via the network. The communications requirements for integrated data that will be identified in the database design include dial-up and communications procedures and other components, such as software, needed by the computer network.

5.4.4.2 Software and Hardware Requirements

Software and hardware requirements for the integrated database depend upon the database design and specifications described above. These include software and hardware choices and requirements for database servers, network communications, data mapping, user interfaces, computer operating systems, and programming environments. Agencies have the option of building the database management system from scratch or adopting a commercial software package, which may be customized.

5.4.4.3 Database Server

The choice of the server software and hardware is important because they are used to store and manipulate the databases. Key factors to consider are the maximum number of users expected to access the database at any one time, the level of uptime needed, the types of programs that will be accessing information from the database, the hardware and operating system the server will be using, and the level of in-house expertise the organization already has in a particular server environment. The server ideally would have adequate speed and storage capacity to handle large and complex data processing jobs. Recent trends in the software market are making it easier and less costly to implement integrated databases.

Many software packages are available that will support hundreds or thousands of simultaneous users logging on from various locations. They all have sophisticated security controls and can be customized to fit particular business needs. Server hardware is also becoming cheaper and faster. While organizations might want to buy multiple servers for redundancy, there is not much need to make significant investments in hardware to obtain improved performance. The Internet also has substantially influenced the database market. Database vendors are adding Internet support and seamless Web connectivity to their products. Most vendors have incorporated Internet-enabling utilities to some extent to make their products more programmable and compatible with Web-based applications.

5.4.4.4 Software

Spatial reference and mapping software, which is used to display and analyze location data, is collectively referred to as GIS software. The spatial nature of most transportation data makes GIS a powerful tool for Asset Management. GIS software is used for constructing spatial databases of transportation networks and features, conducting various types of analyses and applications on the spatial data, and integrating many management and decision-making information and processes.

Some GIS products have external database integrators that enable them to coexist and be integrated with an organization's IS infrastructure. This functionality provides GIS users with the ability to access and use data from a number of relational database management systems. Existing transportation spatial databases or warehouses developed by a number of high way agencies use GIS software and modules to link databases or perform specific database functions such as querying or reporting. GIS software options include several commercial products or suites of products. Each software product offers various data management, analytical, and reporting capabilities. Some products are designed for Web-based mapping and analysis applications. The software runs in different computer operating systems and network environments.

In lieu of building Asset Management applications and data integration routines or software from scratch, agencies have the option to acquire prepackaged COTS software that has the basic, generic functions of Asset Management processes and can be tailored to specific agency applications (FHWA, 2001[1]). This software ranges from large, enterprise-wide suites of applications, commonly referred to as enterprise resource planning (ERP) software, to other products that can be used for several asset types or several Asset Management processes. COTS data integration software may save time and money when compared with writing customized programs.

5.4.4.5 Staffing and Data Management Requirements

Finally, during the database design and specifications stage of data integration, management and administrative responsibilities for the integrated databases are established by identifying the people who will be managing database programming, prototyping, and testing (database development), software and hardware purchases (procurement), computer network setup (systems administration), and database management, maintenance, and upkeep.

5.4.5 Testing and Implementation

The last stage in data integration is software development and system implementation. These include prototyping and use case applications development, computer systems and network communications setup, and populating the database with data. Development activities include testing, evaluation, and modification of database models, data management applications, and communications interfaces. It is advisable that the development approach be as modular and incremental as possible in order to accommodate future additions or changes to the database or any component of the integrated environment.

Database developers usually create prototypes and use case applications to implement the integrated database models. Prototyping and use case modeling ideally are performed in tandem in order to focus on the data users and their use of the system. The initial version of the prototype will consist of major program modules written to move data back and forth between the screens, the database, reports, and the inputs and outputs used to communicate with other data systems. At first, these prototypes may do little data processing. As the prototyping continues, newer versions of programs that perform full-blown data processing will replace the original versions.

The computer network communications components of the integrated system are put in place during the programming and software development stage when the interface or connections between databases are ready for setup and testing. Again, depending upon the scope of integration and type of network configuration chosen, implementing the network communications may require significant effort and agency resources to implement. Specifically, the more complicated the communications requirements of the integrated database system are in terms of computer connectivity, data access rates, data retrieval and processing, or system flexibility and reliability, the more time and money will be spent. The final step in the process involves filling in (populating) the database with the necessary data, both historical and newly acquired.

5.4.6 Database Evaluation

Data base evaluation, give the feed back on the chosen set of data formats, standards, and procedure and help agencies continuously updating the database management system.

5.5 Chapter summary

This chapter introduces some methods of inventory process, data collection, data integration and data base management systems related roadway safety hardware asset management. The data requirements related to the individual component assets are listed. Various automated data collection technologies and methods are explained. Then, data sampling techniques, sample size requirements, and sampling frequencies are introduced. FHWA data integration initiatives and process of data integration are presented in step by step manner. Next section presented various issues involved in the transformation of data between different location referencing systems. Data integration methods are explained briefly. In the last section design, development, and implementation of GIS database is presented.

CHAPTER 6:
METHODOLOGY FOR EVALUATING ROADWAY SAFETY HARDWARE PROJECTS

6.1 General

The traffic operation characteristics concerning a highway segment differ greatly from those of an intersection. Consequently, the methodology can be used for evaluating safety hardware projects for highway segments and intersections, respectively. Without loss of generality, the methodology will primarily focus on safety hardware project evaluation for highway segments.

This report presents the methodology developed for quantifying the safety gains that could be achieved by addressing the safety hardware problems associated with highway segments and intersections, respectively.

6.2 Methodology Overview

6.2.1 General Framework of the Proposed Methodology

The methodology for computing the benefits of safety hardware projects related to highway segments is outlined in Figure 6.1. Highway segments are first classified by land area and highway functional classification. For a specific highway segment, the related vehicle crash types can be determined using historical crash data. For each type of highway segment-related crashes, the crash frequency is mainly affected by detailed safety issue items relevant to geometric design, consistency of design standards, pavement conditions, safety hardware conditions, and roadside features associated with the highway segments. For each type of highway segment-related crashes, the crash severity is primarily influenced by roadside features. The safety index (SI) of the highway segment by crash severity category- fatal, injury, and property damage only (PDO), measured by the crash frequency in number of crashes per year, can be estimated by considering total traffic exposure on the segment, probabilities of occurring different types of crashes, crash frequency for each type of crashes, and crash severity for each type of crashes. This safety index can be called current-case safety index.

If a safety hardware project is implemented to mitigate the safety issues concerning one or more safety hardware assets in the highway segment, it will reduce the crash frequency and crash severity for the specific type(s) of crashes that are potentially affected by the safety hardware issues. Hence, a lower safety index for the highway segment by crash severity category is expected to be achieved. It is reasonable to assume that the hardware-related safety issues could be resolved to allow crash frequency and crash severity being reduced up to the system-wide average levels. Correspondingly, the lower-valued safety index obtained from the implementation of the safety hardware project can be called the base-case safety index.

The difference in the values of the current-case safety index (before implementing the safety hardware project) and the base-case safety index (after implementing the safety hardware project) is regarded as the potential for safety improvement (PSI). It is common that the useful service lives for different types of safety hardware assets vary considerably, and the safety hardware service lives are often shorter than the useful service life of a highway segment. In order to compute the cumulative PSIs for fatal, injury, and PDO crash severity categories in the useful service life-cycle of the highway segment based on the estimated first year PSI and the annual traffic growth rate, it is needed to assume that safety hardware projects are required to be implemented in multiple times so that the multiple service lives of the safety hardware assets match with the service life-cycle of the highway segment. This way, the PSI level could be maintained at a consistent level throughout the useful service life-cycle of the highway segment. Having computed the life-cycle cumulative PSIs for fatal, injury, and PDO crash severity categories and by applying the respective unit rates for fatal, injury, and PDO crashes, the life-cycle cumulative PSIs can be converted into the life-cycle overall vehicle crash cost savings as a result of the safety hardware project implementation. Such crash cost savings are essentially the safety hardware project benefits. In general, the proposed methodology for safety hardware project evaluation is able to generate consistent results as

compared to the results of evaluating major highway assets such as pavements and bridges using the life-cycle costing approach.

The key to the success of methodology applications is to estimate the current-case and base-case safety indices before and after project implementation that are used to compute PSIs. To validate the safety index estimation procedure in the proposed methodology, the Spearman's rank-correlation coefficient and the regression analysis are employed to determine the level of agreement between each PSI established by applying the proposed methodology and the crash frequency estimated from the Empirical Bayesian analysis.

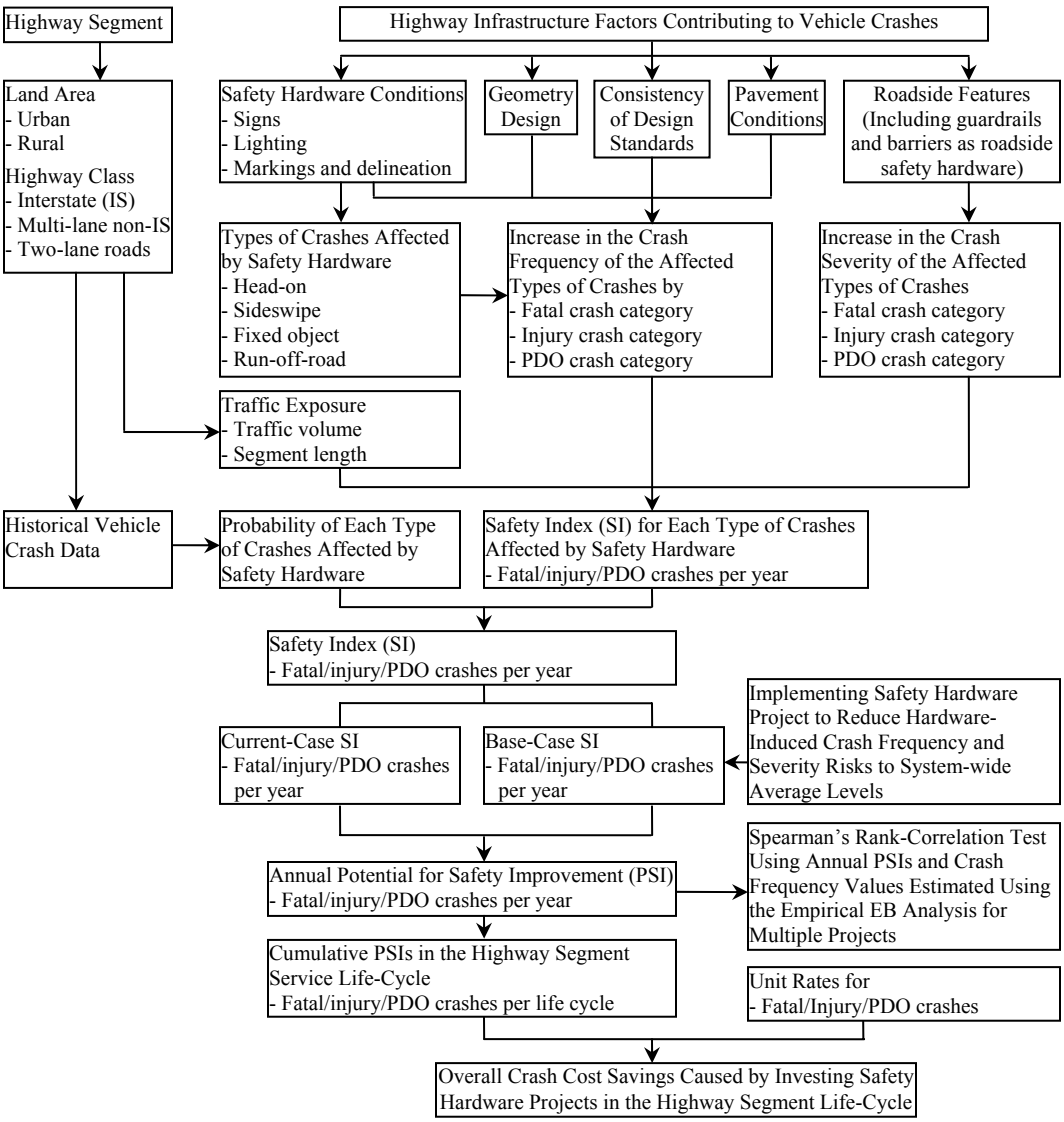


Figure 6.1. Methodology for Computing the Benefits of Safety Hardware Projects in the Highway Segment Service Life-Cycle

6.2.2 Classification of Highway Segments

For the methodology applications, the highway segments are classified as six primary categories by land area and highway functional class, as Table 6.1 (AASHTO, 2001). If needed, the highway segments in each category could be further classified by traffic volume group and/or by speed limit group.

Table 6.1. Classification of Highway Segments by Land Area and Highway Class

Land Area	Highway Functional Class
Rural area	Interstate highways Multi-lane non-Interstate highways Two-lane highways
Urban area	Interstate highways Multi-lane non-Interstate highways Two-lane highways

6.2.3 Highway Infrastructure Factors Contributing to Vehicle Crashes on Highway Segments

Figure 6.2 illustrates the contributing factors to highway vehicle crashes, including highway infrastructure, vehicle dynamics, and driver behavior (Treat, 1980). To sustain traffic safety on highway segments, drivers should maintain correct driving behavior concerning overtaking, vehicular spacing, and speed limit compliance while traveling under normal operation conditions and in the event of congestion, incidents or crashes. Highway engineering can be effective in helping to reduce speed and otherwise improve a driver's behavior.

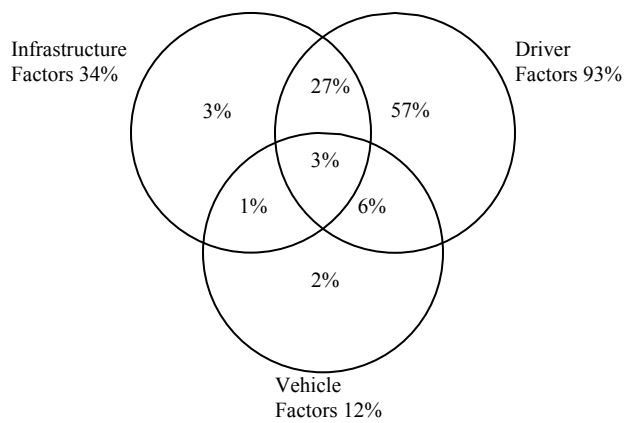


Figure 6.2. Contributing Factors to Highway Vehicle Crashes

As Table 6.2, the major categories of safety issues attributable to highway infrastructure for highway segments include highway geometric design, pavement conditions, safety hardware conditions, and roadside features (Migletz et al, 1994; Ogden, 1996; Lamm et al, 1999; IMIT, 2001; Elvik and Truls, 2004). Safety issues attributable to vehicle dynamics and driver behavior are less tangible. In this study, the 85th percentile traveling speed is compared with the speed limit to capture the combined effect of vehicle dynamics and driver behavior.

Table 6.2. Safety Issues Attributable to Highway Infrastructure for Highway Segments

Safety Issue Category	Safety Issue Type	Detailed Safety Issue Item
Geometric Design	Alignment	Very severe curve realignment needed
		Inadequate sight distance on horizontal curves caused by obstructions
		Inadequate sight distance on vertical curves due to large grades
	Cross section	Lane width (very narrow < 9 ft, narrow < 11 ft)
	Shoulder attributes	Shoulder width (no shoulder, very narrow <1 ft, narrow 1-4 ft, medium 5-8 ft)
	Passing lane	Missing passing lane in section where there are not passing opportunities
	Climbing lane	Missing climbing lane in mountainous terrain where car/truck speeds differ greatly
	Rumble strips	Missing audible edge-lines
		Missing audible center-lines
	Pedestrian crosswalks	Missing or ineffective crosswalks in areas with pedestrian activities
	Access control	Dangerousness of accesses
		Excessive density of uncontrolled accesses
Consistency of Design Standards	Curve sections	Curve section design consistency level
	Tangent sections	Tangent section design consistency level
Pavement Conditions	Skid resistance	Inadequate skid resistance
	Unevenness	Potholes, rutting, shoving on curves or close to intersections
Safety Hardware	Signs	Curve warning missing or not visible on severe curves
		No-passing sign missing or not visible
		Night-time retroreflectivity is lower than the minimum required level
	Lighting	No roadway lighting
		Roadway lighting off
	Pavement markings	Edge-lines marking missing or inadequate
		Centerline marking missing or inadequate
		No-passing line marking missing or inadequate
		Night-time retroreflectivity is lower than the minimum required level
	Delineation	Chevron missing or ineffective on severe curve
Roadside Features	Embankment	Unshielded embankment (9 < height < 18 ft, grade > 0.5%)
		Unshielded embankment (height > 18 ft, grade > 0.5%)
	Guardrails and barriers (Roadside safety hardware)	Embankment shielded with ineffective barrier (9 < height < 18 ft, grade > 0.5%)
		Embankment shielded with ineffective barrier (height > 18 ft, grade > 0.5%)
		Ineffective barrier for overpass bridges
		No breakaway barrier terminals and transitions
		Missing transition between barriers or between barrier and wall
		Guardrail or barrier reflectors missing or damaged
	Bridges	Inadequate bridge rails
	Ditches	Ditches located less than 9 ft from the travel way
	Trees	High diameter trees located less than 9 ft from the travel way
	Rigid utility poles	High diameter rigid utility poles located less than 9 ft from the travel way
	Rigid obstacles	High diameter rigid obstacles located less than 9 ft from the travel way

6.2.4 Crash Types Affected by Safety Hardware-Related Issues

The highway safety hardware on highway segments mainly includes signs, lighting, pavement markings and delineation, and guardrails and barriers. The first three categories of safety hardware virtually affect all type of vehicle crashes and most often they affect head-on, sideswipe, fixed object, and run-off-road crashes. Whereas the last category of safety hardware- guardrails and barriers, it is mainly related to run-off-road crashes. In this study, head-on, sideswipe, fixed object, and run-off-road crash types are explicitly handled.

6.2.5 Crash Severity Categories Affected by Safety Hardware-Related Issues

The crash severity categories considered are fatal, injury, and PDO crashes.

6.2.6 Calculation of Safety Index for a Highway Segment

The Safety Index (SI) gauges the relative safety performance of a road segment (Ogden, 1996; De Leur and Sayed, 2002; Transfund New Zealand, 2003; TAC, 2004; Montella, 2005; Cafiso et al., 2006; Lamm et al., 2006). The SI is computed by considering three components of risks: traffic Exposure factor (measures the exposure of road users to road hazards); crash frequency factor (is the probability of a vehicle being involved in a crash); and crash severity factor (measures the consequences of a crash). The SI is calculated as

$$SI_S = \text{Traffic Exposure Factor} \times \sum_{r=1}^{R} [P(\text{Crash Type r}) \times CFF_{rs} \times CSF_{rs}] \tag{6-1}$$

where

SI_s = Safety index for a highway segment for crash severity category *s*, number of crashes/year

Traffic Exposure Factor = The total vehicle miles of travel (VMT) on the road segment, million VMT/year

P(Crash Type *r*) = Probability of occurring type *r* crashes

CFF_{rs} = Overall crash frequency factor for a highway segment measuring the risk of increasing the crash frequency for crash type *r* in crash severity category *s*

CSF_{rs} = Overall crash severity factor for a highway segment measuring the risk of increasing the crash severity for crash type *r* in crash severity category *s*

r = Crash type (head-on, sideswipe, fixed object, and run-off-road)

s = Crash severity category (fatal, injury, and PDO).

6.3 Calculation of the Traffic Exposure Factor

Traffic exposure factor measures the exposure of highway users to road hazards, and it is calculated as follows:

$$\text{Traffic Exposure Factor: } TEF = L \times (365 \times AADT^{a}) \tag{6-2}$$

where

L = Length of the highway segment under consideration, miles

AADT = Annual average daily traffic, vehicles per day

a = Exponent of AADT in the safety performance function with a < 1 to consider non-linearity between crashes and traffic volume or is set to 1 if pertinent safety performance function is not available.

6.4 Calculation of the Crash Frequency Factor

6.4.1 Basic Concepts for Calculating the Crash Frequency Factor

The crash frequency factor reflects the risk of increasing the crash frequency. The crash frequency factor by crash type *r* and by crash severity *s* for a specific highway segment is computed as the production of multiple crash frequency factors concerning detailed safety issue items *j* under safety issue type *i* for each safety issue category, including geometric design, pavement conditions, and safety hardware conditions. The section first provides equations needed for the computation and it is then followed by detailed descriptions.

$$CFF_{rs} = \prod_{i=1}^{I} CFF_{rsi} \tag{6-3}$$

$$CFF_{rsi} = \sum_{j=1}^{J} CFF_{rsij} \tag{6-4}$$

$$CFF_{rsij} = 1 + W_{rsij} \times \Delta CF_{rsij} \times P_{rsij} \tag{6-5}$$

where

CFF_{rs} = Overall crash frequency factor for a highway segment with respect to crash type *r* and severity category *s*

CFF_{rsi} = Crash frequency factor concerning safety issue type *i* for a highway segment with respect to crash type *r* and severity category *s*

CFF_{rsij} = Crash frequency factor concerning detailed safety issue item *j* under safety issue type *i* for a highway segment with respect to crash type *r* and severity category *s*

W_{rsij} = Proportion of the road segment affected by detailed safety issue item *j* under safety issue type *i* with respect to crash type *r* and severity category *s*

ΔCF_{rsij} = Relative increase in the crash frequency due to detailed safety issue item *j* under safety issue type *i* with respect to crash type *r* and severity category *s*

P_{rsij} = Proportion of crashes on the highway segment affected by detailed safety issue item *j* under safety issue type *i* with respect to crash type *r* and severity category *s*.

Without loss of generality, W_{rsij}, ΔCF_{rsij}, and P_{rsij} that collectively affects the crash frequency factor by crash type *r* related to a highway segment could be largely assumed to be equal for fatal, injury or PDO crash categories. This gives $W_{r,F,i,j} = W_{r,I,i,j} = W_{r,P,i,j}$, $\Delta CF_{r,F,i,j} = \Delta CF_{r,I,i,j} = \Delta CF_{r,P,i,j}$, and $P_{r,F,i,j} = P_{r,I,i,j} = P_{r,P,i,j}$, where the subscribe *s* representing the crash severity category as F, I, and P are for fatal, injury, and PDO crash categories, respectively. Therefore, the computation of the crash frequency factor by crash type for fatal, injury, and PDO crash categories could be just focused on injury crashes that are involved with establishing $W_{r,I,i,j}$, $\Delta CF_{r,I,i,j}$, and $P_{r,I,i,j}$. Table 6.3 shows an example of relative increase in the crash frequency caused by highway infrastructure-related safety issues for rural two-lane roads (Hassan et al., 1996; RDMTD, 1999; Harwood et al. 2000; Hauer, 2002; Lamm et al., 2002; Shen et al., 2004; NCHRP, 2005; Rose and Carlson, 2005).

