

# The Potential for Performance-Based Standards as the Basis for Truck Size and Weight Regulation in the United States

**Final Report**  
**August 1996**

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# **The Potential for Performance-Based Standards as the Basis for Truck Size and Weight Regulation in the United States**

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**Final Report  
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## **EXECUTIVE SUMMARY**

### **Background**

This research project examines truck size (dimensions) and weight regulation in other countries, worldwide, to identify size and weight regulations that are based on standards of truck performance. Such standards, known as performance-based regulations, are intended to ensure that the allowable size and weight of trucks is governed by safety standards and/or by standards for infrastructure (pavement and bridges) wear. The primary goals of this study are to identify performance-based size and weight regulatory practices from a widely diverse group of 32 jurisdictions worldwide, to determine the applicability of such standards in the United States (U.S.) size and weight regulatory framework, and to identify the barriers to adopting this type of approach to truck size and weight regulation.

The current method of U.S. truck size and weight regulation has predominantly evolved into a prescriptive system of fixed size and weight limits regardless of the performance of the vehicle. The objective of performance-based regulations is to base vehicle size and weight on the vehicle's performance rather than by blanket limits for all vehicles regardless of their performance.

### **Project Scope**

The project first conducted a review of pavement and bridge design standards for many industrialized countries to provide an understanding of the engineering principles related to determining axle and gross vehicle weight limits. Similarly, heavy vehicle design literature was studied to provide an understanding of how vehicle parameters and components that are controlled by size and weight regulations significantly impact the way a vehicle interacts with the traffic safety environment.

The truck size and weight regulations in 32 jurisdictions were next examined to determine the type and extent of standards used by these jurisdictions to control vehicle size and weight. This examination revealed 24 standards based on vehicle performance that directly or indirectly determine maximum size and weight. These standards were then classified into two broad categories: those designed to control pavement wear or protect highway infrastructures, and those designed to protect traffic safety and the highway safety environment.

The project next reviewed the enforcement practices among four selected countries to determine the issues related to monitoring the size and weight of trucks operating under performance-based regulations to address the concerns of officials charged with enforcing U.S. truck size and weight regulations. For example, the project examined how the stability requirements of two-trailer "A" trains permitted to operate at maximum weights of 44,000 kilograms (97,000 pounds) are monitored in New Zealand.

The research next provided a summary of the performance-based standards that might be logically included in any U.S. truck size and weight regulation reforms. This summary discussed the enforcement issues, benefits, and potential role of 24 noted performance standards that directly or indirectly based size and weight on the interaction between the vehicle and the

infrastructure and/or the traffic safety environment. A two by two evaluative matrix was used to determine which of the noted standards may or may not be suitable for the U.S. size and weight regulation framework.

The research concluded with a discussion of how the benefits of a shift from prescriptive to performance-based size and weight regulations might be assessed.

### **Key Findings**

The research revealed that the sciences of pavement and vehicle design are complex, and additional research is needed to fully comprehend the vehicle/highway interaction. The following paragraphs summarize those findings:

#### **Pavement and Vehicle Design Principles Related to Performance-Based Standards**

The road wear performance of vehicles depends partially on the vehicle design. For example, to a large degree, vehicle dynamic loadings can be reduced through “road friendly” suspensions. It may be possible to increase the gross vehicle weight limits on vehicles with more benevolent suspensions while simultaneously reducing road wear. The review of pavement and bridge design principles revealed:

- Current pavement design methods are insensitive to dynamic loading conditions.
- The most commonly used pavement design methods in the U.S. have been developed by the American Association of State Highway and Transportation Officials (AASHTO). These methods predominately focused on designing pavements with adequate strength to prevent failure due to fatigue resulting from repetitive vehicular axle loadings forecasted to occur over the projected life of the pavement. However, recent research findings of the Strategic Highway Research Program (SHRP) have shown that factors other than axle loadings, predominately attributable to the effects of the environment, significantly impact the useful life of pavements and pavements’ decline in condition over time. This result clearly indicates that commonly used models of the relationship between axle loadings and pavement life do not account for complex the interaction between road use, pavement life, pavement performance, the pavement’s interaction with the environment and aggregate materials, and other variables. Although AASHTO methods are based on good research and engineering practice, clearly much research remains to be conducted before the science is robust enough to account for the exact pavement life implications of changes in vehicle designs.
  - The current federal bridge formula may need to be evaluated to ensure that limits are the most efficient and properly apportion the costs of highway users and the costs to build and maintain bridges. Implied weight limits of the current bridge formula were set arbitrarily without attempting to design limits which minimize transportation system costs.

With respect to vehicle design principles, the literature review indicated that many complex factors interact to determine vehicle performance. Some of the issues of vehicle performance that should be considered when developing performance-based standards include the following:

- Vehicle performance should be measured in the context of the entire vehicle (e.g., a tractor-trailer combination) because changes in vehicle design to improve one handling property could adversely affect other aspects of vehicle performance.
- Tires dictate many of a vehicle's handling properties. However, many elements of tire performance, such as tire loading, road surface, and tread depth, are controlled by factors beyond the scope of practical enforcement techniques. As a result, vehicle performance should be evaluated under the realm of conditions that could be encountered during routine vehicle operations.
- Many target performance levels can be ensured by controlling such vehicle parameters as wheelbase and rear overhang.
- The complexity of vehicle performance measurement suggests the need for the development of a testing and inspection infrastructure away from the roadside and the need for a multiple-tier inspection process.

### **Existing Application and Enforcement of Performance-Based Size and Weight Regulation**

This study revealed that some countries have begun to account for differences in vehicle performance in their size and weight regulations. Based on the experiences of these countries, the following observations could assist size and weight policy makers in considering size and weight regulations that are tied to vehicle performance:

- Single-axle weight limits among the 32 study jurisdictions range from 5,500 kilograms (12,100 pounds) to 13,000 kilograms (28,660 pounds). Much of the variation in these weight limits can be attributed to the fact that many jurisdictions have developed subcategories of single-axle weight for steering axles, single-tire axles, and drive/driven axles.
- Tandem-axle weight limits vary significantly among jurisdictions with a range from 10,000 kilograms (22,046 pounds) to 21,000 kilograms (46,291 pounds). This is primarily attributable to axle spacing requirements prescribed by many of the study jurisdictions to limit the weight of closely-spaced tandem-axles.
  - Twenty-two of these 32 jurisdictions have separate categories for and allow higher weight on tridem-axles than on tandem-axles. The weight limit of tridem-axles among these jurisdictions ranges from 15,500 kilograms (34,267 pounds) to 30,000 kilograms (66,168 pounds) and is also controlled by axle spacing requirements.
- A wide discrepancy exists among jurisdictions' maximum vehicle weight. The discrepancy appears to be linked to the complexity of the vehicle. For example, the range in the maximum weight for three-axle trucks is 7,000 kilograms (15,400 pounds). However, the range in the maximum weight for five-axle tractor trailer combinations is 34,000 kilograms (75,000 pounds).
- Countries have adopted widely different methods of controlling maximum allowable bridge weight and have significant variation in allowable bridge weights for identically configured vehicles. These differences are illustrated graphically in Figures 4.2, 4.3, and 4.4.
- Eleven jurisdictions recognize and grant higher weight limits for vehicles equipped with "road friendly" or air-ride suspension.
- Jurisdictions are using other standards to control the interaction of vehicles on the highway infrastructure and on traffic safety. These criteria include:

- » Turning circle requirements
- » Static load sharing requirements
- » Braking efficiency standards
- » Load distribution requirements
- » Rear overhang requirements
- » Traction requirements
- » Maximum tire loads
- » Minimum horsepower/weight ratios

The enforcement methods used for performance-based and pure performance-based standards are more complex than those used to enforce prescriptive standards. A review of the enforcement methods of selected countries revealed:

- The development of a vehicle type approval and annual inspection system appears to be crucial to the implementation of some performance-based standards.
- The complexity of measuring some vehicle performance parameters indicates that some vehicle testing should be conducted away from the roadside.
- The existing U.S. investment in inspection facilities, mobile inspection equipment, and enforcement personnel could provide an adequate platform for monitoring many performance-based standards (such as wheelbase, axle weight and spacing, and load distribution) at fixed weigh stations or random roadside locations. Additionally, this existing infrastructure could provide the nucleus for certifying additional test stations and monitoring the credentials of vehicles tested at these additional locations.

### **Standards That Are Feasible for Performance-Based U.S. Size and Weight Regulations**

The potential U.S. role of 24 noted performance-based standards was examined by using a two by two evaluative matrix for comparing enforcement issues versus the benefits associated with each noted standard and groups of standards. Based on a preliminary analysis, this matrix revealed that the benefits attributable to 12 of the noted standards may be equal to or greater than their enforcement issues. Those 12 standards are listed below:

- Maximum vehicle weight based on number of axles
- Maximum axle weight based on number of tires
- Maximum bridge weight based on axle spacing
- Static load sharing requirements
- Braking efficiency standards
- Maximum vehicle weight based on wheelbase
- Maximum tandem/tridem weight based on axle spacing
- Rear overhang requirements
- Maximum weight limits for steering axles
- Maximum trailer weight based on configuration type
- Turning circle requirements
- Maximum weight based on engine horsepower

Truck size and weight policy makers who decide to embrace performance-based regulations could choose from among the above 12 standards based on the goal of such an action. For

example, standards such as maximum axle weight based on number of tires, maximum steering axle weight, and load distribution requirements could be integrated within existing size and weight limits and result in less infrastructure wear, and improved traffic safety.

Similarly, standards such as maximum weight based on number of axles and maximum tandem/tridem axle weight based on axle spacing could be implemented should policy makers decide to expand U.S. size and weight regulations. Under such a scenario, motor carriers willing to invest in equipment conforming to these standards would be rewarded with greater vehicle productivity. The public infrastructure investment would be protected through standards which seek to reduce pavement loads through suspension designs which allow for a more even distribution of loads across axles. The traffic safety environment would benefit from improved heavy vehicle handling and maneuverability.

The enforcement of nearly all of these 12 standards could occur at existing weigh stations, or during random roadside inspections. Most importantly, these standards are based on proven principles of pavement and vehicle design and the experience of other countries has demonstrated that they can be successfully implemented.

The role of the three following performance-based standards in U.S. size and weight regulations is less clear.

- Maximum weight based on static roll threshold
- Maximum weight/length based on offtracking
- Maximum weight based on dynamic load transfer

These standards offer potential benefits in vehicle productivity and improved safety, yet the international experience revealed that these standards cannot be readily enforced at the roadside. The potential role of these standards may be most applicable for a subfleet of specialized or highly productive vehicles such as those found in Australia, Canada, or New Zealand. These countries have focused efforts on improving the safety-related performance parameters of Longer Combination Vehicles (LCVs) using standards such as these. These vehicles offer enhanced productivity and are primarily used in regions with a sparsely distributed economic base. This is not unlike the western United States, where similar issues have promoted the adoption of LCVs and LCV highway networks.

## **Conclusions**

Even though adopting some performance-based standards may be difficult, the concepts underlying them offer too many advantages not to move forward and use a performance-based framework as a foundation for future size and weight reform. The experiences in other countries such as New Zealand and the European Union indicate that performance-based size and weight regulations can be successfully developed and enforced. However, due to the size of the U.S. road network and the population of the U.S. heavy vehicle fleet not all standards used in other countries may be successfully implemented in the U.S. size and weight regulatory framework.

If U.S. truck size and weight policy makers decide to embrace performance-based concepts for size and weight regulations, the U.S. will probably adopt its own unique path of migration toward performance-based size and weight regulation and implement standards that are compatible with its own land-based trading partners.

## CHAPTER 1: INTRODUCTION

This research project examines truck size (dimensions) and weight regulation in other countries, worldwide, to identify size and weight regulations that are based on standards of truck performance. Such standards, known as performance-based regulations, are intended to ensure that the allowable size and weight of trucks are governed by safety standards and/or by standards for infrastructure (pavement and bridges) wear. The purpose of this examination is to determine if similar standards of performance might be integrated into the truck size and weight regulations in the United States and to identify the issues related to integrating this type of size and weight regulation.

In most cases, the imposition of performance-based truck size and weight standards would allow motor carriers to enjoy the benefits of more productive vehicles if the vehicles meet or exceed performance criteria. For example, two trucks with the same axle loads and gross weights but with different suspension systems might impose different amounts of wear to pavements. Using performance-based regulations, the truck with the suspension that causes less pavement wear would be allowed to have higher axle or gross weight.

This study is intended to create a better understanding of how science and engineering affect the implementation of performance-based size and weight standards, and to understand how performance-based standards are applied in countries throughout the world. This information provides the background to understand the economic implications of, and the science and policy issues involved in, the integration of performance standards into truck size and weight regulations in the United States.

One of the principal conclusions of this report is that there are still many issues which remain to be resolved before reasonably accurate estimates can be derived regarding the benefits and costs of applying performance-based standards. For example, the state of the art of pavement design has not yet been developed to the point where pavement life predictions are sensitive to the performance of heavy vehicle components traveling on the pavement. Hence, the science of pavement design does not allow the prediction of improvements in pavement longevity (benefits) due, for example, to better truck suspension systems. However, what is clear is that performance standards can be used to promote the development of vehicles which cause less road wear and are safer. In most cases where performance standards are applied, motor carriers are given the incentive of more productive vehicles (vehicles with higher axle or gross weight or the capability to carry larger volumes) when they operate vehicles that meet or exceed defined standards. As a result, the state of the relevant parties (motor carrier, highway agency, and other vehicles sharing the traffic stream with heavy vehicles) has been improved. Although the exact magnitude of benefits is difficult to establish, there is evidence that there is a positive net improvement from applying performance-based standards. Further, it may be that limiting the size and weight of vehicles based on their compliance with performance standards will provide a more robust and scientifically justified system of vehicle regulation than regulation based on historically prescribed standards.

The interaction of heavy vehicles with the highway infrastructure and other vehicles are two central issues to performance-based standards and ones which have been examined in many other projects. One recent project proposed that the “Regulation of the trucks permitted to use

the highway and apportionment of costs to vehicles in accordance with road wear should be based on a thorough understanding of the way in which trucks interact with and damage pavements.”<sup>1</sup> This chapter begins with a summary of those primary characteristics of vehicles most affecting vehicle/roadway interaction. Subsequent sections define the concept of performance-based standards for heavy vehicles, detail the history of truck size and weight regulation in the U.S., examine the current mood towards size and weight reform, and review the project scope and document structure.

### **The Interaction of Heavy Vehicles with the Traffic Safety Environment**

A study in Australia revealed that inequalities in vehicle handling characteristics had implications on traffic safety.<sup>2</sup> The goal of the study was to define the heavy vehicle performance criteria affecting traffic safety and to assess the range of performance capabilities of the existing Australian heavy vehicle fleet. The study used computer simulations to determine the differences in roll stability, rearward amplification, low-speed offtracking, and high-speed offtracking of 19 common heavy-vehicle configurations. Briefly summarized, roll stability is a measurement of the lateral force that a vehicle can sustain before tipping over, rearward amplification is a measure of how much side to side motion increases as you move back towards the rear of the vehicle, and off-tracking is a measure of the difference in wheel path from the front to the rear of the vehicle. (A more detailed description of vehicle handling properties is provided in Chapter 3.) The study results are summarized below:

- Non-articulated vehicles and truck-trailer configurations have less roll stability and exhibit a greater tendency to tip over at a given lateral force than tractor-trailer configurations.<sup>3</sup>
- Rearward amplification varied considerably among vehicle configurations. Generally, multiple truck-trailer configurations (such as long wheelbase non-articulated vehicles coupled to single or twin-trailers) and complex longer combination vehicles (such as triple-trailer combinations) exhibited greater rearward amplification than single tractor-trailer configurations.<sup>4</sup>
- Total length and/or wheelbase have a significant effect on low-speed off-tracking for all vehicle configurations.<sup>5</sup>
- Single unit vehicles have the least high-speed off-tracking while longer, heavier vehicle configurations have the greatest high-speed off-tracking.<sup>6</sup>

### **The Interaction of Heavy Vehicles and the Roadway**

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<sup>1</sup>T.D. Gillespie, et. al. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance*. Transportation Research Board, National Research Council. NCHRP Report 353. 1993. p 4.

<sup>2</sup>Peter F. Sweatman. *Overview of the Dynamic Performance of the Australian Heavy Vehicle Fleet*. Technical Working Paper No. 7. National Road Transport Commission. Melbourne, Australia. July, 1993.

<sup>3</sup>Peter F. Sweatman. p19–30.

<sup>4</sup>Peter F. Sweatman. p 33.

<sup>5</sup>Peter F. Sweatman. p 37.

<sup>6</sup>Peter F. Sweatman. p 40.

A recent National Cooperative Highway Research Program (NCHRP) study identified, through computer simulations, the truck properties that are most crucial to vehicle/highway interaction.<sup>7</sup> In that research, computer models were developed to represent 29 different vehicle configurations ranging from two-axle non-articulated vehicles to nine-axle turnpike doubles. Simulation programs were then used to quantify the fatigue and rutting caused by the computer-modeled vehicles to asphalt and concrete pavements. The simulation programs revealed not only that all vehicles are not equal in the wear caused to pavements, but also, the vehicle characteristics that are most influential in vehicle/highway interaction. The following paragraphs summarize the findings of that research:

### **Axle Loads**

Axle loads are the greatest single vehicle factor of fatigue to both rigid and flexible pavements. The primary reason for this is that pavement fatigue has been assumed to increase exponentially with respect to axle load. Assuming that a fourth power relationship exists between axle load and pavement wear, a single axle that is loaded to 20,000 pounds causes 16 times as much pavement wear as a single axle that is loaded to 10,000 pounds.

### **Gross Weight**

Heavier trucks are not necessarily more damaging to pavements. For example, the computer simulations revealed that a three-axle refuse hauling vehicle weighing 64,000 pounds causes over twice the pavement fatigue of a nine-axle twin-trailer Turner vehicle weighing 114,000 pounds.<sup>8</sup> However, the researchers found that gross weight is the primary determinant of rutting in asphalt pavements. Simply stated, the total rut depth caused by a truck on flexible pavements is the sum of the ruts created by each individual axle.

### **Tandem-Axle Suspension Systems**

The performance characteristics of tandem-axle suspensions were found to be a source of differences in the amount of pavement wear. This is caused by inequalities in load sharing among the individual axles and the dynamic loads produced by the suspensions. Specifically, those tandem-axles with poor static load sharing caused between two and 54 percent more pavement wear than tandem-axles that divided their loads equally.

Additionally some suspension types were found to produce greater dynamic loads than others. Specifically, walking beam suspensions were found to cause twice as much wear to pavements as other suspensions because of “tandem-hop” created by walking beam suspensions. “Tandem-hop” is a condition in which a force (such as a bump in the roadway surface) that causes one axle of the tandem group to move upward also causes the other axle in the tandem to simultaneously move downward because the rigid beam connecting the two axles is pivoted in the center. The computer models revealed that air-ride suspensions caused the least amount of dynamic loads to pavements because each axle of a tandem acts independently.

### **Axle Spacing**

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<sup>7</sup>T.D. Gillespie, et. al.

<sup>8</sup>T.D. Gillespie, et. al. p 14.

The spacing of axles within a group was found to have little effect on the fatigue of flexible pavements and a noticeable effect on the fatigue of concrete pavements. This occurs because rigid pavements behave like a steel beam and distribute their loads over distances similar to common axle spacings. As a result, at certain axle spacings, the compressive, (pushing) forces immediately under one axle of the tandem group are offset (reduced) by the tensile (pulling) forces exerted on the pavement immediately below the other axle.

The computer simulations revealed that on 10-inch thick concrete pavements a tandem-axle group loaded to 36,000 pounds with axles spaced 6.75 feet apart caused the same amount of pavement wear as a single axle loaded to 18,000 pounds. However, if the tandem axles were spaced only 4.25 feet apart they would cause roughly 1.40 times as much pavement wear as a single axle loaded to 18,000 pounds.<sup>9</sup> This same relationship also existed for tridem-axles. The researchers noted that tridem axles loaded to 54,000 pounds with axles spaced at four-foot intervals caused no more damage than a single 18,000 pound axle on thin concrete pavements.

Of course the above results depend on a number of assumptions made in the computer simulation about the properties of the pavement and the supporting materials. For example, the researchers assumed the pavement materials were isotropic and without such common imperfections as cracks.

### **Tire Configurations**

Three types of tire configurations (single tires, dual tires, and wide-based single tires) were studied. The findings revealed that axles equipped with single 11R×22.5 tires produce a 15 to 21 percent higher stress per pound of load than axles equipped with dual tires of the same size. Although the pavement wear was reduced when wide-based single tires were used, they still elevated pavement stress by two to nine percent over that applied by dual-tire axles.

### **Tire Inflation Pressure**

The computer simulations revealed that increases in tire inflation pressure above 75 PSI greatly increased the pavement wear on asphalt pavements. Raising the inflation pressure of a 15R×22.5 tire from 75 PSI to 120 PSI was shown to cause 9 times greater pavement wear for asphalt pavements. For dual tire axles equipped with common tire sizes (11R × 22.5) raising the tire inflation pressure from 75 PSI to 120 PSI was shown to cause 2.8 times greater wear to asphalt pavements.

Taken collectively, these two major reports emphasize that not all vehicles are equal with respect to attributes related to their safety performance and the wear they impose on the highway infrastructure. A more rational set of truck size and weight regulations could capitalize on this research and grant the more benevolent vehicles greater size and weight limits than other vehicles or restrict the maximum size and weight of vehicles with poor performance attributes (such as those with suspensions shown to be harmful to pavements). This concept is the foundation of performance-based standards for truck size and weight regulations.

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<sup>9</sup>T.D. Gillespie et al. p 17.

## Truck Size and Weight Regulations

Truck size and weight regulation standards can be divided into three types: prescriptive standards, like most currently applied in the United States; parametric performance-based standards, which include parameters known to be related to performance; and pure performance-based standards. Most size and weight regulations in the United States are not based on pure performance standards or on performance related parameters; they are based on historical compromises between trucking and shipping interests, the concerns of highway agencies to protect the infrastructure and promote traffic safety, and implementation and enforcement considerations. These are prescriptive standards. For example, maximum axle load limits, that are independent of such variables as tire pressure, suspension properties, tire width, axle spacing and other variables shown to impact road wear, are prescriptive standards. Enforcement of prescriptive standards is quite specific because a truck axle load either does or does not meet maximum axle load limits.

Parametric performance-based standards, also known in abbreviated terms as performance-based standards, include performance criteria and regulate truck size and weight based on parameters known to be related to performance. For example, some suspensions have lower dynamic loads and thus cause less road wear than other suspensions.<sup>10</sup> Parametric performance-based standards take into account the natural frequency and damping ratio of a suspension. These standards are enforced through tests to monitor suspension rebound rates and the ability of the suspensions to reduce or moderate rebound. In this case, the objective is to regulate the road wear performance of the vehicle and the regulation is applied through parameters related to the suspension. For the balance of this report, the terms parametric performance-based standards and performance-based standards will be used interchangeably

Pure performance standards govern size and weight limits based only on performance. In this case, the vehicle designer develops a vehicle which meets or exceeds the performance criteria. A pure performance criterion would specify either the maximum wear the vehicle could impose on bridges and pavements or the allowable impact on the safety environment of the roadway. Only the vehicle's performance is regulated, not the mechanisms that make the vehicle capable of meeting the performance criteria. In the example above, where the objective is to regulate the road wear performance of a vehicle, a pure performance standard might require that the vehicle travel repeatedly over a pavement until the pavement fails due to fatigue. The pure performance standard would govern the number of times the vehicle must traverse before pavement failure. If the number of passes exceeded the limit, then the vehicle design passes. Of course, such a test would be extremely ambitious and time consuming. Instead, the road wear properties of the vehicle are governed through parameters believed to be related to its road wear performance.

