Comprehensive Truck Size and Weight Limits Study

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Linkage between the Revised Desk Scans and Project Plans Report

Final Draft

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CHAPTER 1 - INTRODUCTION

The purpose of this Linkage between the Revised Desk Scans and Project Plans report is to document how the information and understanding gained through the revised Desk Scans informed the technical methodology undertaken in the USDOT *2014 Comprehensive Truck Size and Weight (CTSW) Limits Study*. The technical methodology was initially provided in the 2014 CTSW Study Tasks Project Plans and subsequently revised throughout the course of the project as details about available data emerged and analytical approaches were refined. As such, the linkages in this report reference the Project Plans as manifested in the 2014 CTSW Study Tasks technical reports. The original 2014 CTSW Study Project Plans have not been revised.

This report includes linkages between the revised desk scans and the project plans for the 2014 CTSW Study five Tasks technical analysis: Modal Shift Comparative Analysis; Compliance Comparative Analysis; Highway Safety and Truck Crash Comparative Analysis; Pavement Comparative Analysis; and Bridge Comparative Analysis.

CHAPTER 2 - MODAL SHIFT COMPARATIVE ANALYSIS

2.1 Purpose

This section highlights linkages between the Revised Desk Scan and the project plan developed for the modal shift analysis, the energy and environmental impact analysis, and the traffic operations impact analysis in the Modal Shift Comparative Analysis. The focus is on how the desk scans shaped the general technical approach outlined in the project plans and the specific data and analytical techniques available to produce information needed to meet overall 2014 CTSW Study objectives.

2.2 Modal Shift Analysis Linkages

The most direct linkage between the desk scan and the project plan for the modal shift analysis was the identification of required outputs from the modal shift analysis. These outputs included not only aggregate changes in mode choice, but also changes in the distribution of truck traffic by operating weight, vehicle configuration, and highway functional class. These latter outputs are required to estimate impacts of truck size and weight scenarios on infrastructure, safety, compliance, traffic operations, energy consumption and environmental emissions.

The primary focus of the desk scan was to identify past studies that had developed outputs corresponding to the outputs required for the 2014 CTSW Study. The scope of the desk scan was broadened, however, to include studies that focused primarily on the issue of modal choice, but that might be able to be extended to produce the full range of outputs required for the current study.

The modal shift desk scan identified several different approaches that have been used in past studies to estimate impacts of potential truck size and weight policy changes on modal shifts. Those methods were generally categorized as disaggregate approaches, aggregate econometric approaches, and expert opinion. Disaggregate approaches use characteristics of actual or representative shipments as the basis for estimating modal shifts. They are data intensive, especially if actual data are used, and require analytical tools that capture the major transportation and logistics costs that shippers/carriers consider when making mode choice decisions. Most of the disaggregate studies identified in the desk scan used the Intermodal Transportation Inventory Cost (ITIC) model. This model is described in detail in the Revised Desk Scan. Others used different formulations of economic order quantity logistics cost models that consider the same types of transportation and non-transportation logistics costs as are included in ITIC to analyze mode choice decisions. The disaggregate approaches were found to be particularly robust for the type of analysis required for the CTSW Study since they analyzed mode choice decisions on a shipment by shipment basis, thereby allowing detailed assessments of the impacts of network restrictions, commodity attributes, and vehicle attributes on the choice of mode, vehicle configuration, vehicle operating weights, and VMT by highway functional class. Econometric approaches generally are based on estimates of the cross-elasticities of demand for one mode as a function of changes in prices for another mode. For instance if the price of truck transportation falls as a result of truck size and weight policy changes, the demand for rail transportation would be expected to fall based on the cross-elasticity of demand with respect to truck prices. Econometric approaches generally are applicable only to choices between truck and other modes, and generally have not been used to estimate shifts in traffic between different truck configurations. Several freight demand modeling studies have examined choices between type of carrier (truckload, less-than-truckload, parcel delivery) based on characteristics of individual shipments, but like other econometric studies, these freight demand study approaches could not produce the detailed outputs that must be considered in the CTSW Study. The third major approach to estimating modal shifts is reliance on opinions of transportation experts who are familiar with freight transportation markets in the area being studied. Expert opinion has most often been used in State studies where there was insufficient budget to apply disaggregate approaches.

Disaggregate approaches that explicitly consider total transportation and non-transportation logistics costs associated with the use of different modes and different vehicle configurations thus were judged to be superior to other mode choice modeling approaches for purposes of the 2014 CTSW Study. In reviewing the disaggregate approaches that had been used in previous studies, the one most frequently used was the ITIC Model. That model had been used in the USDOT Comprehensive Truck Size and Weight Study, 2000 (2000 CTSW Study), the Western Uniformity Scenario Analysis, and in an analysis of potential mode shifts along the I-81 corridor in Virginia. Using that model for the 2014 CTSW Study has several advantages. First, it facilitates a comparison of results of the 2014 CTSW Study with those other studies, especially the 2000 CTSW Study. Second, ITIC was developed by USDOT and has been used both by FHWA and FRA. This reduces any claims that the model is biased toward one mode or the other. Third, the ITIC model has undergone recent updates that reduced the need for extensive updating. Fourth, ITIC is publicly available, which was an important study criterion. No other publicly available models that had the capabilities of ITIC to meet study requirements were uncovered in the desk scan. If a superior analytical tool had been found, that certainly would have been considered for use in the 2014 CTSW Study

2.2.1 Commodity Flow Data

Another important linkage between the desk scan and the project plan was the data required to produce outputs required from the modal shift analysis. The desirability of using a disaggregate approach to modeling mode choice required that a disaggregate commodity flow database be identified.

As noted, ITIC is very data intensive and it was important to identify nationwide commodity flow databases that contained shipments by mode, by commodity, and by origin and destination. Several databases were identified including the Commodity Flow Survey; Transearch, a proprietary database maintained by IHS Global Insight; the Freight Analysis Framework (FAF) developed by the Federal Highway Administration (FHWA); and the Surface Transportation Board's (STB) Carload Waybill Sample. No other nationwide commodity flow databases that would meet study requirements were identified during the desk scan. Advantages and disadvantages of each database are discussed in detail in the desk scan report. Ultimately the FAF was selected as the database for truck movements because it is more complete than the Commodity Flow Survey which is a data source for the FAF and it is more accessible than the proprietary Transearch database.

An important consideration in selecting the FAF was whether the data could be disaggregated to a finer level of geography than the 123 zones into which origins and destinations are reported. With just 123 zones, many States are represented by just a single zone. This was insufficient geographic detail for purposes of network routing and analyzing the impacts of restricting access for triples to a limited network of highways. Oak Ridge National Laboratory disaggregated the FAF to produce county-to-county flows. FHWA does not disaggregate the FAF to this level of detail because the accuracy of individual flows is not as high as with the 123 zone-to-zone flows, and use of county-to-county flows by State and local planning agencies could produce unreliable results when used for infrastructure investment decisions. However for a national-level policy study, the lower accuracy of individual flows was more than offset by the ability to provide greater network resolution and to analyze how restricting network access might affect shifts to triples.

The FAF includes rail shipments, but data in the STB's Carload Waybill Sample are more detailed in terms of origin and destination, the type of equipment used, rates charged, and whether short-line railroads were involved in the rail moves. Because of this greater detail, the Waybill Sample was used as the database for rail moves. The Waybill Sample had also been used in the 2000 CTSW Study.

Another important set of data required for all impact assessments including modal shift was the base case distribution of traffic by vehicle class, operating weight, and highway functional class. These data served as control totals for estimating overall shifts in VMT by vehicle class, operating weight, and highway functional class which in turn are important in estimating safety, infrastructure, energy and environmental impacts of truck size and weight policy changes. All of these impacts are sensitive to changes in traffic by vehicle class, weight, and highway functional class. The development of the base case traffic estimates is summarized in the modal shift desk scan. This same type of VMT breakdown by vehicle class, weight group, and highway functional class was used in the 2000 CTSW Study, but for the 2014 CTSW Study the data were broken down into more vehicle classes and more weight groups to add precision to estimates of infrastructure impacts.