Table 6.3. Relative Increase in the Crash Frequency Caused by Highway Infrastructure-Related Safety Issues for Rural Two-Lane Roads

Safety Issue Category	Safety Issue Type (i)	Detailed Safety Issue Item (j)	Affected Crash Type (r)	Related Effect	Increase in the Fatal, Injury or PDO Crash Frequency ΔCF_{rsij} (%)
Geometric Design	Alignment	Very severe curve realignment needed	All	650 ft	100
		Inadequate sight distance on horizontal curves	All	650 ft	5
		Inadequate sight distance on vertical curves	All	650 ft	50
	Cross section	Lane width			
		- very narrow < 9 ft	Run-off-road	Segment	5-50
		- narrow < 11 ft	Head-on, sideswipe	Segment	2-30
	Shoulder attributes	Shoulder width			
		- no shoulder	Run-off-road	Segment	9-40
		- very narrow <1 ft	Run-off-road	Segment	9-40
		- narrow 1-4 ft	Head-on, sideswipe	Segment	6-20
		- medium 5-8 ft	Head-on, sideswipe	Segment	6-20
	Passing lane	Missing passing lane	All	Segment	33
	Climbing lane	Missing climbing lane	All	Segment	33
	Rumble strips	Missing audible edge-lines	Run-off-road	Segment	40
		Missing audible center-lines	Head-on	Segment	11
	Pedestrian crosswalks	Missing or ineffective crosswalks	Hit pedestrian	Segment	60
	Access control	Dangerousness of accesses	All	Segment	135
		Excessive density of uncontrolled accesses	All	Segment	75
Consistency of Design Standards	Curve sections	Curve section design consistency level	All	Segment	700
	Tangent sections	Tangent section design consistency level	All	Segment	700
Pavement Conditions	Skid resistance	Inadequate skid resistance	Wet	Segment	30
	Unevenness	Potholes, rutting, shoving	All	Segment	10
Safety Hardware Conditions	Signs	Curve warning missing or not visible	All	650 ft	10
		No-passing sign missing or not visible	Head-on	Segment	50
		Night-time retroreflectivity not met	All	Segment	50
	Lighting	No roadway lighting	All	Segment	10
		Roadway lighting off	All	Segment	10
	Pavement markings	Edge-lines marking missing or inadequate	All	Segment	8
		Centerline marking missing or inadequate	All	Segment	13
		No-passing line marking missing or inadequate	Head-on	Segment	50
		Night-time retroreflectivity not met	All	Segment	50
	Delineation	Chevron missing or ineffective on severe curve	All	650 ft	20

6.4.2 Computation of the Crash Frequency Weighting Factor W_{rsij}

The detailed safety issue items affecting the crash frequency are primarily related to geometric design, consistency of design standards, pavement conditions, and safety hardware conditions. The geometric design, pavement conditions, and safety hardware conditions collectively contribute to highway infrastructure-related crash occurrences. However, the consistency of design standards of curved and tangent sections in a highway segment greatly influences vehicle running characteristics and its impacts on highway safety differ greatly from purely infrastructure-related safety issues. To this end, the weighting factors for safety issue items related to geometric design, pavement conditions, and safety hardware conditions and the weighting factors for safety issue items concerning the consistency of design standards are separately established using different approaches (Proctor et al., 2001; Transfund New Zealand, 2003).

6.4.2.1 Weighting Factors for Safety Issue Items Related to Geometric Design, Pavement Conditions, and Safety Hardware Conditions

The weighting factor W_{rsij} for each detailed safety issue item *j* under safety issue type *i* represents the proportion of the highway segment affected by the safety issue item. First, data on individual safety items that reflect the geometric design, pavement conditions, and safety hardware conditions along the highway segment alignment need to be collected. Practically, the highway segment can be hypothetically broken into multiple sections and each section maintains approximately one-tenth of a mile in length. Then, 0/1 values can be assigned to each section representing absence/presence of a specific safety issue item in the section. This helps determine the actual fraction of the length of the highway segment exposed to each safety issue. The ratio between the safety issue item affected length and the total length of the highway segment is exactly the weighting factor for the safety issue item.

6.4.2.2 Weighting Factors for Safety Issue Items Associated with the Consistency of Design Standards

For a specific highway segment, different design elements are involved with the curved sections and tangent sections in the segment. As such, the weighting factors are separately estimated for curved sections and tangent sections.

6.4.2.2.1 Weighting Factor for the Curved Section-Induced Safety Issue

A consistently designed highway will provide uniform driving conditions and thereby produces good driving performances. Drivers often changes speeds according to the posted speed limits and alignment changes. If a highway segment under safety evaluation has more than one curved sections, the weighting factor for the curved section-induced safety issue is computed as

$$W_{rsij_CURVE} = \frac{\sum_{m=1}^{M}\left(W_{rsij_m,CURVE} \times L_{m,CURVE}\right)}{\sum_{m=1}^{M} L_{m,CURVE}} \tag{6-6}$$

$$W_{rsij_m,CURVE} = \frac{\sum_{n=1}^{N_{SC}} W_{rsij_m,n,CURVE}}{N_{SC}} \tag{6-7}$$

where

W_{rsij_CURVE} = Weighting factor for safety issue item *j* under safety issue type *i* induced by all curve sections in the highway segment with respect to crash type *r* and severity category *s*

$W_{rsij_m,CURVE}$ = Weighting factor for safety issue item *j* under safety issue type *i* induced by curve section *m* in the highway segment with respect to crash type *r* and severity category *s*

$W_{rsij_m,n,CURVE}$ = Weighting factor for safety issue item *j* under safety issue type *i* induced by safety criterion *n* of curve section *m* in the highway segment with respect to crash type *r* and severity category *s*

$L_{m,CURVE}$ = Length of the mth curve section in the highway segment, ft

m = Number of curve sections in the highway segment, 1, 2,…., M

n = Number of safety criteria considered for the evaluation, 1, 2,…., N_{SC}.

a. Criteria for Evaluating the Crash Risk Affected by a Curve Section
The following four safety criteria are adopted for evaluating the weighting factor for the crash risk affected by a curve section:

- Curve length consistency: comparing the curve length L with the acceptable minimum curve length L_{min} and maximum curve length L_{max} for each curve section
- Design speed consistency: comparing the difference between the 85th percentile speed V_{85} and the design speed V_D on each curve section
- Operating speed consistency: comparing the difference in V_{85}'s between successive curve sections in the highway segment
- Driving dynamic consistency: comparing the difference between the design speed V_D-based side friction f_D and 85th percentile speed V_{85}-based side friction f_{85} on each curve section. Three criteria are depicted in Table 6.4.

Table 6.4. Criteria for Evaluating the Crash Risk Affected by a Curve Section

Safety Criterion	Design Class		
	Good	Fair	Poor
Curve Length Consistency	$(3L_{min}+L_{max})/4 < L < (L_{min}+3L_{max})/4$	$L_{min} < L < (3L_{min}+L_{max})/4$ or $(L_{min}+3L_{max})/4 < L < L_{max}$	$L < L_{min}$ or $L > L_{max}$
Design Speed Consistency	$\lvert V_{85,i} - V_{D,i}\rvert \le 6.5$ mph	6.5 mph $< \lvert V_{85,i} - V_{D,i}\rvert \le 13$ mph	$\lvert V_{85,i} - V_{D,i}\rvert > 13$ mph
Operating Speed Consistency	$\lvert V_{85,i} - V_{85,i+1}\rvert \le 6.5$ mph	6.5 mph $< \lvert V_{85,i} - V_{85,i+1}\rvert \le 13$ mph	$\lvert V_{85,i} - V_{85,i+1}\rvert > 13$ mph
Vehicle Dynamics Consistency	$f_{s,D} - f_{s,85} \ge +0.01$	$-0.04 \le f_{s,D} - f_{s,85} < +0.01$	$f_{s,D} - f_{s,85} < -0.04$

where
L = Length of the curve, ft
L_{min} = Minimum curve length, $L_{min} = 100+10(V_D-30)$, ft
L_{max} = Maximum curve length, L_{max} = 1 mile for multilane, 0.5 mile for high speed two-lane, and 0.25 mile for low speed two-lane curve section
V_D = Design speed of curve section, mph
V_{85} = 85th percentile speed on curve, $V_{85}= 63.67 + 0.0007L - (18{,}341 + 3.56L)/R$, mph
R = Radius of the curve, ft
$f_{s,D}$ = Design speed V_D-based side friction, $f_{s,D}= 0.32745 - 0.001674V_D + 0.00000324V_D^2$
$f_{s,85}$ = 85th percentile speed V_{85}-based side friction, $f_{s,85}= V_{85}^2/(15R) - e$
R = Radius of the curve, ft
e = Superelevation, $e = \tan\beta$ (β is the superelevation angle of the curve).

b. Weighting Scales for $W_{rsij\text{-}m,n,CURVE}$
The following weighting scales can be used:

- A weight of "+1" is given to the curve section indicating the good design class
- A weight of "0" is given to the fair design class
- A weight of "-1: is given to the poor design class.

The weights given to each safety criterion $W_{rsij\text{-}m,n,CURVE}$ is added and then it will be averaged to get the weighting factor $W_{rsij\text{-}m,\,CURVE}$ for each curve section.

$W_{rsij\text{-}m,CURVE} \ge 0.75$ represents a good design class for curve sections of a highway segment; $-0.75 < W_{rsij\text{-}m,CURVE} < 0.75$ shows a fair design class; and $W_{rsij\text{-}m,CURVE} \le -0.75$ indicates a poor design class.

6.4.2.2.2 Weighting Factor for Tangent Section-Induced Safety Issue Items

a. Criteria for Evaluating the Crash Risk Affected by a Tangent Section

Tangent sections in a highway segment also need to be checked for consistency of design standards. Two criteria may be used for the evaluation:

- Maximum length of tangent section TL_{max}
- Minimum length of tangent section, TL_{min}

For the maximum length, the tangent section must have a length less than 115 times the design speed: $TL_{max} < 115V_D$, where TL in ft and V_D in mph.

The minimum length of the tangent section needs to be checked for reverse curves that are closely spaced with deflections in opposite directions. There are two cases for this situation: one case is to achieve a normal crown section between the reverse curves, the other case is without providing a normal section and the pavement will be continuously rotated in a plane about its axis. The minimum length of the tangent section for each case is determined by using the following (IDOT, 2002):

- Tangent Section with a Normal Crown: $TL_{min} = 0.67L_A+TR_A+2.94V_D+0.67L_B+TR_B$
- Tangent Section Continuously Rotated in a Plane: $TL_{min} = 0.67L_A+ 0.67L_B$

where

TL_{min} = Minimum length of a tangent section measured between PT of the first curve and PC of the section curve, ft

TL_{max} = Maximum length of a tangent section measured between PT of the first curve and PC of the section curve, ft

L_A = Superelevation runoff length for the first curve, ft

TR_A = Tangent runout length for the first curve, ft

L_B = Superelevation runoff length for the second curve, ft

TR_B = Tangent runout length for the second curve, ft

Table 6.5 lists the superelevation runoff length and tangent runout length for different design speeds recommended by the American Association of State Highway and Transportation Officials (AASHTO, 2001).

Table 6.5. Superelevation Runoff Length and Tangent Runout Length for Different Design Speeds

Design Speed (mph)	Superelevation runoff length (ft)	Tangent Runout Length (ft)				
		Superelevation Rate (%)				
		2	4	6	8	10
15	44	44	-	-	-	-
20	59	59	30	-	-	-
25	74	74	37	25	-	-
30	88	88	44	29	-	-
35	103	103	52	34	26	-
40	117	117	59	39	29	-
45	132	132	66	44	33	-
50	147	147	74	49	37	-
55	161	161	81	54	40	-
60	176	176	88	59	44	-
65	191	191	96	64	48	38
70	205	205	103	68	51	41
75	220	220	110	73	55	44
80	235	235	118	78	59	47

b. The Weighting Factor for the Tangent Section Length that Potentially Increases the Crash Risk The weighting factor W_{rsij} for the potential safety issue item of tangent section length under the safety issue type of consistency of design standards represents the proportion of the tangent sections in the highway segment possessing inadequate lengths that potentially increases the crash risk. First, data on the length of each tangent section and the requirements of minimum tangent length and maximum tangent length for each tangent section need to be collected. By comparing the actual length with the minimum length and maximum length for each tangent section, the list of tangent sections with inadequate length can be identified. The ratio between the total length of all inadequate tangent sections and the total length of all tangent sections in the highway segment is the weighting factor for the tangent length safety issue item.

6.4.3 Relative Increase in the Risk of Crash Frequency ΔCF_{rsij}

For safety issue items related to geometric design, pavement conditions, and safety hardware conditions, the relative increase in crash frequency ΔCF_{rsij} is related to the Accident Modification Factor AMF_{rsij} and it can be computed as $\Delta CF_{rsij} = AMF_{rsij} - 1$, where the AMF_{rsij} can be readily obtained from safety performance functions applicable to the highway segment.

For safety issue items related to the consistency of design standards, the increase in crash risk on poor curved sections and inadequate tangent sections as compared to adequate tangents is reported as 700% (Lamm, et al., 2002).

6.4.4 Proportion of Crashes Affected by a Detailed Safety Issue Item P_{rsij}

The proportion of crashes by crash type *r* and severity category *s* P_{rsij} affected by a detailed safety issue item *j* under safety issue type *i* can be established in a similar manner as the weighting factor for each detailed safety issue item. First, historical crash data and crash locations associated with the highway segment need to be collected. Again, the highway segment can be hypothetically broken into multiple sections and each section maintains approximately one-tenth of a mile in length. Then, 0/1 values can be assigned to each section representing absence/presence of a specific safety issue item in the section. If a crash by type and by severity category occurred in the highway section that is also affected by a specific safety issue item, this section may be considered as being affected by the specific safety issue item. The ratio between cumulative number of sections affected by the safety issue item and the total number of sections in the highway segment is exactly the proportion of crashes affected by the safety issue item.

The proportions of crashes by type and severity affected by curve sections and tangent design standards under consistency of design standards P_{rsij} are listed in Table 6.6 (Cafiso et al., 2006).

Table 6.6. Proportion of Crashes Affected by the Safety Issue Type of the Consistency of Design Standards

Safety Issue Item	Crash Type Affected	Criterion		P_{rsij}
Curve Section Consistency	Run-off-road, partially head-on, sideswipe	Curve Length Design Speed Operating Speed Vehicle Dynamics	Good	20%
		Curve Length Design Speed Operating Speed Vehicle Dynamics	Fair	50%
		Curve Length Design Speed Operating Speed Vehicle Dynamics	Poor	100%
Tangent Section Consistency	Run-off-road	Minimum Length		10%
		Maximum length		10%

6.5 Computation of the Crash Severity Factor

6.5.1 Basic Concepts

Crash severity factor represents the consequence after being involved in vehicle crashes. Both operating speed and roadside features of a highway segment play a significant role in calculating this factor. The crash severity factor by crash type *r* and by crash severity *s* for a specific highway segment is computed as the production of multiple crash severity factors concerning detailed safety issue items *j* under safety issue type *i* for the operating speed and safety issue category of roadside features as follows:

$$CSF_{rs} = \left(\frac{V_{85}}{V_{SL}}\right) \times CSF_{rs_RSH} \tag{6-8}$$

$$CSF_{rs_RSH} = \prod_{i=1}^{I} CSF_{rsi_RSH} \tag{6-9}$$

$$CSF_{rsi_RSH} = \sum_{j=1}^{J} CSF_{rsij_RSH} \tag{6-10}$$

$$CSF_{rsij_RSH} = 1 + W_{rsij_RSH} \times \Delta CS_{rsij_RSH} \times P_{rsij_RSH} \tag{6-11}$$

where

CFF_{rs} = Overall crash severity factor for a highway segment with respect to crash type *r* and severity category *s*

V_{85} = 85th percentile of speed distribution weighted along the segment, mph

V_{SL} = Speed limit distribution weighted along the segment, mph

CFF_{rs_RSH} = Roadside hazards induced crash severity factor for a highway segment with respect to crash type *r* and severity category *s*

CSF_{rsi_RSH} = Roadside hazards induced crash severity factor concerning safety issue type *i* for a highway segment with respect to crash type *r* and severity category *s*

CSF_{rsij_RSH} = Roadside hazards induced crash severity factor concerning detailed safety issue item *j* under roadside safety issue type *i* for a highway segment with respect to crash type *r* and severity category *s*

W_{rsij_RSH} = Proportion of the road segment affected by roadside safety issue item *j* under roadside safety issue type *i* with respect to crash type *r* and severity category *s*

ΔCS_{rsij_RSH} = Relative increase in the roadside hazards induced crash severity risk due to detailed safety issue item *j* under roadside safety issue type *i* with respect to crash type *r* and severity category *s*

P_{rsij_RSH} = Proportion of crashes on the highway segment affected by roadside safety issue item *j* under roadside safety issue type *i* with respect to crash type *r* and severity category *s*.

For each type of crashes affected by roadside features, the roadside hazards induced crash severity factor concerning detailed safety issue item *j* under roadside safety issue type *i* for fatal, injury, and PDO crashes can be separately computed on the basis of Equation (6.6-6.9) with details shown in the following:

$$CSF_{r,I,i,j_RSH} = 1 + W_{r,I,i,j_RSH} \times \Delta CS_{r,I,i,j_RSH} \times P_{r,I,i,j_RSH} \quad (6\text{-}12)$$

$$CSF_{r,F,i,j_RSH} = 1 + W_{r,I,i,j_RSH} \times \left[\Delta CS_{r,I,i,j_RSH} \times \left(1 + \Delta S_{r,F,i,j}\right)\right] \times P_{r,I,i,j_RSH} \quad (6\text{-}13)$$

$$CSF_{r,P,i,j_RSH} = 1 + W_{r,I,i,j_RSH} \times \left[\Delta CS_{r,I,i,j_RSH} \times \left(1 + \Delta S_{r,P,i,j}\right)\right] \times P_{r,I,i,j_RSH} \quad (6\text{-}14)$$

where

$CSF_{r,I,i,j\text{-}RSH}$ = Roadside hazards induced injury crash severity factor concerning detailed safety issue item *j* under roadside safety issue type *i* for a highway segment with respect to crash type *r*

$CSF_{r,F,i,j\text{-}RSH}$ = Roadside hazards induced fatal crash severity factor concerning detailed safety issue item *j* under roadside safety issue type *i* for a highway segment with respect to crash type *r*

$CSF_{r,P,i,j\text{-}RSH}$ = Roadside hazards induced PDO crash severity factor concerning detailed safety issue item *j* under roadside safety issue type *i* for a highway segment with respect to crash type *r*

$W_{r,I,i,j\text{-}RSH}$ = Proportion of the road segment affected by detailed safety issue item *j* under roadside safety issue type *i* in the injury crash risk with respect to crash type *r*

$\Delta CS_{r,I,i,j\text{-}RSH}$ = Relative increase in the roadside hazards induced injury crash severity risk due to detailed safety issue item *j* under roadside safety issue type *i* with respect to crash type *r*

$P_{r,I,i,j\text{-}RSH}$ = Proportion of injury crashes on the highway segment affected by detailed safety issue item *j* under roadside safety issue type *i* with respect to crash type *r*

$\Delta S_{r,F,i,j\text{-}RSH}$ = Relative increase in the roadside hazards induced fatal crash risk over injury crash risk due to detailed safety issue item *j* under roadside safety issue type *i* with respect to crash type *r*

$\Delta S_{r,P,i,j\text{-}RSH}$ = Relative increase in the roadside hazards induced PDO crash risk over injury crash risk due to detailed safety issue item *j* under roadside safety issue type *i* with respect to crash type *r*.

Table 6.7 lists an example of relative increase in the crash severity risk caused by roadside safety issues for rural two-lane roads (Harwood et al. 2000; Hauer, 2002; Lamm et al., 2002; Shen et al., 2004).

Table 6.7. Relative Increase in the Crash Severity Caused by Roadside Safety Issues for Rural Two-Lane Roads

Roadside Safety Issue Type (i)	Detailed Safety Issue Item (j)	Affected Crash Type (r)	Related Effect	Increase in Injury Crash Severity (%)	Additional Increase in Fatal/ PDO Crash Severity (%)	
				Injury, $\Delta CS_{r,I,i,j}$	Fatal, $\Delta S_{r,F,i,j}$	PDO, $\Delta S_{r,P,i,j}$
Embankment	Unshielded embankment					
	- 9< height< 18 ft, grade> 0.5%	Run-off-road	Segment	80	800	800
	- height> 18 ft, grade> 0.5%	Run-off-road	Segment	100	1,400	1,400
Guardrails and barriers	Embankment shielded with ineffective barrier					
	- 9< height< 18 ft, grade> 0.5%	Run-off-road	Segment	10	70	100
	- height> 18 ft, grade> 0.5%	Run-off-road	Segment	11	100	100
	Ineffective barrier for overpass bridges	Run-off-road	100 ft	60	70	100
	No breakaway barrier terminals and transitions	Run-off-road	100 ft	60	300	300
	Missing transition	Run-off-road	100 ft	60	300	300
	Reflectors missing or damaged	Run-off-road	100 ft	8	0	100
Bridges	Inadequate bridge rails	Run-off-road	100 ft	6	2,000	2,000
Ditches	Ditches located less than 9 ft	Run-off-road	Segment	50	150	150
Trees	Trees located less than 9 ft	Run-off-road	200 ft	90	1,000	1,000
Utility poles	Utility poles located less than 9 ft	Run-off-road	200 ft	90	1,000	1,000
Obstacles	Obstacles located less than 9 ft	Run-off-road	100 ft	90	1,000	1,000

6.5.2 Computation of the Injury Crash Weighting Factor $W_{r,I,i,j}$

The injury crash weighting factor $W_{r,I,i,j}$ for each roadside safety issue item *j* under roadside safety issue type *i* represents the proportion of the highway segment affected by the safety issue item. First, data regarding individual roadside safety issue items affecting the safety performance of the highway segment under investigation need to be collected. Practically, the highway segment can be hypothetically broken into multiple sections and each section maintains approximately one-tenth of a mile in length. Then, 0/1 values can be assigned to each section representing absence/presence of a specific roadside safety issue item in the section. This eventually helps determine the actual fraction of the length of the highway segment influenced by each roadside safety issue. The ratio between the roadside safety issue item affected length and the total length of the highway segment is the injury crash weighting factor for the safety issue item.

6.5.3 Relative Increase in Fatal, Injure and PDO Crash Risks

The relative increase in injury crashes $\Delta CS_{r,I,i,j}$ caused by roadside safety issue items is related to the Accident Modification Factor for injury crashes $AMF_{r,I,i,j}$ and it can be computed as $\Delta CS_{r,I,i,j} = AMF_{r,I,i,j} - 1$, where the $AMF_{r,I,i,j}$ can be established from safety performance functions applicable to the highway segment.