An example of a pure performance standard is in Annex I of the European Union's Directive 85-

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<sup>10</sup>Dynamic loads are the theoretical increase in pavement stress caused by a vehicle in motion, over the static loads caused by a vehicle at rest. One study concluded that the theoretical increase in damage done by dynamic wheel loads of three suspensions was torsion bar–19 percent, four-spring–22 percent, and walking beam–37 percent. David Cebon. *Interaction Between Heavy Vehicles and Roads*. Society of Automotive Engineers, Thirty Ninth L. Ray Buckendale Lecture. Warrendale, PA. March, 1993. p. 53.

3 turning circle performance standard.<sup>11</sup> To meet the performance test, the vehicle in motion must be able to turn a 360-degree circle within a 12.5 meter radius without off-tracking into a 5.3 meter radius inner circle. This test has the effect of regulating a combination of dimensions which impact the vehicle's ability to maneuver.

In regard to suspensions, a pure performance specification would regulate the level of dynamic loads imposed on pavements or the relative pavement stress the vehicle imposes regardless of the design of the suspension and the static axle loads. As an incentive to operate with a suspension which imposes less road wear for a given axle load, motor carriers should be allowed to carry more payload weight. Annex I of the European Union Directive 85-3 allows tractor-trailer combinations equipped with dual tires on all but the steer axle and with suspensions which are more benevolent ("road friendly") to carry four additional metric tonnes. Suspensions judged to be road friendly must meet parameters measuring their suspension damping and frequency of rebound following the application of a standard suspension loading.<sup>12</sup>

### **History of U.S. Truck Size and Weight Regulation**

To understand the issues relating to a potential change in size and weight policy, it is first necessary to understand how current U.S. truck size and weight policy has evolved.<sup>13</sup> Current size and weight limits for interstate commercial vehicle operations on the interstate system and National Network in the United States have evolved from an amalgamation of state-generated size and weight standards. Between 1913 and 1933 every state generated its own size and weight standards. Sometimes the standards were consistent from one state to the next, but often each state developed its own size and weight standards without considering uniformity among states. The legacy of independently developed size and weight standards became the base upon which national standards were enacted. As a result, national standards were achieved through compromise among a number of non-uniform historical standards.

In 1932, the American Association of State Highway Officials (AASHO), which later became the American Association of State Highway and Transportation Officials (AASHTO), recommended a 16,000 pound (7.25 metric tons) axle load limit. AASHO revised its policy in 1946 and recommended a single-axle load limit of 18,000 pounds (8.15 metric tons) and a tandem-axle limit of 32,000 pounds (14.5 metric tons). To limit the stress on bridges, the AASHO policy recommended a maximum weight limit of 73,280 pounds (33.25 metric tons) for vehicles with extreme axles at least 57 feet (17.4 meters) apart. To help implement its policy AASHO officials recommended a method for computing maximum vehicle weight based on the number of axles and the distance between them. This method is known as the bridge formula. Using this method, vehicle operators determine maximum allowable vehicle weight by

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<sup>11</sup>*Laying Down the Maximum Authorised Weights and Dimensions for Road Vehicles Over 3.5 Tonnes Circulating Within the Community.* Commission of the European Communities. Brussels, Belgium. December 15, 1993. p. 26.

<sup>12</sup>Most commonly, a load is applied by rolling the vehicle off an 80-millimeter high ledge.

<sup>13</sup>The description of the evolution of size and weight policy is extracted from T.H. Maze, C.K. Walter, and A.G. Smadi, *Policy Issues of an Iowa Longer Combination Vehicle Network*, (Ames, Iowa), Midwest Transportation Center, November, 1994, pp. 3-5.

measuring the distance between the vehicle's furthest spaced axles.

The Federal-Aid Highway Act of 1956 applied the AASHO standards to the interstate highway system. The act also allowed states to continue to use weight and size limits greater than those recommended in the AASHO policy, thus grandfathering higher weight and size limits in place. In 1974, Congress adopted increased axle limits of 20,000 pounds (9.05 metric tons) per single axle and 34,000 pounds (15.4 metric tons) per tandem axle. It also adopted a bridge formula to allow gross vehicle weight to increase to 80,000 pounds (36.3 metric tons). The new axle and gross weight limits were caps for states that did not already have higher limits. Other states that already had higher limits were allowed to grandfather the higher pre-existing limits. States that did not want to increase their weight limits to the higher limits on the interstate highway system could stay at their prior gross weight and axle load levels. The 1974 legislation (as well as the 1956 legislation) included provisions for states that already issued permits for oversized and/or overweight trucks to continue to exercise that authority (e.g., longer combination vehicles (LCVs)).<sup>14</sup>

Realizing that truck size and weight uniformity was an important issue, Congress mandated in the Surface Transportation Assistance Act (STAA) of 1978 that the Federal Highway Administration (FHWA) perform a study of size and weight issues. The response to Congress generated by this study contained one of the earliest references to performance-based size and weight criteria in a U.S. Department of Transportation policy document. One of the policies proposed by the FHWA was the adoption of performance-based size and weight regulations.<sup>15</sup> However, no action was taken on this recommendation.

The STAA of 1982 removed the option of states to have lower than the uniform standard for weight limits on the National Highway Network, thus promoting uniformity. With few exceptions, states could no longer impose limits on weights, widths, lengths, or combinations that were more restrictive than the federal limits. The STAA introduced an increased federal role in vehicle size and weight regulation by preempting states' right to limit overall length of singles or doubles and requiring "reasonable access between the National Highway Network and terminals and facilities for food, fuel, repairs, and rest."<sup>16</sup> The STAA also grandfathered state limits that exceeded federal limits and continued to allow states to authorize the operation of larger trucks under special permits. Since the enactment of the STAA in 1982, national truck size and weight regulations have remained constant. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 even froze current limits on the use of oversize and/or overweight trucks operating under divisible load permits to highways where states permitted their operation as of

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<sup>14</sup>B.L. Geuy. *Longer Combination Vehicles*, Private Carrier, Vol. 26, December, 1989, p. 14.

<sup>15</sup>*An Investigation of Truck Size and Weight Limits: Final Report of the Secretary of the Department of Transportation to the Congress pursuant to Section 161 of Public Law 95-599, the Surface Transportation Assistance Act of 1978*, (Washington, D.C.), U.S. Department of Transportation, 1981, pp. S-4, S-5.

<sup>16</sup>*Guide for Monitoring and Enhancing Safety on the National Truck Network*, Federal Administration, (Washington, D.C.), 1986, p. 2.

June 1, 1991.<sup>17</sup>

The last national policy on truck size and weight was promulgated through the 1982 STAA. Since the 1982 enactment of STAA, 14 states had adopted some type of LCV system before the incremental expansion (state-by-state) of LCV highway systems was halted by ISTEA. However, the ISTEA freeze was only intended to provide a pause while truck size and weight policy is examined, and ISTEA legislation even directs the conduct of studies of longer combination vehicle safety, use, and economics to support the future development of new truck size and weight policy.<sup>18</sup> The expiration of the ISTEA legislation and the need to create a new transportation authorization bill during 1997 has created an environment which is favorable for truck size and weight policy reforms.

### **Productivity and Safety Innovations Since 1982**

A recent survey examined the profitability strategies planned by the chief executive officers of 220 class one truckload motor carriers over the next three years.<sup>19</sup> In this research, executive officers were asked to rate the relative importance level of 49 possible profitability strategies that their firm might undertake. Of the 49 strategies, respondents indicated “increase equipment productivity” as most important, and “control costs” as second in importance. These CEO strategies have remained consistent since the motor carrier industry was economically deregulated in 1980 and have partially contributed to innovations in transportation productivity and safety.

Productivity improvements in the period from 1983 to 1993 have driven costs out of the logistics supply chain and resulted in a reduction in our nation’s freight bill from 14.5 percent of gross domestic product (GDP) to 9.8 percent of GDP.<sup>20</sup> During the same period the medium/heavy duty truck fatal accident rate fell by 37 percent while miles driven by medium and heavy trucks have increased by 41 percent.<sup>21</sup> Pressure resulting from the increased global competitiveness of the U.S. economy and public concerns for improved safety will motivate motor carriers to seek

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<sup>17</sup>Summary - Motor Carrier Act of 1991, Title IV of the Intermodal Surface Transportation Efficiency Act of 1991. Federal Highway Administration, (Washington, D.C.), Publication No. FHWA-MC-92-005, p. 7.

<sup>18</sup>Three General Accounting Office reports on longer combinations vehicles were prepared in response to the ISTEA legislation. They include: *Truck Safety: The Safety of Longer Combination Vehicles is Unknown*. United States General Accounting Office, (Washington, D.C.), 1992, GAO/RCED-92-66; *Longer Combination Truck Drivers Controls and Equipment Inspection Should Be Improved*. United States General Accounting Office, (Washington, D.C.), 1993, GAO/RCED-94-21; and *Longer Combination Trucks: Potential Infrastructure Impacts, Productivity Benefits, and Safety Concerns*. United States General Accounting Office, (Washington, D.C.), 1994, GAO/RCED-94-106.

<sup>19</sup>Frederick J. Stephenson, and Theodore P. Stank. “Truckload Motor Carrier Profitability Strategies.” *Transportation Journal*. Winter, 1994. pp 5-17.

<sup>20</sup>Steve Davis. *1994 State of Logistics Annual Report*. Cass Information Systems. Bridgeton, MO. May 10, 1995.

<sup>21</sup>Thomas J. Donohue. *The Truth About Highway Safety*. Address to the Commercial Vehicle Safety Alliance. Sun Valley, Idaho. October 23, 1995.

similar improvements during the next decade. However, continued improvements will be more difficult to achieve without either reforms of size and weight regulation or unforeseen technological innovation. The integration of performance-based standards into the United States truck size and weight regulation framework could provide the motor carrier industry the necessary incentive to develop more productive and safer equipment without additional impacts on our nation's highway infrastructure.

### **Current Mood Towards Size and Weight Regulatory Reform**

The end of the ISTEA legislation and the need to create a new transportation authorization bill during 1997 have created an environment which is favorable for truck size and weight policy reforms. Other factors which have made the issue of size and weight regulation reform more timely include the following:

- The North American Free Trade Agreement (NAFTA) requires that the trading partners implement a working program to make compatible standards related to vehicle weights and dimensions within three years after the agreement went into force.<sup>22</sup> NAFTA went into force on January 1, 1994; thus the program to develop compatible standards must be in place by January 1, 1997. Because the three countries have different size and weight standards at the national level, some harmonization of size and weight regulation will be necessary.
- Prior size and weight regulation promulgated by states was based on political considerations and is a result of compromise among a number of constituent parties. Existing national legislation seeks to promote uniformity, but national legislation only loosely ties together state based regulation. These compromises were not necessarily based on safety concerns of the roadway environment, engineering concerns of the roadway infrastructure, and economic concerns of an efficient motor freight industry. In fact, some relaxation of size and weight requirements at the state level has resulted in innovative designs that fit the requirements but has had the perverse affect of increasing wear to pavements and bridges. As a result, reform would provide the opportunity to make size and weight regulation more rational and support an efficient balance among all these considerations: safety, roadway infrastructure impacts, and motor carrier economics.
- Over the course of the history of the trucking industry, from the 1920s until the enactment of the STAA of 1982, truck weights have incrementally grown as technology has improved and as states and the federal government have relaxed size and weight restrictions. However, from the early 1980s to the present, the average gross weight of loaded trucks on highways in the United States has remained almost unchanged.<sup>23</sup> During the same period, truck transportation technology has changed dramatically, and, due to advances in technology and

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<sup>22</sup>*Land Transportation Standards Subcommittee: Annex 913.5.a-1*, North American Free Trade Agreement, pp. 9-17.

<sup>23</sup>Maze, Walter, and Smadi, p. 18.

safety policy, truck transportation has improved its safety record.<sup>24</sup> Although increased size and weight limits through further regulatory reform are not inevitable, many segments of the industry want further reforms, and history illustrates that further relaxation of size and weight regulation is likely. To allow that increase to occur, while simultaneously providing for public safety and protection of the investment in highway infrastructure, is an opportunity which should not be missed.

These coinciding factors provide an environment ripe for size and weight reform. It is, therefore, incumbent on transportation policy makers to provide size and weight reforms which support North American trade, are compatible with an intermodal transportation system, and are based on engineering and science supporting superior safety and reduced road/bridge wear performance.

The above factors, and possibly others, have coincided in time and have led the U.S. Department of Transportation to reexamine truck size and weight policy. The FHWA is currently conducting a two-phase study of size and weight policy.<sup>25</sup> One possible result of the FHWA's analysis is to recommend the movement of U.S. truck size and weight regulation away from current prescriptive standards to standards based on the vehicle configuration's performance. A separate chapter of this report highlights the possible infrastructure and safety benefits of implementing performance standards into U.S. size and weight regulations.

The current standards for size and weight regulation are based on political compromise and historical reasons rather than on striking an efficient balance among vehicle safety, wear imposed on highways/bridges, and freight transportation productivity. The current prescriptive size and weight standards provide no incentives for developing or purchasing vehicles with dimensions and components that allow the vehicle to operate more safely or cause less pavement/bridge wear. Performance-based standards have been proposed as a method for improving the productivity of freight vehicles while promoting motor carrier industry innovation.<sup>26</sup> Further, performance-based standards create a completely new structure for size and weight regulation, thus allowing states and the federal government to evolve to a new and more rational size and weight regulation system.

## Project Scope

The research began with a review of pavement and bridge design standards for many industrialized countries to provide an understanding of how axle and gross vehicle weight limits are derived. Similar to infrastructure design standards, the properties of vehicle handling were

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<sup>24</sup>From 1982 to 1993 fatal accidents involving combination trucks in the United States declined by 15 percent. Over the same period, ton miles carried by trucks increased by 69 percent. *Fatality Facts 1994 - Large Trucks*, Insurance Institute for Highway Safety, (Arlington, Virginia), and R.A. Wilson, *Transportation in America*, Eno Transportation Foundation, Inc, (Lansdowne, Virginia), 1994, p. 44.

<sup>25</sup>*Comprehensive Truck Size and Weight Study*, Federal Register, Vol. 6, No. 22, (February 2, 1995), pp. 6587 - 6590.

<sup>26</sup>P.F. Sweatman, *Overview of the Dynamic Performance of the Australian Heavy Fleet*, (Melbourne, Australia): National Road Transport Commission, Technical Working Paper No. 7, July, 1993, p. 1.

also examined to reveal how size and weight regulations affect the safe operation of a vehicle on the roadway.

This research examined the truck size and weight regulations in 32 jurisdictions including the United States and the size and weight regulations of several states within the United States. The purpose of this examination was to determine the type and extent of performance criteria applied to vehicles operating at various gross weights. The study-countries' regulations were organized into a uniform arrangement to support classification of performance criteria. The classification was used to group the identified performance criteria into two broad categories: those designed to control pavement wear or protect highway infrastructure, and those designed to protect traffic safety and the highway safety environment.

Because the truck size and weight enforcement community is also included in the set of transportation stakeholders, any size and weight regulation reforms should address the concerns of this group. For example, the truck size and weight enforcement officials might wonder if the roadside verification of a vehicle's stability characteristics is acceptable or even practical, given the influence of cargo loading and placement. To address the concerns of these officials, the project reviewed the study-countries' enforcement practices to determine the issues related to monitoring the performance criteria of trucks operating under performance-based regulations. For example, the project examines how the stability requirements of two-trailer "A" trains permitted to operate at gross weights up to 97, 000 pounds (44 metric tonnes) are checked in New Zealand.

The research next provided a summary of the performance-based standards that might be logically included in any U.S. truck size and weight regulation reform. This summary discussed the enforcement issues, benefits, and potential role of 24 noted performance standards that directly or indirectly based size and weight on the interaction between the vehicle and the infrastructure and/or the traffic safety environment.

The research concluded with a discussion of the methods of assessing the benefits of a shift from prescriptive to performance-based size and weight regulations.

### **Document Structure**

This report consists of seven subsequent chapters. Chapters two and three present an overview of infrastructure design principles and elements of vehicle handling and performance. The purpose of these discussions is to provide an understanding of the issues related to performance-based truck size and weight regulations.

Chapter four presents a summary of the size and weight regulations and the performance criteria for selected countries. The chapter concludes with a classification of the performance criteria used to control the interaction between vehicles and the highway infrastructure (pavement and bridges) and traffic safety environments.

Chapter five summarizes the size and weight enforcement methods used by selected countries in our study to ensure that vehicles are operating within the defined performance envelopes. The

material presented in this chapter is primarily based on interviews and correspondence with individuals from regulatory agencies, industry suppliers, and trade organizations.

Chapter six summarizes the potential U.S. role, benefits, and enforcement issues associated with governing size and weight based on 24 standards that were noted among the 32 study jurisdictions.

Chapter seven summarizes the potential benefits of a shift from prescriptive to performance-based size and weight regulations. The chapter also examines several methods of assessing the benefits of such a shift.

Chapter eight summarizes the findings of the pavement and vehicle design literature review, existing applications of performance-based standards among the 32 study jurisdictions, and current size and weight enforcement practices among selected countries known to be using performance-based standards for regulating truck size and weight. The chapter also summarizes the likelihood of implementing various performance-based standards into U.S. size and weight regulations and discusses the issues associated with such an incorporation.

## CHAPTER 2: INFRASTRUCTURE DESIGN OVERVIEW

The issue of determining the benefits and costs of performance-based truck size and weight standards presents significant challenges to designers, builders, and maintainers of pavements and bridges. At the crux of this issue is the variability of pavement performance.<sup>27</sup> Some of the forces creating variability in pavement performance are well understood and can be controlled. Other issues defining the variability in pavement performance still remain to be researched.

The purpose of this chapter is to provide an understanding of the infrastructure issues related to performance-based standards through a review of principles of pavement and bridge design.

### Pavement Design Overview

Most proposals to create truck size and weight performance-based standards to reduce road wear deal with reducing the level of dynamic loads applied to the pavement as the truck travels along the highway. Other attributes which may be regulated to reduce road wear include tire pressure and tire width to weight ratio. However, the variability in pavement performance makes it difficult to understand exactly how changes in size and weight standards will impact pavement performance.

In non-technical terms, this section will provide the background information needed to understand why performance-based specifications for truck dimensions are such a difficult issue with which to contend. The section will also explain why it is difficult to offer solid forecasts of the implications of performance-based standards on pavement life.

### Pavement Design Evolution

Road building has been a function of most civilizations since the discovery of the wheel. The Persians and later the Romans were early long-distance road builders. The Romans first applied scientific methods to the building of roads. Generally, Roman road construction started by digging two trenches roughly five meters apart to act as drains.<sup>28</sup> The soil between the two trenches was removed down to a firm foundation. The soil was then replaced by layers of locally available granular materials. Where materials were available, the surface was paved with flat quarry stones. These roads were intended mostly to withstand the loads of hooved animals. Because travel speeds were low, the smoothness of the road was not a concern in the design of the road. The Roman roads were generally three to five feet thick and the roadway structure was built to support the loads placed on the surface rather than relying on the subsurface materials to support the roadway.

The Roman designs were the standard for paved roadway structures until the late eighteenth century. A French road builder and engineer, Pierre Marie Jerome Tresaguet, introduced the concept that a relatively light surface, compared to the massive road structures of the Romans,

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<sup>27</sup>Pavement managers generally define pavement condition through a series of measurable properties (e.g., roughness, crack, patching, etc.). The change in condition over time is known as the pavement's performance.

<sup>28</sup>David Croney and Paul Croney, *The Design and Performance of Road Pavements: Second Edition*, McGraw-Hill Book Company, London, England, 1991, p.5.

could be built on a well drained subsurface.<sup>29</sup> The importance of this new concept is that it allowed the natural subsurface materials to play a role in supporting the pavement and the subsurface materials become part of the entire paving structure. The road building concept used by the Romans was to replace the surface and to allow the materials laid in the paving process to be the paving structure.

Thomas Telford introduced other important concepts into road building when, in 1816, he directed the construction of the Carlisle-Glasgow Road. In this roadway, emphasis was placed on level grades and a smooth road surface. John MacAdam, however, provided the innovation leading to modern road design procedures. His design was based on the principle that a well-drained and compacted base should support the load applied to the pavement. The paving stone surface should act only as wearing surface. His original approach was to let the normal traffic compact the material. The use of compacted and drained layers below the pavement wear surface to support the wearing surface is the principle underlying all modern roads. In a modern highway, the surface material of a paved road is the strongest material, in order for it to resist the compressive and tensile stresses induced in the pavement due to heavy wheel loading. With increasing depth within the pavement, the stress becomes less as the stress is distributed throughout the pavement structure. Particularly in asphalt concrete pavements, this allows gradation of layers from stronger and more expensive materials to weaker and less expensive materials.

Roads which were built based on MacAdam's principles of pavement design, where layers of compacted and drained materials were used to support a wearing surface, are known as macadam roads. In the mid-1800s, mechanical compaction techniques (e.g., steamrollers), as opposed to compaction by traffic, resulted in an increase in the speed of road building. In the 1870s, the use of oils and other agents came into play for reducing dust, and in the mid-1870s the first asphalt surfaced roads in the United States were built.<sup>30</sup> In the early 1900s several bituminous surfaced (surfaced with varying bituminous materials) macadam roads were built, and in 1909 the first Portland concrete paved road was built.

Early pavement designers developed designs based on experience. The primary difficulty with the use of experience was that soil conditions could vary dramatically between locations resulting in variations in pavement life even under similar traffic loading. Subsequent pavement design methods were based on empirical observations and measured or predicted strength of the soils. Common methods required the designer to categorize the soil based on standard classifications. The classification was then used to estimate the needed pavement subbase and total pavement thickness.

The California Bearing Ratio (CBR) became the most popular method of testing the strength of soil. The soil strength was then used to determine the needed subbase and pavement structure. The CBR measures the soil penetrating resistance relative to standard

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<sup>29</sup> American Association of State Highway Officials, "Public Roads of the Past: 3500 B.C. - 1800 A.D.," AASHO, Washington, D.C., 1952.

<sup>30</sup>Yang H. Huang, *Pavement Analysis and Design*, Prentice Hall Englewood Cliffs, New Jersey, 1993, p.1.

crushed rock.<sup>31</sup> Original methods for using the CBR were first developed by the California Highway Department in 1929 and were employed extensively by the Corps of Engineers during World War II and became quite popular after the war.

In addition to early methods based on soil strength and experience, Huang has categorized other pavement design methods into four additional categories:<sup>32</sup>

- Shear failure methods, which are based on developing a pavement thick enough to resist shear failures under wheel loading.
- Limiting deflection methods, which are based on determining the pavement thickness where the vertical deflection will not exceed an allowable limit.
- Regression methods, which use road test data or data collected from test sites and relate pavement performance to loading.
- Mechanistic-empirical methods, which use mechanics of materials methods to relate inputs, such as a wheel loading, to output or pavement response, such as stress or strain.