In addition to information on the distribution of total traffic by vehicle class, ITIC also required information on the body types used to haul various commodities since different body types have different operating costs, payloads, and other operating characteristics. The only nationwide source of information on characteristics of the vehicles used to haul various commodities is the Vehicle Inventory and Use Survey (VIUS) conducted by the Census Bureau. The last VIUS was conducted in 2002 and it was recognized that data might not precisely reflect operations in 2011, the base year for the 2014 CTSW Study. While information in the VIUS is dated, the importance of reflecting body type and other operational characteristics of vehicles used to haul various commodities was essential to the analysis and the 2002 VIUS data were used. Updating the VIUS data is a key research need.

In summary, the linkage between the desk scan and the project plan for the modal shift analysis was largely driven by the study requirements. Estimates of modal shifts were important in their own right, but were perhaps more important as the basis for estimating safety, infrastructure, energy, environmental and traffic operations impacts associated with truck size and weight policy changes. The importance of producing the best estimates possible of these various impacts dictated that analytical techniques and data that would provide detailed changes in VMT by vehicle class, operating weight, and highway functional class be used if available. The 2000 CTSW Study and the Western Uniformity Scenario Analysis both provided guidance on the analytical tools, data sources, and study approaches that could provide the best estimates of impacts of the truck size and weight policy options. If those analytical techniques and data sources were not available, the modal shift project plan would have been quite different and would not have been able to provide the detailed estimates of traffic shifts needed to estimate other impacts.

2.3 Energy and Environmental Analysis Linkages

As with the modal shift analysis, study requirements were important considerations in reviewing the literature on heavy truck fuel consumption and emissions and in formulating a plan to conduct the analysis. The modal shift analysis produced changes in VMT by vehicle class, operating weight, and highway functional class, and methods were required that could take all those factors into consideration when estimating impacts on fuel consumption and emissions.

The literature review indicated an evolution of approaches to estimating heavy truck fuel consumption and emissions. The evolution was driven in part by Federal regulations that set maximum emission levels and the need to develop methods to objectively measure emissions from different vehicles. Because regulations were aimed at truck tractors, these methods focused on truck tractors rather than the tractor-trailer combination as a whole. Increasingly the methods included tire rolling resistance and aerodynamic drag in addition to engine efficiency in estimating fuel consumption and emissions.

The Environmental Protection Agency, the Northeast States Center for a Clean Air Future (NESCCAF) and other environmental groups have been investigating a broad range of potential strategies to reduce greenhouse gas and other environmental emissions, including the use of trucks with higher gross vehicle weights that could move more freight with each trip. These studies required analysis not only of emissions associated with the truck tractor, but also consideration of the impact of different trailer lengths, numbers of trailers, and numbers of tires to understand emissions associated with the whole vehicle combination.

Other key developments found in the literature were improved vehicle simulation models that made it possible to extrapolate findings from one vehicle class to another and the development of drive cycles that represented the mix of driving conditions that vehicles would encounter in actual use. These capabilities suited requirements to estimate fuel consumption and emissions by different vehicle classes operating at different weights on different highway classes. The project plan for estimating fuel consumption and environmental emissions associated with the truck size and weight scenarios being analyzed in the 2014 CTSW Study was developed based on the capabilities of the analytical tools and data found in the desk scan.

The specific modeling tools chosen for the analysis were those used in the 2009 NESCCAF study of options for reducing CO_2 emissions associated with heavy trucks. Those same analytical tools also are being used by members of the Study team in an on-going project for the National Highway Traffic Safety Administration (NHTSA) and had been verified as part of that NHTSA project. Tire rolling resistance and vehicle aerodynamic drag coefficients for different vehicle classes were based on work for the NESCCAF study that had examined fuel consumption and emissions for heavy 6-axle tractor-semitrailers, 33-foot doubles, and triple trailer combinations among other vehicle classes. The NESCCAF study focused on long-distance trucking operations and the drive cycles used in that study were consistent with that focus. Drive cycles for the 2014 study were modified to be more representative of the full range of trucking operations.

Thus, as for the modal shift analysis, study requirements strongly influenced the preliminary project plan for energy and environmental emissions analysis and they also focused the desk scan on past studies that had conducted the same types of analyses as were required for the 2014 CTSW Study. Analytical techniques and data were discovered that met study requirements, and the final project plan was structured around the use of those techniques. Unlike the modal shift analysis, the methods and data were quite different from those used in the 2000 CTSW Study since the state-of-the-art in emissions modeling has advanced so much since the 2000 CTSW Study.

2.4 Traffic Operations Analysis Linkages

As noted in the traffic operations desk scan, traffic operations involves a number of specific elements including maintaining speed on grades; weaving, merging, and changing lanes; highway capacity and level of service; and maneuvering through signalized intersections. A common thread in all of these elements is the impact on vehicle delay and traffic congestion. Since delay and congestion costs are critical factors affecting all traffic, the focus of the traffic operations analysis was on estimating those two items, although past truck size and weight studies were scanned for analyses of all aspects of traffic operations.

As with modal shift and energy and environmental analysis, the starting point in developing the preliminary project plan for traffic operations was the study requirements. The product of the modal shift analysis was changes in VMT by vehicle class, operating weight and highway class. The objective of the traffic operations analysis was to translate those changes in VMT into changes in traffic operations.

The *Highway Capacity Manual* (HCM) is the recognized source of relationships between traffic volumes and highway level of service, delay, and congestion. Over the years relationships in the HCM have been updated and refined. The HCM was last updated in 2010; relationships in that edition of the HCM were the basis for estimating how changes in traffic resulting from truck size and weight scenarios would affect levels of delay and congestion costs.

An important step in estimating traffic delay is to translate truck volumes into passenger car equivalents (PCEs). PCE values are specified in the HCM to account for the effects of different volumes and characteristics of truck traffic. The value of PCEs depends on the operating speed and grade of the highway section, the vehicle's length, and its weight- to-horsepower ratio which measures how a vehicle can accelerate. PCE values in the HCM do not include the vehicle lengths, however. The desk scan identified several studies that had estimated the PCEs for different vehicle configurations not included in the HCM. PCE values estimated for the 2000 CTSW Study were selected for use in the 2014 CTSW Study.

The HCM is not a network or system analysis tool. Techniques are required to apply relationships in the HCM to system-wide highway conditions to estimate total delay and congestion costs. An analytical tool had been developed for the 2000 CTSW Study to estimate changes in system-wide delay. This tool was selected for use in the 2014 CTSW Study, but speed volume relationships had to be updated to reflect changes in the 2010 HCM.

The analytical tool requires data on highway characteristics on different highway functional classes. The critical highway characteristics are the percentage of different types of highways with different grades and the percentage of different types of highways that are congested with volume/service flow ratios greater than or equal to 0.8. The source for those characteristics was FHWA's *Highway Statistics* publication.

The only nationwide study that had attempted to estimate changes in highway delay and congestion costs associated with truck size and weight policy options was the 2000 CTSW Study and only two State studies were found that included estimates of impacts on delay and congestion costs. Analytical tools had been developed for the 2000 CTSW Study that met requirements of the current study, but relationships in those tools had to be updated to reflect changes in highway characteristics since the 2000 CTSW Study and changes in speed – flow relationships in the 2010 HCM.

CHAPTER 3 - COMPLIANCE COMPARATIVE ANALYSIS

3.1 Purpose

The purpose of this section is to document how the information and understanding gained through the Desk Scan informed the technical methodology undertaken in the Compliance Comparative Analysis. The technical methodology was initially provided in the Project Plan and subsequently revised throughout the course of the project as details about available data emerged and analytical approaches were refined. As such, the linkages in this report reference the Project Plan as manifested in the Compliance Comparative Analysis technical report. The original Project Plan has not been revised.

This report establishes linkages in two principal areas:

- *Linkages regarding the general technical approach*: The report establishes the linkage between literature findings on approaches to analyze enforcement costs and effectiveness with the development and application of the performance-based approach applied in the 2014 CTSW Study.