As the vehicle crash rate in term of crashes per VMT reflects the crash risk faced by each traveler making a unit distance of travel, it can therefore be used to determine the relative increase in fatal and PDO crash risks over the injury crash risk. The relative increase in fatal crash risk $\Delta S_{r,F,i,j\text{–}RSH}$ over the injury crash risk due to a roadside safety issue item can be determined as the percentage change in the fatal and injury crash rate over injury crash rate only using historical crash data. Similarly, the relative increase in PDO crash risk $\Delta S_{r,P,i,j\text{–}RSH}$ over the injury crash risk can be estimated as the percentage change in the injury and PDO crash rate over injury crash rate only using historical crash data.

6.5.4 Proportion of Injury Crashes Affected by a Detailed Safety Issue Item $P_{r,I,i,j}$

The proportion of injury crashes by crash type *r* $P_{r,I,i,j}$ affected by a roadside safety issue item can be established as explained below. First, historical injury crash data and injury crash locations associated with the highway segment need to be collected. Again, the highway segment can be hypothetically broken into multiple sections and each section maintains approximately one-tenth of a mile in length. Then, 0/1 values can be assigned to each section representing absence/presence of a specific roadside safety issue item in the section. If an injury crash by crash type occurred in the highway section that is also affected by a specific roadside safety issue item, this section may be considered to be affected by the roadside safety issue item. The ratio between cumulative number of sections affected by the roadside safety issue item and the total number of sections in the highway segment is the proportion of injury crashes by crash type affected by the roadside safety issue item.

6.6 Calculation of the Safety Index for a Highway Segment by Crash Type and by Severity

The safety index is computed as the production of traffic exposure factor, crash frequency factor, and crash severity factor. The traffic exposure factor for a highway segment measures the extent of highway users exposed to road hazards when traversing the highway segment. Equation (6-2) in Section 6.2.2 can be used to compute the traffic exposure factor as the production of segment length and traffic volume.

The procedure in Section 6.2.3 facilitates computing the crash frequency factor for a highway segment by crash type (head-on, sideswipe, fixed object, and run-off-road) and by crash severity category (fatal, injury, and PDO). The crash frequency factor by crash type and by severity category considers a number of detailed safety issue items under various safety issue types that can be grouped into safety issue categories regarding geometric design, consistency of design standards, pavement conditions, and safety hardware conditions. The crash frequency factors for multiple safety issue items under a specific safety issue type can be added to obtain the safety issue type-specific crash frequency factor. The production of crash frequency factors corresponding to multiple safety issues types can be computed to establish the

overall crash frequency factor for the highway segment by crash type and by crash severity. In the analysis process, equal chance of the relative increase in the fatal, injury, and PDO crash risks is assumed. This yields identical crash frequency factors by crash type for fatal, injury, and PDO crashes. For the matter of data convenience, the injury crash frequency factor for each crash type is directly computed and this factor is used for the fatal crash frequency factor for each crash type and for the PDO crash frequency factor for each crash type.

The procedure in Section 6.2.4 helps estimate the crash severity factor for a highway segment by crash type (head-on, sideswipe, fixed object, and run-off-road) and by crash severity category (fatal, injury, and PDO). The crash severity factor by crash type and by severity category considers a number of detailed safety issue items in the roadside safety issue category. The crash severity factors for multiple safety issue items under a specific roadside safety issue type can be added to obtain the roadside safety issue type-specific crash severity factor. The production of crash severity factors corresponding to multiple roadside safety issues types can be computed to establish the overall crash severity factor for the highway segment by crash type and by crash severity. In the analysis process, the injury crash severity factor for each crash type is first computed. The fatal crash severity factor and PDO crash severity factor for each roadside safety issue item by crash type are derived on the bases of the injury crash severity factor for the same roadside safety issue item by crash type.

The production of estimated traffic exposure factor, crash frequency factor, and crash severity factor by crash type and crash severity category is the safety index for the highway segment by crash type and crash severity category. In order to establish the safety index for the highway segment only by severity category, the probability of vehicle crashes by crash type must be determined. The next section introduces an approach to establish the probability of vehicle crashes by crash type using data on historical crashes on a highway segment.

Table 6.8. Systematic Procedure for Computing the Safety Index for a Highway Segment

I. Traffic Exposure Factor (TEF)

Traffic	Annual average daily traffic (AADT), vehicles per day
Length	Segment length, miles

$TEF = L\times(365\times AADT^{a})$, a < 1 to consider non-linearity between crashes and usage or a= 1 if without safety performance function

II. Crash Frequency Factor (CFF_{rs})

Safety Issue Category (k)	Safety Issue Type (i)	Detailed Safety Issue Item (j)	CFF_{rsij}
Geometric Design (k=1)	Alignment (i=1) $CFF_{rs1} = CFF_{rs11} + CFF_{rs12} + CFF_{rs13}$	Very severe curve realignment needed (j=1)	$CFF_{rs11}=1+W_{rs11}\times\Delta CF_{rs11}\times P_{rs11}$
		Inadequate sight distance on horizontal curves (j=2)	$CFF_{rs12}=1+W_{rs12}\times\Delta CF_{rs11}\times P_{rs12}$
		Inadequate sight distance on vertical curves (j=3)	$CFF_{rs13}=1+W_{rs13}\times\Delta CF_{rs13}\times P_{rs13}$
	Cross section (i=2) $CFF_{rs2} = CFF_{rs21}$	Lane width (j=1)	$CFF_{rs21}=1+W_{rs21}\times\Delta CF_{rs21}\times P_{rs21}$
	Shoulder attributes (i=3) $CFF_{rs3} = CFF_{rs31}$	Shoulder width (j=1)	$CFF_{rs31}=1+W_{rs31}\times\Delta CF_{rs31}\times P_{rs31}$
	Passing lane (i=4) $CFF_{rs4} = CFF_{rs41}$	Missing passing lane (j=1)	$CFF_{rs41}=1+W_{rs41}\times\Delta CF_{rs41}\times P_{rs41}$
	Climbing lane (i=5) $CFF_{rs5} = CFF_{rs51}$	Missing climbing lane (j=1)	$CFF_{rs51}=1+W_{rs51}\times\Delta CF_{rs51}\times P_{rs51}$
	Rumble strips (i=6) $CFF_{rs6} = CFF_{rs61}+CFF_{rs62}$	Missing audible edge-lines (j=1)	$CFF_{rs61}=1+W_{rs61}\times\Delta CF_{rs61}\times P_{rs61}$
		Missing audible center-lines (j=1)	$CFF_{rs62}=1+W_{rs62}\times\Delta CF_{rs62}\times P_{rs62}$
	Pedestrian walks (i=7) $CFF_{rs7} = CFF_{rs71}$	Missing or ineffective crosswalks (j=1)	$CFF_{rs71}=1+W_{rs71}\times\Delta CF_{rs71}\times P_{rs71}$
	Access control (i=8) $CFF_{rs8} = CFF_{rs81}+CFF_{rs82}$	Dangerousness of accesses (j=1)	$CFF_{rs81}=1+W_{rs81}\times\Delta CF_{rs81}\times P_{rs81}$
		Excessive density of uncontrolled accesses (j=2)	$CFF_{rs82}=1+W_{rs82}\times\Delta CF_{rs82}\times P_{rs82}$
Consistency of Design Standards (k=2)	Curve sections (i=9) $CFF_{rs9} = CFF_{rs91}$	Curve section design consistency level (j=1)	$CFF_{rs91}=1+W_{rs91}\times\Delta CF_{rs91}\times P_{rs91}$
	Tangent sections (i=10) $CFF_{r,s,10} = CFF_{r,s,10,1}$	Tangent section design consistency level (j=1)	$CFF_{r,s,10,1}=1+W_{r,s,10,1}\times\Delta CF_{r,s,10,1}\times P_{r,s,10,1}$
Pavement Conditions (k=3)	Skid resistance (i=11) $CFF_{r,s,11} = CFF_{r,s,11,1}$	Inadequate skid resistance (j=1)	$CFF_{r,s,11,1}=1+W_{r,s,11,1}\times\Delta CF_{r,s,11,1}\times P_{r,s,11,1}$
	Unevenness (i=12) $CFF_{r,s,12} = CFF_{r,s,12,1}$	Potholes, rutting, shoving (j=1)	$CFF_{r,s,12,1}=1+W_{r,s,12,1}\times\Delta CF_{r,s,12,1}\times P_{r,s,12,1}$
Safety Hardware Conditions (k=4)	Signs (i=13) $CFF_{r,s,13} = CFF_{r,s,13,1} + CFF_{r,s,13,2} + CFF_{r,s,13,3}$	Curve warning missing or not visible (j=1)	$CFF_{r,s,13,1}=1+W_{r,s,13,1}\times\Delta CF_{r,s,13,1}\times P_{r,s,13,1}$
		No-passing sign missing or not visible (j=2)	$CFF_{r,s,13,2}=1+W_{r,s,13,2}\times\Delta CF_{r,s,13,2}\times P_{r,s,13,2}$
		Night-time retroreflectivity not met (j=3)	$CFF_{r,s,13,3}=1+W_{r,s,13,3}\times\Delta CF_{r,s,13,3}\times P_{r,s,13,3}$
	Lighting (i=14) $CFF_{r,s,14} = CFF_{r,s,14,1}$	No roadway lighting (j=1)	$CFF_{r,s,14,1}=1+W_{r,s,14,1}\times\Delta CF_{r,s,14,1}\times P_{r,s,14,1}$
		Roadway lighting off (j=2)	$CFF_{r,s,14,2}=1+W_{r,s,14,2}\times\Delta CF_{r,s,14,2}\times P_{r,s,14,2}$
	Pavement markings (i=15) $CFF_{r,s,15} = CFF_{r,s,15,1} + CFF_{r,s,15,2} + CFF_{r,s,15,3} + CFF_{r,s,15,4}$	Edge-lines marking missing or inadequate (j=1)	$CFF_{r,s,15,1}=1+W_{r,s,15,1}\times\Delta CF_{r,s,15,1}\times P_{r,s,15,1}$
		Centerline marking missing or inadequate (j=2)	$CFF_{r,s,15,2}=1+W_{r,s,15,2}\times\Delta CF_{r,s,15,2}\times P_{r,s,15,2}$
		No-passing line marking missing or inadequate (j=3)	$CFF_{r,s,15,3}=1+W_{r,s,15,3}\times\Delta CF_{r,s,15,3}\times P_{r,s,15,3}$
		Night-time retroreflectivity not met (j=4)	$CFF_{r,s,15,4}=1+W_{r,s,15,4}\times\Delta CF_{r,s,15,4}\times P_{r,s,15,4}$
	Delineation (i=16) $CFF_{r,s,16} = CFF_{r,s,16,1}$	Chevron missing or ineffective on severe curve (j=1)	$CFF_{r,s,16,1}=1+W_{r,s,16,1}\times\Delta CF_{r,s,16,1}\times P_{r,s,16,1}$

$CFF_{r,F,i,j}= CFF_{r,P,i,j}= CFF_{r,I,i,j}=1+W_{r,I,i,j}\times\Delta CF_{r,I,i,j}\times P_{r,I,i,j}$

$CFF_{rs} = CFF_{rs1}\times CFF_{rs2}\times\ldots\times CFF_{r,s,15}\times CFF_{r,s,16}$

$CFF_{r,F} = CFF_{r,I} = CFF_{r,P}$

Table 6.8. Systematic Procedure for Computing the Safety Index for a Highway Segment (Cont')

III. Crash Severity Factor (CSF_{rs})

Safety Issue Category (k)	Safety Issue Type (i)	Detailed Safety Issue Item (j)	CSF_{rsij}
Roadside Features (k=5)	Embankment (i=1) $CFF_{rs2} = CFF_{rs21}$	Unshielded embankment (j=1)	$CSF_{rs11}=(V_{85}/V_{SL})\times(1+W_{rs11_RSH}\times\Delta CS_{rs11}\times P_{rs11_RSH})$
	Guardrails and barriers (i=2) $CFF_{rs2} = CFF_{rs21} + CFF_{rs22} + CFF_{rs23} + CFF_{rs24}$	Embankment shielded with ineffective barrier (j=1)	$CSF_{rs21}=(V_{85}/V_{SL})\times(1+W_{rs21_RSH}\times\Delta CS_{rs21}\times P_{rs21_RSH})$
		Ineffective barrier for overpass bridges (j=2)	$CSF_{rs22}=(V_{85}/V_{SL})\times(1+W_{rs22_RSH}\times\Delta CS_{rs22}\times P_{rs22_RSH})$
		No breakaway barrier terminals and transitions (j=3)	$CSF_{rs23}=(V_{85}/V_{SL})\times(1+W_{rs23_RSH}\times\Delta CS_{rs23}\times P_{rs23_RSH})$
		Missing transition (j=4)	$CSF_{rs24}=(V_{85}/V_{SL})\times(1+W_{rs24_RSH}\times\Delta CS_{rs24}\times P_{rs24_RSH})$
		Reflectors missing or damaged (j=5)	$CSF_{rs25}=(V_{85}/V_{SL})\times(1+W_{rs25_RSH}\times\Delta CS_{rs25}\times P_{rs25_RSH})$
	Bridges (i=3) $CFF_{rs3} = CFF_{rs31}$	Inadequate bridge rails (j=1)	$CSF_{rs31}=(V_{85}/V_{SL})\times(1+W_{rs31_RSH}\times\Delta CS_{rs31}\times P_{rs31_RSH})$
	Ditches (i=4) $CFF_{rs4} = CFF_{rs41}$	Ditches located less than 9 ft (j=1)	$CSF_{rs41}=(V_{85}/V_{SL})\times(1+W_{rs41_RSH}\times\Delta CS_{rs41}\times P_{rs41_RSH})$
	Trees (i=5) $CFF_{rs5} = CFF_{rs51}$	Trees located less than 9 ft (j=1)	$CSF_{rs51}=(V_{85}/V_{SL})\times(1+W_{rs51_RSH}\times\Delta CS_{rs51}\times P_{rs51_RSH})$
	Utility poles (i=6) $CFF_{rs6} = CFF_{rs61}$	Utility poles located less than 9 ft (j=1)	$CSF_{rs61}=(V_{85}/V_{SL})\times(1+W_{rs61_RSH}\times\Delta CS_{rs61}\times P_{rs61_RSH})$
	Obstacles (i=7) $CFF_{rs7} = CFF_{rs71}$	Obstacles located less than 9 ft (j=1)	$CSF_{rs71}=(V_{85}/V_{SL})\times(1+W_{rs71_RSH}\times\Delta CS_{rs71}\times P_{rs71_RSH})$

$CSF_{r,I,i,j}=1+W_{r,I,i,j}\times\Delta CS_{r,I,i,j}\times P_{r,I,i,j}$
$CSF_{r,F,i,j}=1+W_{r,F,i,j}\times(\Delta CS_{r,F,i,j}\times(1+\Delta S_{r,F,i,j}))\times P_{r,F,i,j}$
$CSF_{r,P,i,j}=1+W_{r,P,i,j}\times(\Delta CS_{r,P,i,j}\times(1+\Delta S_{r,P,i,j}))\times P_{r,P,i,j}$
$CSF_{rs} = CSF_{rs1}\times CSF_{rs2}\times \ldots\times CSF_{rs6}\times CSF_{rs7}$

IV. Safety Index

Head-on Crashes (r=1)	Fatal (s=1)	$SI_{11}= TEF\times CFF_{11}\times CSF_{11}$
	Injury (s=2)	$SI_{12}= TEF\times CFF_{12}\times CSF_{12}$
	PDO (s=3)	$SI_{13}= TEF\times CFF_{13}\times CSF_{13}$
Sideswipe Crashes (r=2)	Fatal (s=1)	$SI_{21}= TEF\times CFF_{21}\times CSF_{21}$
	Injury (s=2)	$SI_{22}= TEF\times CFF_{22}\times CSF_{22}$
	PDO (s=3)	$SI_{23}= TEF\times CFF_{23}\times CSF_{23}$
Fixed Object Crashes (r=3)	Fatal (s=1)	$SI_{31}= TEF\times CFF_{31}\times CSF_{31}$
	Injury (s=2)	$SI_{32}= TEF\times CFF_{32}\times CSF_{32}$
	PDO (s=3)	$SI_{33}= TEF\times CFF_{33}\times CSF_{33}$
Run-off-Road Crashes (r=4)	Fatal (s=1)	$SI_{41}= TEF\times CFF_{41}\times CSF_{41}$
	Injury (s=2)	$SI_{42}= TEF\times CFF_{42}\times CSF_{42}$
	PDO (s=3)	$SI_{43}= TEF\times CFF_{43}\times CSF_{43}$
Total	Fatal (s=1)	SI_1 = P(Head-on Crashes)$\times SI_{11}$+ P(Sideswipe Crashes)$\times SI_{21}$ +P(Fixed Object Crashes)$\times SI_{31}$+ P(Run-off-Road Crashes)$\times SI_{41}$
	Injury (s=2)	SI_2 = P(Head-on Crashes)$\times SI_{12}$+ P(Sideswipe Crashes)$\times SI_{22}$ +P(Fixed Object Crashes)$\times SI_{32}$+ P(Run-off-Road Crashes)$\times SI_{42}$
	PDO (s=3)	SI_3 = P(Head-on Crashes)$\times SI_{13}$+ P(Sideswipe Crashes)$\times SI_{23}$ +P(Fixed Object Crashes)$\times SI_{33}$+ P(Run-off-Road Crashes)$\times SI_{43}$

Note: F- Fatal crashes, I- Injury crashes, P- PDO crashes, RSH- Roadside hazards, and P(.) is the probability.

6.7 Calculation of the Safety Index by Crash Severity

6.7.1 Determination of the Crash Probability by Crash Type

Of the total vehicle crashes on a highway segment, only a fraction can be classified as a specific type of crashes. For a highway segment, the distribution of vehicle crashes by crash type can be readily determined using historical crash data. However, such distribution reflects the possibility of experiencing a specific type of crashes. It can not be directly used as the probability of having a specific type of crashes occurred. Hence, the relevant crash possibility distribution can not be directly applied in the reversed computation process that synthesizes different types of crashes into the expected total crashes. The following section discusses an approach to convert the possibility distribution into the probability

distribution that helps establish the safety indices of fatal, injury, and PDO crashes for a highway segment using information on safety indices computed by crash type and by severity category.

For the set of head-on, sideswipe, fixed object, and run-off-road crashes, the possibility distribution is given by CT= $\{CT_1, CT_2, CT_3, CT_4\}$. the possibility distribution can be normalized to a possibility profile defined as r= $<r_1, r_2, r_3, r_4>$, where $1=r_1 \geq r_2 \geq \ldots \geq r_n \geq 0$. The possibility profile r= $<r_1, r_2, \ldots, r_n>$ can be transformed into a probability distribution p=$<p_1, p_2, \ldots, p_n>$ according to the principle of randomness invariance. Specifically, the generalized Hartley measure of the possibility profile is set equal to the Shannon entropy of the derived probability distribution (Klir and Parviz, 1992; Klir, 2006). Common approaches for the possibility-probability transformation include interval, log-interval, and ordinal scaling. The log-interval scaling transformation is illustrated in the following example.

Given the possibility distribution of four types of crashes as 30% head-on, 20% sideswipe, 40% fixed object, 10% run-off-road, reorder it to CT $\{CT_1= 40\%, CT_2=30\%, CT_3=20\%, CT_4=10\%\}$. The Mobius function m= $<m_1, m_2, m_3, m_4>$ is

$$m_1 = \frac{40\%}{[40\% + (40\% + 30\%) + (40\% + 30\% + 20\%) + (40\% + 30\% + 20\% + 10\%)]} = 0.1333$$

$$m_2 = \frac{(40\% + 30\%)}{[40\% + (40\% + 30\%) + (40\% + 30\% + 20\%) + (40\% + 30\% + 20\% + 10\%)]} = 0.2333$$

$$m_3 = \frac{(40\% + 30\% + 20\%)}{[40\% + (40\% + 30\%) + (40\% + 30\% + 20\%) + (40\% + 30\% + 20\% + 10\%)]} = 0.3000$$

$$m_4 = \frac{(40\% + 30\% + 20\% + 10\%)}{[40\% + (40\% + 30\%) + (40\% + 30\% + 20\%) + (40\% + 30\% + 20\% + 10\%)]} = 0.3333$$

The possibility profile r= $<r_1, r_2, r_3, r_4>$ is

$r_1 = m_1+m_2+m_3+m_4 = 0.1333+0.2333+0.3000+0.3333 = 1.0$
$r_2 = m_2+m_3+m_4 = 0.2333+0.3000+0.3333 = 0.8667$
$r_3 = m_3+m_4 = 0.3000+0.3333 = 0.6333$
$r_4 = m_4 = 0.3333$

For the possibility profile r= <1, 0.8667, 0.6333, 0.3333>, the log-interval scaling transformation is accomplished as follows:

Step 1: Compute generalized Hartley measure

$GH(r) = \sum_{i=2}^{4}\left[r_i \cdot \log_2\left(\frac{i}{i-1}\right)\right] = 0.8667x\log_2^{(2/1)}+0.6333x\log_2^{(3/2)} +0.3333x\log_2^{(4/3)} = 1.3755$

Step 2: Determine Shannon entropy

$S(p) = -\sum_{i=1}^{n}\left(p_i \cdot \log_2^{p_i}\right)$, where $p_i = \left(r_i^{1/\alpha}/s\right)$ and $s = -\sum_{i=1}^{4} r_k^{1/\alpha}$, determine α from GH(r)= S(p)

$$1.1462 = -(1/s)\cdot \log_2^{(1/s)} - \left(0.8667^{1/\alpha}/s\right)\cdot \log_2^{\left(0.8667^{1/\alpha}/s\right)} - \left(0.6333^{1/\alpha}/s\right)\cdot \log_2^{\left(0.6333^{1/\alpha}/s\right)} - \left(0.3333^{1/\alpha}/s\right)\cdot \log_2^{\left(0.3333^{1/\alpha}/s\right)}$$

where $s = 1 + 0.8667^{1/\alpha} + 0.6333^{1/\alpha} + 0.3333^{1/\alpha}$

Then α= 0.2594.

Step 3: Obtain probability distribution $p_i = r_i^{1/\alpha}/s$

$p_1= 1/(1+0.8667^{1/0.2594}+ 0.6333^{1/0.2594}+ 0.3333^{1/0.2594}) = 0.5674$
$p_2= 0.8667^{1/0.2594}/(1+0.8667^{1/0.2594}+ 0.6333^{1/0.2594}+ 0.3333^{1/0.2594}) = 0.3269$
$p_3= 0.6333^{1/0.2594}/(1+0.8667^{1/0.2594}+ 0.6333^{1/0.2594}+ 0.3333^{1/0.2594}) = 0.0975$
$p_4= 0.3333^{1/0.2594}/(1+0.8667^{1/0.2594}+ 0.6333^{1/0.2594}+ 0.3333^{1/0.2594}) = 0.0082$

Therefore, the respective probabilities for head-on, sideswipe, fixed object, and run-off-road crashes are 0.3269, 0.0975, 0.5674, and 0.0082.