The most prevalent technique for designing pavements throughout the world is based on regression analysis. The AASHTO pavement design methods are based on regressions relating pavement performance to traffic loading. The primary source of data for the AASHTO design equations was a large-scale road test conducted in the late 1950s and early 1960s. The most significant disadvantage of these methods is that the design equations are based only on conditions that existed during field data collection. Conditions other than those under which the equations were estimated require modifications based on experience or theory. In addition, the validity of the application of the regression equations is limited by the stability of statistical relationships. Although there is good reason to believe that there should be a relationship between the variables in the regression equations, there is no underlying theoretical explanation for the regression equations or their functional form. More specifically, the variables are statistically related but the functional form of the relationship is not explained by theory. The ability of equations to predict pavement life under differing conditions is dependent on the stability of the empirically observed relationships. Recent results of the performance of in-service pavement test sections have provided considerable evidence which tends to question the validity of the assumed stability of the AASHTO design equations when used in different environmental and loading conditions than those under which the relationships were originally estimated.

Mechanistic design methods are intended to bridge the shortcomings of regression techniques. Mechanistic design methods are based on mechanics of materials and employ the behavior of materials and not simply on statistical relationships between empirically observed variables. Current mechanistic models are calibrated using laboratory tests and field performance information. Dependence on empirical data is necessary because theory alone has not been proven to be sufficient to design pavements realistically.

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<sup>31</sup>Huang, p.2.

<sup>32</sup>Huang, pp. 3-4.

All current methods are based on static or moving loads without considering the inertial impacts due to dynamic loads or the variations of impacts due to any vehicle properties (e.g., tire pressure).<sup>33</sup> For example, the vehicles used in the road tests which generated the data supporting the AASHTO design methodology exerted dynamic loads on the test pavements. During the test, however, vehicle and road surface properties (e.g., suspension type or pavement roughness) were not varied to determine the impact of dynamic loads on pavement life. Because dynamic loads are not a variable in pavement design methodologies, current methodologies are incapable of determining the impact on pavement life or pavement condition due to changes in dynamic loads due to vehicle design, although simulation techniques have been employed to estimate the likely impacts of reduced dynamic loads due to improved suspensions.<sup>34,35</sup>

### **Regression Design Techniques**

Many empirical design methodologies are used throughout the world, all involving the development of test sections of varying designs and exposing them to either controlled loads or normal traffic. Since the 1940s in Britain, hundreds of experiments have been conducted where test sections have been built on heavily trafficked highways.<sup>36</sup> Each test section is then routinely monitored. Traffic loading in several locations is monitored through the use of weigh-in-motion devices (known as weigh bridges in Britain) installed in the traffic lanes. The data collected at these locations are then used to statistically identify relationships between traffic loading, age, and pavement wear.

In the United States, commonly used pavement design methodologies are supported by data collected through road tests. The principal road test in the United States was the AASHO road test conducted in Ottawa, Illinois between 1957 and 1961. The object of the AASHO road test was to test a variety of road construction designs when exposed to repetitive truck traffic.

As part of the AASHO road test, a measure, termed serviceability, was developed for determining relative road wear and deterioration. Pavement engineers first established a benchmark for the existing condition of a road from which other pavement measures could be compared. Then relative to this measure, a determination could be made as to when the pavement had reached an unacceptable condition (the pavement had reached failure) and how quickly the pavement deteriorated due to repetitive loading. Serviceability was based on the users' opinions of pavement condition.<sup>37</sup> The assumption was that highways are for the comfort and convenience of the traveling public; therefore, it is the public's opinion of the condition of

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<sup>33</sup>Huang, p.5.

<sup>34</sup>T.D. Gillespie, S.M. Karamihas, M.W. Sayers, M.A. Nasim, W. Hansen, N. Ehsan, and D. Cebon, "Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance," National Cooperative Highway Research Program, Report 353, 1993.

<sup>35</sup>James W. Stoner and M. Asghar Bhatti, "Estimating Pavement Damage from Longer and Heavier Combination Vehicles," Midwest Transportation Center, Iowa State University, 1994.

<sup>36</sup>David Croney and Paul Croney, p. 11.

<sup>37</sup>W.N. Carey and P.E. Irick, *Pavement Serviceability Performance Concept*, Highway Research Board, Bulletin 250, 1960.

the pavement that is important.

To learn the opinions of motorists, AASHO testers had panels of individuals drive over pavement sections and individually rate the condition of the pavement on a score ranging from zero to five, where zero was very poor and five was very good. The individual scores were termed Individual Present Serviceability Ratings, and the mean of the individual scores was termed Present Serviceability Ratings (PSR). Given that it would be practically impossible to obtain subjective ratings for an entire pavement network, PSR was then correlated to mechanical measurements. Predominantly, it was found that PSR was most highly correlated with pavement roughness, a measure of distortions of the pavement surface. To estimate PSR, a regression equation was developed which is predominantly dependent on the mechanically measured profile of the pavement. The equation also includes the variables representing the portion of the pavement which is patched and cracked and, for asphalt pavements, the depth of wheel path ruts. The data collected on the pavement conditions are put into a regression equation and the results are an estimate of the PSR. The PSR estimates were named Present Serviceability Index (PSI). Hence, PSI is based on mechanically measured conditions of the pavement and is an estimate of PSR, which is based on subjective opinions.

An important concept used in concert with serviceability is performance. PSI measures the condition of a pavement at any point in time. The condition of a pavement over time is considered the pavement's performance. For example, Figure 2.1 illustrates a typical plot of a pavement's decline in serviceability over time. In this case, when the pavement's condition declines to a PSI of 2.5 it has reached its minimum acceptable condition. The curve defining the PSI over time represents the pavement's performance. The AASHO road test sought to define the relationship between repetitive axle loading and the pavement's performance to be able to predict when pavements of varying designs would reach a terminal PSI (minimum acceptable PSI).

Although the PSI concept and the equation were developed in the late 1950s, until recently most state transportation departments used PSI as a measure of pavement condition and performance. Many agencies have converted to other subjective measures similar to PSI. The underlying concepts of condition, performance, and minimum acceptable levels of condition remain in use today, and they are fundamental concepts for monitoring the performance of pavements in the field and directing resources through pavement management systems.

### **Figure 2.1: Pavement Serviceability Over Time**

The test track of the AASHO road test consisted of loops of highway constructed on the site of Interstate Highway 80. Each loop consisted of test sections of asphalt and concrete pavement. Trucks of varying weights were driven around the loops 24 hours per day. The test sections varied in thickness and the base material under the asphalt sections varied in construction. From the road test, pavement condition data and truck axle weight data were collected. Ultimately, the data collected showed that the relative wear imposed on a pavement by an axle load is approximately proportional to the fourth power of the axle load, irrespective of the type or thickness of the pavement. For example, if the wear of two axle loads were compared, and one axle carries twice the static

weight of the other, the wear imposed by the heavier axle would be roughly 16 times ( $2^4 = 16$ ) the wear imposed by the lighter axle. In this case, pavement wear is measured as a reduction in PSI.

To develop a standard for pavement wear, during the AASHO road tests the concept of Equivalent Single Axle Loads (ESAL) was refined. An ESAL was the method developed to express units of road wear. One ESAL is an 18,000 pound static load on a single axle. Therefore, one 18,000-pound axle load imposes one unit of road wear. Because road wear generally increases with respect to the fourth power of the increase in static axle loads, doubling the axle load to 36,000-pounds would impose roughly 16 units of road wear. In other words, a 36,000-pound single-axle load causes 16 ESALs of pavement wear.

The ESALs concept was not an original concept developed as part of the AASHO road tests, but the AASHO road tests did develop a formal structure for the use of ESALs in pavement design. Initial attempts to develop a measure of road wear equivalency involved the design of pavements for runways during World War II.<sup>38</sup> Design criteria at the time focused on the design of runway pavements for single wheel loading. Dual wheels became an issue for runway designers when B-29 bombers were introduced into combat missions. Since the pavement wear imposed by a dual wheel is not the same as the pavement wear imposed by a single wheel, pavement designers developed measures to equate the pavement wear of a B-29 dual wheel to a single. Later, this same concept was used to develop equivalence between single-axle loads and tandem-axle loads.

The AASHO pavement design methods require that design engineers work through a series of steps. First they determine the number of ESALs the pavement is intended to withstand over its design life. Estimates of the ESALs a pavement is expected to receive are based on the forecasted future traffic over the design life of the facility and the projected weight distribution of the forecasted traffic. Because the relative wear due to static loads tends to vary with the base materials (in the case of asphalt cement concrete [ACC] pavements) and pavement thickness (in the case of Portland cement concrete [PCC] pavements), different tables are used to convert traffic volumes to ESALs depending on the values of these properties. Once the number of ESALs have been projected over the design life, calculations are made to determine the strength of supporting soil and the quality and durability of the materials to be used in the pavement. The designer enters the calculations into a series of nomographs to determine the paving material's required thickness.

Separate ESAL tables are used for ACC and PCC pavements. ACC and PCC pavements fundamentally differ in how they carry loads imposed to pavement surfaces. Engineers refer to ACC as flexible pavement and PCC as rigid pavement. These names provide a useful framework for characterizing these two types of pavements. In a rigid pavement, the PCC surface provides the predominant structural layer. In flexible pavements, the ACC surface provides a wearing course, and the surface layer in conjunction with layers underneath provides the structure needed to withstand the imposed loads.

Flexible pavement will generally distribute the loads through shear deformation. Immediately

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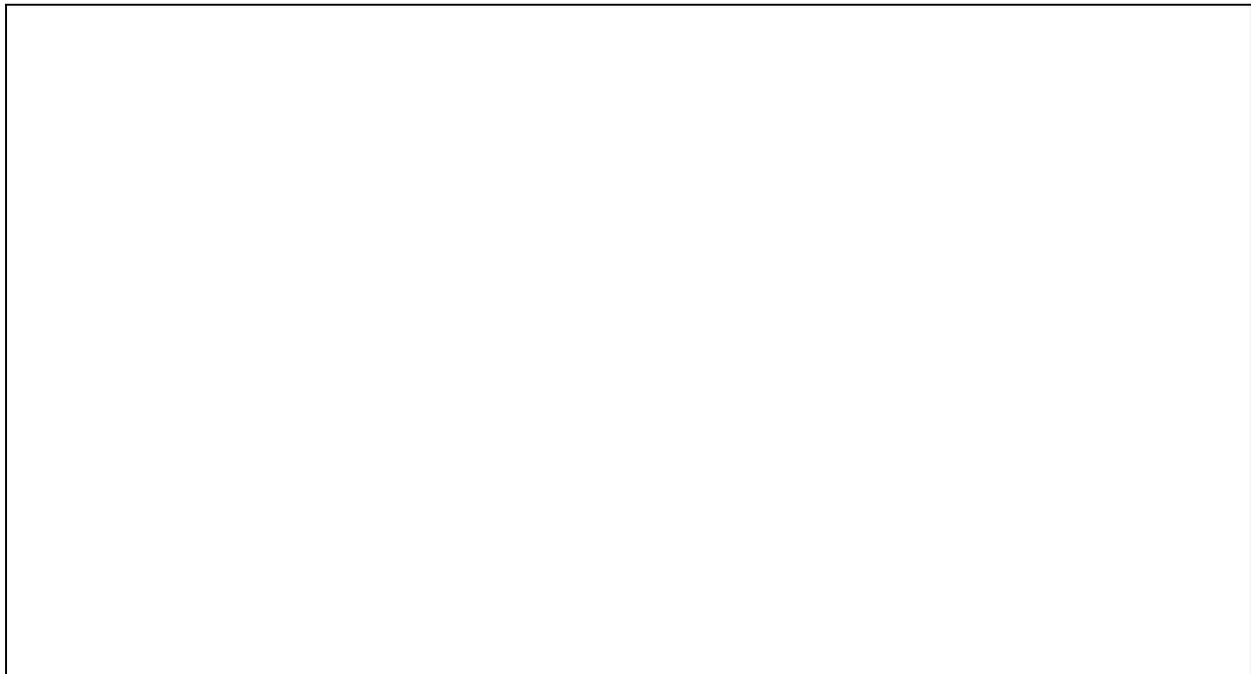
<sup>38</sup>Huang, p. 283.

under a load, downward stress is placed on the pavement and to keep from deforming, cohesion with pavement around the loaded location creates a force upward. These forces within the pavement layer are shear stress and are illustrated in Figure 2.2, which demonstrates a load placed on flexible pavement. Arrows within the pavement indicate the shear forces within the pavement. Unlike a flexible pavement, rigid pavements distribute loads much as beams do and resist loads without bending.

**Figure 2.2: Shear Forces on Flexible Pavement**

The difference in how the two types of pavements (ACC and PCC) resist loads is important in understanding the differences in the pavement designs. The surface layer (course) of an ACC (flexible) pavement must be strong enough to withstand the shear stress placed on the pavement by wheel loading. It must also have the resilience to resist permanent deformations due to wheel loading. In conjunction with the surface course, the layers beneath the asphalt layer work together to resist wheel loads. On the other hand, the surface layer of a PCC (rigid) pavement distributes the load across the layers below the pavement by transferring loads like a beam. Figure 2.3 illustrates a load placed on rigid pavement.

**Figure 2.3: Forces Exerted on Rigid Pavements**



AASHTO pavement designs also defined the pavement stresses created by tandem and tridem axles. Figure 2.4 illustrates stresses created by tandem axle loads according to traditional AASHTO pavement design standards. The figure illustrates the two axles of a tandem imposing a load on the pavement and causing stress in the pavement structure. As the stress is transmitted deeper into the pavement it is distributed through the pavement in an increasingly wider cone. According to AASHTO calculations, the stress cones of each wheel could intersect and overlap

under the center of the tandem, thus applying a greater stress on the bottom of the pavement than would two equally loaded wheels spread further apart. Hence, closely-spaced tandem axles on thick pavements may cause more wear than two single axles, each with half the load of the tandem. Thus, prescribing tandem axle spacings at a distance that ensures that stress cones do not overlap could reduce pavement wear. However, tandem axle spacing is not a parameter used in the AASHTO equation for determining the equivalent axle loading factors.

### **Figure 2.4 Areas of Overlapping Stress**

Recently, researchers have applied finite element analysis to more precisely determine the effect of tandem axle spacing on pavement stress. These researchers found that the influence of axle spacing on pavement wear is dependent on the extent to which the net response under one axle is affected by the forces created by the adjacent axle. When an axle passes over a point, two forces, tension and compression as shown in Figure 2.3, exist in the pavement structure near the axle. Tension is a pulling force immediately adjacent to the axle created by the downward forces exerted by the load. Compression is a pushing force originating immediately under the axle. Compression forces can counteract tension forces in rigid pavements because these forces are distributed over distances that are in the same order as common axle spacings. According to research results, the pavement wear resulting from one pass of a tandem axle can be less than the pass of two single axles carrying the same load, depending on the thickness of the pavement and the spacing of the axles within the tandem axle group. Researchers found that commonly spaced tandem axles (e.g., 4.25 ft) loaded at 36,000 pounds cause 1.40 ESALs of pavement wear, which is a 40 percent reduction over the wear caused by two 18,000 pound single axle passes (e.g., 2.0 ESALs).<sup>39</sup>

### **The 1986 and 1993 AASHTO Guide for Design of Pavement Structures and SHRP**

Since the AASHTO road tests, the design guide has gone through several revisions. However, the most recent versions of the design guides, the 1986 guide, and modifications made to the 1986 guide in the 1993 guide, are all primarily based on the same fundamental relationships developed through the AASHTO road tests.<sup>40, 41</sup> The AASHTO road tests were limited to a very few types of paving materials, one subgrade, homogenous traffic (and loading), and one environment. Further, the objective of the AASHTO road test was to determine the performance of pavement under repetitive axle loading. Although failure due to repetitive loading is important to the structural design of the initial pavement, there are many other factors which determine the service life of a pavement (e.g., failure due to environmental or material problems).

As a result of the many additional variables related to the life of pavements not taken into

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<sup>39</sup>Thomas Gillespie, et.al. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance*. Transportation Research Board, National Research Council. NCHRP Report 353. 1993. pp 16–17.

<sup>40</sup>*AASHTO Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials. AASHTO, Washington, D.C., 1986.

<sup>41</sup>*AASHTO Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials. AASHTO, Washington, D.C., 1993.

account during the original road tests, revisions of the design procedures have attempted to take these additional variables into account. The 1986 manual first included factors to qualify the reliability of a design. Other new factors deal with adjustments for freeze-thaw cycles, drainage, subbase erosion, and shoulder design. However, the design parameters are still fundamentally based on the same data and principles derived from the original AASHO road tests, and thus the design techniques reported in the 1986 manual and refined in the 1993 manual have the shortcoming of limited data and limited variation in the environment within which the data were collected.

The Long Term Pavement Performance (LTPP) program of the Strategic Highway Research Program (SHRP), begun in 1989, was intended to address many of the shortfalls of the AASHO road test. Among other things, LTPP would test the performance of pavements under varied conditions and provide information to improve the design equations for new and reconstructed pavements. SHRP evolved from an FHWA sponsored project on the role of research in revitalizing the United States highway transportation system.<sup>42</sup> The project, Strategic Transportation Research Study, was conducted by the Transportation Research Board during 1983 and early 1984. Focusing on the issue that the United States was under-investing in highway research, the project report identified six areas where more research needed to be conducted. They included asphalt, maintenance cost-effectiveness, protection of concrete bridge components, cement concrete in highway structures, control of snow and ice on highways, and long-term pavement performance.

The six issues were eventually combined into four strategic problem areas, and the SHRP was established as an independent unit of the National Research Council. The four strategic problem areas were:

- Asphalt
- Highway Operations
- Concrete and Structures
- Long-Term Pavement Performance

SHRP began in 1987 with a five-year budget of \$150 million, which was authorized by Congress through the Surface Transportation and Uniform Relocation Assistance Act of 1987. Later, the ISTEA of 1991 authorized another \$108 million for SHRP product implementation and for continuation of the 20-year LTPP program.<sup>43</sup>

The main feature of the LTPP program was to monitor test road sections located throughout the country and exposed to actual field conditions. This was the first massive field test since the AASHO road test. This was an effort to quantify the impacts of climate, maintenance practices, long-term loading effects, materials variations, and construction practices. SHRP devoted \$510 million for the first five years of the LTPP program to support the massive effort of establishing

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<sup>42</sup>William O. Hadley, *SHRP-LTPP Overview: Five-Year Report*. Strategic Highway Research Program, National Research Council, Washington, D.C., 1994, pp. 2-3.

<sup>43</sup>*SHRP Product Catalog*. Strategic Highway Research Program. National Research Council, Washington, D.C., 1992 (Foreword).

field test sections (a good share of the funding came from state highway agencies which installed the test sections and not from SHRP's budget).<sup>44</sup> The LTPP is scheduled to continue for an additional 15 years (20 in total). The objectives given the LTPP by the advisory committee were to:

- Evaluate existing methods
  - Develop improved strategies and design procedures for the rehabilitation of existing pavements
- Develop improved design equations for new and reconstructed pavements
- Determine the effects on pavement distress and performance of 1) loading, 2) environment, 3) material properties and variability, 4) construction quality, and 5) maintenance levels
- Determine specific design procedures to improve pavement performance
- Establish a National Pavement Performance Database (NPPDB) to support these objectives and future needs

After five years of data had been collected from the test sections through December, 1992, an SHRP research project was conducted to evaluate the AASHTO design equations.<sup>45</sup> The evaluation was conducted by analyzing the relationship between pavement performance in the field tests to the pavement performance predicted by the AASHTO design equations. Included in the evaluation were 244 sections of asphalt pavement and 120 sections of concrete pavement. The concrete sections consisted of unreinforced jointed concrete pavement, reinforced jointed concrete pavement, and continuously reinforced concrete pavement.

Based on reductions in serviceability in the test sections over the five-year period and based on the test section pavement cross sections, the researchers used the AASHTO design equations to predict the number of ESALs the pavement received. The AASHTO equations were used to predict the number of ESALs required to cause the observed loss in serviceability. If the AASHTO equations were accurate, then the predicted ESALs and the observed ESALs would be identical or nearly the same.

When the comparison was made for the predicted ESALs for asphalt pavement (using the AASHTO design equations) versus the observed traffic, the traffic predicted by the AASHTO equations consistently provided predictions which were much higher than estimates made from historical traffic records. This means that the pavements were wearing out faster than planned through the design equations. Only nine of the 244 traffic volumes predicted with the AASHTO equations were lower than the estimates of traffic made from historical information.<sup>46</sup> Almost half of the predicted traffic levels were more than one hundred times the estimated traffic volumes. Although the extreme lack of correlation between the ESALs predicted with the

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<sup>44</sup>Hadley, p. 5.

<sup>45</sup>Jerome F. Daleiden, J. Brent Rauhut, Brian Killingsworth, Emmanuel Owusu Antwi, Michael I. Darter, and Riaz Ahmad, *Evaluation of the AASHTO Design Equations and Recommended Improvements*. Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

<sup>46</sup>Jerome F. Daleiden, et al., p. 35.

AASHTO equations and the in-service data may be largely due to the shortcomings of the AASHTO equations, it is also partly due to the data limitation. For example, it was difficult to estimate the level of traffic exposure to pavement test sections which were in service prior to the test or the condition of these sections at the time of construction. In addition, the original AASHTO road tests, the basis of the AASHTO equations, were continued until the pavements completely failed. None of the test sections experienced this level of exposure.

When trying to explain the differences in predicted versus estimated traffic, the researchers developed a regression equation where the dependent variable was the ratio of the predicted ESALs, using the AASHTO design equation, to the estimated ESALs based on historical information. The regression resulted in a relatively good fit between the regression equation and the dependent variable, and 77 percent of the dependent variable variance was accounted for in the regression equation ( $R^2 = 0.77$ ). The independent variables included in the model were the average annual rain fall, the average annual number of days below freezing, subgrade modulus (a measure of soil strength), serviceability loss, structural number (a measure of the strength of combined pavement layers), and the thickness of the existing seal coats. The researchers felt that the results indicated the importance of environmental variables which are not adequately taken into account in the AASHTO design equations.

Similar comparisons were made for the concrete test sections where the predicted number of ESALs, based on the AASHTO design equations, were compared to the historical estimate of the level of traffic exposure. The results showed that nearly half of the estimated traffic volumes were greater than the predicted volumes and nearly half were below. Although, on the average, the predictions based on the AASHTO equations were close to the average estimated traffic volumes levels, the variation about the mean was dramatic. Using the ratio of the predicted traffic to the estimated traffic, the standard deviation of the ratio was four (the mean being roughly one). Although the AASHTO equation for rigid pavements is an unbiased estimator of life, it is highly inaccurate.

The results of these evaluations show that the use of the AASHTO design equations can result in considerable error and, in the case of flexible pavements, they tend to grossly overestimate the life of the pavement. In the case of asphalt pavement, the researchers suggest that serviceability, which is largely a function of pavement roughness, is not a very good predictor of pavement condition. Instead, they suggest that other individual distresses, such as fatigue cracking, rutting, and thermal cracking, may be better indicators of performance.