- *Linkages regarding available data/analysis methods*: Based on the assessment of research and data needs summarized in the revised Desk Scan, this report links literature findings with the use and integration of the data sources used in the 2014 CTSW Study. Details are also provided about linkages concerning the more detailed aspects of the technical approach (*e.g.*, the use of state-level and vehicle-specific comparisons).

3.2 Linkages Regarding the General Technical Approach

This section describes the linkage between the general technical approach applied in the Compliance Comparative Analysis and the approaches used and/or recommended in the literature. Portions of the text are excerpted directly from the Compliance Comparative Analysis technical report and the revised Desk Scan.

3.2.1 Summary Description of the 2014 CTSW Study's Technical Approach

The analysis of the costs and effectiveness truck size and weight (TSW) enforcement programs undertaken in the Compliance Comparative Analysis applies a performance-based approach. This approach considers enforcement program performance (or effectiveness) in terms of inputs, outputs, outcomes, and pertinent relationships between these measures. Effective enforcement of TSW limits is critical to the realization of regulatory compliance (*i.e.*, the primary performance outcome of an enforcement program) and its impacts on safety, infrastructure, and industry competitiveness (Organisation for Economic Co-operation and Development (OECD) 2011; U.S. Department of Transportation 2000 (USDOT); Transportation Research Board (TRB) 1990).

Enforcement program inputs reflect the resources available to carry out the TSW enforcement task. As shown in **Table 3-1**, the measures of input included in the Compliance Comparative Analysis are program cost (disaggregated into costs for personnel and facilities) and the number and type of weigh scales used to enforce truck weights, including weigh-in-motion (WIM) sites used for screening truck weights.

Outputs reflect the way enforcement resources are used, the scale or scope of activities performed, and the efficiency of converting allocated resources into a product. Outputs help answer the question: what will/did we do with the resources given to us? As shown in **Table 3-1,** the measures of output used in the Compliance Comparative Analysis are the number of weighings, number of citations, number of vehicles required to shift loads or offload cargo to achieve compliance, and the number of permits issued for oversize/overweight (OS/OW) loads. While these outputs on their own provide some indication of program effectiveness, effectiveness can be further understood by relating certain program outputs and inputs. Three pertinent relationships are established, namely: the weighing cost-efficiency (weighings per personnel cost), the citation rate (citations per weighing), and the relationship between citation rate and enforcement intensity (measured as the number of weighings per truck vehicle-miles of travel).

Outcomes reflect the degree of success of the TSW enforcement program in achieving its goals and objectives. Outcomes help answer the question: what will/did we achieve in relation to our purpose? From an operational and programmatic perspective, the goal of enforcement is to achieve compliance with TSW regulations. Success in achieving compliance ultimately improves safety, mitigates infrastructure deterioration, and promotes fairness and competitiveness within the trucking industry. As shown in **Table 3-1**, the outcome measures used in the Compliance Comparative Analysis are the proportion of underweight axle or truck observations and the severity of overweight observations.

Table 3-1: Performance Measures Used in the Compliance Comparative Analysis

Type of Measure	Performance Measures
Input	• Enforcement program cost • Number of weigh scales by type • Number of WIM sites used for screening truck weights
Output	• Number of weighings • Citations • Number load shifting or offloading vehicles • Number of oversize/overweight permits issued • Weighing cost-efficiency • Citation rate • Citation rate as a function of enforcement intensity
Outcome	• Proportion of underweight observations • Severity of overweight observations

The distinction between outputs and outcomes, while subtle, is important because measuring outputs may encourage efforts to increase certain output measures (*e.g.,* the number of citations observed or reported), which should in fact decrease if enforcement achieves its overall goal of better compliance. In contrast, outcome-oriented measures may describe the proportion of compliant events (which may suggest successful enforcement) or the severity of overweight observations (which may suggest a lack of enforcement success). Conventional evaluations of enforcement programs have relied on outputs more than outcomes, presumably because outputs are easier to measure and monitor over time.

3.2.2 Justification for the 2014 CTSW Study's Technical Approach

The performance-based approach has been widely recommended by recent research and development concerning TSW enforcement programs at the state and national levels. This approach enabled a systematic analysis of the performance—in terms of cost and effectiveness—of TSW enforcement from a programmatic perspective. Principal examples of relevant literature on this topic are summarized briefly below (the revised Desk Scan contains additional details about each of these documents):

- Hanscom (1998) recognizes the need to develop performance measures to support better analysis and understanding of the costs and effectiveness of enforcement programs. The research develops performance measures for truck weight enforcement activities. The focus of the research is to identify quantifiable measures that reflect the goals of an enforcement program rather than using traditional indicators such as the number of trucks weighed, the number of violators detected, or the amount of fines collected. The measures proposed in this report provided the basis for the selection of the performance measures used in the 2014 CTSW Study (see **Table 3-1**).

- URS (2005) describes what a performance-based approach to enforcement would involve and makes the distinction between inputs, outputs, and outcomes (*i.e.*, performance). These distinctions are generally consistent with those discussed above for the 2014 CTSW Study. Many of the performance measures proposed by URS are similar to those identified by Hanscom (1998). A more recent report by URS (2013), also recommends the development of an outcome-driven truck weight compliance program.

- Fekpe *et al.* (2006) encourage the use of a performance-based compliance program and describe how this type of program may be designed and applied, particularly in the context of OS/OW permitting. The authors indicate that a performance-based program should be robust and simple to administer, implement, and monitor, and should use performance measures (or surrogate measures) that are easy to obtain using simple and quick roadside tests. They acknowledge that this may require an approach that differentiates trucks by configuration, commodity, and highway type in terms of enforcement and data collection. The 2014 CTSW Study particularly requires differentiation of performance measures by truck configuration.

- DalPonte *et al.* (2015) evaluate the performance measures used in Oregon's truck weight enforcement program and suggest how Oregon's approach may improve federal oversight of states' enforcement programs. Some of the measures and relationships among the measures are consistent with those used in the 2014 CTSW Study.

The performance-based approach applied in the Compliance Comparative Analysis extends the scope of analysis undertaken at the federal level concerning TSW enforcement programs beyond what was considered in the previous USDOT 2000 CTSW Study, but also maintains a general consistency in the type of analysis performed (see USDOT 2000). As in the 2014 CTSW Study, the 2000 CTSW Study provided national-level statistics concerning enforcement program costs (for one year) and a number of enforcement program outputs (*e.g.*, weighings, citations, and citation rate). To support the objectives of the 2014 CTSW Study, these measures are also examined at a state-specific level and new measures are introduced (*e.g.*, weighing cost-efficiency, citation rate as a function of enforcement intensity). Moreover, the costs and effectiveness of enforcing truck weights for specific vehicle configurations are investigated through a scenario analysis.

3.3 Linkages Regarding Available Data/Analysis Methods

This section describes linkages between the data/analysis methods used in the Compliance Comparative Analysis and the data/analysis methods discussed in the literature. Portions of the text are excerpted directly from the Compliance Comparative Analysis technical report and the revised Desk Scan.

3.3.1 Summary Description of the Data/Analysis Methods Used in the CTSW Study

Application of the performance-based approach provides the supporting framework for a comparative analysis designed to reveal insights about the costs and effectiveness of TSW enforcement programs. Data limitations, consistency, and availability constrain a comprehensive, representative understanding of enforcement costs and effectiveness (Transportation Research Board 2002; Carson 2011), particularly for specific vehicle configurations. Therefore, the Compliance Comparative Analysis integrates three primary data sources to support a multi-faceted analysis of truck weight enforcement costs and effectiveness at the national-level, using state-level comparisons, and through vehicle-specific comparisons within the scenario analysis. These three data sources are: (1) federal data on enforcement costs and activities; (2) WIM data; and (3) experiential data.

3.3.1.1 Federal Data on Enforcement Costs and Activities

State Enforcement Plans (SEPs) submitted annually by states to the FHWA provide the primary source data for the analysis of enforcement costs and resources (*i.e.*, program inputs). Tabulated summaries for key input measures from 2008 to 2012 are analyzed (*i.e.*, total costs, facilities costs, personnel costs, quantity of weigh scale equipment). The data enable state-level comparisons of enforcement program costs; however, the SEPs do not contain any systematically reported information about TSW enforcement costs for specific vehicle configurations, routes, networks, industries, commodities, or permitted versus non-permitted trucks.