6.7.2 Synthesis of the SI by Crash Type and Crash Severity into SI by Crash Severity

The derived probability distribution from the possibility profile can then be used to establish the expected safety indices for fatal, injury, and PDO crashes, as Part IV of Table 6.8.

6.8 Evaluation of Safety Hardware Projects for a Highway Segment

After identifying safety hardware issues in a highway segment, a safety hardware project may be recommended as a countermeasure to mitigate the existing safety issues. It is assumed that the crash frequency factor and the crash severity factor concerning the detailed safety hardware issue items would be reduced from the existing values of greater than one to a value of one as the result of hardware project implementation, representing an improvement of the hardware condition to the system-wide average level. Such reductions will eventually reduce the overall crash frequency factor and the crash severity factor for the entire highway segment. This will generate lower fatal, injury, and PDO crash safety indices for different types of crashes. The reduction in the safety index value after implementing the safety hardware project in the highway segment (base-case safety index) from the safety index value associated with the existing safety hardware in the highway segment (current-case safety index) is regarded as the potential for safety improvement (PSI). The PSI can be separately established for fatal, injury, and PDO crashes for different types of crashes.

It is common that the useful service lives for different types of safety hardware assets vary considerably, and the safety hardware service lives are often shorter than the useful service life of a highway segment. In order to compute the cumulative PSIs for fatal, injury, and PDO crashes in the useful service life-cycle of the highway segment based on the estimated first year PSI and the annual traffic growth rate, it is needed to assume that safety hardware projects are required to be implemented in multiple times so that the multiple service lives of the safety hardware assets would match the service life-cycle of the highway segment. This way, the PSI level could be maintained at a consistent level throughout the useful service life-cycle of the highway segment.

The computed life-cycle cumulative PSIs for fatal, injury, and PDO crashes as a result of the safety hardware project implementation could be converted into the overall life-cycle vehicle crash cost savings by applying the unit rates for fatal, injury, and PDO crashes, respectively. The following section describes the details of estimating overall vehicle crash cost savings in the highway segment useful service life-cycle by implementing safety hardware projects that improve safety hardware conditions using the concept of consumer surplus.

6.8.1 Calculation of the Annual PSIs

Having established the current-case safety index without hardware improvement, base-case safety index with hardware improvement, the current-case crash rate and base-case crash rate in terms of vehicle crashes per million VMT (MVMT) can be computed as follows (Agent et al., 2003).

Without hardware improvement: $$CR_{r,current\text{-}case} = \frac{SI_{r,current\text{-}case}}{MVMT_{current\text{-}case}} = \frac{SI_{r,current\text{-}case}}{365 \times 10^6 \times L \times AADT_{current\text{-}case}} \quad (6\text{-}15)$$

With hardware improvement: $$CR_{r,base-case} = \frac{SI_{r,base-case}}{MVMT_{base-case}} = \frac{SI_{r,base-case}}{365 \times 10^6 \times L \times AADT_{base-case}} \quad (6\text{-}16)$$

where

$CR_{r,current\text{-}case}$ = Current-case crash rate of the highway segment without safety hardware improvement for crash severity category r, number of crashes/ MVMT

$CR_{r,base\text{-}case}$ = Base-case crash rate of the highway segment with safety hardware improvement for crash severity category r, number of crashes/ MVMT

$SI_{r,current\text{-}case}$ = Current-case safety index of the highway segment without safety hardware improvement for crash severity category r, number of crashes/ year

$SI_{r,base\text{-}case}$ = Base-case safety index of the highway segment with safety hardware improvement for crash severity category r, number of crashes/ year

L = Length the highway segment, mile

$AADT_{current\text{-}case}$ = Current-case annual average daily traffic of the highway segment without safety hardware improvement, vehicles/day

$AADT_{base\text{-}case}$ = Base-case annual average daily traffic of the highway segment with safety hardware improvement, vehicles/day

r = Crash severity category, including fatal, injury, and PDO crashes.

Figure 6.3 illustrates the demand shift due to the improvement of safety hardware conditions. Highway user benefits in terms of PSI as a result of implementing a safety hardware project is computed by using the concept of consumer surplus, as the area of the hatched portion in Figure 6.3 (Miller, 1992; AASHTO, 2003, Li and Kaini, 2007).

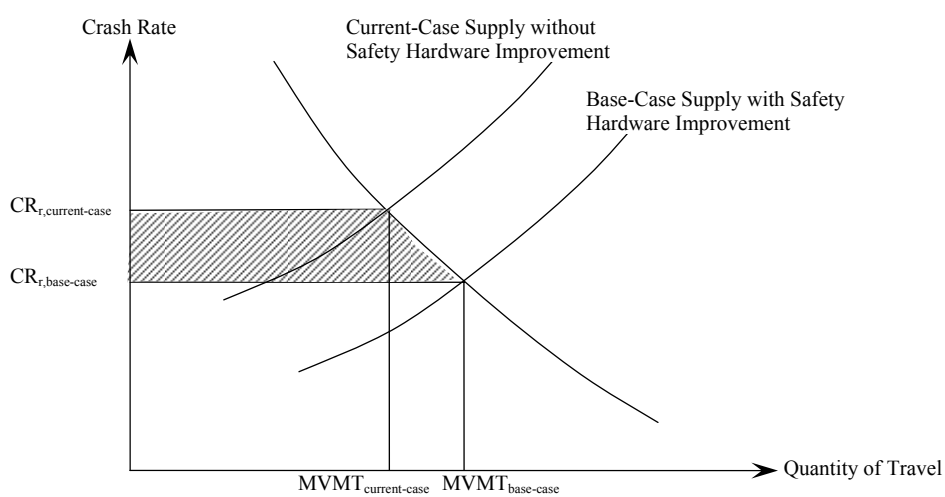


Figure 6.3. Illustration of User Benefits of a Safety Hardware Improvement Project

$$\text{Annual PSI}_r = \frac{1}{2} \times \left(CR_{r,current-case} - CR_{r,base-case}\right) \times \left(MVMT_{current-case} + MVMT_{base-case}\right) \quad (6\text{-}17)$$

where
Annual PSI_r= Annual potential for safety improvement for crash type r, number of crashes/year
$MVMT_{current-case}$ = Current-case annual vehicle miles of travel without safety hardware improvement, million VMT/year
$MVMT_{base-case}$ = Base-case annual vehicle miles of travel with safety hardware improvement, million VMT/year
r = Crash severity category, including fatal, injury, and PDO crashes.

6.8.2 Calculation of the Annual Crash Cost Savings

After computing the annual PSIs for fatal, injury, and PDO crashes, dollar amount saving can be computed by applying the unit costs for fatal, injury, and PDO crashes. Annual crash benefits as the crash cost savings are computed as follows:

$$ASB_r = \text{Annual PSI}_r \times UCC_r \quad (6\text{-}18)$$

where
ASB_r = Annual safety benefits from the reduction in crashes of crash type *r*, $/year
Annual PSI_r= Annual potential for safety improvement for crash type *r*, number of crashes/year
UCC_r = Unit crash cost for crash type r, $/crash
r = Crash severity category, including fatal, injury, and PDO crashes.

Total annual safety benefits as a result of safety hardware improvement become:

$$ASB = ASB_F + ASB_I + ASB_P \quad (6\text{-}19)$$

where
ASB = Annual total safety benefits from the reduction in all crashes on a highway segment, $/year
ASB_F = Annual safety benefits from the reduction in fatal crashes, $/year
ASB_I = Annual safety benefits from the reduction in injury crashes, $/year
ASB_P = Annual safety benefits from the reduction in PDO crashes, $/year

6.8.3 Calculation of the Overall Life-Cycle Crash Cost Savings

Assuming an equal annual growth rate of safety benefits and also assuming that the annual safety benefits increase the same as the annual traffic growth rate, the safety benefits in the highway segment useful service life can be computed as below:

$$r' = \left[\ln\left(\frac{(1+g)^N}{1} \right) \right] / N \tag{6-20}$$

$$f = \frac{[e^{(r'-i)\times N} - 1]}{(r'-i)\times N} \tag{6-21}$$

$$PW_{LCSB} = ASB \times f \tag{6-22}$$

$$EUA_{LCSB} = PW_{LCSB} \times \left[\frac{i \times (1+i)^N}{(1+i)^N - 1} \right] \tag{6-23}$$

where

r' = Effective growth rate of annual safety benefits using infinite number of times of compounding for the geometric gradient

g = Geometric gradient annual traffic growth rate

f = Present worth factor

N = Useful service life of a highway segment

PW_{LCSB} = Present worth of safety benefits in the useful service life of a highway segment

EUA_{LCSB} = Equivalent uniform annual safety benefits in the useful service life of a highway segment

6.8.4 Estimation of Project Costs

A safety hardware project may be implemented at the beginning of the useful service life-cycle of a new highway segment or in the middle of an in-service highway segment. In addition, a safety hardware project may be implemented to mitigate safety issues of one or more types of safety hardware assets. It is common that the useful service lives for different types of safety hardware assets vary considerably, and the safety hardware service lives are often shorter than the useful service life of a new highway segment or the remaining service life of an in-service highway segment. Since the life-cycle safety benefits are computed using the annual safety benefits estimated based on the first-year PSIs for fatal, injury, and PDO crashes, it is needed to assume that the safety hardware project is required to be implemented in multiple times so that the multiple service lives of the safety hardware asset(s) would match the useful service life of a new highway segment or match the remaining service life of an in-service highway segment. Therefore, the estimated overall life-cycle safety benefits actually correspond to repeating the project capital costs in multiple times, along with costs of maintenance and repairs in the hardware useful service life-cycle. As Figure 6.4, if a guardrail project is implemented to an in-service highway segment, the overall life-cycle safety benefits computed using the first-year guardrail-induced PSIs for the remaining years of the highway segment are the combined effects of two rounds of capital costs and additional maintenance and repair costs needed in the remaining service life of the highway segment.

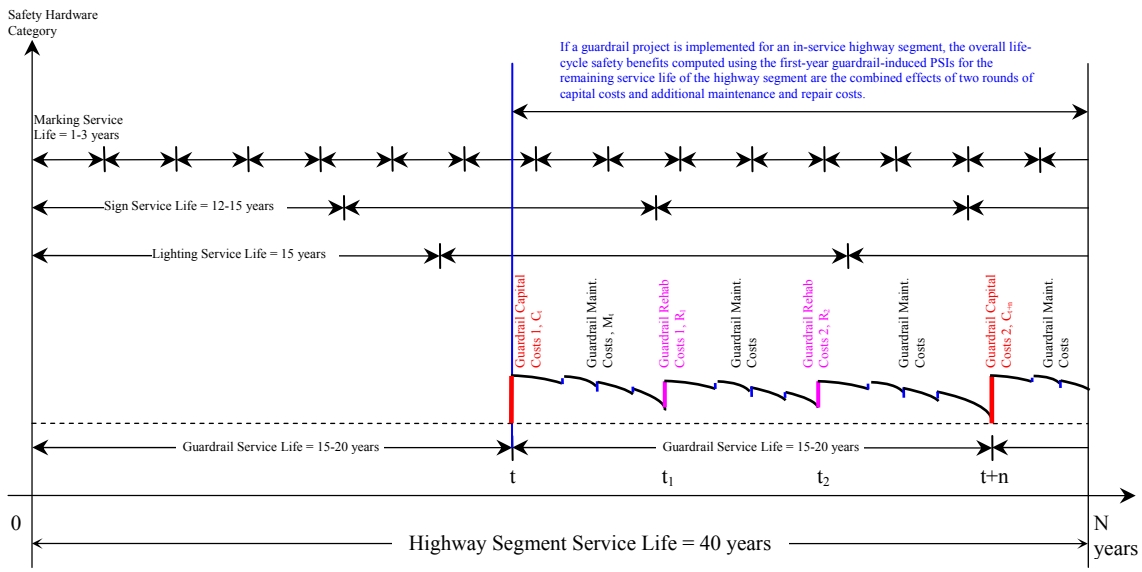


Figure 6.4. Illustration of Differences in Safety Hardware and Highway Segment Useful Service Life-Cycle

The estimation of the capital costs, maintenance and repair costs, and salvage value (if any) of any safety hardware assets in a highway segment in year t of the analysis period is based on the following procedure:

- If the analysis year is less than the critical year for the candidate location, then the safety hardware improvement cannot be implemented and hence the project costs are zero;
- If the analysis year is the same as the critical year for the candidate location, then project costs for the critical year are adjusted using the road construction cost index.
- If the analysis year is greater than the critical year then the analysis year represents a competing investment alternative and hence the projects costs are compounded to the analysis year using the compound amount factor with the base year as the critical year.

As Figure 4, the cumulative costs of safety hardware projects in the remaining service life-cycle of the highway segment are computed as follows:

$$PW_{PC} = \left[(C_t - S_t)\times\left(\frac{1}{(1+i)^t}\right) + (C_{t+n} - S_{t+n})\times\left(\frac{1}{(1+i)^{t+n}}\right)\right] + \left[R_{t_1}\times\left(\frac{1}{(1+i)^{t_1}}\right) + R_{t_2}\times\left(\frac{1}{(1+i)^{t_2}}\right)\right] + \left[\sum_{t=t}^{N}\left(M_t\times\left(\frac{1}{(1+i)^t}\right)\right)\right] \quad (6\text{-}24)$$

$$\begin{aligned} EUA_{PC} = {} & \left[(C_t - S_t)\times\left(\frac{1}{(1+i)^t}\right) + (C_{t+n} - S_{t+n})\times\left(\frac{1}{(1+i)^{t+n}}\right)\right]\times\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \\ & + \left[R_{t_1}\times\left(\frac{1}{(1+i)^{t_1}}\right) + R_{t_2}\times\left(\frac{1}{(1+i)^{t_2}}\right)\right]\times\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \\ & + \left[\sum_{t=t}^{N}\left(M_t\times\left(\frac{1}{(1+i)^t}\right)\right)\right]\times\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \end{aligned} \quad (6\text{-}25)$$

where

PW_{LCPC} = Present worth of costs for safety hardware project implemented in year *t* in the service life-cycle of the highway segment
EUA_{LCPC} = Equivalent uniform annual costs for safety hardware project implemented in year *t* in the service life-cycle of the highway segment
C_t = Initial safety hardware construction cost in year *t*
C_{t+n} = Initial safety hardware construction cost in year *t+n*
S_t = Salvage value of the safety hardware in year *t*
S_{t+n} = Salvage value of the safety hardware in year *t+n*
R_{t_1} = Safety hardware rehabilitation cost in year t_1
R_{t_2} = Safety hardware rehabilitation cost in year t_2
M_t = Annual hardware maintenance cost in year *t*
i = Discount rate
t = Safety hardware project implementation year
n = Safety hardware useful service life-cycle
N = Useful service life-cycle of the highway segment.

6.8.5 Cost-Effectiveness of a Safety Hardware Project

Net present worth method and benefit-to-cost ratio method are commonly adopted methods for project comparison. The following equations present these methods.

$$NPW = PW_{LCSB} - PW_{LCPC} \tag{6-26}$$

$$B/C = PW_{LCSB} / PW_{LCPC} \tag{6-27}$$

where
NPW = Project net present worth, in constant dollars of the base year
B/C = Project benefit-to-cost ratio
PW_{LCSB} = Present worth of safety benefits in the useful service life of a highway segment
PW_{LCPC} = Present worth of project costs in the useful service life of a highway segment.

6.9 Validation of the Procedure for Computing the Safety Index

One of the key procedures in the proposed methodology for safety hardware project evaluation is to estimate the current-case and base-case safety indices that are needed to compute the PSIs for fatal, injury, and PDO crashes. Cross comparisons of Empirical Bayesian (EB) crash estimates and PSIs by crash severity using two approaches can be conducted for the procedure validation: Spearman's rank correlation and regression correlation.

6.9.1 Estimation of Vehicle Crashes Using the Empirical Bayesian Approach

The safety performance functions for highway segments are an important instrument for evaluating road safety performance. These models explain crash occurrence as a function of traffic and geometric characteristics associated with a highway segment. The safety performance function with a basic formula of two independent variables (segment length and AADT) is as:

$$\hat{E}(CF_i) = e^{a_0} \times L_i^{a_1} \times AADT_i^{a_2} \quad (6\text{-}28)$$

where
$\hat{E}(CF_i)$ = Predicted crashes frequency for highway segment *i*, crashes /year
L_i = Length of highway segment *i*, mile
$AADT_i$ = Annual average daily traffic on highway segment *i*, vehicles/day
a_0, a_1, a_2 are model coefficients.

It is not always possible to predict the exactly same number of crashes as observed. The EB procedure provides a method to combine predictions from the safety performance function, $\hat{E}$ (CF_i), with observed site-specific history data, O_i (Hauer, 1997; Persaud and Lyon, 2005). The EB crash estimate (EB_i) considering both the predicted and the observed crash frequencies for the highway segment is computed as:

$$EB_i = w \times \hat{E}(CF_i) + (1 - w) \times O_i \quad (6\text{-}29)$$

where
EB_i = EB crash estimate for highway segment *i*
$\hat{E}$ (CF_i) = Crash frequency predicted by a safety performance function for highway segment *i*
O_i = Observed number of crashes during the specified period for highway segment *i*
w = Relative weight between the predicted and observed crash frequencies, $w = \frac{1/k}{1/k + \hat{E}(CF_i)}$

k = Overdispersion factor of the negative binomial safety performance function.

6.9.2 Goodness of Fit of the Safety Performance Function

The prediction power of the safety performance function directly affects the accuracy of the EB crash estimates. The goodness of fit of a safety performance function can be evaluated by several measures, including the scaled deviance, Pearson χ^2 statistic, and dispersion parameter Φ.

6.9.2.1 Scaled Deviance (SD)

The scaled deviance is defined as the likelihood ratio test statistic measuring twice the difference between the log likelihoods of the studied model and the full model. The full model has as many parameters as there are observations so that the model fits the data perfectly. Therefore, the full model, which possesses the maximum log likelihood achievable under the given data, provides a baseline for assessing the goodness of fit of an intermediate model with parameters. For negative binomial error structure, the scaled deviance is as follows:

$$SD_i = 2\sum_{i=1}^{n}\left[O_i \ln\left(\frac{O_i}{\hat{E}(CF_i)}\right) + (O_i + k)\ln\left(\frac{E(CF_i) + k}{O_i + k}\right)\right] \quad (6\text{-}30)$$

where
SD_i = Scaled deviance for highway segment *i*
k = Overdispersion factor of the negative binomial safety performance function.

6.9.2.2 Pearson χ^2 Statistic

The Pearson χ^2 and is calculated as:

$$\text{Pearson } \chi^2 = \sum_{i=1}^{n} \left[\frac{\left(O_i - \hat{E}(CF_i)\right)^2}{Var(O_i)} \right] \tag{6-31}$$

where

$Var(O_i)$ = Variance of observed number of crashes on highway segment *i*.

Both the scaled deviance and the Pearson χ^2 have exact χ^2 statistic distributions under normality assumptions. They are asymptotically χ^2 distributed with (n-p) degrees of freedom for other distributions of the exponential family. The asymptotic results may not be relevant to statistics calculated from a small sample size. Therefore, the generalized Pearson χ^2 statistics sometimes can not be used as an absolute measure for assessing the goodness of fit of a model. For the model to be considered significant, the two measures should be less than the χ^2 critical value.

6.9.2.3 Dispersion parameter (Φ)

Another measure of model goodness of fit test is the dispersion parameter Φ:

$$\Phi = \frac{\text{Pearson } \chi^2}{(n - p)} \tag{6-32}$$

where

n = Number of observations

p = Number of model parameters.

As shown above, Φ can be obtained by dividing the Pearson χ^2 by (n-p), and it is a useful measure for assessing the fit of model. A value near 1.0 means that the error assumption of the model is equivalent to that found in the observed data. If the value of dispersion parameter is greater than 1.0, the observed data has greater dispersion than in the model.

6.9.3 Correlation between PSIs and EB Crash Estimates

6.9.3.1 Spearman's Rank Correlation Coefficient ρ_s

Spearman's rank correlation coefficient is a measure of association between the rankings of intersection safety by PSIs and by EB crash estimates using a number of highway segments (Siegel and Castellan, 1988). To calculate the Spearman's rank-correlation coefficient, it is necessary establish the PSI values and EB crash estimates for individual highways segments and then rank the paired data sets in ascending or descending order. The Spearman's rank-correlation coefficient ρ_s is often used as a non-parametric alternative to a traditional coefficient of correlation and can be applied under general conditions. An advantage of using ρ_s is that when testing for correlation between two sets of data, it is not necessary to make assumptions about the nature of the populations sampled.

The correlation coefficient is calculated from the two vectors of ranks for the samples: Let $X = \{X_1, X_2, X_3, ..., X_N\}$ and $Y = \{Y_1, Y_2, Y_3, ..., Y_N\}$ be the vectors of ranks for sample 1 and sample 2 respectively, then ρ_s is computed based on the vector of differences between ranks: $D_i = X_i - Y_i$; for i= 1, 2, 3,..., N by:

$$\rho_s = 1 - \frac{6 \times \sum_{i=1}^{N} D_i^2}{N \times (N^2 - 1)} \tag{6-33}$$

where
ρ_s = Spearman's rank-correlation coefficient
D_i = Differences between ranks of ith pair
N = Number of paired sets.

A score of 1.0 represents perfect correlation and a score of zero indicates no correlation. The t-approximation for this statistic, T, is valid for samples of size 8 upwards, and is calculated by:

$$T = \rho_s \times \sqrt{\frac{N-2}{1-\rho_s^2}} \tag{6-34}$$

where
T = *t*-approximation for this statistic ρ_s.

It has approximately a *t*-distribution with (N-2) degrees of freedom, and can be used for a test of the null hypothesis of independence between samples.

6.9.3.2 Regression Correlation Analysis

The PSIs and EB crash estimates for multiple highway segments can be used to construct a linear regression model that establishes the correlation between the two estimates. The adjusted R^2 can be used as an indicator for their correlation significance (McCullagh and Nelder, 1989).

6.10 Evaluating Safety Hardware Projects for Intersections Using the Proposed Methodology

With some modifications, the proposed methodology described in Sections 6.2.1-6.2.8 can be readily applied for evaluating safety hardware projects for intersections. The intersections can be classified by rural and urban land area and be further classified as unsignalized, 3-leg signalized, and 4-leg signalized intersections within each category. Two major category of safety hardware assets need to be added to analysis are signals and detection devices. Likewise, the current-case safety index without safety hardware improvement and base-case safety index with safety hardware improvement can be computed on the basis of the traffic exposure factor, crash frequency factor, and crash severity factor.