### **Pavement Design Methodologies in Other Countries**

Methods used to structurally design pavement in the United States and in other countries are empirical methods based on past experience in road tests or, as the British have done, test sections placed in normal traffic. There are fundamentally two types of design techniques. One technique is like the AASHTO methods where the designer starts with a standard set of input data (e.g., materials strength values, measure of the adequacy of drainage, and traffic projections) and works through a number of tables and nomographs to determine a pavement design. The other technique uses predefined design solutions identified in a catalog. As is done in the French concrete pavement catalog, the designer may only need to input information regarding traffic and the classification of the subgrade and the catalog identifies a

standard design.<sup>47</sup>

The Germany Federal Ministry of Transportation also uses a design catalog for selecting pavement designs. In 1965 the original catalog was developed by a panel of experts based on the findings of the AASHO road tests.<sup>48</sup> Since then there have been only relatively minor modifications to the design catalog. Unique designs for projects are not used, and modifications to standard designs are only allowed when the modification is supported by testing done at Germany's Federal Highway Research Institute.

In theory, methods like the AASHTO method treat each design as unique. Depending on the environmental/climatic conditions, the properties of materials, and the expected traffic, a unique design is developed. In practice, agencies may tend to use standard designs which meet or exceed the requirements identified in the analysis, mixed with experience related to what does and does not work well. In theory, pavements which are uniquely designed to fit the specific characteristics of each application will be more efficient than pre-selected designs specified in a catalog. Unique designs focus on developing the best designs possible for each situation. However, given the unreliability of designs using the AASHTO design equations in practice, the benefits of using design equations rather than preselected standards which have historically been shown to work well, are questionable.

### **Pavement Failure**

Although pavement design methods most squarely focus on the structural strength of pavements and the designing of pavements which will survive over their design life without failing due to fatigue from repetitive axle loading, pavement failure may be due to several causes other than structural failure. Characteristics indicating the failure of a pavement may be a loss of surface friction, pavement rutting, pavement roughness, or the high cost of pavement maintenance. Each of these failure mechanisms is related to repetitive axle loading in some regard, but the primary cause of failure is not structural fatigue. Friction loss due to polishing of aggregate, for example, is believed to be unrelated to the weight of the axle loads and more closely related to the passage of axles regardless of their weight. More specifically, the AASHO road tests found that serviceability loss is proportional to roughly the fourth power of the weight of repetitive axle loads. Loss of skid resistance of the pavement is, however, not proportional to the weight of the axle loads (e.g., zero power) and is a function of the number of passage of axles.<sup>49</sup> Similarly, in asphalt pavement the rate of increasing alligator cracking is proportional to the 1.3 power of the weight of repetitive axle loads, rutting is proportional to the 4.37 power, and transverse cracking is proportional to the 1.7 power. Each type of distress could result in failure and trigger the need to restore the pavement; however, all are more or less related to wear imposed by the axle loading of heavy trucks.

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<sup>47</sup> A. De Boissoudy, M. Th. Goux, and P.Genre. *New Concrete Pavement Structures in the Revision of the French Catalogue of New Pavements and in the Technical Guide of Overlays*. 1988.

<sup>48</sup> Roger M. Larson, Suneel Venikar, and Stephen Forster. *U.S. Tour of European Concrete Highways (U.S. Tech) - Follow-up Tour of Germany and Austria - Summary Report*. Federal Highway Administration, Washington, D.C., 1993, p. 2.

<sup>49</sup> D.F. Kinder and M.G. Lay. *Review of the Fourth Power Law*. Australian Road Research Board, Vermont South, Victoria, 1988, p.4.

In addition to structural failures due to repetitive loading, pavements can also suffer material-related failures. Material failures may be accelerated or aggravated by repetitive heavy axle loads, but the primary cause of material-related pavement failures may be related to either:

- A chemical reaction between material used in the paving and materials in the pavement environment. One of the serious chemical reactions is alkali-silica reactivity (ASR) in concrete pavements. This is a complex reaction between silica or silicate in the aggregates with alkalizes in the cement. The silica and alkali react to create a gel, and in the presence of moisture the gel expands, creating tensile forces within the concrete and ultimately causing failure of the pavement.
- A physical reaction (usually the result of water absorbed into the paving materials expanding when temperatures are below freezing) and environmental effects. Although there are numerous physical/environmental related failures, the most serious is caused by porous aggregate in concrete pavement which absorbs water. When the pavement freezes, the aggregate expands and breaks the aggregate-cement bond. After repetitive freeze-thaw cycles, the pores in the pavement open allowing more moisture to enter the concrete slab and expand during the next freeze. This activity, known as “D” line cracking, can create serious structural damage.

Pavement failures are caused by a myriad of interrelated issues, some of which are highly dependent on loads imposed by heavy trucks (e.g., rutting in asphalt pavements) and some which are completely independent of axle weights (e.g., loss of surface friction). Thus it is very difficult to understand the implications of changes in static axle loading to the additional costs of construction, maintenance, and rehabilitation of highways. For example, the SHRP evaluation of the AASHTO asphalt pavement design equations found that their insensitivity to environmental impacts caused the resulting predicted pavement life to be grossly unreliable. This result makes it even more difficult to predict the impacts of trucks with suspensions which minimize dynamic loads.

### **The DIVINE Project**

The DIVINE (Dynamic International Vehicle-INfrastructure Experiment) project is a cooperative international research program managed through the Organization for Economic Cooperation and Development (OECD).<sup>50</sup> The purpose of the DIVINE project is to better quantify the impact of heavy vehicle dynamic loading on pavements and bridges. It involves 17 OECD member countries and includes specialists in vehicles, pavement, bridges, pavement management, and transportation policy. The project began in October 1993 and is expected to be completed in the winter of 1995-96, with reporting of the results to be drafted and interpreted during the ensuing months.

The project is designed to answer a number of questions. The four primary research questions

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<sup>50</sup>C.G.B. Mitchell and R.R., Addis, *Dynamic Pavement Loads and Road Wear: Scientific Questions the OECD Divine Projects is Intended to Answer*. Presented at the Fourth International Symposium on Heavy Vehicles Weights and Dimensions, Ann Arbor, Michigan, June, 1995.

are:

1. Under controlled conditions, by how much do dynamic loads reduce the life of road pavements?
2. How do the results obtained under controlled conditions transfer to real road conditions with mixed traffic?
3. How should we specify and test heavy vehicles for road friendliness?
4. How much increase in pavement life should we expect from road friendly, heavy vehicles in practice?

Two important but secondary questions addressed by the project are:

1. Are vehicles that are friendly to roads also friendly to bridges?
2. Which computer simulation models of heavy vehicle dynamics are accurate and easy to use?

The project has been designed in six elements where each element is intended to answer one of the research questions above. Each of the six elements is being addressed by a multinational team. Clearly the project will create much new information regarding the dynamic interaction between vehicles, pavements, and bridges, as well as help to better calibrate simulation tools intended to analyze the impacts of vehicle dynamics. How and if these results can be incorporated into pavement or vehicle design, vehicle size and weight regulation, highway use cost allocation, and transportation policy will probably evolve over the next several years.

## Bridge Design Overview

The following provides a brief overview of bridge stress terminologies, bridge design codes, and the background of and issues related to the current federal bridge formula.

### Bridge Stress

Heavy vehicles create two kinds of stress of concern in bridge structures: overstress and fatigue.

**Overstress** Overstress is defined as the possibility of severe damage and possible structure collapse caused by a single extreme overloading event. The loading event that governs bridge capacity in most instances is when two or more heavy vehicles are on a bridge simultaneously. The likelihood of this happening increases as heavy truck traffic increases. The other variables that augment this effect are the dynamic impact of the load and the load distribution. Bridge engineers are cautious when calculating the stresses in bridges caused by a given loading instance. Therefore, the actual measured bridge stresses are generally much less than the bridge stresses used to develop bridge designs.

**Fatigue** Fatigue is defined as the cumulative wear caused by thousands or even millions of loading events. These events can cause cracks or ruptures in the bridge structure. Each vehicle that crosses a bridge produces one or more stress cycles, each of which consume a portion of the bridge's total fatigue life. A widely held assumption was that only steel bridge components are susceptible to fatigue. However, recent studies indicate that prestressed concrete bridges are also susceptible to fatigue. A generally accepted bridge design principle is that bridge stress (bridge wear) due to loading increases with respect to the third power of the increase in load. Therefore, a doubling of stress during a single loading event causes eight times greater bridge wear.<sup>51</sup>

### Bridge Design Codes

Codes developed by AASHTO specify the vehicles that are to be used in the design and evaluation of bridges. Table 2.1 provides the AASHTO vehicle gross weight and load distribution for three common bridge designs.

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<sup>51</sup>J.W. Fisher. *Bridge Fatigue Guide*. American Institute of Steel Construction. Chicago, IL. 1977.

**Table 2.1: AASHTO Bridge Design Vehicles**

<b>Bridge Design Type</b>	<b>Gross Weight</b>	<b>Load Distribution</b>	
		<b>Front Axle</b>	<b>Rear Axles</b>
HS-15	30,000 lb (2 axles)	6,000 lb	24,000 lb
HS-20	40,000 lb (2 axles)	8,000 lb	32,000 lb
HS-20	72,000 lb (5 axles)	8,000 lb	32,000 lb
HS-25	90,000 lb (5 axles)	10,000 lb	40,000 lb

The vehicle for the HS-20 bridge design was introduced in the 1940s to better resemble truck and trailers of that time and has been used to design most interstate highway bridges.<sup>52</sup> This design provides for variable axle spacing between the tractor and trailer tandems ranging from 14 to 30 feet and is capable of assessing worst-case loading for long continuous spans. Even though the specified tractor to trailer axle spacings are not a legal load for one vehicle because the spacing between the tractor and trailer tandems is shorter than bridge formula B specifications, the bridge design assesses the effects of multiple legally loaded vehicles that are closely following each other.

The HS-15 and HS-20 designs are supplemented by a uniform lane load for longer spans. Some states have introduced the HS-25 bridge design that accommodates 25 percent larger loads than the HS-20 design type. This stronger bridge design was introduced to reflect the increase in permitted vehicle gross weight in recent years.

AASHTO has also developed three theoretical “typical legal load types” that are used by some states as an alternative to the HS-20 theoretical vehicle for evaluating bridge design. The three theoretical load types were selected to closely match the federal bridge formula that governs vehicle gross weights up to 80,000 pounds. Figure 2.5 illustrates a “typical legal load type” for a 5 axle 3S-2 unit at 72,000 pounds gross weight.

**Figure 2.5: AASHTO “Typical Legal Load Type” (3S-2 Unit)**

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<sup>52</sup>*Truck Weight Limits: Issues and Options*. Transportation Research Board. National Research Council. Special Report Number 225. Washington, D.C. 1990. pp.91-105.

### **Background of Federal Bridge Formula**

The current bridge formula for governing multiple axle group weights is Bridge Formula B. It was derived from assumptions regarding the extent to which legal vehicles should be allowed to exceed the stresses assumed in bridge design. The current bridge formula was derived to avoid overstressing HS-20 bridges by more than five percent and H-15 bridges by more than 30 percent.<sup>53</sup> The HS-20 bridge design is the AASHTO recommended minimum for interstate highways. The rationale for adopting these overstress limits was that the majority of heavier loads would travel on the interstate and primary road systems. Thus, adopting more conservative overstress limits would minimize the fatigue that occurred on the most heavily used bridges.

It should be noted that the adopted overstress limits of five percent (for HS-20 bridges) and 30 percent (for H-15 bridges) were set arbitrarily. In addressing acceptable bridge overstress criteria, one recent truck size and weight policy study by the Transportation Research Board stated:<sup>54</sup>

“New truck weight regulations should be evaluated on the basis of overall costs rather than arbitrary overstress criteria. Arbitrary assessments such as 5 percent overstress on HS-20 have no meaning in terms of either consistent reliability or impact costs. In assessing the bridge impacts of a change in truck weight regulations, costs to be considered include new design, replacement of bridges that become structurally deficient by the new weight regulations, and fatigue life reduction for existing and new bridges.”

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<sup>53</sup>*Truck Weight Limits: Issues and Options.* p.104.

<sup>54</sup>*Truck Weight Limits: Issues and Options.* p.105.

## Issues Related to Current Bridge Formula

Two issues pertaining to the current bridge formula have implications related to performance-based standards. They are the conservative weight limits that have been developed for short wheelbase vehicles to protect HS-15 bridges and the 80,000 pound upper weight limit cap.

The current bridge formula specifies a conservative weight limit for shorter trucks when evaluating the interstate highway system because fewer than 1,000 of the 50,000 bridges on that system have design limits of HS-15 or less.<sup>55</sup> The bridge formula would allow much higher gross weight limits for shorter vehicles if the 30 percent overstress criteria for HS-15 bridges were dropped. For example, the current bridge formula limits the gross weight of a four-axle vehicle with extreme axle dimensions of 20 feet to 55,000 pounds. However, this same vehicle could carry weights up to 66,000 pounds without overstressing HS-20 bridges beyond the five percent limit.

The primary factor for determining vehicle gross weight limits under the current bridge formula is the distance between the extreme (farthest spaced) axles of any axle group. Therefore, length and load distribution are the most important requirements of protecting bridges. Quite apart from AASHTO pavement design methods, the number of axles and individual axle loads bears little relationship to the stress applied to bridges.

The relationship between dynamic loading and bridge wear is less likely to be a factor in determining the benefits of performance-based size and weight specifications than the relationship between dynamic loads and pavements. However, unlike a roadway surface where there is assumed to be no elastic interaction between the vehicle and the road, there may be elastic interaction between the vehicle and bridges. Some long span bridges have fundamental bending frequencies which are in the range where low frequency air spring suspensions could cause a dynamic interaction between the vehicle and the bridge.<sup>56</sup> As a result, vehicle suspensions which are considered road friendly could possibly be more damaging to certain bridges. One of the elements of the DIVINE project is addressing this issue.

## Conclusions

Size and weight limits for both pavement and bridge considerations have often been arbitrarily established. In the future, as the results of the DIVINE project and the findings of other similar research are put into practice, methods will be developed which more optimally match infrastructure to expected traffic exposure and performance attributes of the heavy vehicles in the traffic stream. Although the performance attributes of vehicles have a much greater impact on pavements than on bridges, in both cases state-of-the-practice design techniques do not take dynamic forces into account. Because of these limitations and the clear limits in the reliability and accuracy of design methods, it is difficult (and probably impossible) to accurately determine the benefits and costs of performance-based standards to the highway infrastructure. What is clear, however, is that

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<sup>55</sup>*Truck Weight Limits: Issues and Options.* p. 98.

<sup>56</sup>*Dynamic Pavement Loads and Road Wear: Scientific Questions the OECD Divine Projects is Intended to Answer.* p. 6.

examination of relationships between vehicle performance standards and infrastructure design and costs will support a more rational structure for regulating the dimensions of trucks. There is, unfortunately, much research remaining before the relationships are fully understood. The SHRP LTPP's evaluation of the AASHTO pavement design equations has shown that decades of research and practice have resulted in methods which are unreasonably unreliable and point out the need to invest in research to continue to better understand the relationship between infrastructure performance and repetitive heavy vehicle loading.

### **CHAPTER 3: ELEMENTS OF HEAVY VEHICLE PERFORMANCE AFFECTING THE TRAFFIC SAFETY ENVIRONMENT**

The types of vehicles and vehicle combinations operating on the roads continue to increase as the trucking industry meets the continuously increasing demand for the transport of goods. Vehicle designers are developing new designs to increase the productivity of trucks. Standard test procedures that can be used to test the handling characteristics of new designs need to be developed in order to assure that the new designs are safe to operate on the road and minimize road wear.

The purpose of this section is to provide an overview of the critical elements of heavy vehicle performance. Performance-based standards can and do consider these critical elements either through pure performance standards or through parameters which are related to safety or road wear performance. This section is primarily for the vehicle designers and transportation officials who would be responsible for setting the values and specifying test procedures for assessing the ability of a vehicle to safely carry additional weight. However, the operators whose trucks have to meet these requirements should also be familiar with the vehicle parameters that are used to set performance-based standards.

This section reviews some of the vehicle components and parameters that have significant impact on dynamic vehicle performance. New Zealand's performance-based standards for "A" trains provides a good example of the actual application of parameters related to safety standards.

New Zealand enacted regulations in 1989 to increase the allowable gross weight of certain vehicles (two-trailer "B" trains) from 39,000 kilograms (86,000 pounds) to 44,000 kilograms (97,000 pounds). However, certain other vehicle configurations (e.g., two-trailer "A" trains used in the dairy industry) may also operate at the higher gross weights provided they meet the following minimum, parameter-based, performance standards:

- Static roll threshold = 0.45 g or greater
- Dynamic load transfer ratio = 0.6 or less
- High speed transient off-tracking = 0.5 meters or less

These three measures provide an indication of the dynamic performance of the vehicle. The static roll threshold is the maximum tilt angle or lateral acceleration which a vehicle can attain before it tips over. The dynamic load transfer ratio measures how close a vehicle is to rollover in a highway speed evasive steering maneuver. High speed transient off-tracking is the lateral offset between the trajectory of the lead and trailing units during a turn. The purpose of this measurement is to ensure that the vehicle will not strike a curb, potentially resulting in a rollover, or hit a vehicle in an adjacent lane.

The remainder of this chapter describes critical elements which dictate the safety and road wear performance of trucks. For example, the following section discusses the role of tires in the ability to maneuver a truck. Tire cornering stiffness, for example, is important in defining a vehicle's ability to maneuver in a high speed turn or in an emergency avoidance situation. Although a parameter-based performance standard would not measure tire cornering stiffness

itself, tire cornering stiffness may be a factor taken into account when developing a parametric standard for vehicle performance. High-speed transient off-tracking is dependent on tire cornering stiffness (as well as other vehicle properties) and, therefore, maximum permissible levels of high-speed transient off-tracking govern tire cornering stiffness. Several of these individual critical elements are discussed in the remainder of this chapter.

## Tires

Tires are the primary ingredient in determining vehicle performance during maneuvers. The interaction of the tires and the roadway surface govern the response of a truck to steering maneuvers. Therefore, the mechanical properties of the tire must be fully understood if the directional performance characteristics of heavy vehicles are to be understood. The properties of a tire which have the largest effect on vehicle handling need to be identified so that standards can be set for determining regulations.

The forces required to keep a vehicle on the selected course are provided by the frictional coupling between the tires and the pavement and the cornering stiffness of the tire. The following paragraphs provide an overview of the concepts of friction coupling and cornering stiffness and the issues related to monitoring tire performance.

### Friction Coupling

The friction coupling between the tire and road is generated by two primary mechanisms: surface adhesion and hysteresis. Surface adhesion results from the intermolecular bonds between the rubber and the aggregate in the road surface. Surface adhesion provides a larger portion of friction coupling on dry roads, but on wet roads its emphasis is substantially reduced.<sup>57</sup>

Hysteresis is the other mechanism that creates friction coupling. Hysteresis is the energy lost from the deformation of the rubber as it slides over the aggregate in the road. Hysteresis friction is not as affected by wet roads; therefore, tires designed for wet conditions will have a high hysteresis rubber in the tread compound.<sup>58</sup>

### Cornering Stiffness

A very important property of a tire is cornering stiffness, which is defined as the rate of change in lateral force generated per degree of tire slip angle. Slip angle is defined as the difference between the center plane of a wheel and the direction that the wheel is actually traveling. Tire manufacturers measure the cornering stiffness by plotting the lateral force generated by the tire against the slip angle. The cornering stiffness is then defined as the slope of the curve evaluated at a slip angle of zero degrees. Figure 3.1 illustrates how cornering stiffness is measured. In the figure, the line denoted as  $C_{\alpha}$  is the plane of reference from which slip angle is measured. Figure 3.1 also shows how the lateral force of a tire varies with the slip angle. Lateral force continues to build until it

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<sup>57</sup>Thomas Gillespie. *Fundamentals of Vehicle Dynamics*. Society of Automotive Engineers. Warrendale, PA. ISBN 1-56091-199-9.

<sup>58</sup>Gillespie. p. 342.

reaches a peak, after which it drops down and stays constant. The maximum lateral force generally occurs around 15 to 20 degrees of slip angle. Increasing the slip angle further only causes the tire to begin to slide across the pavement instead of rolling. Tires with higher cornering stiffness will generate more lateral force per degree of slip angle.

### **Figure 3.1: Cornering Stiffness Calculation**

The main factors that influence cornering stiffness are the normal load on a tire and the depth of the tread, given tire size and inflation pressure are constant.<sup>59</sup> The normal load, which is the force applied on the tire by the road in a plane perpendicular to the road surface, is the dominant factor. Generally, increasing the normal load on a tire will increase its cornering stiffness. The relationship between cornering stiffness and normal load is nearly linear for radial tires. However, the change in cornering stiffness of a radial tire increases as it approaches the maximum rated load. Figure 3.2 shows how the cornering stiffness changes with increasing normal load for radial tires. The loop, or envelope, illustrated in the figure is generated by plotting the results for numerous tires on the same graph. Thus changes in cornering stiffness occur more rapidly when steering maneuvers create considerable load transfer, which could allow the vehicle to become unstable in an emergency maneuver.<sup>60</sup>

### **Figure 3.2: Change in Cornering Stiffness with Increasing Load**

Tread depth is the other factor in determining the cornering stiffness of a tire. The relationship between tread depth and cornering stiffness is illustrated in Figure 3.3. The plotted curves in the figure illustrate the changes in cornering stiffness with increasing loads for four heavy duty truck tires (11R × 22.5). The bottom two curves represent changes in cornering stiffness for tires with full tread depths and the top two curves represent changes in cornering stiffness for two tires at one half and one third tread depth. The figure illustrates that cornering stiffness can significantly increase as a tire wears. Thus, the worst handling should occur when tires are new. Since the worst handling occurs when a tire is new, all performance-based standards tests should specify that trucks are tested with new tires, assuming that the handling should improve as the tire wears.

### **Figure 3.3: Effect of Tread Depth on Cornering Stiffness**

The change in cornering stiffness with load and wear is very predictable for a given tire. For dry roads, the change in cornering stiffness as the tire wears is generally not a factor in normal driving, but may become a factor in how the truck responds during emergency maneuvers when large load transfers occur. Changes in the cornering stiffness can easily be included in computer simulations of dynamic response and directional stability to determine if a tire will cause problems as it wears. Running a computer simulation can determine if increasing the gross weight will cause a vehicle to handle poorly in accident avoidance maneuvers. Vehicles which do not meet minimum standards would not be allowed to have a higher gross weight.

## **Testing Tire Performance**

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<sup>59</sup>Gillespie. p.351.

<sup>60</sup>Paul Fancher. *Directional Dynamics Considerations for Considerations for Multi-Articulated, Multi-Axled Heavy Vehicles*. Society of Automotive Engineers SAE 892499. Warrendale, PA. 1989. pp19-29.

The development of recommended practices for determining the characteristics of a tire during free-rolling cornering, straight line braking, and combined cornering and braking is being conducted by Pottinger, et al. as a Society of Automotive Engineers Cooperative Research project under the supervision of the Truck Tire Characteristics Task Force.<sup>61,62</sup> The tire tests were conducted at the CALSPAN Corporation using the TIRF tire test machine and at the University of Michigan Transportation Research Institute (UMTRI) using the Mobile Truck Traction Dynamometer.

The TIRF machine uses a stainless steel belt coated with an emery cloth or sand paper to simulate the pavement surface. The belt rotates on two 67-inch steel drums and is supported by an air bearing under the tire contact region. A five component load cell is used for sensing tire forces and moments.