The Annual Certifications of Truck Size and Weight Enforcement database provides the primary source data for the analysis of key enforcement program output measures (*i.e.*, weighings, citations, load shifting and off-loading requirements, permit issuance activities, and output-based relationships). Data from 2008 to 2012 are included in the analysis. As with the SEP data, this database enables state-level comparisons but precludes any disaggregation of enforcement activity for specific vehicle configurations. Moreover, citation data cannot be linked to the enforcement method (*e.g.*, fixed weighing, portable weighing, semi-portable weighing) used to obtain the citation.

3.3.1.2 WIM Data

WIM data from selected locations are used to assess truck weight compliance outcomes (in terms of the proportion of underweight observations and the severity of overweight observations) at a vehicle-specific level. Comparing the distributions of axle and gross vehicle loads with static weight limits enables the assessment of truck weight compliance for certain control and alternative truck configurations. WIM devices measure the axle weights (and by summing these, the gross vehicle weight), the spacing of these axles, and speed of a passing vehicle without requiring the vehicle to stop.

While WIM data enable a vehicle-specific analysis of weight compliance, they are subject two limitations (among others). First, properly installed and calibrated WIM devices are subject to measurement errors, which vary in magnitude depending on the type of equipment used. Second, many factors influence the axle weights recorded by a WIM device. For example, the intensity of enforcement present, the weight limits on proximal highway networks, the industries operating in the region, and the proportion of permitted trucks in the traffic stream all influence weight measurements. The effects of these factors are generally unquantifiable.

3.3.1.3 Experiential Data

Experiential data, gained from the insights of commercial motor vehicle state enforcement officials, are integrated into the Compliance Comparative Analysis. These insights pertain mainly to: (1) the designation of “federal” and “non-federal” states; and (2) weighing times for various truck configurations using common types of weigh scales. The integration of these insights helps fill data gaps in the analysis and ensure that the analysis findings are grounded in the practical realities of on-road truck weight enforcement.

3.3.2 Justification for the Data/Analysis Methods Used in the 2014 CTSW Study

The application of each of the three foregoing data/analysis methods within the context of TSW enforcement programs has been addressed in the literature, as summarized below.

3.3.2.1 Federal Data on Enforcement Costs and Activities

Literature published in the early-1990s recommends continued development of a national-level data program to support evaluations of states’ TSW enforcement programs (TRB 1990; Office of Inspector General 1991). By 2000, the USDOT notes a general improvement in the level of enforcement activity resulting from requirements for states to develop and certify state enforcement plans (SEPs) and the adoption of technologies such as WIMs for pre-screening. This state-submitted data has been used to track enforcement costs and effectiveness, principally in terms of the number of trucks weighed, the number of citations issued, violation rates, and requirements for vehicle offloading and load shifting (USDOT 2000).

The 2014 CTSW Study provides a national-level analysis of TSW enforcement program costs and effectiveness, similar to the analysis conducted as part of the 2000 CTSW Study. However, the current 2014 CTSW Study also disaggregates the data to support state-level comparisons.

3.3.2.2 WIM Data

The use of WIM data to assess truck weight compliance has been evident in the literature for several decades, albeit with some notable limitations. Principal references on this topic follow (the revised Desk Scan contains additional details about each of these documents):

- TRB (2002) cites recommendations made in the 1991 Office of Inspector General report which identifies the need to develop standards and technological improvements for WIM systems.
- URS (2005) identifies WIM devices as a data source for the calculation of TSW enforcement program performance measures.
- Regehr *et al*. (2010) use WIM data to assess truck weight regulatory compliance for three long truck configurations (Rocky Mountain doubles, Turnpike doubles, and triple trailer combinations) operating under special permit in the Canadian Prairie Region. The authors do not attempt to link their results to on-road enforcement methods.
- The OECD (2011) recognizes the value of applying WIM to support truck weight enforcement programs. This report states that WIM technologies have the potential to deliver more detailed, continuous data about weight compliance, specifically by utilizing axle spacing measurements to isolate the compliance record of higher capacity configurations.

The 2014 CTSW Study utilizes available WIM data to assess truck weight compliance for the control vehicles and alternative configurations specified for the scenario analyses. The limitations and assumptions of applying WIM data for this purpose are noted.

3.3.2.3 Experiential Data

The integration of experiential data into the more empirical analyses conducted in the 2014 CTSW Study is an approach supported by the literature, particularly where known data gaps exist. The revised Desk Scan references several reports that utilize industry surveys to develop an understanding of the performance of TSW enforcement programs. Four recent reports are particularly noteworthy (the revised Desk Scan contains additional details about each of these documents):

- Straus and Semmens (2006) estimate the cost of overweight vehicle travel on Arizona highways. To support this work, the authors provide results from a survey of 25 states concerning their experiences with truck weight enforcement and overweight trucking.
- Honefanger *et al.* (2007) summarize and evaluate procedures and technologies for enforcing TSW laws in Europe (Belgium, France, Germany, the Netherlands, Slovenia, and Switzerland), based on an international scanning tour which involved interviews with TSW enforcement officials from each of these countries.

- Ramseyer *et al.* (2008) report findings from a state-based survey of TSW enforcement officials which provides useful information about truck weights and overloading.
- Cambridge Systematics (2009) interviews nine states to determine best practices in the deployment of roadside enforcement technologies.

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CHAPTER 4 - SAFETY COMPARATIVE ANALYSIS

4.1 Purpose

The purpose of this section is to document how the information and understanding gained through the Desk Scan informed the technical methodology undertaken in the Safety Comparative Analysis. The technical methodology was initially provided in the Project Plan and subsequently revised throughout the course of the project as details about available data emerged and analytical approaches were refined. As such, the linkages in this report reference the Project Plan as presented in the Highway Safety and Truck Crash Comparative Analysis technical report (USDOT, 2014).

This report establishes linkages in two principal areas:

- *Linkages regarding the general technical approach*: The report establishes the linkage between literature findings on approaches to assess the safety implications of control and alternative vehicle configurations, and

- *Linkages regarding available data/analysis methods*: Based on the assessment of research and data needs summarized in the revised Desk Scan, this report links literature findings with the use and integration of the data sources used in the 2014 CTSW Study.

4.2 Linkages Regarding General Technical Approach

4.2.1 Background

The general technical approach to the safety analysis is based on the USDOT 2000 CTSW Study (USDOT, 2000). In that study, separate analyses were attempted for crash analysis and vehicle stability and control. The 2000 study crash analysis was largely unsuccessful, owing to data problems in identifying crashes and matching exposure for the control and alternative truck configurations. A similar problem occurred during the 2004 Western Governor's Association Study (USDOT (2004). In 2014, the safety team attempted 3 different crash analyses, described in the following paragraph, in an effort to obtain more meaningful and useful crash analysis results. The team retained and enhanced the use of vehicle stability and control simulations to obtain insights on configuration performance that could not be obtained from the crash-based studies. Finally, inspection and violation data are compared to better understand the violations associated with the control and alternative configurations.

In considering these challenges, the safety team structured the analysis, where possible, to respond to the original Congressional request for the study which sought to explore differences in safety risk and truck crash frequency between truck configurations currently operating on the nation's roadways at and below current federal limits compared to those operating above such limits. This wording led to a focus on existing operations where truck configurations of interest were allowed to operate through the complex series of state exemptions and other special provisions. The safety team worked with others within the Study team to identify states where control and alternative configurations were in current operation. Identifying these states help direct the data collection and modeling efforts described in further detail in section 4.3.