For the estimation of traffic exposure factor, the million vehicle miles of travel associated with a highway segment is replaced by million vehicles entering the intersection. For the computation of crash frequency factor and crash severity factor, additional types of crashes need to be considered. Major intersection-related crash types may include turning, right angle, sideswipe, rear end, head-on, pedestrian, parked vehicle, fixed object, and highway-railroad crossing.

The relative increase in the risks of crash frequency and crash severity by crash type and crash severity category can be derived using the intersection-related safety performance functions. The probability distribution of different types of crashes concerning intersections can be established using historical crash data through the process of possibility-probability transformation. Table 6.9 lists detailed safety issues items recommended for determining safety indices for intersections.

Table 6.9. Safety Issues Attributable to Highway Infrastructure for Highway Intersections

General Safety Issue Category	Safety item Type	Detailed Safety Issue Item
Geometric Design	Alignment	Intersection angle
		Average grade rate for all vertical curves within 800 ft of the intersection
		Horizontal curvature index
		Vertical curve grade index
		Grade of vertical curve tangent
		Length of vertical curve
		Grade rate for all vertical curves within 250 ft of the intersection along the major and minor roads
	Cross section	Major road outside shoulder width
		Major road median width
		Major road number of lanes
		Major-road through lanes
		Presence of right-turn lane on the major road
	Channelization	Major road right-turn channelization
		Major road left-turn channelization
		Minor-road channelization
	Speed limit	Major road design speed, mph
	Terrain	Level
		Mountainous
	Access control	Number of driveways on the major-road legs within 250 ft of the intersection
		Major road access control
Traffic Characteristics	Turning traffic	Percentage of minor-road traffic that turns left at the signal during the morning and evening peak hours combined
	Truck traffic	Percent trucks during the peak hour
Safety Hardware Conditions	Signs	Sign control type
	Signals	Signal phasing indicator variable
		Presence of protected-only left-turn signal phase
	Lighting	Intersection lighting indicator variable
Roadside Features	Road side hazards	Roadside hazard rating within 250 ft of the intersection on the major road

6.11 Chapter Summary

This methodology is developed for estimating the benefits and costs of safety hardware projects implemented for highway segments and intersections using risk-based assessment procedures. The safety index, which measures safety performance of a highway segment or an intersection, is calculated by combining the traffic exposure factor (the exposure of road users to road hazards), crash frequency factor (the probability of a vehicle being involved in a crash), and crash severity factor (the consequence of a crash).The traffic exposure factor is a function of segment length and traffic volume. Crash frequency factor is computed using detailed safety issue items under various safety issue types concerning geometric design, consistency of design standards, pavement conditions, and safety hardware conditions. Crash frequency factor is estimated using detailed safety issue items within different safety issue types regarding roadside features, including guardrail safety hardware assets.

Both crash frequency factor and crash severity factor are computed on the basis of a base-case crash risk added by additional crash risks by crash type and by crash severity category for individual safety issue items. The respective crash frequency factors or crash severity factors corresponding to multiple safety issue items under the same safety issue type are added to establish a safety issue type-specific crash frequency factor or a crash severity factor. The production of traffic exposure factor, safety issue type-specific crash frequency factor, and safety issue type-specific crash severity factor helps establish the safety index by crash type and by severity.

The proposed methodology also introduces a procedure to establish the probability distribution of vehicle crashes by crash type using historical crash data. This helps further combining the safety index by crash type and by severity into the safety index by crash severity.

The difference in current-case safety index without safety hardware improvement and the base-case safety index with safety hardware improvement is regarded as the potential for safety improvement as a result of safety project implementation. The annual potential for safety improvement is computed using the concept of consumer surplus. It is subsequently converted into dollar values to reflect crash cost savings as safety benefits generated by the safety hardware project.

The annual safety benefits are expanded to life-cycle safety benefits using extrapolation. Correspondingly, life-cycle project costs are computed. Both life-cycle safety benefits and project costs are expressed in present worth and equivalent uniform annual values. Net present worth method and benefit-to-cost ratio method ca be used as the basis for project tradeoff analysis.

The proposed methodology for safety hardware project evaluation is centered on the systematic procedure for computing the current-case and base-case safety indices that are needed to compute the PSIs for fatal, injury, and PDO crashes. The Spearman's rank correlation test and regression analysis are introduced to compare EB crash estimates and PSIs for the procedure validation.

CHAPTER 7:
AN ANALYTICAL FRAMEWORK FOR INTEGRATING SAFETY HARDWARE ASSET MANAGEMENT INTO THE OVERALL ASSET MANAGEMENT SYSTEM

7.1 Introduction

Many state transportation agencies have developed individual asset management systems and use them as an analytical tool to make more informed decisions related to the highway infrastructure. The most common management systems dealing with physical highway assets are those for pavements, bridges, and maintenance. In addition, there are management systems handling highway system operations, namely, congestion and safety. In most cases, these management systems work independent of each other or only partially integrated. Each system will only help in choosing subset of projects related bridge, pavement or safety that at best produces locally optimal investment decision results. This report introduces a new methodology for achieving integrated project selection of all types of highways projects to yield globally optimal investment decision results.

7.2 Overview of the Proposed Methodology for System Integration

Figure 7.1 presents the general framework of the proposed methodology for system integration. In general, the entire investment decision-making process follows the principle of highway asset management. The entire process performs the following tasks: i) establishing system goals and performance measures, ii) monitoring system performance pertaining to physical asset conditions or system levels of service, iii) predicting future performance trends, iv) recommending candidate projects to sustain system performance, v) evaluating project costs and benefits, vi) conducting project selection, and vii) providing feedbacks after project implementation to refine the analysis in subsequent decision cycles.

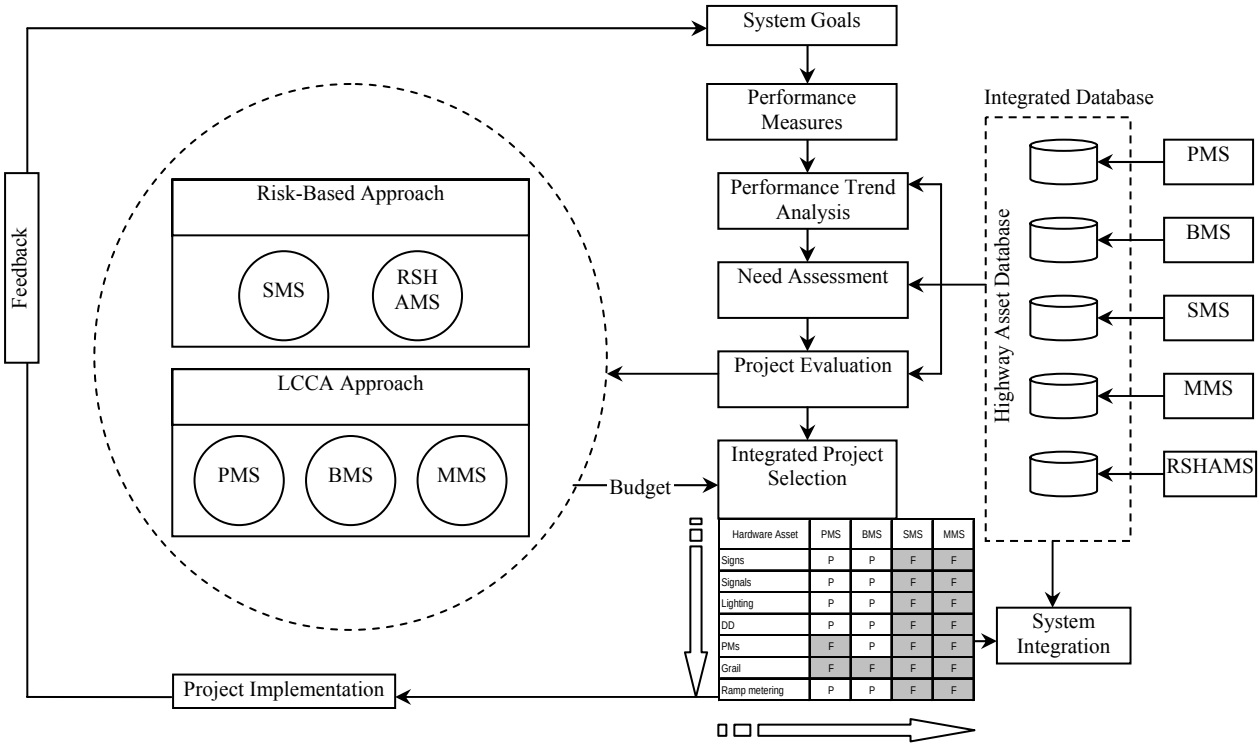


Figure 7.1. A Proposed Methodology for Integrating Roadway Safety Hardware Asset Management into the Overall Asset Management Program

In particular, the proposed methodology explicitly addresses issues of data integration, consistent approaches for project evaluation, and integrated project selection (Adams et al., 2001; Li and Kaini, 2007; Li and Patel, 2007). The first step towards system integration is to maintain interoperable data on

both major highway assets and roadway safety hardware assets. Major issues related to data integration include data integration strategies, referencing, and transformations using different data integration techniques. Conventionally, the life-cycle cost analysis (LCCA) approach is used for evaluating pavement, bridge, and maintenance projects, while the risk-based approach is used for safety hardware project evaluation. Due to the close linkage between roadway safety hardware and roadway safety performance, in the broad sense safety hardware projects can be assessed following the general principle of safety project evaluation. Maintaining the consistency of the LCCA approach and the risk-based approach will ensure generating consistent benefits for projects that belong to major highway assets and safety hardware assets. Integer optimization models will facilitate integrated project selection.

7.3 Analytical Framework for Integrating Safety Hardware Asset Management into Overall Management System

This section presents the analytical framework developed for long-term and short-term roadway safety hardware investment programming and project selection. This framework uses the risk-based methodology for safety hardware project evaluation to separately compute Safety Indices of highway segments or intersections. The associated Safety Indices are compared with the target crash level set by the transportation agency to identify highway segment or intersection safety hardware deficiencies. Safety hardware improvement countermeasures applicable to deficient roadway segments or intersections are then recommended. Further, the impacts of different countermeasures are assessed. Finally, the countermeasure projects are prioritized using optimization models on the basis of project impacts. The proposed framework consists of seven analytical components as below:

1) Definition of network and analysis period
2) Estimation of expected crash frequency over the analysis period
3) Network screening
4) Diagnosis
5) Identification of alternative safety improvement countermeasure projects
6) Computation of costs and benefits of safety improvement projects
7) Optimization of investment options under budgetary and other constraints.

The individual components are described in the following sections. Figure 7.2 presents the flowchart for the decision-making procedure for the network-level safety hardware project programming and project selection.

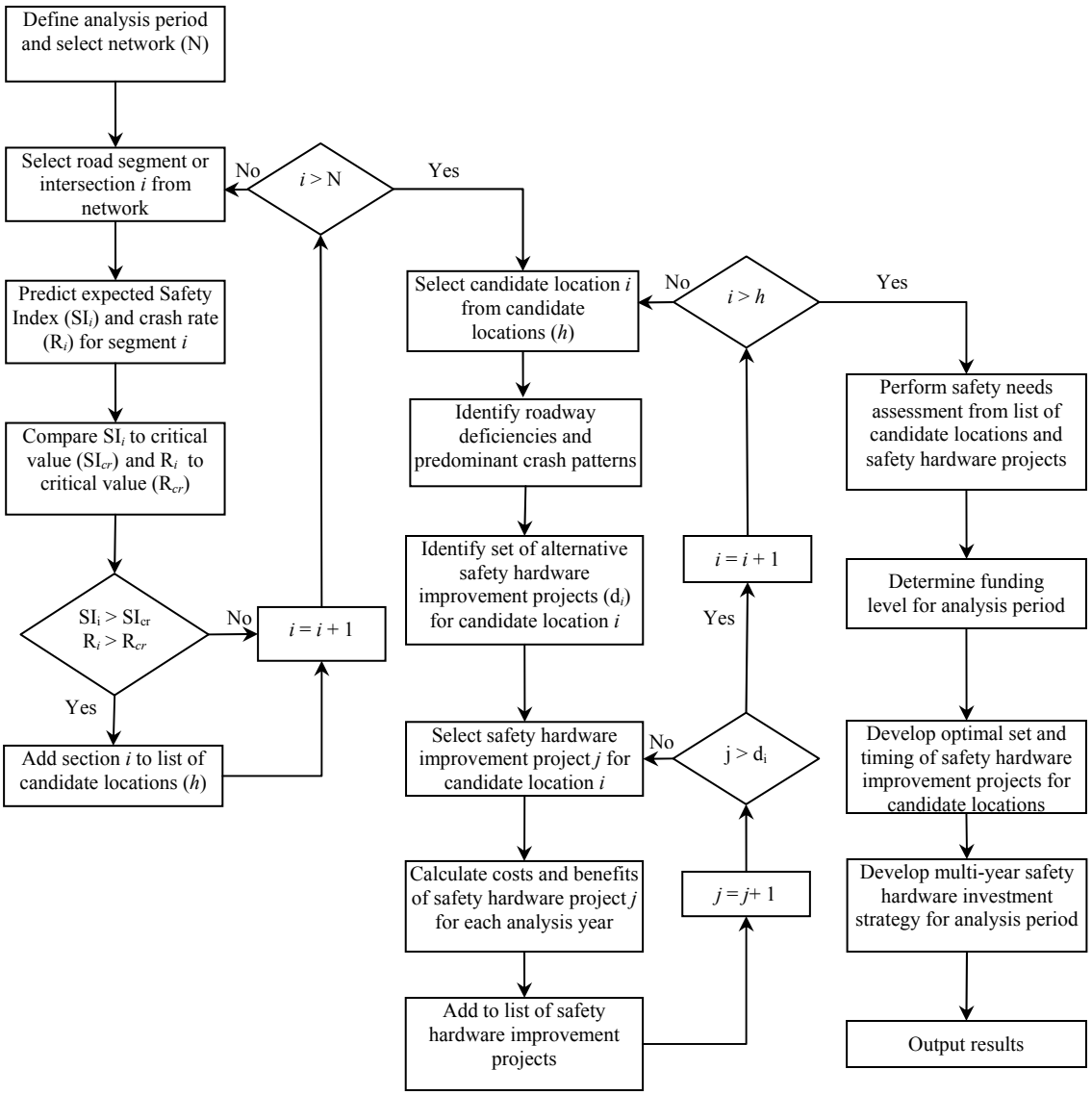


Figure 7.2. Analytical Procedure for Network-Level Roadway Safety Hardware Project Programming and Selection

7.3.1 Network Selection and Definition of Analysis Period

Network selection involves the definition of a subset of road segments and/or intersections of interest from the entire highway network within the agency jurisdiction on the basis of attributes such as route type, functional class, intersection type or combinations of these attributes. The analysis period for the safety hardware investment could either be a long-term (10-20 years) or a short-term horizon (3-5 years).

7.3.2 Estimation of the Expected Safety Index over the Analysis Period

The expected safety index of a highway segment or an intersection is estimated by taking the production of traffic exposure factor, crash frequency factor, and crash severity factor (Lamm et al., 2002, 2006; Cafiso et al., 2006). The traffic exposure factor for a highway segment measures the extent of highway users exposed to road hazards when traversing the highway segment or intersection. The crash frequency factor for a highway segment or an intersection can be computed by safety hardware related crash type and by crash severity category as the aggregated effect of geometric design, design consistency, pavement condition, and safety hardware condition. The crash severity factor captures the excessive crash risk of

severe crashes caused by different roadside conditions. Detailed procedure for estimating the Safety Index can be found in the methodology for highway safety hardware project evaluation.

7.3.3 Network Screening

Network screening helps identify the candidate highway segment and/or intersection locations that need safety improvements. It is defined as the process of reviewing a highway network to identify and rank sites in the view point of getting benefits from safety hardware improvement projects. The sites which are likely to gain safety benefits from safety hardware improvements can then be further studied in more details. Network screening can also be integrated into the agency's long-range planning process.

7.3.3.1 Network Screening Process

There are four major steps in network screening:

Step 1: Establish the focus of network screening
Step 2: Identify the network elements for screening and establish reference populations
Step 3: Select the network screening method
Step 4: Screen and evaluate results.

Step 1 establishes the reasons for conducting network screening. It determines the sites to be screened in the network analysis. Step 2 focuses on identifying the network elements that are to be screened and organizing these elements into reference populations. Examples of roadway network elements that can be screened include highway segments (regular segments and ramps) and intersections (regular intersections, ramp terminal intersections, and at-grade rail crossings). A reference population is a grouping of sites with similar characteristics. The performance at a particular site in a given reference population is compared to the expected crash frequency measured by the Safety Index for the reference population, thereby yielding a relative measure of potential for safety improvement at each location. Step 3 aims to select one or more screening methods. Step 4 conducts screening analysis and evaluates the results.

7.3.3.2 Screening Methods

Table 7.1 briefly describes screening methods for selecting candidate locations based on selection criteria.

Table 7.1. Network Screening Methods

Screening Method	Description
Crash Frequency	Sites are ranked based on the number of crashes occurred at the given location
Equivalent Property Damage Only (EPDO)	Crashes at the given location, depending upon the severity, are multiplied with equivalent weights of PDO only crashes. Then site are ranked based upon the sum of weighted crashes.
Relative Severity Index	Monetary values are assigned to each crash based on the crash type. Total average crash costs per site are compared to an overall average crash cost for the site's reference population.
Crash Rate	Normalizes crash frequency with traffic volume (Crashes per million entering vehicles for intersections or million vehicle-miles traveled for segments). Sites are ranked from highest to lowest crash rate.
Critical Crash Rate	Compares the observed crash rate at each site with a calculated critical crash rate unique to each site. The critical crash rate is a threshold value that allows for comparison among sites with similar characteristics. Sites that have observed crash rates greater than the critical rate are identified for further analysis.
Method of Moments	A site's observed accident frequency is adjusted based on the variance in the crash data and average crash counts for the site's reference population. The adjusted observed frequency for the site is compared to the average frequency of crashes for the reference population. This comparison yields the potential for improvement.
Level of Service of Safety (LOSS)	The Level of Service of Safety (LOSS) at a given site depends on crashes estimated. Safety Index is used to estimate an expected number of crashes for a given reference population. The observed crashes are compared to the estimated number of crashes. Sites are assigned to one of four levels, ranging from LOSS I to LOSS IV. LOSS I indicates a low potential for crash reduction and LOSS IV indicates a high potential for crash reduction.
Excess Expected Crashes	Empirical Bayesian (EB) methods are used to adjust observed number of crashes at a site to account for regression to the mean. The adjusted crash frequency is then compared to a crash frequency prediction from a SI .The difference between these two values is considered the Potential for Safety Improvement (PSI). The sites are ranked from highest to lowest PSI.
High Proportion of Specific Crash Types	Sites are listed according to their probability that a long-term expected number of crashes at the site exceed a threshold proportion for the particular crash type. The threshold proportion is either calculated

	from historic data or user data depending on the data available.

7.3.3.3 Selecting a Screening Method

Adopting different screening methods would produce variations in the screening results. Each method has its strengths and weaknesses. Data availability and the stability of network screening results are the key factors influencing the selection of a specific network screening method. It is useful to apply more than one screening method. The following items will influence the choice of screening methods:

Data Availability. It refers to the amount and type of information that is available regarding the sites being screened. Types of data include roadway characteristics, pavement condition, safety hardware condition, roadside features, crash data and traffic volumes. The less the available data, the more elementary screening methods are available for use.

Regression to the Mean. Regression to the mean (RTM) is a statistical phenomenon that can make natural variation in repeated data look like real change. It happens when unusually large or small measurements tend to be followed by measurements that are closer to the mean. It is a statistical characteristic that can influence the stability of screening results. Some methods correct for regression to the mean creating more stable results. But, these methods demands more extensive data.

Performance Threshold. It is a numerical value that establishes a threshold of expected crash frequencies (i.e. safety performance) for candidate locations. The benefits of having a safety performance threshold are that it provides a statistically significant cut-off or threshold for identifying sites for further study.

7.3.4 Diagnosis

Diagnosis is defined as the identification of factors that may contribute to a crash. In order to identify the contributing factors, the analyst needs to study: i) the available site crash data for patterns related to crash type, severity, and environmental conditions; ii) background information about the site characteristics-geometric design, consistency of design standards, pavement conditions; iii) field conditions at the site-safety hardware conditions and roadside features to observe how the system is operating and highway users are traveling through the site. Tables 7.2-7.4 present possible crash contributing factors for roadway segments, signalized intersections, and unsignalized intersections, respectively.

Table 7.2. Possible Crash Contributing Factors for Roadway Segments

Crash Type	Possible Contributing Factor
Bridge-related	Alignment Narrow roadway Visibility Vertical clearance Slippery surface Rough surface Inadequate barrier system
Fixed object	Obstruction in or near roadway Inadequate lighting Inadequate pavement markings Inadequate signs, delineators, guardrail Wet pavement surface Inadequate roadway shoulders Inadequate maintenance Inadequate roadway geometry such as sharp horizontal curves Excessive speed
Head-on or sideswipe in opposite-direction	Inadequate road geometry such as sharp horizontal curves Inadequate shoulders Excessive vehicle speed Inadequate pavement markings Inadequate signing
Nighttime	Poor nighttime visibility or lighting Poor sign visibility Inadequate channelization or delineation Excessive speed Inadequate sight distance

Table 7.2. Possible Crash Contributing Factors for Roadway Segments (Cont')

Crash Type	Possible Contributing Factor
Run-off-road	Slippery pavement Inadequate roadway design Inadequate maintenance Inadequate roadway shoulders Poor delineation Poor visibility Excessive speed
Vehicle rollover	Roadside design such as steep slopes Inadequate shoulder
Wet Pavement	Slippery pavement Inadequate pavement markings Inadequate maintenance Excessive speed

Table 7.3. Possible Crash Contributing Factors for Signalized Intersections

Crash Type	Possible Contributing Factor
Left- or right-turn	Misjudge speed of on-coming traffic Pedestrian or bicycle conflicts Inadequate signal timing Inadequate sight distance Conflict with right-turn-on-red vehicles
Nighttime	Poor nighttime visibility or lighting Poor sign visibility Inadequate channelization or delineation Inadequate maintenance Excessive speed Inadequate sight distance
Rear-end or Sideswipe	Inappropriate approach speeds Poor visibility of signals Unexpected lane changes on approach Narrow lanes Unexpected stops on approach Wet pavement surface Excessive speed
Right-angle	Poor visibility of signals Inadequate signal timing Excessive speed Wet Pavement surface Inadequate sight distance Drivers running red light
Wet Pavement	Inadequate sight distance Slippery pavement Inadequate pavement markings Inadequate maintenance Excessive speed

Table 7.4. Possible Crash Contributing Factors for Unsignalized Intersections

Crash Type	Possible Contributing Factor
Angle	Restricted sight distance High traffic volume High approach speed Unexpected crossing traffic Drivers running STOP sign Wet pavement surface
Collisions at driveways	Left-turning vehicles Improperly located driveway Right-turning vehicles Large volume of through traffic Large volume of driveway traffic Restricted sight distance Excessive speed
Head-on or sideswipe	Inadequate pavement markings Narrow lanes
Left- or right-turn	Inadequate gaps in traffic Restricted sight distance
Nighttime	Poor nighttime visibility or lighting Poor sign visibility Inadequate channelization or delineation Excessive speed Inadequate sight distance
Rear-end	Pedestrian crossing Driver inattention Slippery pavement surface Large number of turning vehicles Unexpected lane change Narrow lanes Restricted sight distance Inadequate gaps in traffic Excessive speed
Wet Pavement	Slippery pavement Inadequate pavement markings Inadequate maintenance Excessive speed

7.3.5 Identification of Alternative Safety Hardware Improvement Projects

After the candidate segment and intersection location for possible safety hardware improvements have been identified, the next step is to define the set of alternative safety hardware improvement projects for each candidate location. These improvements vary from location to location and are based on the identification of safety hardware related crash contributing factors that would need to be addressed so that the associated crashes will be reduced or eliminated.