The Mobile Truck Traction Dynamometer has two testing stations on a long wheelbase, three-axle highway tractor towing a single-axle semitrailer. The semitrailer is used for straight line braking tests only. The other station is a special axle mounted at the midpoint of the wheelbase on the tractor. A six component load cell for sensing tire forces and moment vectors is used on the right side spindle while the left side serves to counteract the forces generated by the right side so that disturbances to the truck's path are reduced.

The CALSPAN TIRF machine produced the more repeatable results, but since the UMTRI Mobile Truck Traction Dynamometer uses an actual road surface, the data produced may be more realistic. This is not to say that the data produced by one machine are better than the other, only that the data are different. Therefore great caution should be used before the data from the two machines are mixed. See Pottinger, et al. for a complete description of the tire tests.<sup>63,64</sup>

The results of these tests indicate that a standard test procedure must be set to determine the properties of tires which are to be used for performance-based regulations. Otherwise a situation could arise that would allow a vehicle to pass a performance-based regulation when the tires are tested on one machine but fail when tested on another machine.

### **Friction Demand**

Friction demand is a measure of the friction needed between the tire and road for a truck to negotiate a tight turn. The friction level needed for the rear axles of the tractor may exceed the available friction on slippery surfaces if the semitrailer has a widely spaced axle set. Values for the coefficient of friction which are used as a pass/fail criteria are 0.1 and 0.2 for high and low

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<sup>61</sup>Marion Pottinger, et al. *A Free-Rolling Cornering Test for Heavy Duty Truck Tires*. Fourth International Symposium on Heavy Vehicle Size and Weight. Ann Arbor, MI. June, 1995.

<sup>62</sup>Marion Pottinger, et al. *A Combined Cornering and Braking Test for Heavy Duty Truck Tires*. Fourth International Symposium on Heavy Vehicle Size and Weight. Ann Arbor, MI. June, 1995.

<sup>63</sup>Pottinger, et al., 1995a.

<sup>64</sup>Pottinger, et al., 1995b.

speed friction demand respectively.<sup>65</sup> A vehicle which has a friction demand greater than 0.2 will have a tendency to jackknife on low friction surfaces.

Lateral friction utilization is another measure of how the vehicle interacts with the pavement. The lateral friction utilization of an axle group can be expressed as:<sup>66</sup>

where:

LFU = Lateral force utilization

abs = Absolute value

$F_y$  = Lateral force

$F_z$  = Normal load

$\mu_p$  = Peak tire/road coefficient of friction

The lateral friction utilization shows which axle group is likely to skid first during a high speed path change maneuver. This can be useful in determining the handling limits of the vehicle. For example, increasing the gross weight limit may allow a vehicle to carry larger loads. Larger loads may in turn raise the center of gravity and cause higher normal loads. Higher normal loads may reduce the lateral friction utilization to the point where the vehicle could go out of control. Performance-based standards based upon the friction utilization would ensure that increasing the gross weight of a vehicle would not adversely affect its handling.

### **High-Speed Transient Off-tracking**

Generally, vehicles driven at highway speeds are steered to follow a desired path around a curve and the trailing units are expected to follow the path of the lead unit. At low speeds, the trailing units of a combination tend to track towards the inside of the turn, creating a phenomena known as low-speed offtracking. However, off-tracking towards the inside of the turn begins to diminish and becomes zero at some speed. At speeds above that point, the trailing units may track to the outside of the path of the lead unit.<sup>67</sup> Tires play an important role in determining the amount of high-speed transient off-tracking. When a vehicle goes around a curve, the load on the tires changes, but the sum of all the loads still equals the total vehicle weight. High-speed transient off-tracking occurs because the load of the tires on the outside of the curve increases, while the load of the tires on the inside of the curve decreases by the same amount. This transfer of load, known as lateral load transfer, is the amount of load that shifts from one side of the vehicle to the other.

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<sup>65</sup>M. El-Gindy. *The Use of Heavy Vehicle Performance Measures for Design and Regulation*. DSC-Vol 44, Transportation Systems - ASME 1992.

<sup>66</sup>M. El-Gindy. p. 373.

<sup>67</sup>Paul S. Fancher and Arvind Mathew. *Safety Implications of Various Truck Configurations - Vol III: Summary Report*. Report No. FHWA-RD-89-085. Turner-Fairbank Highway Research Center. FHWA. McLean, VA. 1990. p 15.

The amount of lateral load transfer, which occurs during the cornering of the vehicle, is dependent upon the loading of the trailer, roll stiffness of the suspension, and width of the axle track. A trailer with a higher center of gravity will have higher load transfer rate. This higher load transfer rate accelerates the change in the normal loads on the tires. The interaction of the lateral load transfer and the lateral forces makes it very hard to know if a vehicle would pass a high speed off-tracking test. A driver would have no way of knowing whether a particular combination of tires, suspension, and center of gravity of the load would be within the limit prescribed by a performance-based regulation. The only way to test it would be to actually drive the vehicle on a test course or run a computer simulation. One recent study recommended the following target performance level for high-speed transient offtracking:<sup>68</sup>

“The vehicle is envisioned to be in a steady turning situation on a radius of 1,200 ft and traveling at 55 miles-per-hour. The selected target is for the center of the vehicle’s last axle to track not more than one foot outside of the path of the center of the front axle.”

### **Rearward Amplification**

With the use of multiple trailers, the lateral stability of the vehicle becomes one of the primary safety concerns. Rearward amplification is one measure that can be used to determine the lateral stability of a vehicle. Rearward amplification has the same effect as cracking a whip. A small movement at the tractor can result in a large motion at the rearmost trailer. Rearward amplification is a measure of how much the side-to-side motion increases, relative to the lead unit, as you move farther back toward the rear of the vehicle. Rearward amplification typically expresses the ratio of either the lateral acceleration or the yaw velocity gain of the last unit in a combination relative to the first unit.

The factors which affect the sensitivity of measured rearward amplification values need to be identified if an acceptable standard is to be developed. It is well known that the rearward amplification is dependent upon the frequency of the input steer excitation. A single lane change maneuver is generally used as the input steer excitation. Winkler and Aurell investigated the influence of maneuver severity, instrument type and location, and data reduction method.<sup>69</sup> The effect of path compliance, which is how closely the vehicle’s steer axle follows the prescribed path, on rearward amplification was investigated by El-Gindy and Preston-Thomas.<sup>70</sup>

The influence of maneuver severity on the lateral acceleration and yaw velocity is a result of the rear tires’ ability to generate lateral forces. As the level of input excitation for the lead unit increases, the level of traction required by the rear tires quickly begins to exceed the available traction, due to the amplification factor. The available traction of the rear tires limits the level of

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<sup>68</sup>Fancher and Mathew. p 15.

<sup>69</sup>Chris Winkler and John Aurell. *Standard Test Procedures for the Lateral Stability of Heavy Vehicle Combinations*. Fourth International Symposium on Heavy Vehicle Size and Weight. Ann Arbor, MI. June, 1995.

<sup>70</sup>M. El-Gindy and J. Preston-Thomas. *Path Compliance In Lane-Change Tests Designed To Evaluate Rearward Amplification*. Heavy Vehicle Systems, International Journal of Vehicle Design. Vol. 1, No. 1. 1996.

lateral acceleration, but increases the yaw gain.<sup>71</sup> The type of accelerometer and the mounting point were found to have a significant impact on the level of lateral acceleration measured. The roll motion of the trailer contributed significantly to the readings and was dependent upon the mounting height of the accelerometer.<sup>72</sup> The three types of data reduction used were: 1) maximum absolute value from the trace of the acceleration over time and through the maneuver; 2) the average of the absolute values of the positive and negative peaks of the lateral acceleration; and 3) an equivalent peak derived from the root mean square (RMS) of the lateral acceleration at the tractor. The different data reduction methods resulted in a significant spread of values, particularly for the yaw velocity.<sup>73</sup> The average peak and RMS peak methods had the best agreement. The variability indicates that the standard for rearward amplification also needs to include specifics on the method of data collection and analysis. All other performance standards should specify the procedure for data collection and analysis, since they would be subject to similar variations.

The influence of the path compliance was found to have a large impact on the measured values of rearward amplification. The  $\pm 150$  millimeter path compliance tolerance specified in the SAE J2179 and proposed International Standards Organization (ISO) standards introduces uncertainty in the magnitude and frequency of the actual path traversed by the steer axle. Analysis of the fixed path compliance tolerance in the SAE J2179 standard for rearward amplification showed that it has the potential to allow input steer frequencies to vary by 60 percent to 200 percent of the specified 0.4 Hertz (Hz), which results in variations of 40 percent to 300 percent in the lateral acceleration.<sup>74</sup> A variable path tolerance has been proposed to reduce the problems of the fixed path tolerance. A variable path tolerance would have the effect of making the path-based experimental errors relatively independent of frequency and magnitude.<sup>75</sup>

The current rearward amplification standards are most likely not detailed enough to use for performance-based regulation. The single test frequency which is used in the SAE test is a result of experimental tests which indicate that peak rearward amplification for the majority of heavy combination vehicles occurs when the input steer frequency is around 0.4 Hz.<sup>76</sup> However, the test procedure was considered sufficiently general that the authors recommended its extension to other frequencies and amplitudes when the circumstances warranted it.<sup>77</sup> In order to eliminate experimental errors, it may be best to use a validated computer simulation to conduct tests that would be used for performance-based regulation.

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<sup>71</sup>Winkler and Aurell. p. 4.

<sup>72</sup>Winkler and Aurell. p. 4.

<sup>73</sup>Winkler and Aurell. p. 5.

<sup>74</sup>El-Gindy and Preston-Thomas. p. 11.

<sup>75</sup>El-Gindy and Preston-Thomas. p. 11.

<sup>76</sup>El-Gindy and Preston-Thomas. p. 2.

<sup>77</sup>El-Gindy and Preston-Thomas. p. 2.

### **Static Roll Threshold**

The static roll threshold measures the angle at which a vehicle can be tilted before it tips over. The static roll threshold can also be defined as the maximum lateral acceleration that a vehicle can sustain in a steady turn before rollover occurs.

Studies of accident investigations have shown that the static roll threshold of trucks correlates well with the incidence of rollover. It would be possible to install a device that would measure the tilt angle at weigh stations, but the cost of the equipment and time needed to perform the tests make it an impractical solution for widespread use.

### **Dynamic Load Transfer**

The dynamic load transfer of a vehicle can be used to determine the dynamic roll stability of a vehicle. The dynamic load transfer can be defined by the load transfer ratio (LTR) which is calculated using the following equation:<sup>78</sup>

where

abs = absolute value

$F_{ZR}$  = wheel loads on the right side of the vehicle

$F_{ZL}$  = wheel loads on the left side of the vehicle

$F_Z$  = wheel loads of the entire vehicle

A value of 0.6 for the LTR has been recommended as the maximum acceptable value when traveling at 100 kilometers per hour, the vehicle is subjected to a sinusoidal steer input of 1.0 degrees with a period of 3.0 seconds resulting in a steering frequency of 2.1 radians/sec.<sup>79</sup> This is another test that would require much instrumentation, space, and time to perform, which makes it impractical to conduct at a roadside station.

### **Dynamic (Lateral) Stability**

The dynamic, or lateral, stability of a vehicle configuration consists of two components, rearward amplification and yaw damping. Rearward amplification is defined as the amount of the lateral acceleration, or yaw velocity of the first vehicle in a configuration (e.g., tractor), amplified to the last vehicle in the configuration (e.g., rear trailer of a twin-trailer vehicle). The effect of rearward amplification is like cracking a whip. High rearward amplification ratios signify an increased roll-over tendency for the rear vehicle because it is subjected to high lateral accelerations. Yaw damping is defined as the extent that a vehicle resists the tendency to oscillate, or sway without additional steering inputs. High yaw damping ratios indicate higher

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<sup>78</sup>M. El-Gindy. p. 372.

<sup>79</sup>M. El-Gindy. p. 372.

resistance to oscillation or swaying while the vehicle is in a free-rolling or straight-ahead state.<sup>80</sup>

Vehicle combinations with longer wheelbases have higher dynamic stability. Specifically, as trailer wheelbase is decreased the rearward amplification increases and the yaw damping decreases. This condition is most prevalent for center axle, or pup trailers equipped with long hitch tongues. Performance-based standards could regulate the maximum vehicle gross weight based on the wheelbase of tractors and trailers.

### Dynamic Load Measurements

Dynamic loads are the loads generated by the pitching and rolling of the vehicle and suspension as it travels down the road. The dynamic loads are believed to be a significant cause of increased road damage. In the worst cases, the magnitude of the dynamic loads can be twice the static load. The dynamic load coefficient (DLC) is one measure that is frequently used to define the magnitude of dynamic tire forces. The DLC is a quantifiable measure that could be incorporated into performance standards that would allow trucks shown to be less damaging to the roads to have increased axle weights. The DLC is defined as:<sup>81</sup>

where

- RMS= Root Mean Square
- RMS dynamic tire force = the square root of the area under the curve on a tire force spectral density graph
- Static tire force = force exerted on the road when the truck is stationary

Dynamic loads can be illustrated using a tire force spectral density graph. This graph plots the parameter *tire force<sup>2</sup>/frequency* on the Y axis and the parameter *bounce frequency* on the X axis. This plot illustrates and easily identifies the frequency at which the maximum dynamic loads occur.

The increased loads can be divided into two frequency ranges:<sup>82</sup>

- 1.5-4 Hz(cycles/sec): The bounce, pitch and roll vibration modes of the suspended mass which is the mass of the tractor and trailer that is supported by the suspension.
- 8-15 Hz(cycles/sec): The bounce and roll modes of the unsprung mass, which is any mass not supported by the suspension (e.g. wheels and tires) and load sharing suspension (e.g., walking beam) pitch modes.

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<sup>80</sup>John Aurell and Thomas Wadman. *Impact of European Size and Weight Policies on the Characteristics of Heavy Vehicles*. The Fourth International Symposium on Heavy Vehicle Size and Weight. Ann Arbor, MI. June, 1995.

<sup>81</sup>David Cebon. *Interaction Between Heavy Vehicles and Roads*. Society of Automotive Engineers SAE 930001, SP-951, 81p, (L. Ray Buckendale Lecture), ISBN 1-56091-336-3, 1993.

<sup>82</sup>Cebon. p. 38.

The European Community Directive Step Test is an attempt to take advantage of the fact that air suspensions typically have the lowest DLC. The European Community Directive states that in order to carry 11.5 tonnes on the drive axle instead of 10 tonnes, the suspension must have a bounce frequency less than 2 Hz and a damping coefficient greater than 0.2.

The European Community Directive Step Test consists of measuring the natural frequency and damping ratio of the suspension during a transient motion. The excitation of the suspension can be accomplished in one of three ways:<sup>83</sup>

- 1) Slowly drive the vehicle off an 80 millimeter (3.15 inch) step.
- 2) Pull the chassis down to increase the drive axle tire force by 50 percent, then suddenly release.
- 3) Lift the chassis so that the spacing between the drive axle and chassis is 80 millimeter, then suddenly release.

Critics of the step test argue that the test is not a true measure of a truck's road damaging potential. They asserted that the actual road damaging potential of a vehicle cannot be measured by the step test because:<sup>84</sup>

- It does not use assessment criteria that are based on road damaging potential.
- It does not provide excitation comparable to normal highway operating conditions.
- The dynamic forces generated by an axle cannot be characterized by a single natural frequency and damping ratio.
- The frequency which dominates dynamic tire forces changes with vehicle speed and the amplitude of the input excitation.

The Commission of the European Community (EC) has recognized that future research needs to produce a quantifiable definition of the road damaging potential of a vehicle. The current EC Directive Step Test is a step towards implementing a performance-based standards approach to reducing road damage and increasing trucking productivity. It provides a simple way for manufacturers and enforcement officials to determine if a suspension is allowed to carry additional weight.

Adding air suspension may reduce the dynamic loads from the drive axle, but simulations have shown that it can also increase the dynamic loads from the trailer's axles.<sup>85</sup> Changing the suspension on one axle causes the frequency at which the pitch and bounce modes are excited to change. The frequencies of the pitch and bounce modes are dependent upon many factors, including the stiffness of the suspensions, wheelbase, moments of inertia, and speed. Therefore the entire vehicle must be considered, not just the individual axle group suspensions, when regulations regarding the suspension are proposed.

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<sup>83</sup>Cebon. p. 61.

<sup>84</sup>Cebon. p. 61.

<sup>85</sup>Cebon. p. 63

## Whole Vehicle Handling Properties

As mentioned previously, changing the suspension on one axle in an attempt to reduce pavement wear can increase the wear done by other axles of the vehicle combination. Changing the suspension on one axle without consideration of the entire vehicle can also cause an adverse change in the handling of the vehicle combination. El-Gindy has brought up the concept of “married vehicle combinations” in the regulation of heavy vehicles.<sup>86</sup> The “married vehicle combinations” concept would only allow certain trailers to be pulled with certain tractors. El-Gindy tested an eight-axle B-train double with different tractor wheelbases and auxiliary roll stiffness of the axles to determine the effect on the dynamic stability of different combinations of tractors and trailers. By changing the wheelbase of the tractor and roll stiffness of the axles, the loads on the tires are changed. As stated before, the load on a tire is a major factor in determining the handling properties of a tire. The results of his study showed that changing the wheelbase of the tractor or altering the roll stiffness of the suspension could result in a combination that would not meet minimum safety standards. Any performance-based regulations need to take into account the different properties of tractors and trailers and their effect on the dynamic performance of the entire vehicle combination. In some cases, a certain tractor trailer combination would not be allowed to operate above a given weight. In other cases, the instability of a certain combination may prevent its operation on the roads at all.

## Conclusions

The various elements of heavy vehicle performance are a complex subject and cannot be treated individually. To ensure that changes to one part of the vehicle do not adversely affect other aspects of the vehicle’s performance, the entire vehicle combination must be considered when developing performance-based regulations. The development of test procedures to monitor and control each of the vehicle handling properties will not be an easy task. Given the complexity of the tests, it is unlikely that any of the tests will be able to be conducted in the field. This does not mean that performance-based standards should not be implemented. Any idea which can increase the safety and productivity of the trucking industry should not be ignored simply because it is not an easy idea to implement.

Although tires dictate many of the handling properties of heavy vehicles, many factors controlling tire performance are beyond the scope of practical enforcement techniques. Tire load has been shown to have the largest effect on the lateral forces generated by the tire. However, the load placed on the tires depends upon many factors, including the weight of the cargo, height of the center of gravity, moments of inertia, and roll stiffness of the suspension. There is no way to control the loading of a vehicle to ensure that all of the factors will fall within certain ranges. Loading could only be guaranteed for tankers or other vehicles that carry a homogeneous cargo. This is not a very practical technique given that most vehicles can be legally-loaded (e.g., comply with maximum axle weight and maximum gross weight standards) yet have different

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<sup>86</sup>M. El-Gindy. *The Use of Heavy Vehicle Performance Measures for Design and Regulation*. Transportation Systems. DSC-Vol. 44. American Society of Mechanical Engineers. 1992. pp.367–381.

load distribution patterns. Currently, computer simulations are the most practical method of determining the handling characteristics of a heavy vehicle combination. Computer simulations provide a relatively inexpensive method for testing multiple designs, and help eliminate errors that are present when testing is done with the actual vehicle.

For many of the elements of vehicle performance described in this chapter, a target performance level can be provided by restricting certain vehicle parameters that are related to the performance criteria that you are trying to control. For example, wheelbase has been shown as one of parameters controlling the stability of a vehicle combination. Therefore by regulating the wheelbase of the tractor and the trailer, some of the factors affecting the stability of the combination can be controlled. The parameters regulated are one step removed from the elements to be controlled, and relate to them by theoretical calculation. Other examples of regulating vehicle parameters to control vehicle performance could include setting parameters for the electrical wattage of headlights to control night vision. Using parameters to control vehicle performance are the basis of performance-based standards and regulations such as these would enable quick checks at weigh stations to determine if the vehicle meets the standards.

Annual inspections is another method of enforcement that could be used to monitor some performance-based standards. Annual inspections would provide a means to inspect parts of the vehicle which are subject to wear, such as the suspension and brakes. Tests of suspension components such as bushings or shock absorbers could be conducted to ensure that the vehicle is not producing unacceptably high dynamic loads, which would cause increased pavement wear.

## **CHAPTER 4: EXAMINATION OF TRUCK SIZE AND WEIGHT REGULATIONS**

This chapter provides the foundation of our research objectives by examining the size and weight regulations from the 32 jurisdictions tabulated in the appendix of this document. The goal of the examination is to extract and classify the standards used in these countries to control the interaction between the vehicle and the highway infrastructure and/or the traffic safety environment.

The information is presented in three sections: methodology, review of size and weight regulations, and classification of noted standards. The methodology section provides the procedure for selecting the study country set, the literature sources used to assemble the data, and the issues and concerns that were resolved in producing the categorized set of size and weight regulations, contained in the appendix. The review of size and weight regulations examines 11 size and weight categories, assembles an inventory of the standards used among the study countries to control the axle weight, gross weight, or other requirements placed on vehicles operating under their jurisdiction, and labels each of the standards according to the previous definitions (e.g. prescriptive, parametric-performance-based, or pure performance). The classification of standards provides a grouping of truck size and weight standards—those designed to protect the highway infrastructure and those designed to protect the traffic safety environment.

### **Methodology**

This section describes the process for selecting the study countries, the sources and procedures used in producing the tabulated size and weight data set, and the issues, concerns, and limitations of the tabulated material.

#### **Selection of Study Countries**

The first step in producing the set of size and weight regulations was to choose an appropriate group of countries to include in the study. As all countries could not be included in the study because of budget and time constraints, the judgment was made to include only countries with a sizable motor carrier industry, that are major United States trading partners, and where performance-based size and weight regulations are currently or may soon be included in their size and weight regulations.

The countries of the European Community were included because the motor carrier industry is experiencing changes as a result of the European Union Directive 85-3, which seeks to harmonize size and weight regulations governing the international transportation of goods among EC countries. South Africa was selected because of the size of its economy and the emphasis placed on restricting the travel of overloaded trucks. The South American countries of Argentina, Brazil, and Chile were included because their economies and their motor carrier industry are dominant in that region and thus provide a strong indication of trends of truck size and weight regulation in that region of the world.

Mexico and Canada were included in our study because of the major trading implications of the NAFTA. This legislation provides trade initiatives among those countries and the United States and mandates the formation of a Land Transportation Surface Standards (LTSS) subcommittee to

promote international truck traffic.

Australia and New Zealand were included because of their emphasis on performance-based regulations for size and weight controls. New Zealand implemented performance-based standards in 1989 with the overhaul of their size and weight regulations.<sup>87</sup> Australia is currently considering performance-based standards as part of truck size and weight regulatory reform. A recent study identified 21 different vehicle configurations routinely operating in Australia. As a result, Australia is reviewing the performance capabilities of each of these configurations to ascertain the implications of implementing performance-based standards for size and weight regulations of heavy vehicles.<sup>88</sup>

Some of the countries included in our study had more than one jurisdiction that govern truck size and weight regulations. For example, truck size and weight regulations in Canada are governed at the provincial level and at the national level by an interprovincial Memorandum of Understanding (M.O.U.). The truck size and weight regulations used in the state of Michigan to govern 11-axle vehicles that are “grandfathered” to operate at gross weights up to 164,000 pounds are included in this study to provide an example of innovative jurisdictional regulations that are significantly different than those applied at the national level. The appendix of this report provides footnotes denoting the set of regulations examined for those countries with more than one jurisdiction governing truck size and weight regulations. Based on the above selection process, the countries and/or jurisdictions included in our study are shown in Table 4.1

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<sup>87</sup>John P. Edgar. *Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards*. Fourth International Symposium on Heavy Vehicle Size and Weight. Ann Arbor, MI. June, 1995.