4.2.2 Crash Analysis

The crash analysis portion of the safety plan sought to overcome the problems in the 2000 CTSW Study by pursuing 3 crash analysis approaches (see summary in Table 4.1):

1. Segment-level crash comparisons using crash and exposure data from states allowing travel of control and alternative vehicles. This approach initially required that control and alternative configurations be identified in crash data (including the weight of involved configurations). This is similar to the approach unsuccessfully taken in the 2000 CTSW Study; it was also unsuccessful in the 2014 effort, again due to lack of configuration data in weight records. In response to this challenge, the team developed an approach in which states were identified that allowed both control and comparison configurations that could be identified in crash records by their axle counts and/or number of trailers. While this approach did not allow the identification of weight-specific individual crash records, it identified groups of configurations that *were allowed to be* operating above federal limits. This was interpreted as consistent with the intent of the federal legislation. It resulted in the comparison of control vehicles operating at a range of weights with alternative vehicles also operating at a range of weights. The team believes this type of comparison reflects how groups of vehicles may respond to changes in size and weight regulation: all trucks do not operate at the maximum allowable weight at all times; so a more realistic comparison may be one that includes a range of crashes (of unknown weight) involving vehicle that are allowed to carry maximum loads in excess of current federal limits.
2. Route-level crash comparisons using WIM data and exposure data from states to identify routes in which only control vehicles operated and could be compared to routes in which primarily alternative configurations operated. This is another method that does not require crash-level configuration weight data, but is built on the assumption that alternative configurations are limited in the routes of their operations. Information received from candidate states for this method, however, revealed that travel by alternative configurations of interest are ubiquitous in most states, so the underlying assumption of this method was incorrect. As a result, the method was not used.
3. Fleet-based analyses were attempted to obtain crash details from the carriers involved. Investigations led to an understanding that only few carriers used tractor triple-trailer in their regular operations. It was felt that this knowledge could be used to increase the sample size of triples crashes in a way that would facilitate the comparison with tractor double-trailers. This was a new approach not previously attempted in the 2000 CTSW Study. Jovanis had used a similar approach in a study from the 1980s (Jovanis et al., 1989). Crash data were successfully assembled from carriers, but consistent data on exposure could not be obtained; crash rates could thus not be computed and compared. The crash data were useful in a set of severity analyses, however.

4.2.3 Analysis of Vehicle Stability and Control

An alternative to relying on crash data analysis is to conduct detailed simulations of vehicle performance using available computationally intensive computer software. Both the 2000 CTSW Study and 2004 Western Uniformity Analysis used this method to gain insight into the potential safety performance of a range of vehicle configurations. The advantage of the simulation of vehicle stability and control simulations is that one has experimental control over the vehicle configuration and the test protocols used to assess vehicle configuration performance.

Table 4.1 Summary of Crash Analysis Methods Used in 2014 CTSW Study

Method	Critical Assumptions	Comments
State-based	WIM data allows classification of travel exposure at segment level for all roadway functional classes. Identify control and alternative vehicle configurations using axle count and number of trailers in crash data.	Similar to 2000 CTSW approach and study by Abdel-Rahim, but chose states to compare groups of control and alternative vehicles in crash reports. Results still affected by small crash sample size for some configurations. Only able to compute rates for interstates due to WIM limitations
Route-based	Alternative configurations operate on subset of all routes that can be identified by WIM and/or state data. Safety estimated by comparing these routes, without knowing configuration weight from individual crashes	Control and alternative vehicles operate ubiquitously in states; unable to compare routes as planned
Fleet-based	Collecting data from fleets would result in an increased number of alternative configuration crashes for analysis	Obtained crash data but unable to obtain reliable fleet-based exposure data. Crash data used for severity analysis but not crash rate comparisons.

Many details of the vehicle configurations are specified in standard test protocols (*e.g.*, vehicle speed, weight and distribution of weights within trailer units, brake condition). So all vehicle configurations can be compared under controlled, nearly identical, conditions. The weakness is that the simulations are unable to replicate the range of real-world conditions experienced in the field, including variation in traffic, weather, roadway and driver attributes. What is gained in experimental control is lost in the ability to encapsulate real-world operating conditions.

4.2.4 Analysis of Inspections and Violations

The third component of the safety analysis was a study of inspections and violations of control and alternative configurations. This component of the safety study explored potential connections between truck configuration (*e.g.*, tractors pulling two trailers and tractors pulling three trailers) and their record of operating violations (other than over-weight). This approach compared the violation record of control vehicle configurations from a set of states identified as allowing legal operations of alternative configurations in excess of current federal limits for weight and configuration. There was no study identified in the literature that is comparable to the one completed concerning inspections and violations in the 2014 CTSW Study.

4.3 Linkages Concerning Available Data and Methods

4.3.1 Crash Analysis

The state-level data analysis was similar to the study conducted by Abdel-Rahim (Abdel-Rahim, 2006) and discussed within the desk scan with one important difference: the 2014 CTSW Study team specifically chose states for inclusion that allowed a comparison of groups of control and alternative vehicle configurations. Abdel-Rahim used a roughly similar approach in choosing states that operated LCV's and using WIM data to estimate configuration exposure. The 2014 CTSW Study team sought a more precise comparison of crash rates by selecting states that allowed legal operations of truck configurations exceeding federal limits for configuration and weight (as described in the 2014 CTSW Study safety report, USDOT, 2014). The team selected states where, for example, tractor semi-trailers with 6 axles were allowed at weights beyond 80,000 lb. *and* identified as six-axle trailers in crash reports. This allowed the team to assemble crash records for both the control and alternative vehicles and conduct a comparison of rates using number of trailers and axles alone; without vehicle weight. The state-level analysis is thus associated with the methods of Abdel-Rahim, but sought a more precise crash rate comparison. Exposure data and crash data were assembled on a segment-by-segment basis; rates computed and compared.

The route-based method was conceived from the same foundation as the state-level analysis but was used to provide a contingency in the event that no useful vehicle configuration information could be obtained from the state crash records. In this event, the team proposed to compute truck crash rates for road segments with different levels of configuration flows (as measured by WIM stations). This approach has its foundation in the state-level analyses described above, but was novel in its use of WIM data. The assumption underlying the approach was that there were specific route that could be identified that had only control vehicle exposure and little or no alternative vehicle exposure. A comparison of crash rates could, hypothetically, provide some information about the crash risk of alternative configurations. Unfortunately, discussions with state DOT personnel in the selected states revealed that alternative configuration travel was widespread across all route and road segments with virtually no sites with zero exposure of either controls or alternative configurations. As a result, the method was infeasible in all selected states.

The fleet analysis was based on a study publish by TRB in the 1980s (Jovanis, *et al.*, 1989). The study method was a matched pair approach where crash rates for tractors with two semi-trailers were compared to crash rates for single combination tractor semi-trailers on identical routes for the same firm. This matched pair design controlled for route geometric characteristics, type of operation, driver management, safety culture and other factors except for driver age and experience. The matched-pair design was unfortunately not feasible for the study of tractors pulling 3 semi-trailers because companies that operated these vehicles in western states operated virtually no doubles on the same routes because triples were more economical. When the matched – pair approach became infeasible, the team sought to compare crash rates for doubles and triples throughout the fleet's national network. This proved difficult because exposure data were more difficult to obtain than expected. As a result, the primary value of the fleet-based analysis was to compare severity of crash outcome, given a crash, for double and triple combination vehicles with each fleet. These results were reported in the safety technical report (USDOT, 2014).

4.3.2 Analysis of Vehicle Stability and Control

Table 4.2 summarizes the analysis of vehicle stability and control for the 2000 CTSW Study (USDOT 2000a, b) and the 2014 CTSW Study. The simulations in 2014 were defined in conjunction with USDOT subject matter experts. In vehicle stability and control simulations, researchers define input data based on the vehicle configurations and performance characteristics of interest. The 2000 CTSW Study was concerned with rollover events and off-tracking; the simulations reflected these concerns. Performance during both high-speed and low-speed turns was simulated, along with an evasive maneuver. Metrics derived from the simulations are listed in the last column. The 2014 CTSW Study included similar off-tracking simulations (*e.g.,* high and low speed turns and an evasive maneuver), updated reflecting more contemporary models. In addition, much more attention was paid to braking comparisons and performance during straight-line and curve traversals, including simulations with brake failures on some axles. These more extensive tests better illustrated the effects of brake failures on both control and alternative vehicle configurations. There is a clear connection between the data and models used in the 2014 CTSW Study and its predecessor study in 2000.