7.3.5.1 Crash Contributing Factors

Crash risk will increase if the connection of factors concerning highway infrastructure, vehicle dynamics, and driver behavior fails. In the present study, the proposed procedure focuses primarily on the roadway infrastructure factors. For each candidate location, factors considered in selecting an appropriate safety hardware improvement project are condition of roadway safety hardware assets, roadway geometrics, geometrical design consistency, pavement condition, and roadside features.

7.3.5.2 Expected Predominant Crash Pattern

The types of crashes considered to be occurred on a roadway segment due to roadway safety hardware deficiencies are head-on, fixed object, side-swipe, and run-off road crashes. The types of crashes at an intersection due to safety hardware deficiencies may include turning, right angle, sideswipe, rear end, head-on, pedestrian, parked vehicle, fixed object, and highway-railroad crossing. A crash pattern is identified as predominant on a road segment or at an intersection if the expected frequency of the particular crash pattern at a given location significantly exceeds its critical crash frequency.

7.3.5.3 Identification of Countermeasures

Having identified the roadway deficiencies and predominant crash patterns at each candidate location, the next step is to identify the set of appropriate safety improvement countermeasures that would effectively mitigate or eliminate these deficiencies. Tables 7.5-7.7 provide lists of countermeasures applicable to highway segments, signalized intersections, and unsignalized intersections, respectively.

Table 7.5. List of Safety Improvement Countermeasures for Roadway Segments

Crash Type	Possible contributing factor	Possible countermeasure
Bridges	Alignment	Install advance warning signs Improve delineation/pavement markings Realign bridge or roadway
	Visibility	Improve delineation/pavement markings Install advance warning signs
	Vertical clearance	Improve delineation/pavement markings Install advance warning signs Provide height restriction warning device
	Slippery surface	Provide warning signs
	Inadequate barrier system	Improve delineation/pavement markings Remove hazardous curb Upgrade bridge rail Upgrade bridge approach guardrail transitions or end treatments
Fixed object	Obstruction in or near roadway	Delineate roadside hardware Remove or relocate fixed objects Install breakaway safety features Shield objects with barrier Install accident attenuation device
	Inadequate lighting	Improve roadway lighting
	Inadequate pavement markings	Improve retroreflectivity of existing markings Install raised pavement markers (RPMs)
	Inadequate signs, delineators, and guardrails	Improve retroreflectivity of signs Install delineators on fixed objects Add supplemental signing Upgrade barrier system
Head-on or side swipe in opposite direction	Inadequate road geometry or maintenance	Sign and mark unsafe passing areas Provide roadside delineation
	Inadequate pavement markings or channelization	Improve centerline, edge line, visibility Install raised pavement markers (RPMs)
	Inadequate signing	Provide improved guide and warning signs Add illuminated directional signs Provide warning signs
	Inadequate roadway design or maintenance	Install/improve roadside barrier Flatten side slopes/ditches Install edge line or shoulder rumble strips
	Poor delineation	Install roadside delineators Install advance warning signs Improve/install pavement markings
	Poor visibility	Increase sign size Improve or install roadway lighting
Run-off Road	Inadequate guardrail	Install/ Upgrade guardrail along embankment slope
	Poor visibility or lighting	Install/improve warning signs Install/improve delineation Install/improve roadway lighting
	Poor sign visibility	Upgrade sign visibility Provide illuminated signs
	Inadequate channelization or delineation	Install/improve pavement markings Improve channelization
	Inadequate sight distance	Eliminate obstructions on inside of curves Flatten crest vertical curves Nighttime Flatten horizontal curve

Table 7.5. List of Safety Improvement Countermeasures for Roadway Segments (Cont')

Crash Type	Possible contributing factor	Possible countermeasure
Vehicle rollover	Roadside design	Provide traversable culvert end Extend culvert Install/enhance roadside barriers Flatten side slopes of ditches Relocate drainage facilities
	Inadequate shoulder	Widen travel lane or shoulder Remove curb or other obstructions Widen travel lane or shoulder
	Pavement design	Eliminate edge drop-off Improve pavement cross-slope or super elevation
Wet pavement	Slippery pavement	Provide advance warning signs
	Inadequate pavement markings	Improve retroreflectivity of existing markings Inadequate pavement markings Install raised pavement markers (RPMs)

Table 7.6. List of Safety Improvement Countermeasures for Signalized Intersections

Crash Type	Possible contributing factor	Possible countermeasure
Left- and right-turn	Misjudge speed of on-coming traffic	Improve signal visibility Use protected signal phasing Improve clearance interval Decrease access points
Rear-end or sideswipe	Inappropriate approach speeds	Remove sight obstructions Install advance warning signs Improve delineation of lanes and stop bars
	Poor visibility of signals	Install advance warning devices Install signal head visor Install signal back plates Remove sight obstructions Add additional signal heads Install larger signal lens Install overhead signals Use retroreflective tape on signal back plate Provide strobe light to emphasize red signal display
	Unexpected lane change on approach	Install guide signs or larger signs Install lane-use control signs
Right-angle	Poor visibility of signals	Install advance warning devices Install signal head visor Install signal back plates Remove sight obstructions Add additional signal heads Install larger signal lens Install overhead signals Use retroreflective tape on signal back plate Provide strobe light to emphasize red signal display
	Wet Pavement Surface	Install warning signs

Table 7.7. List of Safety Improvement Countermeasures for Unsignalized Intersections

Crash Type	Possible contributing factor	Detailed Safety Issue Item
Angle	Restricted sight distance	Install advance warning signs Install stop signs Install yield signs Restrict parking on intersection approaches Remove sight obstructions Install traffic signal Improve lighting Channelize intersection Reduce intersection skew angle
Collisions at driveways	Restricted sight distance	Install/improve street lighting Collisions at driveways Remove sight obstructions
Head-on or sideswipe	Inadequate pavement markings	Install or improve pavement markings
Left- or right-turn	Restricted sight distance	Improve intersection sight lines Eliminate or flatten curves on intersection approach or move intersection away from curves Install advance warning signs on approach
Nighttime	Poor night Install or improve lighting visibility	Install or improve lighting Install post-mounted delineators
	Poor sign visibility	Install warning signs, larger signs, or illuminated signs
	Inadequate pavement markings	Install or improve pavement markings
	Inadequate sight distance	Improve intersection sight lines
		Install advance warning signs on approach
		Eliminate or flatten curves on intersection approach or move intersection away from curves
Rear-end	Restricted sight distance	Install intersection warning signs on approach Eliminate curves on approach or move intersection away from curves on approach Improve intersection sight lines
Wet pavement	Slippery pavement	Improve roadway surface drainage
		Install warning signs
	Inadequate pavement markings	Install or improve pavement markings

7.3.6 Estimating Costs and Benefits of Alternative Safety Hardware Improvement Projects

For a given candidate location, the final selection of safety hardware improvement projects from a set of viable alternatives involves the determination of the costs and benefits of each alternative over the analysis period. A safety hardware improvement project can be implemented at a given location in any year within the analysis period provided its implementation year equals or exceeds the "critical" year of that location. The "critical" year for a given location is defined as the year at which that location qualifies as a candidate location.

7.3.6.1 Estimation of Project Costs

A safety hardware project may be implemented at the beginning of the useful service life-cycle of a new highway segment (intersection) or in the middle of an in-service highway segment (intersection). In addition, a safety hardware project may be implemented to mitigate safety issues of one or more types of safety hardware assets. It is common that the useful service lives for different types of safety hardware assets vary considerably, and the safety hardware service lives are often shorter than the useful service life of a new highway segment or the remaining service life of an in-service highway segment. Since the life-cycle safety benefits are computed using the annual safety benefits estimated based on the first-year PSI (Potential for Safety Improvement) for fatal, injury, and PDO crashes, it is needed to assume that the safety hardware project is required to be implemented in multiple times so that the multiple service lives of the safety hardware asset(s) would match the useful service life of a new highway segment (intersection) or match the remaining service life of an in-service highway segment (intersection). Therefore, the estimated overall life-cycle safety benefits actually correspond to repeating the project capital costs in multiple times, along with costs of maintenance and repairs in the hardware useful service life-cycle.

7.3.6.2 Calculation of the Overall Life-Cycle Crash Cost Savings

After estimating the annual PSIs for fatal, injury, and PDO crashes using the concept of consumer surplus, dollar amount savings can be computed by applying the unit costs for fatal, injury, and PDO crashes, respectively. Assuming an equal annual growth rate of safety benefits and also assuming that the annual safety benefits increase the same as the annual traffic growth rate, the safety benefits in the highway segment or intersection useful service life can be computed.

7.3.6.3 Cost-Effectiveness of a Safety Hardware Project

Net present worth method and benefit-to-cost ratio method are commonly adopted methods for project comparison.

Detailed procedure for estimating project costs, calculating overall life-cycle crash cost savings, and determining cost-effectiveness of a safety hardware project can be found in the methodology for highway safety hardware project evaluation.

7.3.7 Integrated Project Selection Using Optimization Models

Transportation agencies at all levels typically have a budgetary limit for improvement projects. It is therefore needed to consider the limitations of available budget in the quest to establish optimal safety programs at network level. The establishment of optimal asset management programs involves identifying the most appropriate improvement project and optimal time for implementation at each candidate location within the available budget over the analysis period. An integer optimization model was chosen, which is presented in the next section, with an objective to maximize the total economic value for all the improvement projects selected during the analysis period.

The life-cycle cost approach (LCCA) is used for evaluating pavement, bridge, and maintenance projects, while the risk-based approach is used for safety project evaluation. Due to the close linkage between roadway safety hardware and roadway safety performance, in the broad sense safety hardware projects can be assessed following the general principle of safety project evaluation.

The Safety Index (SI) associated with a highway segment or an intersection obtained from risk-based methodology for safety hardware project evaluation will give the expected number of crashes per year by crash type and severity category. The annual potential for safety improvement as the difference in the safety index value after implementing the safety hardware project can be established using the concept of consumer surplus. The annual potential for safety improvement can be further converted into annual safety benefits by applying the respective unit rates. The annual safety benefits can be further expanded to life-cycle safety benefits using the LCCA approach. Thus, the consistency between the approach used for estimating the benefits of safety hardware projects and the approaches used for pavement, bridge, safety, and maintenance projects is maintained.

The estimated project life-cycle benefits will be used as inputs of the optimization models which facilitate integrated project selection. The project selection can be conducted for candidate projects within the safety hardware asset category, for safety hardware improvement projects and general safety improvement projects, and for safety hardware improvement projects, general safety improvement projects, and all other candidate projects associated with major highway assets such as pavement, bridge, and maintenance. The candidate projects are herein in all called improvement projects. The optimization models for integrated project selection consider the following alternative formulations:

- Unconstrained funding optimization
- Multi-year budgeting without year-by-year carry-over of unspent funds
- Multi-year budgeting with year-by-year carry-over of unspent funds.

7.3.7.1 Unconstrained Funding Optimization

The unconstrained funding optimization scenario does not involve any budgetary constraint and is consistent with the highway network level needs assessment. The funding needs can be determined by solving the following integer formulation.

$$\text{Maximize} \quad \sum_{i}^{h}\sum_{j}^{d_i}\sum_{t}^{p}\left(x_{ijt}\cdot b_{ijt}\right) \tag{7-1}$$

$$\text{Subject to} \quad \sum_{j=1}^{d_i}\sum_{t=1}^{p} x_{ijt} = 1 \text{ for all } i \tag{7-2}$$

$$x_{ijt} = 0 \text{ if } t < CR_i \tag{7-3}$$

$$x_{ijt} = 0/1 \text{ integer} \tag{7-4}$$

Where

h = Number of candidate locations within selected network
d_i = Number of alternative improvement projects for candidate location i
p = Number of years in analysis period
t = Analysis year = 1, 2…..p
CR_i = Year when location i becomes hazardous (critical year)
b_{ijt} = Present worth net benefits of the improvement project j at location i in analysis year t
x_{ijt} = $\begin{cases} 1, & \text{if the improvement project j is implemented at location i in analysis year t} \\ 0, & \text{otherwise} \end{cases}$

Equation (7-1) seeks to maximize the total economic value of the selected improvement projects. The benefits b_{ijt} of each alternative improvement project at each candidate location is determined from its net present worth. The constraints on the optimal solution are represented by the equalities and inequalities presented in Equations (7-2) to (7-4). Equation (7-2) ensures that only one improvement project is selected from the alternative improvement projects at each candidate location. Equation (7-3) ensures that the implementation year of a selected improvement project exceeds the critical year of the candidate location. Equation (7-4) ensures that only one alternative project can be selected for each candidate location in the entire analysis period.

7.3.7.2 Multi-Year Budgeting without Year-by-Year Carry-over of Unspent Budget

Multi-year budgeting without year-by-year carry-over of unspent funds represents the situation where an annual budget is specified for each year of the analysis period and any unspent funds are not transferable to the subsequent year. For this scenario, the constraint is the annual funding available for each year of the analysis. The optimization formulation is in the following:

$$\text{Maximize} \quad \sum_{i=1}^{h}\sum_{j=1}^{d_i}\sum_{t=1}^{p}\left(x_{ijt}\cdot b_{ijt}\right) \tag{7-5}$$

$$\text{Subject to} \quad \sum_{i=1}^{h}\sum_{j=1}^{d_i}\left(x_{ijt}C_{ijt}\right) \le B_{c(t)} \text{ for all } t \tag{7-6}$$

$$\sum_{i=1}^{h}\sum_{j=1}^{d_i}\left(\sum_{k=1}^{t-1} x_{ijk}M_{ijk}\right) \le B_{m(t)} \text{ for all } t \tag{7-7}$$

$$\sum_{j=1}^{d_i}\sum_{t=1}^{p} x_{ijt} = 1 \text{ for all } i \tag{7-8}$$

$$\sum_{i=1}^{h}\sum_{j=1}^{d_i} x_{ijt} \geq 1 \text{ for all } t \tag{7-9}$$

$$x_{ijt} = 0 \text{ if } t < CR_i \tag{7-10}$$

$$x_{ijt} = 0/1 \text{ integer} \tag{7-11}$$

where
$B_{c(t)}$ = Annual capital budget for analysis year t
$B_{m(t)}$ = Annual maintenance budget for analysis year t.

Similarly, Equation (7-5) represents the objective function of this integer optimization model while the constraints are represented by the equalities and inequalities presented in Equations (7-6) through (7-11). Equation (7-6) constrains the annual capital expenditure to be less than or equal to the available annual capital budget, while Equation (7-7) constrains the annual maintenance expenditure to be less than or equal to the available annual maintenance budget. In actual practice, capital and maintenance budgets are typically programmed separately. Therefore, the maintenance constraint may be excluded from the analysis. Equation (7-9) requires that at least one improvement project should be implemented in each year of the analysis period. The remaining constraints are similar to those of the previous model.

7.3.7.3 Multi-Year Budgeting with Year-By-Year Carry-over of Unspent Budget

Multi-year budgeting with carry-over of unspent funds represents the situation where an annual budget is specified for each year of the analysis period, but any unspent funds can be transferred to the subsequent year. The optimization formulation is as follows:

Maximize
$$\sum_{i=1}^{h}\sum_{j=1}^{d_i}\sum_{t=1}^{p}\left(x_{ijt}\cdot b_{ijt}\right) \tag{7-12}$$

Subject to
$$\sum_{i=1}^{h}\sum_{j=1}^{d_i}\sum_{k=1}^{t}\left(x_{ijk}C_{ijk}\right) \leq \sum_{k=1}^{t} B_{c(t)} \text{ for all } t \tag{7-13}$$

$$\sum_{i=1}^{h}\sum_{j=1}^{d_i}\sum_{k=1}^{t}\left(\sum_{k=1}^{t-1}\left((t-k)x_{ijk}M_{ijk}\right)\right) \leq \sum_{k=1}^{t} B_{m(t)} \text{ for all } t \tag{7-14}$$

$$\sum_{j=1}^{d_i}\sum_{t=1}^{p} x_{ijt} = 1 \text{ for all } i \tag{7-15}$$

$$\sum_{i=1}^{h}\sum_{j=1}^{d_i} x_{ijt} \geq 1 \text{ for all } t \tag{7-16}$$

$$x_{ijt} = 0 \text{ if } t < CR_i \tag{7-17}$$

$$x_{ijt} = 0/1 \text{ integer} \tag{7-18}$$

Equation (7-12) is the objective function of this integer optimization model, and the constraints are represented by Equations (7-13) through (7-16). Equation (7-13) constrains the annual capital expenditure to the annual capital budget limit and any excess funds carried over from the previous year. The remaining constraints are similar to those shown as Equations (7-8) - (7-11).

7.3.7.4 Solution of Optimization Models

The analytical framework presents in the previous section proposes a set of alternative improvement projects that can be implemented at each candidate location, and computes the economic benefits of each improvement project when implemented in each year of the analysis period. The analytical procedure then utilizes any of the above integer optimization models to select a subset of improvement projects, their respective locations and implementation years that best satisfies the objective function and associated constraints as the optimal solution. The solution of the integer optimization models can be accomplished using optimization software packages such as GAMS/CPLEX Solver and LINDO.

7.4 Chapter Summary

This report presents the methodology for integrating safety hardware asset management into overall highway asset management systems. In particular, the proposed methodology explicitly addresses issues of data integration, consistent approaches for project evaluation, and integrated project selection needed for system integration. The analytical framework developed will facilitate network-level long-term and short-term safety hardware asset management. Same analytical framework can be implemented for integrating roadway safety hardware and general safety management, and integrating roadway safety hardware, general safety, as well as pavement, bridge, and maintenance management by simultaneously considering candidate projects associated with the corresponding types of highway assets in the optimization models for project selection.

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APPENDICES

APPENDIX A:

Questionnaire for Current Practices in Roadway Safety Hardware Asset Management at State Transportation Agencies

PURPOSE OF THIS QUESTIONNAIRE

Funded through the University of Wisconsin's Midwest Regional University Transportation Center, the MRUTC Project 08-06 will i) synthesize the current-state-of-practice techniques for managing roadway safety hardware assets *such as roadway signs; signals; lighting; support and structure for signs, signals, and lighting; guardrails, barriers, and crash cushions; pavement markings and treatments; and deployed detecting devices* across the country; and ii) develop a methodology for integrating roadway safety hardware asset management into the overall pavement, bridge, maintenance, and safety management program. The study results are expected to assist state transportation agencies in acquisition, maintenance, and upgrade/replacement of roadway safety hardware in the most cost-effective manner. This questionnaire is intended to collect information on the current practices of roadway safety hardware asset management at all state transportation agencies in the United States.

Please email, fax, or mail the completed survey form by July 31, 2007 to

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Illinois Institute of Technology
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Phone: (312) 567-3556, Fax: (312) 567-3519, E-mail: lizz@iit.edu

Please spend your valuable time to complete this questionnaire. Your input is very important to make our road safer.

GENERAL INFORMATION

Name: _____

Title: _____

Address: _____

_____

Phone: _____ Fax: _____ E-mail: _____

ROADWAY SAFETY HARDWARE ASSET MANAGEMENT PRACTICES

1. Please check major roadway safety hardware management tasks performed by your agency.

Roadway Safety Hardware Asset	Maintaining an Hardware Asset Inventory	Performing Hardware Routine Inspection	Assessing Condition by Sampling	Proposing, Evaluating, Selecting, and Implementing Hardware Projects	Providing Feedbacks
Signs- Safety and warning	☐	☐	☐	☐	☐
Signs- Information-related	☐	☐	☐	☐	☐
Signals	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐
Detection devices	☐	☐	☐	☐	☐
Pavement markings	☐	☐	☐	☐	☐
Guardrails, barriers, crash cushions	☐	☐	☐	☐	☐
Ramp metering	☐	☐	☐	☐	☐

2. Please check the general goals of your agency's roadway safety hardware asset management program.

- ☐ Meet annual budget targets
- ☐ Share costs equitably with other jurisdictions
- ☐ Maximize safety hardware useful service life
- ☐ Minimize long-term costs over several years or hardware service life-cycle
- ☐ Minimize energy consumption and emission
- ☐ Minimize vehicle crashes
- ☐ Other (please specify) _____

3. Is your agency currently using performance measures to manage roadway safety hardware assets?

- ☐ Always
- ☐ Usually
- ☐ Occasionally
- ☐ Seldom
- ☐ Never

4. At what level(s) of your organization are decisions about roadway safety hardware expenditures made?

Focus	Upper Management (Department Head/ Agency Director)	Middle Management	Front-Line Supervisor/ Maintenance Superintendent	Maintenance Field Personnel
Determine/negotiate overall budget	☐	☐	☐	☐
Determine/negotiate sub-allocation of budget to regions/counties	☐	☐	☐	☐
Negotiate cost share with other agencies	☐	☐	☐	☐
Develop purchasing specifications	☐	☐	☐	☐
Determine maintenance cycles	☐	☐	☐	☐
Determine specific items to repair or replace	☐	☐	☐	☐
Authorize purchases	☐	☐	☐	☐

5. Please specify the adoption phase of your agency's software systems for roadway safety hardware asset management.

Adoption Phase	Not Started	Initiation	Development	Execution	Assessment	Integration
Signs- Safety and warning	☐	☐	☐	☐	☐	☐
Signs- Information-related	☐	☐	☐	☐	☐	☐
Signals	☐	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐	☐
Detection devices	☐	☐	☐	☐	☐	☐
Pavement markings	☐	☐	☐	☐	☐	☐
Guardrails, barriers, crash cushions	☐	☐	☐	☐	☐	☐
Ramp metering	☐	☐	☐	☐	☐	☐

6. What is the geographical coverage of your agency's software systems for roadway safety hardware asset management?

☐ Entire State
☐ One or more regions of the State

7. How are your agency's software systems for roadway safety hardware asset management administrated?

- ☐ By central office
- ☐ By district office
- ☐ Others (please specify) _____

8. Based on the current status of your agency's software systems for roadway safety hardware asset management, how much influence are these systems having on the decision-making of safety hardware maintenance, repair, and replacement/upgrade?