<sup>88</sup>Peter Sweatman. *Overview of the Dynamic Performance of the Australian Heavy Vehicle Fleet*. National Road Transport Commission. Melbourne, Australia. July, 1993.

**Table 4.1: Study Countries/Jurisdictions**

- Argentina
- Australia
- Austria
- Belgium
- Brazil
- Canada (M.O.U)
- Chile
- Denmark
- European Community
- Finland
- France
- Germany
- Great Britain
- Greece
- Ireland
- Israel
- Italy
- Japan
- Jordan
- Korea
- Luxembourg
- Mexico
- Michigan
- Netherlands
- New Zealand
- Norway
- Portugal
- South Africa
- Spain
- Sweden
- Switzerland
- United States (STAA)

### **Literature Sources**

Initial contacts were made with the embassies or trade organizations of the study countries to identify pertinent motor carrier organizations and transportation legislative bodies. Subsequent contacts identified an International Road Transport Union (IRU) document entitled *Handbook of International Transport*.<sup>89</sup> This document provides an overview of size and weight regulations including axle and gross weight limit for all IRU member countries. Although limited in its scope, this handbook presents an overview of the regulations for transporting people and goods in IRU member countries and identified names, addresses, and phone and fax numbers for key motor carrier organizations and legislative branches. However, the handbook does have several shortcomings related to the project objectives.

First, much of the general documentation contained in the IRU handbook is restricted to the size and weight limits for a country, failing to note whether or not that country provides incentives for vehicles that are more benevolent to the highway infrastructure and to the traffic safety environment. Second, there is an information gap between the countries' enacted size and weight regulations and the IRU documentation. For example, the 1994 IRU handbook failed to include the Canadian interprovincial size and weight regulations that were published in September, 1993. Therefore, additional sources were identified to provide detailed documentation of size and weight limits for common vehicle configurations.

A document was obtained from Transport en Logistiek Nederland (a Netherlands association of shippers and motor carriers) that provides an informative summary of the size and weight regulations for 51 countries in Europe, Asia, and the Middle East.<sup>90</sup> This document provides a detailed listing of size and weight regulations and controls for many of the countries in our study.

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<sup>89</sup> *Handbook of International Road Transport, 13th Edition*. International Road Transport Union. Geneva, Switzerland. 1994.

<sup>90</sup> *Weights and Measures of Freight Cargo Vehicles: Survey of International Rules/Standards*. FOCWA and Transport En Logistiek Nederland. Zoetermeer, Netherlands. January, 1995.

Other sources used in this research included vehicle and component manufacturers with manufacturing and distribution facilities in the study countries. For example, individuals from the Eaton Corp. and the Volvo Truck Corp. provided copies of size and weight regulations and technical specifications for countries such as Argentina, Japan, Korea, Norway, and the Netherlands.

### Size and Weight Tabulation Format

Eleven size and weight categories were developed for this examination. These categories are based on those published by the Commission of the European Communities.<sup>91</sup> That publication specifies the maximum size and weight for vehicle configurations commonly used among EC member countries in the ten categories shown in Table 4.2. A discussion and illustration of those categories is provided in the appendix of this document.

**Table 4.2: Size and Weight Categories**

<b>Category Number</b>	<b>Category Name</b>	<b>Subcategories</b>
1.00	Maximum size	Length, width, and height
2.00	Maximum single axle weight	Axle purpose, number of tires
3.00	Maximum tandem axle weight	Axle spacing, number of tires
4.00	Maximum tridem axle weight	Axle spacing, number of tires
5.00	Maximum trailer weight	Number of axles
6.00	Maximum weight of non-articulated trucks	Number of axles
7.00	Maximum weight of truck-trailer combinations	Number of axles
8.00	Maximum weight of tractor-trailer combinations	Number of axles
9.00	Maximum bridge weight	Bridge formula, weight tables, and minimum axle spacing
10.00	Maximum weight of Longer Combination Vehicles	Combinations of two or more trailers

An 11th category, termed “other noted standards”, was developed to classify other standards or requirements used among study countries to control truck size and weight. Examples of standards in this category include load distribution and rear overhang requirements and maximum tire load.

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<sup>91</sup>*Laying Down Maximum Authorised Weights and Dimensions for Road Vehicles Over 3.5 Tonnes Circulating Within the Community.* Commission of the European Communities. Brussels, Belgium. December 15, 1993.

## **Issues, Concerns, and Limitations**

While the information presented in the appendix provides our best assessment of the size and weight limits used among study countries, several issues, concerns, and limitations should be noted. First, the primary purpose of the material in the appendix is to provide an inventory of the nature and extent of standards used in the selected countries to control the interaction of vehicles with the highway and traffic environments. The material provided in the appendix cannot be assumed to be complete or without error. The size and weight regulations in many countries are under review and we may not have provided the most current regulations.

Second, we have not included some measures governed by the jurisdictions in our study countries because these measures are not within the scope of performance-based size and weight regulation. For example, Great Britain requires vehicle operators to use sealed tachographs that record such parameters as driving time, average speed, and stopped time to comply with the strict hours-of-service limits placed on commercial drivers in that country. These measures have not been included in our tabulation because hours-of-service regulation is outside the scope of our study.

## **Review of Size and Weight Regulations**

This review examined each of the size and weight categories, shown in Table 4.2 for every country/jurisdiction included in our study. The objective of the review was to produce an inventory of standards used to govern the dimensions, weight, and performance of common vehicle configurations operating in their jurisdictions. For each size and weight category, the review provides the number of countries regulating that criterion (n) and minimum (min), maximum (max), and median allowable dimension or weight allowed for that category.

Median is a statistical measure of the center of a population, such that half of the observations fall above it, and half the observations fall below it. This definition is often used for describing samples because it is not influenced by extreme observations.<sup>92</sup>

Where appropriate, the review also notes the countries that are near the minimum and maximum limits for that category, and any skew in the distribution of the dimension or weight limits. Using the definitions of types of size and weight standards developed previously in this report, the review then labels the governing standards used among the study countries as prescriptive, performance-based or pure performance. This labeling was based on the judgment of the authors and was intended to illustrate the nature and extent of usage among the jurisdictions shown in Table 4.1 for each type of standard to control the interaction of vehicles with pavements, bridges, and other traffic.

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<sup>92</sup>David S. Moore and George P. McCabe. *Introduction to the Practice of Statistics*. W.H. Freeman and Company, New York, NY. 1989. p.30.

### 1.1: Maximum Length

Maximum length is generally determined by vehicle configuration with separate length limit categories for trucks, trailers, tractor-trailer, and truck-trailer combinations. Summaries of the maximum lengths by vehicle configurations are provided Table 4.3.

**Table 4.3: Summary of Maximum Length Limits by Vehicle Configuration**

<b>Vehicle Configuration</b>	<b>Min</b>	<b>Max</b>	<b>Median</b>
Truck	11.0 m (36.1 ft)	24.0 m (78.8 ft)	12.0 m (39.4 ft)
Trailer	11.3 m (37.1 ft)	16.2 m (53.1 ft)	13.6 m (44.6 ft)
Tractor-Trailer	15.5 m (50.9 ft)	24.0 m (78.8 ft)	16.5 m (54.1 ft)
Truck-Trailer	16.5 m (54.1 ft)	31.0 m (101.7 ft)	18.4 m (60.4 ft)

Most countries within the European community have shorter maximum length limits than countries in North America or Australia. Sweden has the longest maximum length for trucks and tractor-trailer combinations. Norway limits vehicle length by roadway class. For example, tractor-trailer combinations may be 17.0 meters (55.8 feet) long on certain roads while only 12.4 meters (40.7 feet) long on others. Maximum length standards are generally prescriptive and no performance-based methods of regulating vehicle length other than by roadway classification were noted.

### 1.2: Maximum Width

Maximum width is generally consistent among the study jurisdictions with a range of 2.5 meters (8.2 feet) to 2.6 meters (8.5 feet). Generally, one prescriptive standard is applied for all vehicle configurations. Several countries however, do have marginally higher maximum allowable widths for refrigerated vehicles. For example, Denmark allows 2.6 meters (8.5 feet) wide refrigerated vehicles, while 2.55 meters (8.4 feet) is the maximum width of all other vehicles.

### 1.3: Maximum Height

Maximum height among the study jurisdictions ranges from 3.8 meters (12.5 feet) to 4.8 meters (15.7 feet). Countries generally adopt one prescriptive standard as the maximum height, and all vehicles must not exceed that standard. However, several instances of pure performance standards were observed. France and Norway do not have maximum height restrictions. Alternatively, the regulations in those countries state that the vehicles must be able to clear any height obstructions such as tunnels or bridges. Theoretically, a vehicle of unrestricted height would be allowed anywhere on the road network of these countries as long as it could clear overhead obstructions. The maximum height regulations in France further state that the driver/company is responsible for damages caused by over height vehicles.

## 2: Maximum Single-Axle Weight

All of the jurisdictions have established standards to control maximum single axle weight. Additionally, countries in our study have used the following single-axle weight subcategories:

- Single tire axle
- Steering axle

- Drive/driven axle
- Single axle (not drive/driven or not otherwise noted)

The single tire axle subcategory refers to an axle with one tire at each wheel position, regardless of its location on the vehicle. Countries such as Mexico, Great Britain, and Ireland have different maximum single axle weight for single tire axles. Some countries such as Australia, Canada, and New Zealand have a separate category for maximum steering axle weight. Although not noted in the regulations, steering axles are also configured with one tire at each wheel position. A drive/driven axle refers to a single axle in the drive position with two tires at each wheel position. Although vehicles in some countries use single tire axles in the drive position, no weight distinctions were observed for single axles in this subcategory. Table 4.4 provides the minimum, maximum and median allowable single-axle weights for each subcategory.

**Table 4.4: Summary of Maximum Single Axle Weight Limits**

<b>Axle Type</b>	<b>n</b>	<b>Min Weight</b>	<b>Max Weight</b>	<b>Median Weight</b>
Single tire	6.00	6,000 kg (13,200 lb)	7,700 kg (17,000 lb)	7,100 kg (15,700 lb)
Steering axle	10.00	5,500 kg (12,100 lb)	7,500 kg (16,500 lb)	6,500 kg (14,300 lb)
Single axle (dual tires)	31.00	8,200 kg (18,100 lb)	13,000 kg (28,700 lb)	10,000 kg (22,000 lb)
Drive/driven axle (dual tires)	17.00	10,500 kg (23,100 lb)	13,000 kg (28,700 lb)	11,500 kg (25,400 lb)

As the above table illustrates, the range of weight limits within subcategories does not exceed 6,300 kg (10,600 lb), and single tire axles or steering axles have lower weight limits than single axles with dual tires. The weight limits for drive/driven single axles are higher than other single axles. Six countries included in our study (n = 6) have established separate weight limits for single axles with single tires, 10 countries (n = 10) have separate steering axle weight limits, and 17 countries (n = 17) have established separate weight limits for drive/driven single axles with dual tires. Specifying lower weight limits for single tire or steering axles is an example of performance-based standards that could be based on the fact that axles with single tires have been shown to cause greater pavement stress per pound of load than the same axle with dual tires.<sup>93</sup> Countries using only one single axle weight subcategory (single axle) are using a prescriptive standard to control pavement wear.

By subcategory, France, Italy, Israel, Jordan, and Spain have the highest maximum single-axle weight limits, and Canada and the United States have the lowest.

Some countries such as Denmark and Luxembourg allow higher weight limits (approximately 500 kilograms [1,100 pounds] additional) for single axles equipped with “road friendly” or air

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<sup>93</sup>T.D. Gillespie et.al. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance*. National Highway Cooperative Research Program. Report Number 353. Transportation Research Board. National Academy of Sciences. Washington D.C. 1993. p.30.

suspension. This is an example of a performance-based standard that allows a more benevolent vehicle to have higher allowable weight.

### 3: Maximum Tandem-Axle Weight

Similar to single axles, all jurisdictions in our study have established standards to control tandem axle weight. Generally, countries govern tandem-axle weight using one or more of the following criteria:

- Axle spacing requirements
- Number and type of tires
- Additional weight allowance for air-ride or “road friendly” suspension

A summary of the minimum, maximum, and median allowable axle spacing and weight for each governing method is provided in Table 4.5. Axle spacing refers to the distance between the centerlines of the two axles in the group.

**Table 4.5: Summary of Maximum Tandem-Axle Weight Limits**

Governing Criteria	n	Axle Spacing			Weight		
		Minimum	Maximum	Median	Minimum	Maximum	Median
Minimum Spacing	20	.9 m (3.0 ft)	1.3 m (4.3 ft)	1.0 m (3.3 ft)	10,000 kg 22,000 lb	19,000 kg 41,900 lb	14,350 kg (31,600 lb)
Maximum Spacing	20	1.8 m (5.9 ft)	2.4 m (7.9 ft)	1.8 m (5.9 ft)	15,500 kg (34,200 lb)	21,000 kg (46,300 lb)	18,000 kg (39,700 lb)
Single tires	5				10,000 kg (22,000 lb)	16,000 kg 35,300 lb	11,000 kg (24,300 lb)
Dual tires	5				10,000 kg (22,000 lb)	19,500 kg (43,000 lb)	16,400 kg (36,200 lb)
Road friendly susp. allowance	8				975 kg (2,150 lb)	1,000 kg (2,200 lb)	1,000 kg (2,200 lb)
No restrictions	7				14,500 kg (32,000 lb)	21,000 kg (46,300 lb)	16,500 kg (36,400 lb)

As the preceding data indicate, 20 jurisdictions govern tandem-axle weight based on the spacing between the axle centerlines. Belgium, France, Great Britain, Ireland, Israel, and Luxembourg have tandem-axle weight limits at or near the maximum, while Australia, Canada, and New Zealand have tandem-axle weight limits at or near the minimum.

Jurisdictions using this governing method generally allow additional tandem-axle group weight for more widely spaced axles. For example, the European Directive 85-3, governing international traffic among EC member countries, set maximum tandem-axle group weight at 11,000 kilograms (24,000 pounds) for tandem axles spaced 1 meter (3.3 feet) or less. In contrast, this directive allows tandem axle weight of 18,000 kilograms (39,700 pounds) if the axles are spaced at least 1.3 meters (4.3 feet) apart. Mandated axle spacing for this governing method range from 0.9 meters (3.0 feet) to 2.4 meters (7.9 feet). As previously noted, closely spaced

axles have areas of overlapping stress on pavements. Lower allowable tandem-axle group weight on closely spaced axles would minimize pavement damage due to areas of overlapping stress. This is a performance-based standard that could be implemented in other countries such as the United States and could reduce pavement wear by basing maximum tandem axle weight on axle spacing.

Five jurisdictions (Argentina, Chile, Mexico, New Zealand, and South Africa) in the study govern tandem-axle weight based on the number of tires per axle. Single tire tandem-axle groups (one at each wheel position) have maximum allowable weight limits between 10,000 kilograms (22,000 pounds) and 16,000 kilograms (35,300 pounds). Dual tire tandem-axle groups (two at each wheel position) have maximum allowable weight limits between 10,000 kilograms (22,000 pounds) and 19,500 kilograms (43,000 pounds). Controlling tandem axle weight based on the number of tires at each wheel position is also a performance-based standard.

Eight jurisdictions (Belgium, Great Britain, Ireland, Finland, Mexico, Spain, Sweden, and the European Directives for international travel) allow additional tandem-axle weight (averaging 1,000 kilograms [2,200 pounds]) if the group is equipped with air-ride or some other “road friendly” suspension. This is also a performance-based standard.

Seven jurisdictions (Australia, Israel, Jordan, Korea, Mexico, Michigan, and the United States) set prescriptive weight limits on tandem axles ranging from 14,500 kg (32,000 lb) to 21,000 kg (46,300 lb).

#### **4: Maximum Tridem-Axle Weight**

Twenty-two of the 32 study jurisdictions have separate tridem axle weight limits and the methods used to govern tridem weight are similar to those used to control tandem-axle weight. The minimum, maximum, and median axle spacing and weight are provided for each governing method in Table 4.6.

**Table 4.6: Summary of Maximum Tridem Axle Weights**

Governing Method	n	Axle Spacing ( $c_L - c_L$ First to Last Axle)			Weight		
		Minimum	Maximum	Median	Minimum	Maximum	Median
Minimum Spacing	14	2.0 m (6.6 ft)	2.6 m (8.5 ft)	2.4 m (7.9 ft)	15,500 kg (34,200 lb)	25,500 kg (56,200 lb)	21,000 kg (46,300 lb)
Maximum Spacing	14	2.5 m (8.2 ft)	4.8 m (15.8 ft)	3.2 m (10.5 ft)	18,000 kg (39,700 lb)	30,000 kg (66,100 lb)	24,000 kg (52,900 lb)
Single tires	2				14,000 kg (30,900 lb)	23,000 kg (50,700 lb)	18,500 kg (40,800 lb)
Dual tires	2				24,500 kg (54,000 lb)	25,000 kg (55,100 lb)	24,750 kg (54,600 lb)
Road friendly Susp. allowance	5				1,225 kg (2,700 lb)	3,000 kg (6,600 lb)	1,500 kg (3,300 lb)
No restrictions	7				20,000 kg (44,100 lb)	25,500 kg (56,200 lb)	21,000 kg (46,300 lb)

Fourteen of the 22 countries that have separate tridem axle weight limits base those limits on axle spacing. Similar to tandem-axle weight, tridem-axles with greater axle spacing have higher weight limits. For example, European Directive 85-3 limits weight at 21,000 kilograms (46,300 pounds) for tridems with axle spacing (distance from centerline of the first axle to the centerline of the last axle) less than 2.6 meters (6.6 feet) and 24,000 kilograms (52,900 pounds) for tridem-axle groups with axle spacing between 2.6 meters (6.6 feet) and 2.8 meters (9.2 feet). Among the fourteen countries limiting tridem axle weight by axle spacing, Belgium allows the greatest amount of weight on tridem groups—30,000 kilograms (66,100 pounds), while New Zealand allows the least amount of weight on tridem groups—15,500 kilograms (34,200 pounds). Similar to tandem axles, this is a performance-based standard for controlling pavement wear.

Two countries (Mexico and Chile) base tridem-axle weight on the number of tires. For example, Mexico allows tridems equipped with six tires to carry 14,000 kilograms (30,900 pounds) and 24,500 kilograms (54,500 pounds) if they are equipped with twelve tires. This is also a performance-based standard.

Five countries (Belgium, Great Britain, Ireland, Luxembourg, and Mexico) allow tridems equipped with air-ride or equivalent “road friendly” suspension to carry additional weight. The additional weight allowed using this performance-based standard ranges from 1,225 kilograms (2,700 pounds) to 3,000 kilograms (6,600 pounds).

Seven jurisdictions (Argentina, Australia, Finland, Greece, Israel, South Africa, and Switzerland) place prescriptive weight limits on tridem axles. Argentina has the highest prescriptive tridem weight limit, while Australia and Greece have the lowest prescriptive tridem weight limits.

### 5: Maximum Trailer Weight

Slightly over half of the jurisdictions in our study limit maximum trailer weight. Most of the

methods used by these jurisdictions to control maximum trailer weight are performance-based standards, which are shown below:

- Number of axles
- Vehicle configuration
- Wheelbase
- Type of suspension
- Mode of transportation (Intermodal vs. Non Intermodal)

The most common performance-based standard for controlling maximum trailer weight is based on the number of trailer axles. For example, the European Directive 85-3 sets the maximum trailer weight at 18,000 kilograms (39,700 pounds) for two-axle trailers and 24,000 kilograms (52,900 pounds) for three-axle trailers.

In the M.O.U. for interprovincial travel, Canada bases maximum trailer weight on the number of axles and the type of vehicle configuration. The vehicle configurations recognized in the M.O.U. are twin-trailer “A” trains (two trailers coupled by a single pintle hitch converter dolly), twin-trailer “B” trains (two trailers coupled by a frame-extended fifth wheel hitch), and twin-trailer “C” trains (two trailers coupled by a dual pintle hitch converter dolly). This performance-based standard recognizes that some multiple trailer configurations have less tendency to sway or wander at given gross weights. For example, “B” train configurations are allowed the same weight on both trailers. However, the rear trailer of an “A” train has a maximum allowable weight of 16,000 kilograms (35,200 pounds) while the rear trailer of a “C” train is allowed a higher weight—21,000 kilograms (46,300 pounds).

It should be noted that Canada is using two performance-based standards (number of axles and vehicle configuration) in this instance to govern maximum trailer weight. Other study jurisdictions also use two standards to establish maximum trailer weight. These are shown in Table 4.7.

**Table 4.7: Countries Using Two Standards for Maximum Trailer Weight**

<b>Country</b>	<b>Standards Used</b>
Canada	Number of axles and vehicle configuration
France	Number of axles and mode of transportation
Great Britain	Number of axles and wheelbase
Ireland	Number of axles and wheelbase
Luxembourg	Number of axles and type of suspension

Great Britain and Ireland base the maximum trailer weight on the number of axles and wheelbase (according to the standards defined in the *Yearbook of Road Transport Law*, trailer wheelbase is defined as the distance from the center of the last tractor axle to the center of the last trailer axle).<sup>94</sup> Limiting maximum trailer weight using these performance-based standards controls both

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<sup>94</sup>*Yearbook of Road Transport Law; 1995.* Freight Transport Association Limited. Tunbridge Wells, Kent,

the stress on bridges and vehicle stability. Further discussions of bridge stress are provided in category 8: Maximum Bridge Weight

France bases maximum trailer weight on the number of axles and the mode of transportation. Mode of transportation is a prescriptive standard distinguishing between intermodal and road transport. France allows greater trailer weight (4,000 kilograms–8,800 pounds more) for trailers used in combined transport (intermodal transport).

Luxembourg establishes maximum trailer weight based on two performance-based standards, number of axles and type of suspension. For example, the maximum weight of a two-axle trailer is 2,000 kilograms (4,400 pounds) higher if the trailer is equipped with air ride or “road friendly” suspension.

### 6: Maximum Weight of Non-Articulated Trucks

Twenty-eight study jurisdictions have separate maximum weight limits for non-articulated “rigid” vehicles. Twenty-five of these jurisdictions control the maximum weight of these vehicles only by the number of axles. This is a performance-based standard. For these 25 jurisdictions, Table 4.8 provides the minimum, maximum, and median non-articulated truck weight by number of axles.

**Table 4.8: Maximum Non-Articulated Truck Weight by Number of Axles**

Number of Axles	n	Min Weight	Max Weight	Median Weight
2.00	25.00	10,250 kg (22,600 lb)	21,500 kg (47,400 lb)	18,000 kg (39,700 lb)
3.00	25.00	20,500 kg (45,200 lb)	27,000 kg (59,500 lb)	25,000 kg (55,100 lb)
4.00	14.00	27,500 kg (60,600 lb)	34,000 kg (75,000 lb)	32,000 kg (70,500 lb)

As the Table 4.8 illustrates, a wide disparity exists in the maximum non-articulated truck weight among these jurisdictions, with South Africa having the lowest weight limit, while Jordan and Finland have the highest weight limits. Non-articulated trucks equipped with four axles are generally configured as twin-steer vehicles. Figure 4.1 illustrates a twin-steer petroleum transport truck-trailer combination that is commonly used in New Zealand. The front unit of the combination is a four axle twin-steer non-articulated truck.