Table 4.2 Summary of Vehicle Stability and Control Test for 2000 CTSW and 2014 CTSW

2000 CTSW Study		
Maneuver	**Comment**	**Metric**
Steady-state turn-induced rollover	Represents roll propensity during turn	Minimum lateral acceleration to result in wheel lift off ground (static roll stability)
Evasive maneuver induced rollover (SAE J 2179)	Represents roll propensity during high speed evasive maneuver	Rear trailer lateral motion relative to tractor (rearward amplification)
	Shift in load during maneuver	Lateral Load Transfer Ratio – proportion of total axle load carried on one wheel compared to the other
Low-speed off-tracking	Represents difference in tracking of wheels of steering axle and rear axle of last trailer during low speed turn	Offtracking Swept Path Encroachment to inside of track
2014 CTSW Study		
Maneuver	**Comment**	**Metric**
Low-speed off-tracking	Represents an intersection turn	Off-tracking (intersections)
High-speed off-tracking	Represents a curve on a highway	Off-tracking (highway curves)
Straight-line braking (S5.3.1.1 of FMVSS 121, 60mph)	Conducted with fully functioning brakes and with two brake malfunctions	Stopping Distance Maximum Path Deviation
Brake in a curve (S5.3.6.1 of FMVSS No. 121. 30 mph)	Conducted with fully functioning brakes and with two brake malfunctions	Stopping Distance Maximum Path Deviation Lateral Load Transfer Ratio
Avoidance maneuver (similar to ISO 14791, lateral stability test methods. 50 mph)	Run under multiple conditions	Transient off-tracking Rearward amplification Lateral Load Transfer Ratio

4.3.3 Analysis of Inspections and Violations

The 2014 CTSW Study used data from the Motor Carrier Management Information System (MCMIS) for specific states to compare the pattern of inspections and violations for control and alternative configurations. The analysis was conducted to be as consistent as possible with the goal expressed in the enabling federal legislation which sought to explore differences in safety risk and truck crash frequency between truck configurations currently operating on the nation's roadways at and below current federal limits compared to those operating above such limits. As a result MCMIS data were obtained from states allowing legal operation of larger and heavier truck configurations due to state exemptions and special provisions. Mean violation and citation rates were compared for different configurations using a range of statistical approaches. No comparable analysis was identified in the desk scan.

4.4 Summary

Two comparisons have been conducted of the safety analyses undertaken for the 2014 CTSW Study. Concerning general technical approaches, the 2014 CTSW Study borrowed heavily from both the 2000 CTSW Study and the 2004 Western Uniformity Scenario Study. The crash analyses developed with a clear understanding of the difficulties encountered in both these studies. The 2014 CTSW Study team developed 3 alternative crash analysis approaches in the hope that they would yield differing perspectives on safety associated with truck size and weight. In each of the three crash-based approaches the desk scan led the team to expect challenges; and the team experienced them. A more vexing circumstance continued to be the lack of configuration weight data in crash reports, even for the carrier-supplied crash data. While the three crash-based approaches were distinct and used crash data in different ways, they all suffered from the general poor availability of information about truck weight and configuration within crash data.

Vehicle stability and control simulations were, in many ways, much easier to conduct. Once the simulation parameters were defined in consultation with USDOT subject matter experts, the models could be exercised to produce outputs comparing the control and alternative vehicle configurations of interest. The limitation of this approach is, unfortunately, that it does not capture the details and variability of actual crash events as they occur in the field; only analysis of actual crash data can capture those nuances.

The analysis of inspection and violation data from MCMIS was developed within the safety team, again with discussions among the USDOT subject matter experts. While there was discussion of several data challenges, the analysis did not draw on any specific references from the safety desk scan.

4.5 References

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CHAPTER 5 - PAVEMENT COMPARATIVE ANALYSIS

5.1 Purpose

This section highlights linkages between the Desk Scan and the Project Plan developed for Pavement Comparative Analysis. The focus is on how the desk scan informed the general technical approach outlined in the project plans and the specific data and analytical techniques available to produce information needed to meet overall 2014 CTSW Study objectives.

5.2 Pavement Analysis Linkages

The 2014 CTSW Study pavement team's review of previous studies and techniques for analyzing pavement costs associated with changes in traffic loads reveals approaches that fit into three broad categories: (1) using traditional "equivalent single axle loads" (ESALs) derived from the half-century-old AASHO Road Test as a measure of pavement damage, and therefore pavement damage costs, (2) applying pavement deterioration models to a representative group of pavement sections with a large number of traffic loading conditions to derive a new set of load equivalence factors (LEFs) and deterioration curves that vary by distress type, or (3) directly applying current pavement design models to a small number of sample pavement sections under scenario traffic loadings to derive estimates of changes in pavement life and therefore pavement cost changes. Each of these three alternative approaches has been applied to varying degrees to previous studies identified and discussed in the pavement desk scan report.

The first approach, using ESALs as a measure of pavement damage, is ruled out because it relies on ESALs-- widely discredited because (a) calculating ESALs for tridems has no empirical or theoretical validity since it requires extrapolating a dummy variable, and (b) ESALs apply primarily to pavement smoothness which has many components that vary in their sensitivity to magnitude of axle load.

The second approach, deriving and applying pavement damage relationships from pavement performance models, is ruled out because it (a) relies upon LEFs derived from an earlier version of *AASHTOWare Pavement ME Design*® that need to be verified using the latest version, and (b) requires an inventory of distress observations that is currently incomplete.

The third approach, directly applying current pavement design models to a small number of pavement sections, was selected to be the best option based on the information gathered during the desk scan.

The *AASHTOWare Pavement ME Design*® model was used in this analysis and run for each of these sections to determine a base case of the expected pavement performance under traffic conditions appropriate for each thickness (mix of vehicle types and operating weights as well as truck traffic levels). Locations were selected that avoid climate extremes and thus represent typical weather effects for several groups of states. To the extent possible, Long Term Pavement Performance Program (LTPP) sections was used as a basis for each sample section and will adjust base case parameters as required to make sure that each sample section represents the pavement performance history that would typically be expected.

For each sample section, the first step will be to perform a base traffic performance analysis. Next, traffic inputs will be varied in ways that represent traffic shifts that occur as a result of the various truck scenarios. This will require a series of runs of *AASHTOWare Pavement ME Design*® during which all factors except traffic are held constant.

The multiple runs for each sample section enabled an evaluation of changes in pavement service life as a result of changes in truck travel associated with each modal shift scenario. These changes in pavement service life were translated into pavement cost changes associated with size and weight scenarios using rudimentary life cycle cost analysis.

CHAPTER 6 - BRIDGE COMPARATIVE ANALYSIS

6.1 Purpose

The purpose of this section is to document how the information and understanding gained through the Desk Scan informed and affected the approach and methodology undertaken in the Bridge Comparative Analysis. The technical methodology was initially provided in the Project Plan and subsequently revised throughout the course of the project as details about available data emerged, as analytical approaches were refined, This involves both those documents summarized in the revised desk scan that inform with respect to accepted technical approaches and those documents that contain quantitative results pertaining directly to bridge analysis relative to the effects of similar truck configurations and loadings. The bridge task has devolved into four study areas: the first three reflecting the three AASHTO limit states for: Strength, Fatigue and Serviceability; and a fourth sub-study area of the potential effects of the six 'scenario' trucks being studied on bridges. Accordingly, the linkages between the desk scan and the methodology undertaken in the 2014 CTSW Study are considered in that order herein.

6.2 Bridge Analysis Linkages

6.2.1 Structural Impacts Due to Overweight Trucks

6.2.1.1 Strength Limit State

The objective of the Strength Limit Study (Structural Load Rating) is the determination and assessment of the implications of the structural demands on US bridges due to the introduction of the proposed alternative truck configurations with Gross Vehicle Weight (GVW) > 80,000 lb. vs. those due to the control vehicles for the current truck fleet (GVW = 80,000 lb.). This task includes an assessment of one-time bridge costs that may be incurred as a result of not meeting the strength limit state as indicated by the analysis.

In order to achieve the above objective, the first step was to investigate the strength limit state in the bridges of the subject highway networks.