- ☐ Extensive
- ☐ Moderate
- ☐ Minimal
- ☐ No Impact
- ☐ Don't Know

9. List additional improvements needed for roadway safety hardware asset management, including technology, your agency's organizational structure, purchasing, etc.

_____

_____

_____

_____

_____

_____

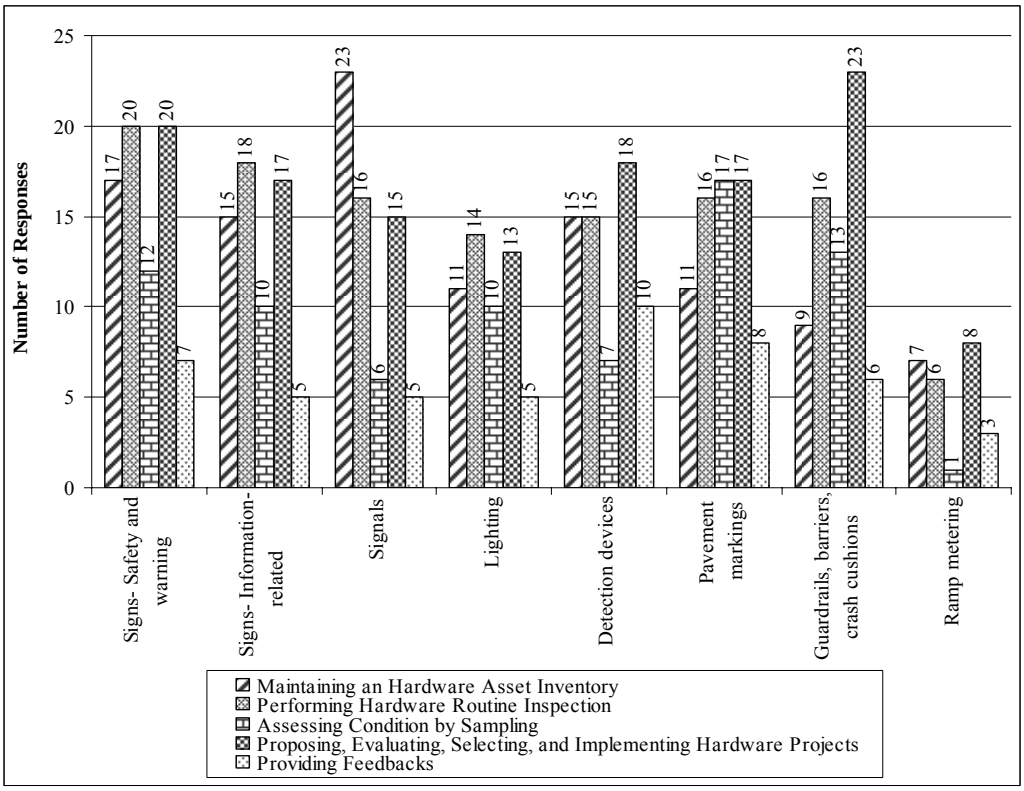
_____

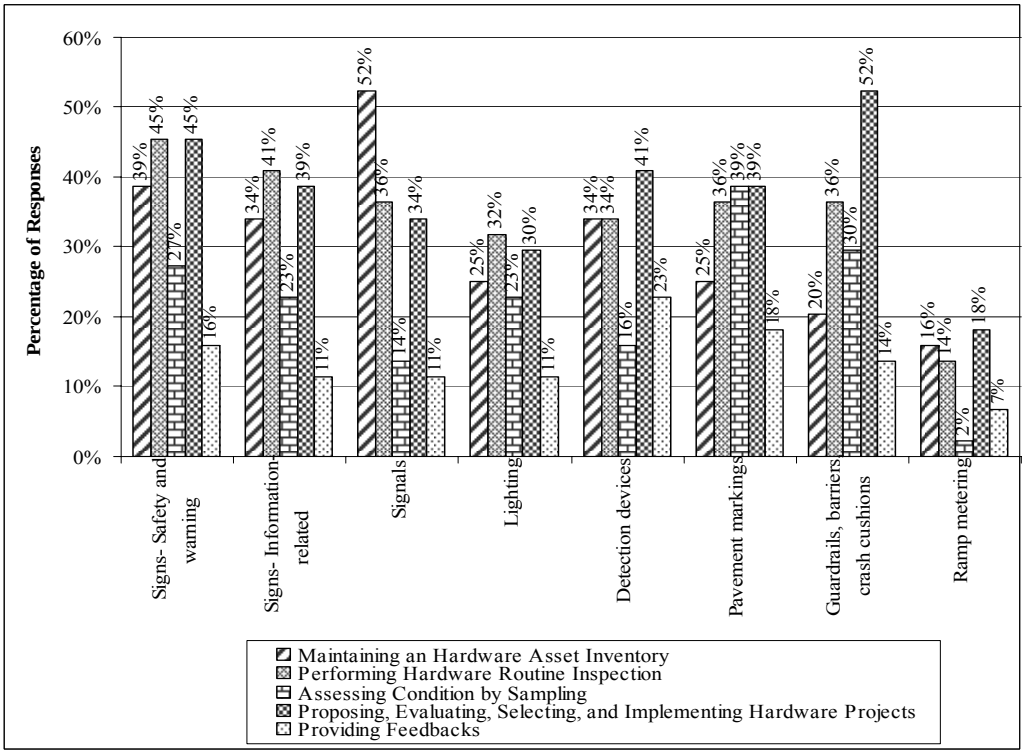
THANK YOU FOR YOUR ASSISTANCE!

APPENDIX B:

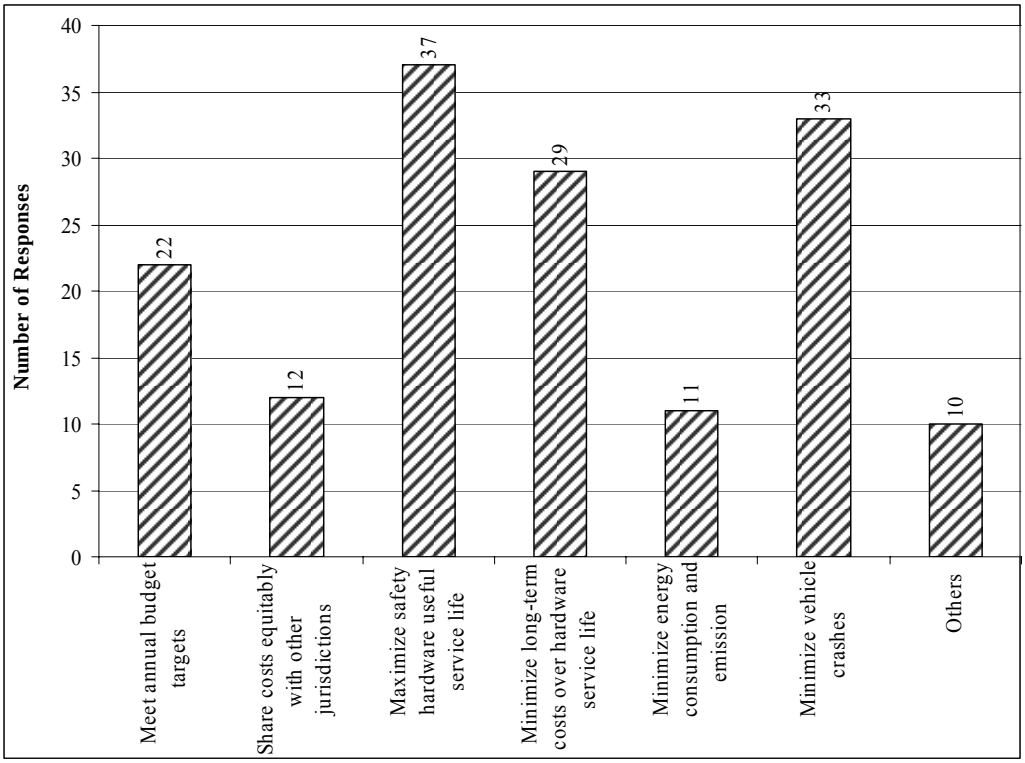
Graphic Presentations of Survey Results

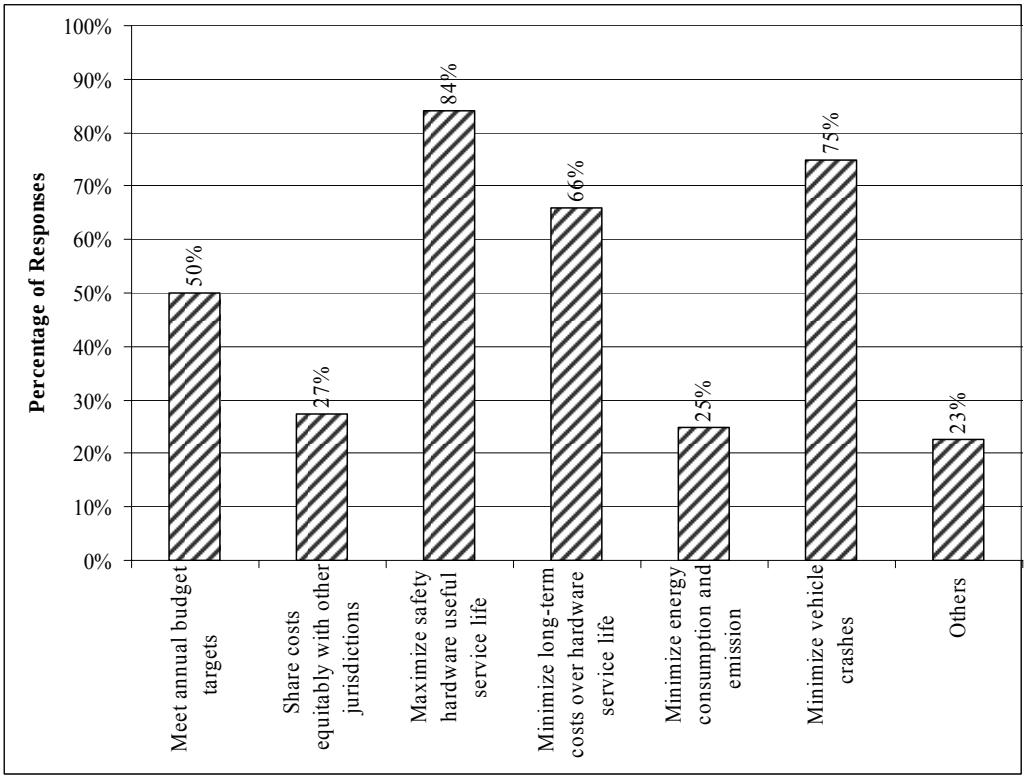
1. Major Roadway Safety Hardware Asset Management Tasks Performed



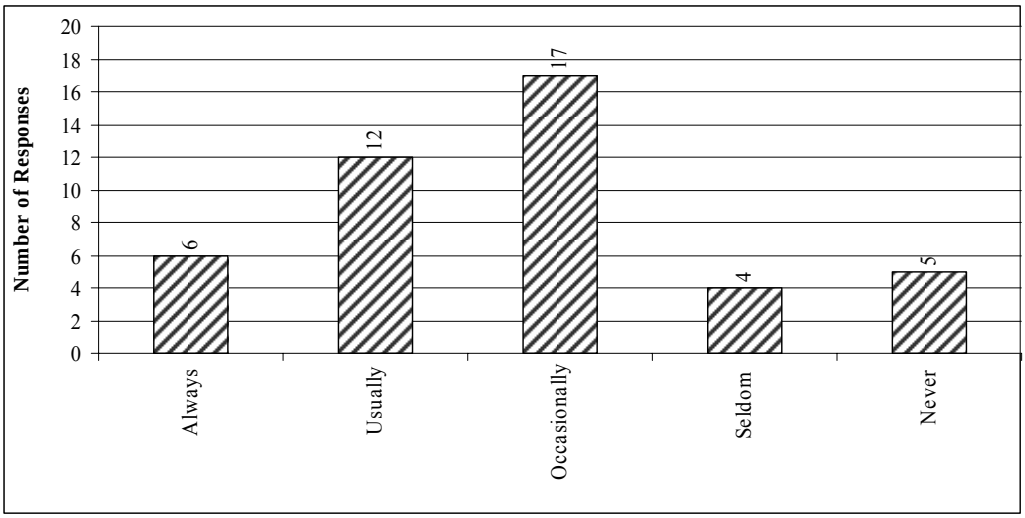


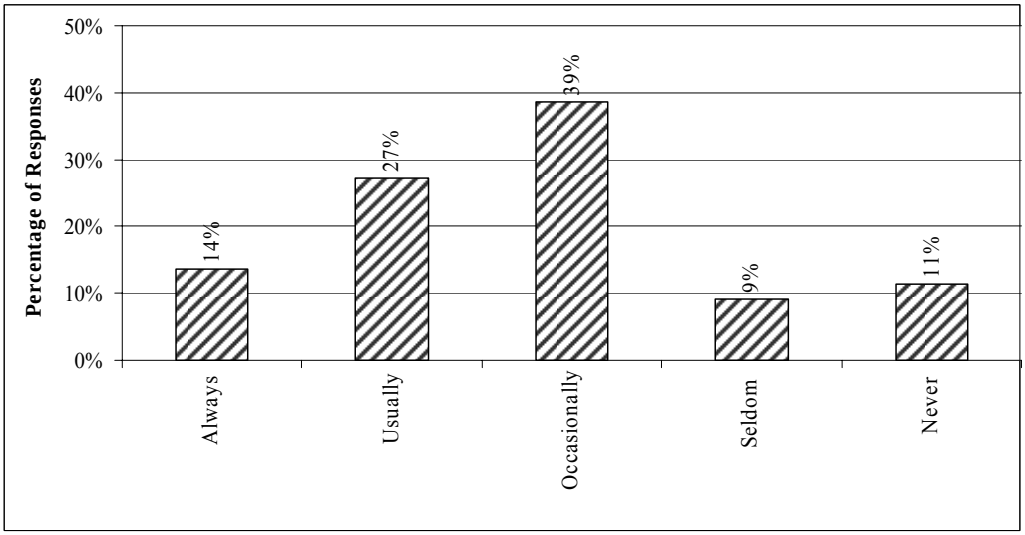
2. General Goals of Roadway Safety Hardware Asset Management Program



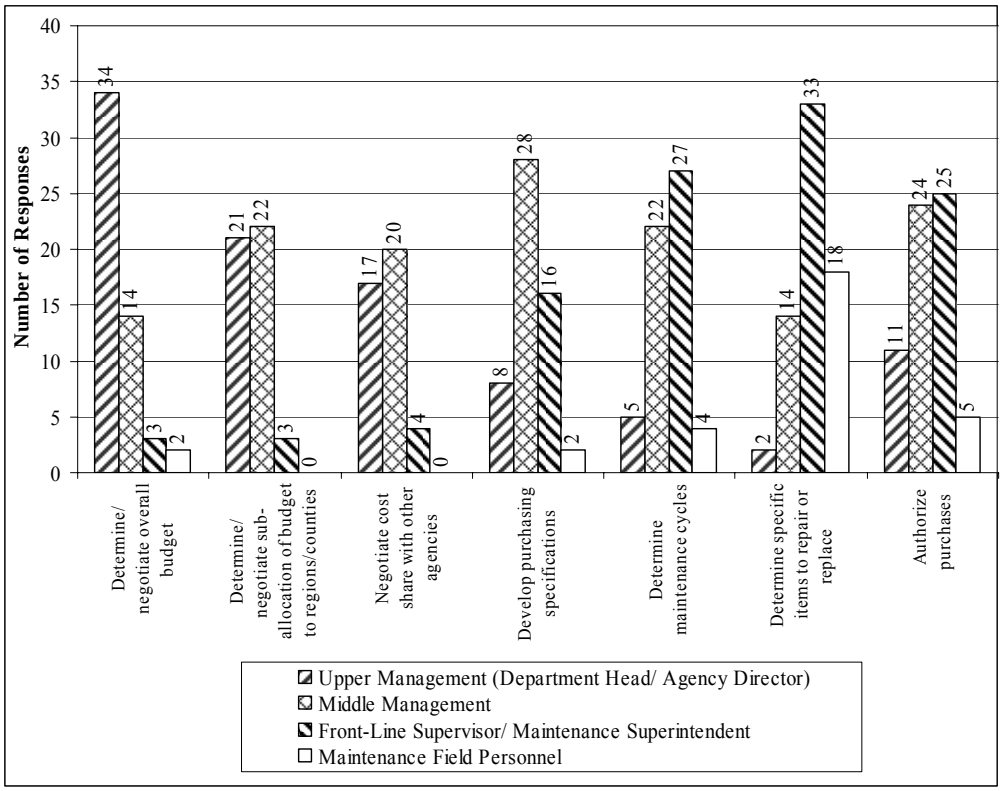


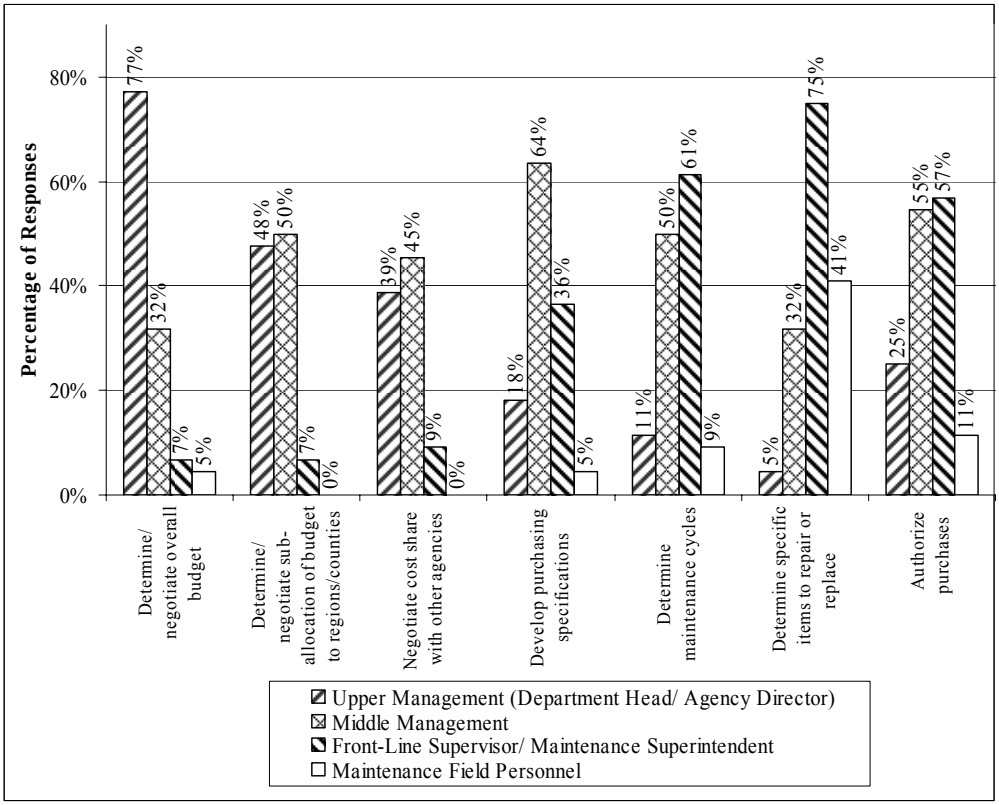
3. Use of Performance Measures for Roadway Safety Hardware Asset Management



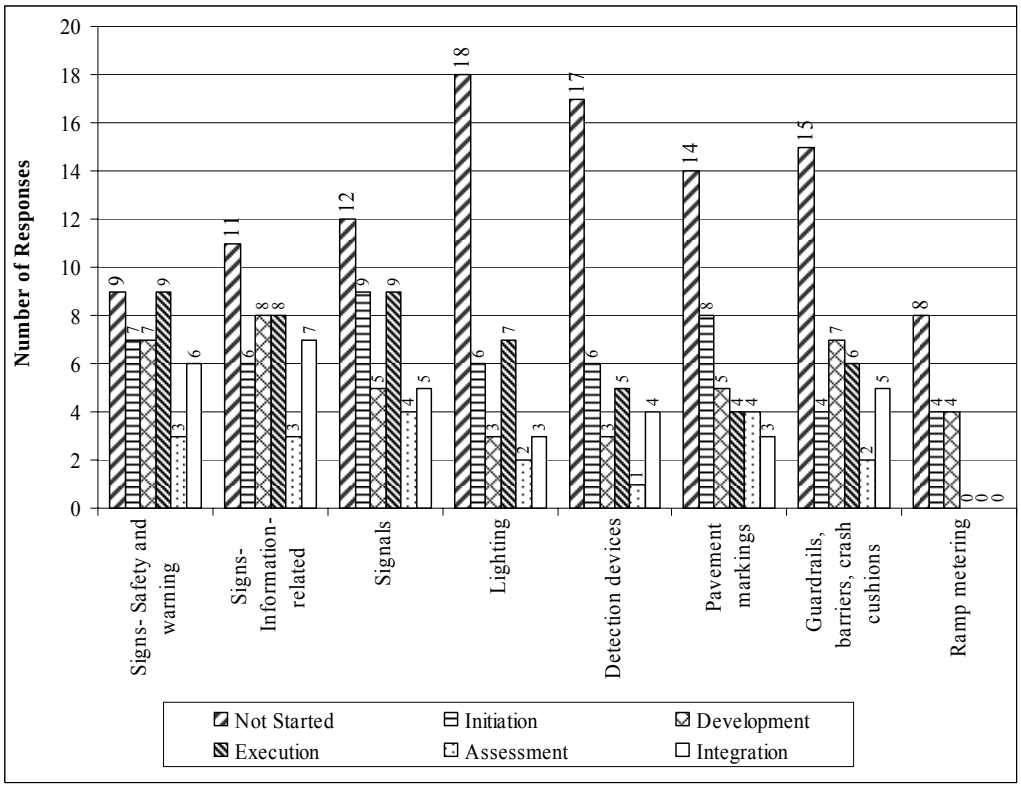


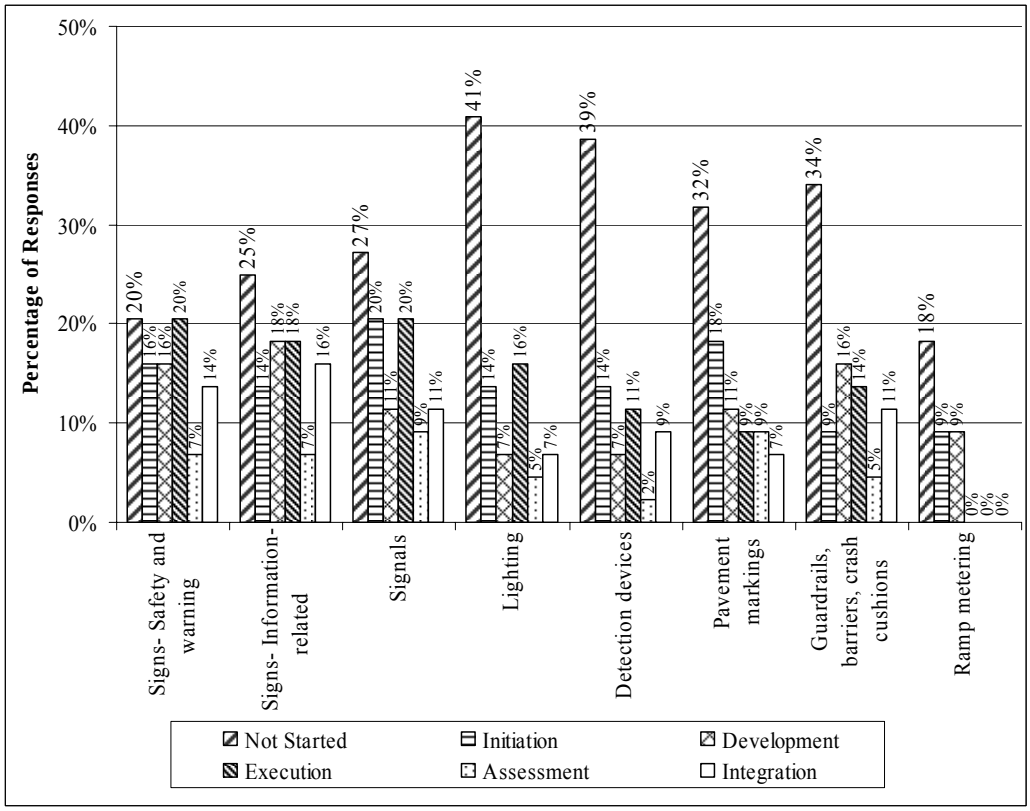
4. Organizational Levels Making Decisions about Roadway Safety Hardware Expenditures