**Figure 4.1: Twin Steer Petroleum Transport Truck-Trailer Combination**

Similar to trailer weight, some jurisdictions in our study group use more than one performance-based standard to limit the maximum weight of non-articulated trucks. For example, Great Britain and Ireland base the maximum weight of a non-articulated truck on both the number of axles and wheelbase. In these two jurisdictions, the maximum weight for a two-axle truck with a wheelbase between 2.65 meters (8.7 feet) and 3.0 meters (9.8 feet) is 16,260 kilograms (35,800 pounds). However, the maximum weight for a two-axle truck with wheelbase greater than 3.00 meters (9.8 feet) is 17,000 kilograms (37,500 pounds).

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England. 1995. p 194.

The performance-based standards used by these jurisdictions to govern the maximum weight of non-articulated trucks are summarized in Table 4.9.

**Table 4.9: Non-Articulated Truck Weight Governing Methods**

<b>Parametric Performance-Based Standards</b>	<b>Countries Employing the Standards</b>
Number of axles and type of suspension	Spain, European Directive 85-3
Number of axles and wheelbase	New Zealand
Number of axles, wheelbase, and roadway class	Norway, Sweden
Number of axles, wheelbase, and suspension type	Denmark, Great Britain, and Ireland

Setting maximum weight based on the number of axles and type of suspension permits higher allowable weight for vehicles having both more axles and air ride or equivalent “road friendly” suspension. For example, Spain allows a weight of 26,000 kilograms (57,300 pounds) for three-axle trucks equipped with air suspension and only 25,000 kilograms (55,100 pounds) for three-axle trucks not equipped with air suspension.

Norway and Sweden use three criteria, or standards (number of axles, wheelbase, and roadway classification) to govern maximum truck weight. For example, a three-axle truck with a wheelbase greater than 8.0 meters (26.3 feet) has an allowable weight of 32,000 kilograms (70,600 pounds) on primary roads (bearing class of BK-1). However, the same three-axle truck is limited to a maximum allowable weight of 27,600 kilograms (60,800 pounds) on secondary roads (bearing class of BK-2).

Denmark, Great Britain, and Ireland also use three criteria (number of axles, wheelbase, and suspension type) to govern maximum truck weight. A three-axle truck with a wheelbase  $\geq 5.2$  meters (17.1 feet) and “road friendly” suspension in Great Britain is allowed a weight of 26,000 kilograms (57,320 pounds), whereas the same vehicle is limited to 25,000 kilograms (55,100 pounds) if it is not equipped with “road friendly” suspension.

**7: Maximum Weight of Truck-Trailer Combinations**

A truck-trailer combination consists of a non-articulated truck (see previous category) coupled to a single trailer using a rear pintle hitch as illustrated in Figure 4.1. Twenty-six of the 32 study jurisdictions have separate categories for this combination, and the most common method used to control maximum weight is by using the total number of axles as a standard. A summary of the maximum weight by number of truck axles and number of trailer axles is provided in Table 4.10. For each combination of truck axles and trailer axles, the table provides the number of countries governing the configuration (n), and the minimum (min), maximum (max), and median allowable weight in kilograms (pounds).

**Table 4.10: Maximum Allowable Truck-Trailer Weights**

Vehicle Combination			Allowable Weight		
Truck Axles	Trailer Axles	n	Min. Weight	Max. Weight	Median Weight
2.00	2.00	22 .0 0	30,600 kg (67,400 lb)	41,500 kg (91,500 lb)	36,650 kg (80,800 lb)
2.00	3.00	9 00	36,300 kg (80,000 lb)	44,000 kg (97,000 lb)	40,000 kg (88,200 lb)
3.00	2.00	16 .0 0	36,300 kg (80,000 lb)	50,000 kg (110,200 lb)	43,500 kg (95,900 lb)
3.00	3.00	14 .0 0	36,300 kg (80,000 lb)	54,000 kg (119,000 lb)	44,500 kg (98,100 lb)
3.00	4.00	2 00	53,500 kg (117,900 lb)	60,000 kg (132,300 lb)	56,750 kg (125,100 lb)

As Table 4.10 illustrates, 22 of the 26 countries having separate maximum weight limits in this category set limits for truck-trailer combinations with 4 total axles (2+2), whereas only 14 of the 26 have separate weight limits for truck-trailer combinations with 6 total axles (3+3). Either these countries do not permit 6 axle combinations or the information used to assemble the data was incomplete. Table 4.10 also illustrates that more weight is allowed for combinations with more axles. Additionally, a wide disparity exists among the maximum weights by combination. For most combinations, Great Britain, New Zealand, and South Africa permit the lowest maximum weight while Chile, Finland, Israel, and Italy have the highest maximum weight. For example, New Zealand allows a total weight of 30,600 kilograms (67,400 pounds) for two-axle truck/two-axle trailer configurations, while Finland allows 41,500 kilograms (91,500 pounds) for the same truck-trailer configuration.

Some jurisdictions govern maximum truck-trailer weight by more than one performance-based standard, which are shown in Table 4.11.

**Table 4.11: Truck-Trailer Combination Weight Governing Methods**

Parametric Performance-Based Standards	Jurisdictions Employing the Standards
Number of axles and suspension type	European Directive 85-3
Number of axles and wheelbase	New Zealand
Number of axles, wheelbase, and roadway class	Norway, Sweden
Number of axles, wheelbase, and suspension type	Denmark, Great Britain, and Ireland

European Directive 85-3 permits higher maximum weights for truck trailer combinations equipped with air-ride or equivalent “road friendly” suspension. New Zealand governs maximum truck-trailer weight based on the number of axles and wheelbase. For example, a five-axle truck-trailer (three-axle truck coupled to a two-axle trailer) with a wheelbase  $\geq$  12.4 meters (40.7 feet) but less than 13.2 meters (43.3 feet) is permitted 37,000 kilograms (81,600 pounds).

The same five-axle truck-trailer with a wheelbase greater than 11.6 meters (38.1 feet) but less than 12.4 meters (40.7 feet) is permitted only 36,000 kilograms (79,400 pounds).

Similar to the method used to govern maximum allowable truck weight, Norway and Sweden specify three performance-based standards (number of axles, wheelbase, and roadway bearing classification) to establish maximum weight.

Four jurisdictions (Argentina, Austria, Korea, and Switzerland) set prescriptive weight limits for truck-trailer combinations. These weight limits range from 28,000 kilograms (61,700 pounds) in Switzerland to 38,000 kilograms (83,800 pounds) in Austria.

**8: Maximum Weight of Tractor-Trailer Combinations**

A tractor-trailer combination consists of a tractor coupled to a single trailer by a frame-mounted coupling device. Twenty-nine of the 32 study jurisdictions have separate categories for the maximum weight of tractor-trailer combinations, and the most common method of governing the weight of these vehicles is based on the number of axles, a performance-based standard. These vehicles are generally allowed more weight with additional axles. For the study jurisdictions governing maximum tractor-trailer weight only by the number of axles, a summary of the maximum weight by number of axles (tractor and trailer) is provided in Table 4.12. For each combination of tractor axles and trailer axles, the table provides the number of countries governing the configuration (n), and the minimum (min), maximum (max), and median weight.

**Table 4.12: Maximum Tractor-Trailer Weights**

Vehicle Combination			Allowable Weight		
Tract. Axles	Trailer Axles	n	Min. Weight	Max. Weight	Median Weight
2.00	2.00	22	29,700 kg (65,500 lb)	51,000 kg (112,400 lb)	38,000 kg (83,800 lb)
		.0			
		0			
2.00	3.00	9	36,000 kg (79,400 lb)	44,000 kg (97,000 lb)	40,000 kg (88,200 lb)
		00			
3.00	2.00	22	36,300 kg (80,000 lb)	60,000 kg (132,300 lb)	40,000 kg (88,200 lb)
		.0			
		0			
3.00	3.00	15	36,300 kg (80,000 lb)	70,000 kg (154,300 lb)	44,000 kg (97,000 lb)
		.0			
		0			

Table 4.12 illustrates that for those study jurisdictions setting maximum weight based only on number of axles, five-axle tractor-trailer weights are highest in Jordan (60,000 kilograms [132,000 pounds]), Netherlands, and Israel (48,000 kilograms [105,800 pounds]) and lowest in the United States (36,300 kilograms [80,000 pounds]), New Zealand (37,500 kilograms [82,700 pounds]), and Australia (39,000 kilograms [86,000 pounds]).

Similar to the previous three categories, several countries set maximum tractor-trailer weight based on more than one standard, as shown in Table 4.13.

**Table 4.13: Tractor-Trailer Combination Weight Governing Methods**

<b>Standards Used</b>	<b>Jurisdictions Employing the Standards</b>
Number of axles and suspension type	European Directive 85-3
Number of axles and wheelbase	New Zealand, and U.S.
Number of axles and mode of transportation	E.C. member countries
Number of axles, wheelbase, and roadway class	Norway, Sweden
Number of axles, wheelbase, and suspension type	Great Britain, and Ireland

Similar to the previous category, New Zealand and the European Directives allow more weight for tractor-trailers equipped with “road friendly” suspension (European Directives) or longer wheelbase (New Zealand).

Also similar to the previous category, Norway and Sweden base maximum tractor-trailer weight on number of axles, wheelbase roadway bearing class, and Great Britain and Ireland base maximum weight on number of axles, wheelbase, and suspension type. These are all performance-based standards. For example, the maximum weight of a five-axle tractor trailer in Sweden is 49,000 kilograms (108,000 pounds) on a BK-1 bearing class roadway, provided that it has a total wheelbase of at least 12.0 meters (39.4 feet). The maximum weight of a five-axle tractor-trailer in Great Britain and Ireland is 38,000 kilograms (83,800 pounds), provided that the tractor is equipped with “road friendly” suspension and the distance from the last axle of the tractor to the last axle of the trailer is at least 6.3 meters (20.7 feet).

Nine E.C. member countries allow 4,000 kilograms (8,800 pounds) more weight for five or six-axle combinations transporting 40-foot ISO containers used in a journey with at least one intermodal link.<sup>95</sup> A 40-foot ISO container is a standard type of freight container that is frequently used for the international movement of products and has standardized attachment points for coupling the container to a trailer chassis. This prescriptive standard was developed to encourage the use of intermodal transportation and facilitate international trade among E.C. member countries.

Three jurisdictions (Austria, Japan, and Switzerland) set prescriptive weight limits for tractor-trailer combinations. These weight limits range from 28,000 kilograms (61,700 pounds) in Switzerland to 38,000 kilograms (83,800 pounds) in Austria.

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<sup>95</sup> Austria, France, Germany, Great Britain, Greece, Ireland, Italy, Portugal, and Spain honor a provision of the European Directive 85-3 for international journeys, which allows five or six-axle tractor-trailers hauling 40-foot ISO containers used in intermodal transportation a maximum weight of 44,000 kg (97,000 lb). *Laying Down the Maximum Authorised Weights and Dimensions for Road Vehicles Over 3.5 Tonnes Circulating Within the Community: Annex 1, 2.2.2 (d)*. Commission of the European Communities. Brussels, Belgium. December 15, 1993. p. 27.

## 9: Maximum Bridge Weight

In addition to the criteria listed above, 11 countries in our study group govern the maximum weight of multiple axle groups (also known as bridge weight) to control the stress placed on bridges. As previously discussed, axle loading and axle spacing are the most important requirements in determining the acceptable fatigue and stress on bridges, and many countries have implemented performance-based standards to control the interaction between vehicles and bridges. The three methods used among the study jurisdictions to govern maximum bridge weight are shown below and described in the following paragraphs.

- Bridge formula
- Bridge weight table
- Wheelbase minimums

**Bridge Formula** Countries using this method provide a formula in their regulations for computing the maximum weight of multiple axles or axle sets. Bridge formulas use the distance between the extreme axles and/or the number of axles as input variables to determine the allowable multiple axle group weight. Computed bridge weight tables sometimes accompany the published formula. The operator uses the bridge formula and/or the accompanying tables to determine the allowable total axle group weight for the vehicle in question. Table 4.14 provides the bridge formula for each of the study countries using this method.

**Table 4.14: Summary of Selected Bridge Formulas**

Country	Input Variables	Result	Formula
Australia	L = distance (meters) between extreme axles	W = allowable axle group weight in kilograms	$W = (3L + 12.5) \times 1,000$
Finland	L = distance (meters $\times$ 10) between extreme axles	W = allowable axle group weight in kilograms	$W = 20,000 + ([L - 1.8] \times 270)$
South Africa	L = distance (meters) between extreme axles	P = allowable axle group weight in metric tons	$P = 2.1L + 15$
United States	L = the distance in feet between the extreme axles of any group of two or more axles N = the number of axles in the axle group	W = the maximum weight in pounds carried by any group of two or more axles to the nearest 500 pounds	$W = 500 (LN/N - 1 + 12N + 36)$

Computing the maximum allowable multiple axle weight for the same vehicle will yield different results with the above formulas. Table 4.15 provides the maximum allowable multiple axle group weight for a vehicle with five axles and a first–last axle spacing of 15.5 meters (51.0 feet).

**Table 4.15: Comparison of Bridge Formula Weights**

Country	Bridge Formula	Number of Axles	Axle Spacing	Allowable Axle Group Weight
Australia	$W = (3L + 12.5) \times 1,000$	5.00	15.5 m (51.0 ft)	59,000 kg (130,100 lb)
Finland	$W = 20,000 + ((L-1.8) \times 270)$	5.00	15.5 m (51.0 ft)	57,000 kg (125,700 lb)
South Africa	$P = 2.1L + 15$	5.00	15.5 m (51.0 ft)	47,550 kg (104,800 lb)
United States	$W = 500 (LN/N-1 + 12N + 36)$	5.00	15.5 m (51.0 ft)	36,300 kg (80,000 lb)

As the above table illustrates, Finland and Australia allow far greater loads on equivalent axle bridge spans than the United States. Graphical comparisons of maximum bridge weight among six study jurisdictions are provided in Figures 4.2–4.4.

**Bridge Weight Table** Great Britain, Ireland, Norway, and Sweden base maximum bridge weight on weight tables. The tables provide the maximum allowable vehicle weight and axle group weight for various extreme axle distance categories. The operator consults the published table to determine the allowable total weight of the axle groups for the vehicle in question.

Great Britain and Ireland have separate tables for two-axle and three-axle power units. For each type of power unit (two axle or three axle) the tables provide the maximum bridge weight based on the distance between the rear axle of the power unit and the rear axle of the trailer.

Norway and Sweden base maximum bridge weight on roadway bearing class and publish different weight tables for each roadway bearing class. As previously discussed, Norway and Sweden have designated that identical vehicles are permitted higher maximum weights on primary highways than on secondary highways. For example, Norway designates primary highways as BK-10 bearing class and secondary highways as BK-8, BK-7 or BK-6 bearing class. Sweden has a similar system and designates primary highways as BK-1 bearing class and secondary highways as BK-2 or BK-3 bearing class. In these countries, the tables provide the maximum bridge weight based on the distance between the first and last axle of the vehicle in question for each roadway bearing class.

Using the previous example vehicle (five axles spaced 15.5 meters apart), Table 4.16 provides a comparison of maximum bridge weights for Great Britain, Ireland, Norway, and Sweden.

**Table 4.16: Comparison of Bridge Table Weights**

Country	Number of Axles	Axle Spacing	Allowable Axle Group Weight
Great Britain	5.00	15.5 m (51.0 ft)	38,000 kg (83,800 lb)
Ireland	5.00	15.5 m (51.0 ft)	38,000 kg (83,800 lb)
Norway	5.00	15.5 m (51.0 ft)	48,500 kg (106,900 lb)
Sweden	5.00	15.5 m (51.0 ft)	54,000 kg (119,100 lb)

Similar to countries using bridge formulas, a wide disparity exists between the maximum bridge weight among these four countries. Further discussions of these differences are provided below.

**Wheelbase Minimums** In the M.O.U. for interprovincial travel, Canada governs the maximum bridge weight by establishing a minimum wheelbase for trucks, tractors, and trailers. The sum of these individual unit wheelbases determine a minimum bridge dimension for a given multi-unit vehicle configuration. Each vehicle configuration named in the M.O.U. has a minimum and maximum wheelbase and minimum spacing between the axles of a tandem or tridem axle set. For example, the minimum dimension for a three-axle tractor and two-axle trailer is the sum of the following dimensions:

- Tractor wheelbase (center of steering axle to center of first tandem axle) = 3.0 m
- Tractor tandem axle spacing (center to center tandem axle distance) = 1.2 m
- Trailer wheelbase (center of rear tractor tandem to center of first trailer tandem) = 6.5 m
- Trailer tandem axle spacing (center to center tandem axle distance) = 1.2 m
- **Total extreme axle distance** = **11.9 m (39.0 ft)**

The total allowable weight for the above multiple axle groups is 39,500 kilograms (87,100 pounds). This is a unique example of a performance-based standard that controls both the interaction between the vehicle and the bridge structure and the traffic safety environment. Previous Canadian studies have noted the relationship between wheelbase and vehicle stability.<sup>96</sup> Specifying a minimum wheelbase ensures adequate bridge spacing and provides a minimum acceptable level of vehicle stability.

The above bridge weight governing methods allow a large variation in maximum bridge weight among the 11 countries. Table 4.17 provides a comparison of the bridge weight by country for two configurations. The first configuration is four axles (two tandem-axle groups) spaced 11.9 meters (39.0 feet) apart. This is equivalent to the *inner bridge dimension* used in the United States to govern the maximum allowable weight on the four axles consisting of the tractor tandem and trailer tandem. The second configuration is five axles (steering axle, drive axle tandem, and trailer axle tandem) spaced 15.5 meters (51.0 feet) apart. This is equivalent to the *outer bridge dimension* used in the United States to govern the maximum allowable weight of a five-axle tractor trailer. The purpose of the table is to provide a comparison of allowable axle

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<sup>96</sup>M. El-Gindy. *The Use of Heavy Vehicle Performance Measures for Design and Regulation*. Transportation Systems. DSC-Vol. 44. American Society of Mechanical Engineers. 1992. pp.367–381.

group weights for identical vehicles among the countries.

**Table 4.17: Comparison of Maximum Bridge Weights Among Eleven Study Countries**

Country	Number of Axles and Extreme Axle Spacing			
	Four Axles @ 11.9 m (39.0 ft)	Five Axles @ 15.5 m (51.0 ft)		
Australia	33,000 kg	72,800 lb	39,000 kg	86,000 lb
Canada	34,000 kg	75,000 lb	41,000 kg	90,390 lb
Finland	38,000 kg	83,800 lb	44,000 kg	97,000 lb
Great Britain	35,000 kg	77,100 lb	38,000 kg	83,800 lb
Ireland	35,000 kg	77,100 lb	38,000 kg	83,800 lb
Japan	27,000 kg	59,500 lb	36,000 kg	79,400 lb
New Zealand	31,000 kg	68,300 lb	37,000 kg	81,600 lb
Norway	36,000 kg	79,400 lb	46,000 kg	101,400 lb
South Africa	32,800 kg	72,300 lb	39,300 kg	86,600 lb
Sweden	39,000 kg	86,000 lb	49,000 kg	108,000 lb
United States	30,800 kg	68,000 lb	36,300 kg	80,000 lb

Generally, regulations specify that maximum bridge weight is preempted by the maximum axle or axle group weight and the bridge formula is capped at the sum of the maximum weight for the axles contained in a given configuration. Most truck size and weight regulations specify that the lesser of the two weights (sum of individual axle and axle groups versus maximum bridge weight) should apply. For example, the bridge formula used in Australia would allow a bridge weight of 42,500 kilograms (93,700 pounds) for two tandem-axles with an extreme axle spacing of 11.9 meters (39.0 feet). However, an individual tandem axle may only carry 16,500 kilograms (36,400 pounds), so two tandem axles are limited to 2×16,500 kilograms or 33,000 kilograms (72,800 pounds). Therefore, the data in the table reflect the lesser of the two weights.

As the table illustrates, the United States, New Zealand, and Japan have the lowest bridge weight, while Finland, Sweden, Canada, and Norway have the highest bridge weight for the example multiple-axle configurations. Further discussions of these differences are provided below.

**Comparison of Maximum Bridge Weights** A graphical comparison of maximum bridge weights for three vehicle configurations among seven study jurisdictions is provided in Figures 4.2–4.4. The vehicle configurations are shown below.

- **Figure 4.2:** Four axles, consisting of two tandem axle sets, provided to represent the *inner bridge* dimension frequently monitored in the United States.
- **Figure 4.3:** Five axles, consisting of a steering axle and two tandems, provided to represent the five-axle configuration most commonly used in the United States
- **Figure 4.4:** Six axles, consisting of a steering axle, one tandem, and one tridem, provided to represent the six-axle configuration commonly used in northern Europe, Australia, New Zealand, and South Africa.

The seven representative countries that were included in the comparison are shown below.

- Australia
- Finland
- New Zealand
- Norway
- South Africa
- Sweden
- United States

These countries were selected because the bridge weight data from our sources was sufficiently detailed to construct a meaningful graph.

**Figure 4.2: Four-Axle Bridge Weight Comparison**

**Figure 4.3: Five Axle Bridge Weight Comparison**

**Figure 4.4: Six-Axle Bridge Weight Comparison**

For the given axle configurations, the preceding graphs and Table 4.17 illustrate that the United States and New Zealand have the lowest maximum bridge weights, while Sweden, Australia, and Finland have the highest maximum bridge weights. This may be attributable to such factors as bridge design or overstress limits adopted by these countries. Bridge design factors could include the thickness and spacing of support beams, and thickness of the bridge deck. Overstress limits refer to the prescriptive limits that countries place on bridge loads to mitigate extreme loading events or total fatigue. Detailed studies of the factors attributable to the difference in maximum bridge weight among the study countries are beyond the scope of this project. However, one possible factor for the higher maximum bridge weight allowed in Sweden was revealed in a research report that was provided by that country's trucking association.<sup>97</sup>

According to this report, bridges that were constructed in Sweden prior to World War II do not have sufficient bearing capacity to support the types of vehicles currently in use. These pre WW II bridges cannot safely accommodate vehicles that are loaded according to the European Directive weight limits. Until recently, these weaker bridges were located approximately every 30 kilometers on various roadways making it difficult for a heavily loaded truck to travel the existing road network without significant detours.

Sweden's Transport Research Institute in cooperation with the Swedish National Road Administration (SNRA) conducted a cost/benefit analysis to determine transportation cost savings for replacing these substandard bridges. The study determined that a savings of approximately 2 billion Swedish Krona (\$300 million) per year could be attained if the older bridges were replaced or reinforced. The study determined that the total cost of replacing or reinforcing these older bridges was estimated at 6 billion Swedish Krona (\$900 million).<sup>98</sup> The

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<sup>97</sup>Anders Lundqvist. *What Swedish Government and the Swedish National Road Administration Have Done for the Heavy Vehicles and National Interest*. Vägverket. Division of Väg and Trafik. Borlänge, Sweden. May 7, 1995. pp 1–3.