Previous studies were based on the Standard AASHTO Specifications. Based on the result of the desk scan, it was concluded that AASHTO's Load Resistance Factor Rating (LRFR) method (AASHTO 2011, 2013) would be utilized in the 2014 CTSW Study to conform to the latest design/analysis methodology. This represents a significant improvement over past studies in that it provides for a reliability based comparison of the 'scenario' vehicles vs. the control vehicle as compared to a simple structural capacity analysis.

Previous studies employed WINBasic (2000 CTSW Study) to assess the impacts of large numbers of bridges grouped as simplified bridge models, or analyzed relatively small samples of bridges directly. For this study, it was determined to use the AASHTOWare Bridge Rating (ABrR, (VIRTIS)) analysis program because it handles most bridge types and allows for the analysis of a relatively large sample of real bridges within the constraints of time and budget associated with a study such as this. ABrR was determined to be a ready tool for the analysis of the load rating capacity of 500 representative bridges, selected to conform statistically to the proportion of bridges by bridge type on the NHS. The eleven most common bridge types were included, representing 96% of all bridges on the roadway networks used in developing the Study scenarios. As stated in the 2014 CTSW Study Bridge Project Plan, verified ABrR LRFR bridge models were used for the structural analysis. The majority of the verified bridge models were obtained directly from state DOTs. The remainder were obtained through the help of the Primary Investigator (PI), Mark Mylanarski of NCHRP Project 12-78 (NCHRP Report 700, A Comparison of AASHTO Bridge Load Rating Methods, 2011). Access to some 1500 verified ABrR models that were being used for that study were made available for possible inclusion in this study, with certain restrictions on the publishing of their state and route number. In all, bridge models from 11 states representing different regions in the continental US were included in the study. Bridge models from the following states were included in the study: Alabama, Illinois, Idaho, Louisiana, Michigan, Missouri, New Jersey, New Mexico, New York, Utah, Virginia and South Dakota.

The results of the analysis were recorded for maximum moment and shear and the Rating Factors (RF) for the alternative truck configurations were compared to (normalized relative to) the 80,000 lb. GVW control vehicles. The LFR method was used for girder-floorbeam systems and through trusses since the ABrR software did not currently support the LRFR methodology for these two bridge types.

One-time bridge replacement costs for all scenario vehicles were developed for both highway networks IS and other NHS), regardless of whether some vehicles (triple trailers for instance) may be excluded from certain routes for safety or other reasons. The cost estimates are based on total project costs and not just the direct construction costs. The methodology used is as follows:

1. Determine the distribution of span lengths in the sample database as percentages separately for IS bridges and other bridges on the NHS. Bridge lengths were taken as the upper limit in the interval (e.g., for 20-40 ft. spans, use 40 ft.). Deck width was taken as 64 ft. (four 12’ lanes and two 8’ shoulders) for IS bridges and as 48 ft. (three 12’ lanes and two 6’ shoulders) for other bridges on the NHS.
2. Calculate the cost of bridge replacement for each span length interval as:
   $$\text{Cost} = \text{Bridge Length x Deck Width x Unit Price for Replacement per ft}^2$$
   The Unit Price for replacement was obtained from using a national average that included incidental costs such as mobilization, work zone traffic control and construction inspection. What it did not include were the so called social costs such as construction traffic delays. There are no published average unit costs that can be applied with respect to those social costs.
3. Determine the percentage of bridges rated less than 1.0 in the structural analysis for each alternative truck configuration (scenario), for each span interval
4. Determine the actual total number of IS Bridges and Other NHS Bridges in the NBI inventory.
5. Estimate the number of actual number of bridges in each span interval, using the distributions observed for the sample database.
6. Determine the projected number of bridges with RF < 1.0 for each scenario, by multiplying the percentage of bridges rated less than 1.0, calculated in STEP 3, by the number of bridges in each span interval, calculated in STEP 5.
7. Determine the cost of bridge rehabilitations for each span interval for each truck type, separately for IS bridges and other bridges on the NHS, by multiplying the cost

calculated for a single bridge for that span interval by the projected number of bridges with RF < 1.0 for each truck scenario.
8. Add costs from each span interval to determine the total costs for each scenario.
9. Calculate Δcost for each scenario. Δcost is the difference in the cost of rehabilitations due to an alternative truck configuration and that from the related control vehicle.

6.2.1.2 Fatigue Limit State

Two primary areas of concern with respect to fatigue are: direct, load induced fatigue; and, distortion induced fatigue, often due to out of plane bending. Distortion induced fatigue requires a very rigorous analysis of each specific fatigue detail. During the 2014 CTSW Study scoping/project plan development phase, it was jointly determined with the FHWA that, given the nature of this study, distortion induced fatigue study would not be included.

Therefore, while distortion induced fatigue was included in the desk scan, only direct 'load induced fatigue' was undertaken:

AASHTO published the first fatigue design provisions in 1965. They were completely revised in the 1977 AASHTO Highway Bridge Design Standard Specification, 12th Edition, based on the research results of Dr. John Fisher of Lehigh University and his colleagues. Many specification changes associated with specific details were incorporated annually by AASHTO to improve design as well as fabrication and field performance. In 1994 the introduction of the AASHTO LRFD Bridge Design Specification incorporated a reliability-based approach with significant changes to the load models for fatigue design.

Load induced fatigue in steel bridges was extensively studied in throughout this period, as reflected in the desk scan. Bridge connection details are grouped into categories A to E' based on their level of fatigue strength/resistance. According to the results of the desk scan, it can be concluded that actual truck traffic closely correlates the effects of the fatigue design truck and that heavy traffic will not cause severe fatigue problems on steel girders with fatigue details of categories A, B or C. Therefore, analysis focused on the categories E and E' (E-prime) will be more meaningful.

Based on desk scan and the purpose of this study, a study methodology was established as follows:

First, four (4) typical existing steel bridges with fatigue categories E and E' (E-prime) were selected for comparative analysis. Two (2) of them are simply supported steel girder bridges and the other two (2) are continuous steel girder bridges. All of these four (4) chosen bridges have finite fatigue life cycles per the analysis.

Second, a baseline for comparison was established for the for the two 80,000 lb. Control Vehicle Truck based on the result of desk scan that fatigue life is inversely proportional to the cube of the effective stress range.

Third, results of the other alternatives can be compared with the baseline, as follows:

1. The desk scan confirmed that fatigue life is inversely proportional to the cube of the effective stress range. Depending on the CAFT limit of AASHTO fatigue prone details, differences in the axle weight and spacing of the vehicle classes and weight groups may

result in significantly different incremental fatigue damage to the bridge inventory. The bridge team was tasked to investigate the potential effects on the nation's bridges in the event of the introduction of each of the six proposed 'scenario vehicles'. Inherent in the assessment is the reality that the national adoption or acceptance of any of the proposed alternative truck configurations would likely only constitute a modest increase (relative to the sheer size of the present truck fleet and truck traffic stream) in total loading cycles for any given bridge. This does not negate the possibility of a significantly larger contribution of incremental fatigue damage that could be attributed to that alternative truck configuration for its loading cycles. It does however put the question in perspective. So, as a result of the desk scan it became clear that any significant difference in the fatigue affects attributable to a particular alternative truck configuration must be considered in light of the relative percent of loading cycles assumed to be attributable to that scenario. Accordingly, it was determined to conduct the fatigue assessment as a comparison of the incremental stress ranges resulting at a given fatigue detail location from a single pass of the 'scenario vehicles' vs. the equivalent results from the control vehicle.

2. To illustrate the fatigue damage potential of each of the proposed 'scenarios vehicles', four (4) typical existing steel bridges were selected for comparative analysis. Two (2) of them are simply supported steel girder bridges and the other two (2) are continuous steel girder bridges. Steel girders of these bridges are comprised of either rolled shape beams with partial length cover plates or plate girders with horizontal lateral bracings welded to the bottom flanges of the girders. The analysis was performed in accordance with the AASHTO Manual of Bridge Evaluation (2nd Edition) with 2014 interim revisions and the AASHTO LRFD Bridge Design Specifications (6th Edition). All of these four (4) chosen bridges have finite fatigue life cycles per the analysis.
3. Utilizing the concept that fatigue life is inversely proportional to the cube of the effective stress range and the assumption that the stress cycles for each truck configuration in the new fleet of trucks is constant, a baseline was established for the two 80,000 lb. Control Vehicle truck configurations and results of the other scenario vehicles were compared with the baseline.