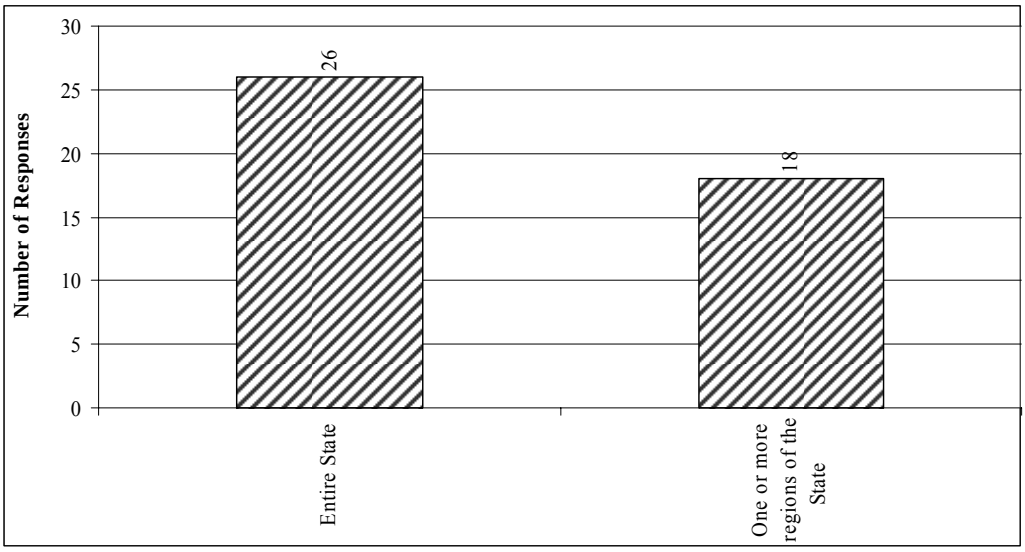


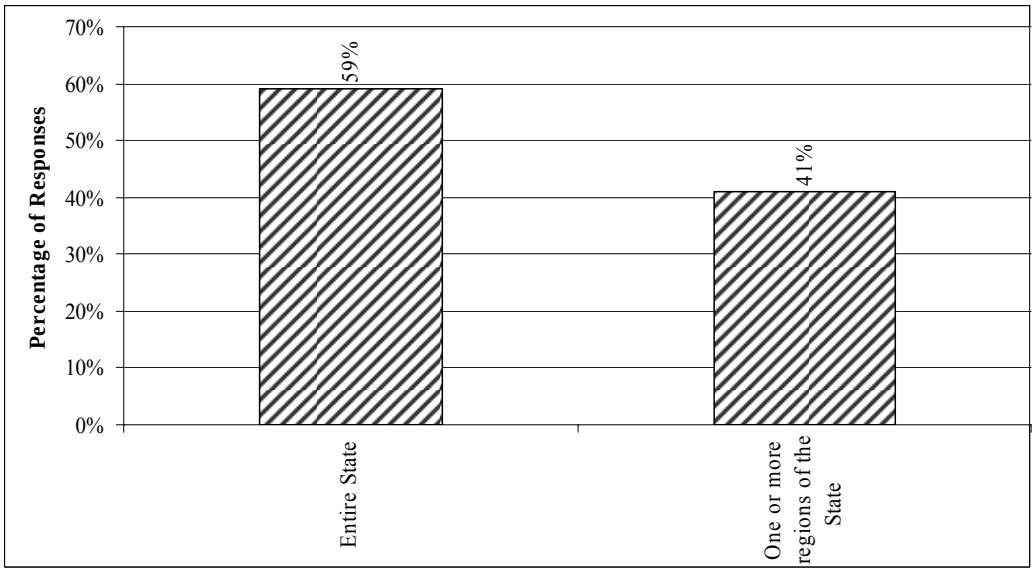
5. Adoption Phases of Software Systems for Roadway Safety Hardware Asset Management



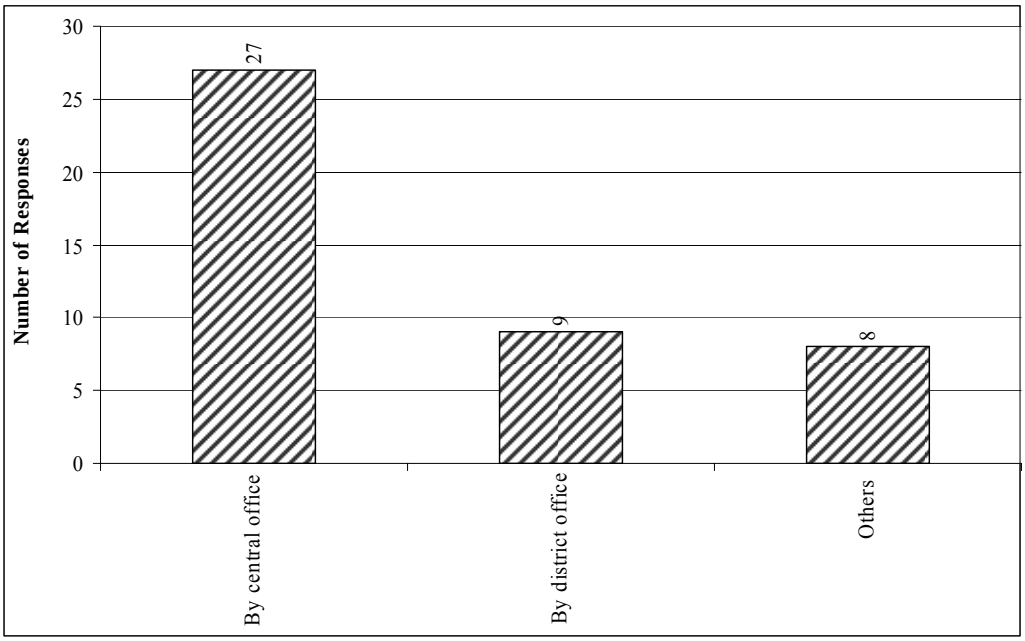


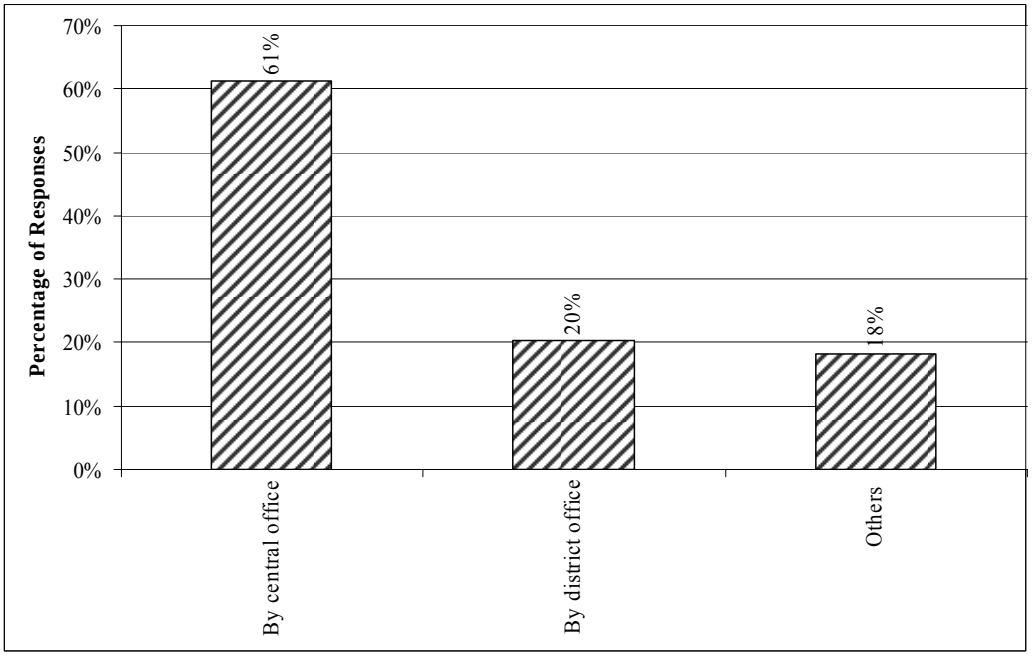
6. Geographical Coverage of Software Systems for Roadway Safety Hardware Asset Management



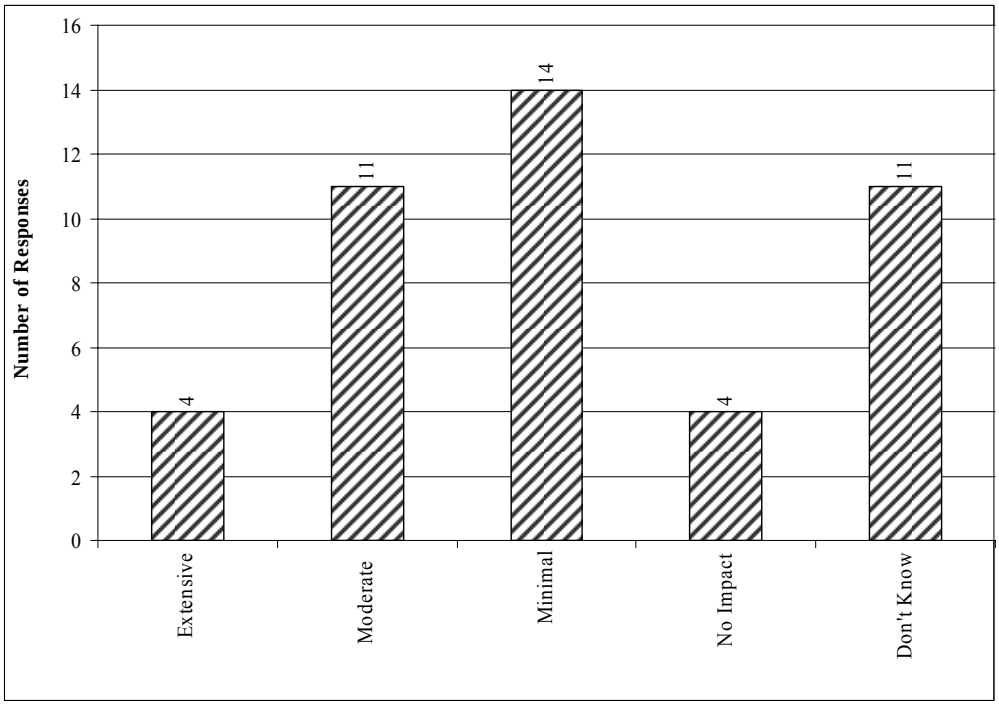


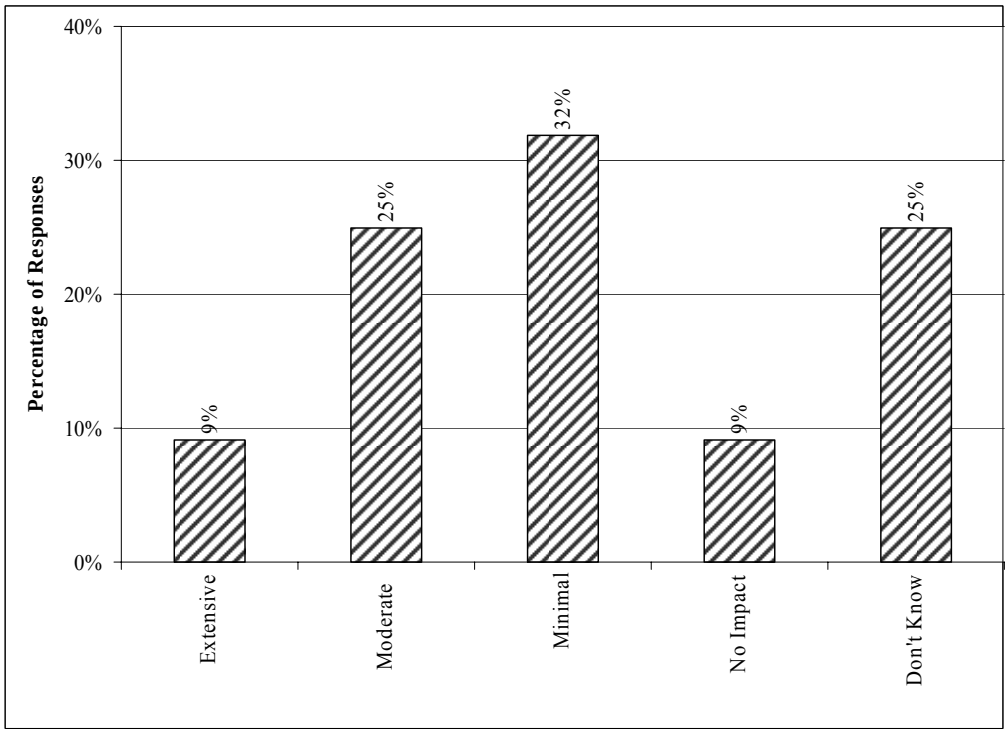
7. Administration of Software Systems for Roadway Safety Hardware Asset Management





8. Influence of Software Systems for Roadway Safety Hardware Asset Management on Investment Decisions





APPENDIX C:

Outline of Interview Questions for Case Studies of Roadway Safety Hardware Management Programs at State Transportation Agencies

I. GENERAL INFORMATION

Name: _____

Title: _____

Division: _____

Agency: _____

State: _____

Phone: _____ Fax: _____ E-mail: _____

II. CURRENT ROADWAY SAFETY HARDWARE ASSET MANAGEMENT PROGRAMS

1. What categories of roadway safety hardware asset are managed by the state transportation agency?

Roadway Safety Hardware Category	Managed by the State Transportation Agency	
	Yes	No
Signs- Safety and warning	☐	☐
Signs- Information-related	☐	☐
Signals	☐	☐
Lighting	☐	☐
Detection devices	☐	☐
Pavement markings	☐	☐
Guardrails, barriers, crash cushions	☐	☐
Ramp metering	☐	☐

2. What are the performance measures of your agency's roadway safety hardware asset management program?

Roadway Safety Hardware Category	Performance Measure
Signs- Safety and warning	
Signs- Information-related	
Signals	
Lighting	
Detection devices	
Pavement markings	
Guardrails, barriers, crash cushions	
Ramp metering	

3. What are the performance targets of your agency's roadway safety hardware asset management program?

Roadway Safety Hardware Category	Performance Target
Signs- Safety and warning	
Signs- Information-related	
Signals	
Lighting	
Detection devices	
Pavement markings	
Guardrails, barriers, crash cushions	
Ramp metering	

4. What are the data coverage and sampling percentage for your agency's asset condition assessment?

Roadway Safety Hardware Category	Data Coverage				Sampling Percentage (Please Specify)			
	Rural		Urban		Rural		Urban	
	Interstate	Non-IS	Interstate	Non-IS	Interstate	Non-IS	Interstate	Non-IS
Signs- Safety and warning	☐	☐	☐	☐				
Signs- Information-related	☐	☐	☐	☐				
Signals	☐	☐	☐	☐				
Lighting	☐	☐	☐	☐				
Detection devices	☐	☐	☐	☐				
Pavement markings	☐	☐	☐	☐				
Guardrails, barriers, crash cushions	☐	☐	☐	☐				
Ramp metering	☐	☐	☐	☐				

5. What is the frequency of your agency's hardware asset routine inspection?

Roadway Safety Hardware Category	Data Collection Frequency				Data Collection Method		
	Every _____ years (Please Specify)	Annually	Semi-Annually	As Needed	Automatic	Semi-automatic	Manual
Signs- Safety and warning		☐	☐	☐	☐	☐	☐
Signs- Information-related		☐	☐	☐	☐	☐	☐
Signals		☐	☐	☐	☐	☐	☐
Lighting		☐	☐	☐	☐	☐	☐
Detection devices		☐	☐	☐	☐	☐	☐
Pavement markings		☐	☐	☐	☐	☐	☐
Guardrails, barriers, crash cushions		☐	☐	☐	☐	☐	☐
Ramp metering		☐	☐	☐	☐	☐	☐

6. How is the database on roadway safety hardware assets managed by your agency?

Roadway Safety Hardware Category	Database Administration		Referencing System	
	Centralized	Decentralized	Milepost	GIS/GPS
Signs- Safety and warning	☐	☐	☐	☐
Signs- Information-related	☐	☐	☐	☐
Signals	☐	☐	☐	☐
Lighting	☐	☐	☐	☐
Detection devices	☐	☐	☐	☐
Pavement markings	☐	☐	☐	☐
Guardrails, barriers, crash cushions	☐	☐	☐	☐
Ramp metering	☐	☐	☐	☐

7. On what basis does your agency allocate budget from the central office to districts, and conduct project evaluation and selection?

Roadway Safety Hardware Category	Budget Allocation					Basic Principle of Project Investment Decision								Analysis Method				
	Lane-mile	Population	Traffic volume	Weather condition	Others	Need for vehicle crash damages	Need for severe weather damages	Hardware upgrade	Part of pavement work	Part of bridge work	Part of maintenance work	part of safety work	Others	Expert opinion	Risk Assessment	Engineering economics	Optimization	Others
Signs- Safety and warning	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Signs- Information-related	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Signals	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Detection devices	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pavement markings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Guardrails, barriers, crash cushions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Ramp metering	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

8. How are the software systems for roadway safety hardware asset management developed? Please indicate the name and cost.

Roadway Safety Hardware Category	Software Development		Software Name	Estimated Cost
	by in-house staff	Purchase from vendor		
Signs- Safety and warning	☐	☐		
Signs- Information-related	☐	☐		
Signals	☐	☐		
Lighting	☐	☐		
Detection devices	☐	☐		
Pavement markings	☐	☐		
Guardrails, barriers, crash cushions	☐	☐		
Ramp metering	☐	☐		

9. How would you rate the extent of success of your agency's roadway safety hardware asset management program?

Roadway Safety Hardware Category	Extremely Successful	Very Successful	Successful	Neutral	Not Successful	Definitely Not Successful
Signs- Safety and warning	☐	☐	☐	☐	☐	☐
Signs- Information-related	☐	☐	☐	☐	☐	☐
Signals	☐	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐	☐
Detection devices	☐	☐	☐	☐	☐	☐
Pavement markings	☐	☐	☐	☐	☐	☐
Guardrails, barriers, crash cushions	☐	☐	☐	☐	☐	☐
Ramp metering	☐	☐	☐	☐	☐	☐

III. SYSTEM INTEGRATION

10. What are the business process challenges faced by your agency in integrating the roadway safety hardware management into the overall pavement, bridge, maintenance, and safety management program?

Agency's Business Process Challenge	Yes	No
Clarity in roadway safety hardware management vision and mission	☐	☐
Consistency of roadway safety hardware asset management system goals and objectives	☐	☐
Consistency of safety hardware management performance measures	☐	☐
Roadway safety hardware asset data collection and database management	☐	☐
Roadway safety hardware performance analysis, needs assessment, and project benefit-cost analysis	☐	☐
Cost-effective resource allocation	☐	☐
Coordination of agency staff in achieving goals and objectives	☐	☐
Level of integration with overall asset management program	☐	☐

Others (Please specify)

11. What are the challenges on inventory, data collection, and database management faced by your agency in integrating the roadway safety hardware management into the overall pavement, bridge, maintenance, and safety management program?

Data Challenge	Yes	No
Inconsistent data coverage	☐	☐
Inconsistent data collection frequency	☐	☐
Significant variations in data collection technologies	☐	☐
Spatial and temporal variations in collected safety hardware data	☐	☐
Lack of funds and coordination in data collection	☐	☐
Lack of qualified personnel in database management	☐	☐
Inconsistent referencing systems used for safety hardware data with data associated with other types of assets	☐	☐

Others (Please specify)

12. What are the technological challenges faced by your agency in integrating the roadway safety hardware management into the overall pavement, bridge, maintenance, and safety management program?

Technological Challenge	Yes	No
Data collection, storage, sharing, and accessibility	☐	☐
Monitoring of safety hardware performance	☐	☐
Analytical capabilities of safety hardware project evaluation	☐	☐
Allocation of budget from central office to districts	☐	☐
Analytical capabilities of safety hardware project selection	☐	☐
Tradeoff analysis of safety hardware projects with projects associated with other types of assets	☐	☐

Others (Please specify)

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IV. ADDITIONAL COMMENTS ON ROADWAY SAFETY HARDWARE ASSET MANAGEMENT
(Including data, technology, institutional, purchasing, etc.)

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