<u>6.2.1.3 Serviceability Limit State</u>

In the 2014 CTSW Study Project Plan, the bridge team had proposed to develop a method to conduct a bridge damage cost responsibility allocation to: 1) assign bridge damage attributable to the Modal Shift Fleets resulting from the potential introduction of each of the Scenario Vehicles onto the national highway networks; and to 2) determine the percentage of vehicles in the existing fleet that are operating excess of the current 80,000 lb. limit. Based on the early desk scan and confirmed by further research and by the FHWA SMEs, it was agreed that there is no generally accepted methodology to accomplish this task. The difficulty is multiplied on a study of a national scale (U.S.).

The goal of the cost responsibility assignment process is to assign bridge cost by truck class, including those of the scenario vehicles. Lacking such a consensus, it was undertaken to develop an axle load based approach, reflecting the generally accepted power formula relationship between axle loads and the resulting bridge damage costs. In a number of states as well as in some other countries, axle load based allocations have been used for bridge costs. These agencies have used various and diverse allocators and exponents to develop expressions of incremental damage resulting from axle loads. As commonly reported in prior studies, 59% to 70% of all bridge capital costs are considered to be non-load induced, or in other words, attributable to environmental factors, aging, and light weight vehicle use. The 2000 FHWA funded “Guidelines for Conducting a State Highway [and bridge] Cost Allocation Study” included examples with as much as 79% assumed to be non-load induced. From the E.U. CATRIN 2008 Deliverable D1, page 30: “Weight dependent [load induced] costs make up between 33% and 46% of all costs.” This would equate to 54% to 67% non-load induced damage. Recognition of this factor is fundamental to determining the range of the bridge damage costs that can be expected to result from changes in the truck fleet.

The axle based method investigated was based on a method developed in the Washington D.C DDOT ‘District-wide Truck Safety Enforcement Plan’, 2010. That approach involves steps to the assignment of cost responsibility to specific truck configurations for the remaining ±41% of Bridge Costs (the load-induced damage costs). However, while the desk scan produced accounts of several state and foreign government agencies applying assumed exponents to allocate bridge damage related costs; the bridge task team did not find a version of the power formula relationship that had passed scientific and engineering scrutiny and was generally accepted and in use.

Given that this specific approach lacked a history of scientific review, was highly dependent on assumptions related to bridge costs, and did not meet the threshold standard of a generally accepted methodology; it was determined that it should not be included in the final report.

6.2.2 Bridge Deck Deterioration, Service Life Preventative Maintenance

The 2014 CTSW Study Bridge Project Plan proposed investigating bridge deck issues in two sub-study areas – Section 1.4.4 Bridge Deck Repair and Section 1.4.5 Replacement Costs and Bridge Deck Preservation and Maintenance Costs.

6.2.2.1 General Technical Approach

The Desk Scan provides a wide array of diverse literature for the Bridge Deck sub-task, however much of the unit cost data was scattered among various DOT web sites. Furthermore, the data format and access was not conducive for inclusion in the desk scan itself. Therefore, as the material was compiled, reviewed and re-worked, it was decided that the two sub-studies Bridge Deck Repairs and Bridge Deck Replacement Costs would be combined into the single undertaking.

The goal of the study was to cover the following topics:

1. Bridge deck behavior under axle loads and environmental stressors: The desk scan provided literature ranging from design guidelines (e.g., AASHTO manuals) to concrete deck research in the US and Japan.
2. Qualitative assessment of the effect or the control and scenario vehicle on bridge decks: The desk scan provided very little information about the specific effect of the control and scenario vehicles on bridge decks. However, research studies regarding generic axle loads on bridge decks were investigated and referenced in the study. In addition a few

agency officials provided some published data (Indiana DOT) and anecdotal information (NY Bridge Authority).

3. Preservation and preventative maintenance procedures and practices: The desk scan provided some literature from various DOT agencies on their specific preservation/maintenance policies and procedures. While the general principles were common, specific practices varied widely and were highly dependent on specific economic and environmental factors (truck traffic volume, type of cargo, weather, salt usage, etc.).

6.2.2.1 Available Data and Models

The study was also charged with finding and extracting unit cost data (to be used in the sub-task itself as well as supporting other Bridge sub tasks), financial and deterioration models.

1. Federal Financial Management Information System (FMIS): FMIS data was obtained from the FHWA for use with regard to bridge cost data. However, the data provided was not in sufficient detail to benefit this sub-task.
2. Unit Cost Data: There is a wide array of data formats (databases, published bids, and estimating unit costs) provided on the various DOT web sites. When, it was clear what elements were included in those costs, the data was extracted. In all, data from 22 states across the continental US was utilized (from various climatic zones).
3. It was difficult to find specific “data points” as to what state DOTs are doing to maintain and preserve their bridge decks and ultimately prolong their bridge service life. What the bridge team found was that state DOTs are more or less evolving their policies as technologies, tools and available information (data) is made available. As such, some agencies are moving to integrate their asset management practices and are using internet technologies to update their databases. As a result, much of the data was inaccessible to the general public and required identity authentication for access and retrieval. However, some state DOT agencies provide a portal with links to data warehouses. The process had to be modified to properly access these data warehouses to glean information. Some web sites provided manuals for their highway maintenance practices which also included bridge deck maintenance. For other agencies we found research papers on bridge decks that generally described how a state DOT approaches maintenance and what threshold they use to decide whether to replace a deck or rehabilitate it. Still further, the bridge team contacted existing client contacts (including from Indiana, New York, Tennessee and South Carolina) to understand their agency maintenance practices and policies, with regards to bridge decks.
4. Another issue that arose in finding usable data was that the reporting format, quality, and content varied widely. This was particularly apparent with respect to unit cost data, which in turn required some analysis and interpretation to allow for comparison of the data from state to state. A specific example of unit cost disparity: some sources just reported raw construction costs, while other sources’ reported costs were inclusive of all programmatic costs, i.e. would include mobilization, work zone traffic control, construction inspection, etc.

5. Deterioration Models:

a. Bridge Deck (Salt induced) Corrosion: The desk scan provided two specific studies that had developed predictive models with respect to salt induced corrosion (Virginia DOT and Michigan DOT). These studies provided a mechanism and timeline for deck deterioration in cold and wet climatic zones where salts are used as de-icing agents. It was desired to investigate the combined effects of truck axle loads in combination with de-icing salts over the service life of bridge decks. However, very little was found in regard to long term studies that investigated both bridge deck stressors together.
b. Inspection Based Deterioration Models: The desk scan provided a study from the Nebraska Department of Roads (NDOR) which utilized a statistical approach to inspection rating data and correlated it to a timeline showing a non-linear deterioration of bridges (and bridge decks) in cold wet climatic states where there is heavy truck traffic.

Search for Models:
The AASHTO Standard Specifications for Bridge Design and Construction establish the current philosophy for bridge deck design and for understanding how bridge decks behave under load. The bridge team searched for models and data that would inform as to deterioration mechanisms including: axle loads, (static vs dynamic), repetitive and sustained loading effects on concrete decks and climatic effects.

No direct analysis of impacts to decks was undertaken in this sub-study area. Rather, it constitutes a synopsis of what could be gleaned from the desk scan. In summary however, the bridge team found an overall industry trend of migrating to comprehensive data bases, data gathering, and bridge asset management technologies. By necessity there is a restriction to general access to this information. In the long run, the data quality is expected to improve but we are not there yet. The data driven approach may also provide a metric that can measure bridge deck damage and a link to damage due to specific axle or wheel loads or load groups. The research indicates that as a whole, owner agencies are realizing the benefits of establishing a national bridge database which can be built by all stakeholders with a unified data format and standards for reporting. However the effort is in its mid-term phase and maybe years away from providing meaningful data. Also, more research is needed in establishing the effects of axle loads applied dynamically on bridge decks in different configurations combined with the effects of chloride (or other chemical) contaminations.