<sup>98</sup>The rates used to convert Swedish Krona to U.S. Dollars are based on an exchange rate of 6.6824 Swedish

study further concluded that the net investment could be paid back within 3 years through the transportation cost savings.

As a result, the Swedish Government gave the SNRA permission to conduct a project that would replace or reinforce selected bridges to meet the European heavy vehicle specifications over a 10 year period beginning in 1988. The Swedish government, in agreement with various industrial and transportation organizations, decided that the project would be funded primarily by the transportation industry through a 50 percent increase in heavy vehicle taxes. Revenue from these increased taxes was projected to be 4 billion Swedish Krona (\$600 million) of the 6 billion Swedish Krona (\$900 million) needed. The bridge replacement and reinforcement program began at the end of 1987 with approximately 1,100 bridges. As early as 1990, some heavier vehicles were allowed on some primary roadways. By January 1, 1993, Sweden's size and weight limits were increased. To date bridge repair and replacement have resulted in over 80 percent of the public road network and 100 percent of the primary roads of importance being opened for heavier vehicles.

The Transportation Research Board recommended a similar bridge evaluation and replacement program for the U.S. in a 1990 study evaluating proposals for new approaches to the regulation of truck size and weight. In that study, researchers found that 7,000 bridges on interstate and primary highways and 19,000 bridges on nonprimary highways would fail to meet adopted overstress criteria. Researchers recommended that the cost of replacing those bridges, estimated then at \$6.9 billion, be shared between highway users, and highway agencies.<sup>99</sup>

### **10: Maximum Weight of Longer Combination Vehicles**

For the purposes of this study, a longer combination vehicle (LCV) is defined as a tractor coupled to two or more trailers. The LCV configurations included in this category are based on the number of axles and the method of coupling the rear trailer(s) to the lead trailer(s) and consist of the following combinations:

- Five-axle "A" train
- Eight-axle "A" train
- Nine-axle "B" train
- Michigan LCV
- Australian triple-trailer road train

A five-axle "A" train consists of a two-axle tractor, and two single-axle trailers, where the rear trailer is coupled to the lead trailer using a single-point pintle-hitch, single-axle converter dolly. These configurations, known as twin-trailers, are used prevalently throughout the United States. An eight-axle "A" train, as illustrated in Figure 4.5, consists of a three-axle tractor and two tandem-axle trailers, where the rear trailer is coupled to the lead trailer using a single-point pintle-hitch, single-axle converter dolly. These configurations are used throughout Canada, New

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Krona per U.S. Dollar, as published in the Wall Street Journal, March 29, 1996.

<sup>99</sup>*New Trucks for Greater Productivity and Less Road Wear; An Evaluation of the Turner Proposal.* Transportation Research Board. National Research Council. Special Report Number 227. Washington, D.C. 1990. pp 188–194.

Zealand, and Australia. A nine-axle “B” train, as illustrated in Figure 4.6, consists of three- axle tractor, tridem-axle lead trailer, and tridem-axle rear trailer, where the rear trailer is coupled to the lead trailer using an extended-frame fifth-wheel hitch. A Michigan LCV consists of a three- axle tractor, a four-axle lead trailer, and tandem-axle rear trailer, where the rear trailer is coupled to the lead trailer using a single-point pintle-hitch, tandem-axle converter dolly. An Australian triple-trailer road train consists of a three-axle tractor and three tridem-axle trailers, where the rear trailers are coupled to the lead and middle trailer using a single-point pintle-hitch, tandem- axle converter dolly.

**Figure 4.5: Eight-Axle “A” Train**

**Figure 4.6: Nine-Axle “B” Train**

Nine jurisdictions in our study have separate maximum weight limits for the above LCV configurations. A summary of the minimum, maximum, and median allowable weight by vehicle combination is provided in Table 4.18

**Table 4.18: Maximum Longer Combination Vehicle Weights**

Vehicle Combination	n	Min. Weight	Allowable Weight	
			Max. Weight	Median Weight
Five-axle “A” train	8. 0 0	36,300 kg (80,000 lb)	52,000 kg (114,600 lb)	43,950 kg (96,900 lb)
Eight-Axle “A” train	8. 0 0	36,300 kg (80,000 lb)	67,000 kg (147,700 lb)	60,250 kg (132,800 lb)
Nine-Axle “B” train	7. 0 0	44,000 kg (97,000 lb)	73,000 kg (160,900 lb)	62,500 kg (137,800 lb)
Michigan LCV	1. 0 0	74,400 kg (164,000 lb)	74,400 kg (164,000 lb)	74,400 kg (164,000 lb)
Australian triple-trailer road train	1	115,500 kg (254,600 lb)	115,500 kg (254,600 lb)	115,500 kg (254,600 lb)

For the five-axle “A” train configuration, the United States allows the lowest maximum weight (36,300 kilograms [80,000 pounds]), while Israel allows the highest maximum weight (52,000 kilograms [114,600 pounds]). For the eight-axle “A” train configuration, the United States also allows the lowest maximum weight (36,300 kilograms [80,000 pounds]), while Brazil allows the highest maximum weight (67,000 kilograms [147,700 pounds]). For the nine-axle “B” train configuration, New Zealand allows the lowest maximum weight (44,000 kilograms [97,000 pounds]), while Brazil allows the highest maximum weight (73,000 kilograms [160,900 pounds]).

## 11: Other Noted Standards

Twenty countries in our study have additional standards, or criteria, to govern vehicles operating in their jurisdictions. The purpose of these standards is to govern minimum acceptable levels of performance for the general population of vehicles or for special purpose vehicles. These standards govern vehicle parameters such as the load distribution between the tractor/truck and trailer or the minimum distance required to complete a 360-degree turn. The following paragraphs discuss each of these additional standards noted among our study countries, list the countries that specify levels for that criterion, and classify the standard as prescriptive, performance-based, or pure performance.

**Load Distribution Requirements** This standard specifies the percent of the total combination vehicle weight that can be carried by each unit (truck/tractor or trailer) of the combination. The purpose of setting a limit on this criterion is to ensure vehicle stability, as heavily loaded trailers pulled by lightly loaded tractors have a tendency to sway or wander. Typically, the regulations specify that the trailer weight cannot exceed a specified percent (e.g., 150 percent) of the tractor or truck weight. For example, Denmark mandates that the total weight of the trailer cannot exceed 1.5 times the weight of the tractor. The study countries governing this criterion are:

- Canada
- Denmark
- Finland
- France
- Germany
- Luxembourg
- Portugal

With the exception of Canada, the above load distribution requirements refer to single trailer vehicles. The load distribution requirements in Canada refer also to double-trailer combination vehicles and specify the maximum allowable weight of the rearmost trailer. For example, the load distribution requirements for “C” Train doubles specify that the second trailer is limited to a maximum weight of 21,000 kilograms (46,300 pounds) or the weight of the lead trailer, whichever is lower. Similar to single trailer combinations, studies have shown that twin-trailer vehicles have an excessive tendency to sway or wander when the rear trailer is heavier than the lead trailer. Limiting rear trailer weight should reduce rear trailer sway and thus is an example of a performance-based standard used to control the interaction of the vehicle with the traffic safety environment.

**Turning Circle Requirements** This requirement specifies the minimum wall-to-wall distance required for a vehicle to complete a 360-degree turn. The purpose of governing this performance attribute is to ensure that vehicles can negotiate tight turns without hitting obstructions. The regulations typically state the minimum diameter or radius of an outer and inner circle. The turning circle requirements for the European Community are illustrated in Figure 4.7.

### Figure 4.7: European Directive Turning Circle Requirements

As the figure depicts, the vehicle in question must negotiate a 360-degree turn without protruding beyond the outer circle dimensions of 12.5 meters (41.0 feet) or inside the inner dimensions of 5.3 meters (17.4 feet). This is a pure performance standard as it is based only on

vehicle performance, not the parameters, such as wheelbase, that make the vehicle capable of negotiating the circle. Stated quite simply, the vehicle must negotiate the 360 degree turn within the wall-to-wall dimensions, regardless of its wheelbase. The following countries have minimum turning circle requirements:

- Australia
- European Directives
- Finland
- Great Britain
- Ireland
- New Zealand
- South Africa

The dimensions of the turning circles are identical in all of the above countries except South Africa, which specifies its outer turning circle dimensions at 13.1 meters (43.0 feet).

**Static Load Sharing Requirements** This measure specifies the maximum deviation in static load between individual axles of an axle group. Although most multi-axle suspensions are designed to share their load equally among the individual axles, tests indicate that load sharing is not perfect during normal on-road conditions.<sup>100</sup> This variation is caused by factors such as friction in the load equalizer assemblies, and inter-axle load transfer due to braking or acceleration. A measure of load sharing in multi-axle suspensions is the load sharing coefficient, which has been defined as:

Where:

Nominal static load =

The purpose of static load sharing standards is to prevent the overloading of any single axle within an axle group. Poor static load sharing may cause an overloaded single axle to exert excessive stress on pavements. The regulations provide the maximum deviation in kilograms or pounds among any axles within a tandem or tridem-axle group. For example, Canada mandates that the load shared between adjacent axles in a group must not vary by any more than 1,000 kilograms (2,200 pounds). The following countries specify static load sharing requirements:

- Brazil
- Canada
- Great Britain
- Ireland
- New Zealand

Brazil has less restrictive static load sharing requirements than Canada. In Brazil, the maximum difference in adjacent axle weights should not be greater than 1,700 kilograms (3,700 pounds). New Zealand's regulations do not specify the maximum difference in adjacent axle loads. However, the regulations do state that all axles within a group must be "load sharing." Great

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<sup>100</sup>T.D. Gillespie et.al. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance*. National Highway Cooperative Research Program. Report Number 353. Transportation Research Board. National Academy of Sciences. Washington D.C. 1993. p.18.

Britain and Ireland use tables that limit the load of axle groups that do not share loads equally. For example, the maximum allowable weight of tandem axles spaced 1.85 meters (6.1 feet) apart that share loads equally is 20,340 kilograms (44,800 pounds). The same tandem-axle group is limited to 19,320 kilograms (42,600 pounds) if loads are not equally shared. This is a performance-based standard developed to control maximum axle load.

**Rear Overhang Requirements** This benchmark is used to set the maximum allowable distance from the center of a vehicle's rear axle to the back of the vehicle. The purpose of this performance-based standard is to limit the reverse swing of vehicles with excessive overhang and reduce the “under-run” distance of vehicles that may collide with the rear of a trailer. The regulations generally specify the maximum rear overhang as the lesser of a predefined distance or a percentage of a vehicle's wheelbase. For example, the maximum rear overhang in Great Britain and Ireland is 60 percent of the trailer wheelbase. The following countries specify maximum rear overhang:

- Australia
- Canada
- Great Britain
- Ireland
- New Zealand

The rear overhang requirements used in these countries may be a result of the short wheelbase vehicles that are in use. For example, the maximum trailer wheelbase that is defined in Great Britain's multiple axle group weight table is 8.0 meters (26.3 feet). However, the maximum allowable trailer length is 14.0 meters (46.1 feet). As a result, the rear axle may frequently be positioned 15 feet ahead of the rear of the trailer.

**Traction Requirements** This requirement mandates the minimum allowable load on a vehicle's driving axles. The purpose of this criterion is to ensure adequate traction on slippery or steep road surfaces. Traction requirements specify the minimum percentage of a vehicle's gross weight that must be carried on the drive/driven axles. For example, European Directive 85-3 states that a minimum of 25 percent of a vehicle's gross weight must be carried by the driving axles. Denmark and European Directive 85-3 are the only countries that have defined traction requirements. Although not frequently used, this is a performance-based standard and could prevent accidents on steep or slippery road surfaces due to lost traction or "spin out."

**Seasonal Load Restrictions** Seasonal load restrictions are standards established by some jurisdictions to protect highways during vulnerable periods such as spring thaw. Many jurisdictions in cold climates, such as South Dakota, Iowa, Minnesota, and Montana that are not among our study countries, employ this standard. Jurisdictions using this type of standard reduce maximum allowable loads by a preset amount or percentage during periods of thaw. The examination of size and weight regulations revealed that Michigan and Norway have also established seasonal load restrictions. The regulations in Michigan specify that axle loads shall be reduced by 25 percent on concrete pavements and 35 percent on asphalt pavements during defined periods of spring thaw. Norway reduces maximum allowable tandem weight by 4,000 kilograms (8,800 pounds) and tridem weight by 3,000 kilograms (6,600 pounds) during spring thaw periods.

**Braking Efficiency Standards** Jurisdictions employ braking efficiency standards to ensure the safety of the heavy vehicle fleet. The European Community's braking standards define minimum brake performance expressed as a percentage of "g"—being the acceleration due to gravity of 32 ft or 9.8 m per second per second.<sup>101</sup> For example, the European Braking Directive specifies the following minimum levels of brake performance:<sup>102</sup>

- Service brake = 0.5 g
- Secondary brake = 0.25 g
- Parking brake = Must hold parked vehicle on a 16 percent grade.

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<sup>101</sup>*Vehicle Engineering Handbook*. Freight Transport Association Limited. Tunbridge Wells, Kent, England. 1993. p12.

<sup>102</sup>These are the standards defined in Directive 71/320/EEC. *Vehicle Engineering Handbook*. p 12.

The service brake is the primary vehicle braking system. The secondary brake is a redundant braking system that provides braking in the event of a primary braking system failure. Common air brake systems used on vehicles in the United States and other countries have dual air reservoirs and braking valves. In the event of an air pressure loss or brake component failure, secondary reservoirs or brake valves supply the required braking forces.

The above figures define the minimum required wheel braking effort. Specifically, the 0.5 g service brake requirement specifies that the sum of the retarding forces produced by the braking system must equal 50 percent of vehicle's plated weight.<sup>103</sup>

Study countries specifying minimum braking efficiency standards include:

- Australia
- European Directive
- United States
- Great Britain
- Ireland
- Netherlands
- New Zealand

The brake efficiency standards for Great Britain, Ireland, and the Netherlands are identical to the European Directive braking standards. The Australian braking standards specify the minimum air brake pressure at the furthestmost brake chamber from the brake treadle valve.

The brake efficiency standards in New Zealand specify the minimum required stopping distance from a specified speed. Specifically, the New Zealand brake efficiency standards specify that a vehicle traveling 30 kilometers/hour (19 miles/hour) must come to a complete stop within 7.0 meters (23.0 feet) regardless of the vehicle gross weight. This specification provides 50 percent braking efficiency.<sup>104</sup>

The brake efficiency standards used in the United States specify minimum levels of brake performance in terms of the required brake force in "g"s (expressed as a percentage of gross weight), deceleration rate from a speed of 20 miles-per-hour, and stopping distance from a speed of 20 miles-per-hour. For example, a combination unit having a manufacturer's GVWR of 10,000 pounds or more must develop a braking force equal to 43.5 percent of its gross weight, decelerate at a rate of 14 ft per second per second from a speed of 20 mph, and stop within 40 feet from a speed of 20 mph.<sup>105</sup>

As currently enacted, braking efficiency standards can be categorized as both performance-based standards and pure performance standards. The European Directive's braking requirement of 0.5 g braking force is a performance-based standard because it defines the vehicle parameters (braking force) necessary to achieve an acceptable stopping distance. The minimum stopping

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<sup>103</sup>*Vehicle Engineering Handbook*. p. 12.

<sup>104</sup>*Heavy Motor Vehicle Safety Inspection Guide: Rev: 1*. Land Transport Safety Authority. Auckland, New Zealand. 1995. p. 169.

<sup>105</sup>*Federal Motor Carrier Safety Regulations, Part 393.52: Brake Performance*. J.J. Keller and Associates, Inc. Neenah, Wisconsin. March, 1993. p113.

distances from specified speeds defined in the New Zealand and U.S. requirements are pure performance standards.

**Maximum Speed Limits** Several jurisdictions have established maximum speed limits for vehicles above certain gross weights. Michigan has a maximum speed limit of 55 miles/hour for vehicles above 10,000 pounds gross weight and the European Directives specify a maximum speed limit of 90 kilometer (56 miles) per hour for vehicles above 12,000 kilograms (26,500 pounds). Some of the jurisdictions within our study specifying maximum speed limits based on vehicle gross weight are:

- Australia
- European Community
- Michigan
- Netherlands

Limiting the speed of vehicles based on gross weight and vehicle configuration is a criterion used to control the interaction of a vehicle with the traffic safety environment. Maximum speed limits are a performance-based standard that have been used frequently in many countries including the United States. For example, many western states have speed restrictions for LCVs.

**Maximum Tire Load or Tire Pressure** This standard is established to specify the maximum load per inch of tread width or maximum inflation pressure that each tire can exert on the pavement surface. The standard is used to ensure the use of dual or wide profile tires for heavily loaded axles. Jurisdictions that specify maximum tire load are:

- Australia
- Canada
- Michigan

As previously noted, inflation pressure and tire load have been shown to be determinants of pavement stress. According to recent studies, this type of performance-based standard may offer great promise in limiting pavement wear. The technology required to continuously monitor factors such as tire inflation pressure is not complex and is readily available. Such standards specifying maximum tire loads could provide the motivation for tire and vehicle manufacturers to develop tire and axle configurations that would minimize pavement loads.

For example, vehicles introduced in the late 1980's with set-back front axles can have steering axle loads in excess of 12,000 pounds (6,000 pounds per tire). An 11R×22.5 (G) tire used on vehicles with set forward axles has a capacity of 6,040 pounds, which could be overloaded if placed on a setback front axle vehicle with a steering axle weight of 13,000 pounds. Such an overloaded tire could be unsafe and create excess pavement wear. In response to this condition, vehicle manufacturers now specify 12R×22.5 (G) tires on vehicles with setback front axles. These larger tires have an increased load carrying capacity (6,590 pounds) and larger contact patch (approximately one-half inch wider than the 11R×22.5 tire) and thus are safer and create less pavement wear than 11R×22.5 tires.

**Minimum Horsepower to Weight Ratios** Chile and Finland have established minimum horsepower to weight ratios. The main purpose of this regulation is to ensure that vehicles have adequate power for climbing grades and accelerating to speed. Chile specifies a minimum of 6.0 horsepower per 1,000 kilograms (2,200 pounds) and Finland specifies 4.4 DIN/kW (5.9 horsepower) for the same weight. Some countries such as Great Britain and Ireland have recently discontinued minimum horsepower to weight ratio requirements because truck operators in these countries are routinely equipping their vehicles with higher powered engines.

**New Zealand's Performance Standards** As mentioned previously, New Zealand amended its truck size and weight limits in 1989 increasing the allowable weight of certain vehicles (two-trailer "B" trains) from 39,000 kilograms (86,000 pounds) to 44,000 kilograms (97,000 pounds). Since that juncture, any further size and weight revisions are subject to performance evaluation. The target performance values for these vehicles are:<sup>106</sup>

- Static roll threshold = 0.35 g or greater
- Dynamic load transfer ratio = 0.6 or less
- High speed transient off-tracking = 0.8 meters or less

These are performance-based standards that are designed to provide a minimum level of vehicle handling and thereby enhance traffic safety. Other vehicle configurations have also been approved to operate at the higher weight limits of 44,000 kilograms (97,000 pounds) following a performance evaluation using computer simulations. For example, twin-trailer "A" trains used in the dairy industry have been approved to operate with the higher weight limits provided they meet the stricter performance standards shown below:<sup>107</sup>

- Static roll threshold = 0.45 g or greater
- Dynamic load transfer ratio = 0.6 or less
- High speed transient off-tracking = 0.5 meters or less

With the exception the stricter standards placed on the "A" trains used in the dairy industry, vehicles whose performance standards meet or exceed those of "B" train configurations are generally allowed to operate on New Zealand roads.

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<sup>106</sup>David M. White and P.H. Bass. *Improving the Safety of Heavy Vehicles in New Zealand through Performance-Based Regulations*. The New Zealand Institute for Research and Development. p.4.

<sup>107</sup>John Edgar. *Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards*. Fourth International Symposium on Heavy Vehicle Weights and Dimensions. Ann Arbor, MI. June 18, 1995. p. 2.

### **Classification of Noted Standards**

The review of size and weight regulations revealed 24 standards, or criteria, used by the study countries to control truck size and weight. Using the researchers best judgments, these standards have been classified into two protective measure categories to understand the jurisdictions' objectives of truck size and weight control. The categories are infrastructure protective measures, which are those implemented to control pavement or bridge wear, and safety protective measures, which are those designed to protect the highway safety environment. For each of the noted standards, Table 4.19 provides the protective measure category and the countries that use it for truck size and weight control.

As Table 4.19 illustrates, 12 of the standards have been classified as infrastructure protective measures, nine have been classified as safety protective measures, and three have been classified as both infrastructure and safety protective measures. On average, the countries in our study use 10 infrastructure control measures and three safety control measures. The countries using more-than-average (over 10) infrastructure control measures are:

- Australia
- Belgium
- Canada
- Denmark
- Great Britain
- Ireland
- Luxembourg
- New Zealand
- Norway
- Sweden

The countries using more-than-average (over three) safety control measures are:

- Australia
- Canada
- Denmark
- Europe
- Finland
- Great Britain
- Ireland
- Luxembourg
- Netherlands
- New Zealand

**Table 4.19: Classification of Noted Size and Weight Standards**

Size and Weight Standard	Classification		Jurisdictions
	Infrastructure	Safety	Using Standard
Maximum length based on roadway class		X	Norway
Maximum height based on obstruction clearance	X	X	France
Maximum axle weight based on number of tires	X		Argentina, Australia, Mexico, New Zealand, South Africa,
Maximum weight limits for steering axles	X		Australia, Canada, Chile, Greece, Israel, Mexico, New Zealand,
Maximum tandem/tridem weight based on axle spacing	X		Austria, Belgium, Brazil, Canada, Chile, Denmark, Europe, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, and Sweden
Axle weight limits based on suspension type	X		Belgium, Denmark, European Directives, Finland, Great Britain, Ireland, Luxembourg, Netherlands, and Sweden
Maximum trailer weight based on configuration type	X	X	Canada
Maximum vehicle weight based on number of axles	X		All
Maximum vehicle weight based on wheelbase	X	X	Canada, Great Britain, and Ireland
Maximum vehicle weight based on suspension type	X		European Directives, Great Britain, Ireland, Italy, and Spain
Maximum vehicle weight based on roadway class	X		Norway
Maximum bridge weight based on axle spacing	X		Australia, Canada, Finland, Great Britain, Ireland, Japan, New Zealand, Norway, South Africa, Sweden, and United States
Load distribution requirements		X	Canada, Denmark, Finland, France, Germany, Luxembourg, and Portugal
Turning circle requirements		X	Australia, European Directives, Finland, Great Britain, Ireland, New Zealand, and South Africa
Static load sharing requirements	X		Brazil, Canada, Finland, Great Britain, Ireland, Luxembourg, and New Zealand
Rear overhang requirements		X	Australia, Canada, Great Britain, Ireland, , and New Zealand
Braking efficiency standards		X	Australia, European Directives, Great Britain, Ireland, Netherlands, and U.S.
Maximum speed limits		X	Australia, European Directives, Michigan, and Netherlands

Size and Weight Standard	Classification		Study Jurisdiction
	Infrastructure	Safety	
Maximum tire load based on tread width	X		Canada and Michigan
Maximum weight based on engine horsepower		X	Chile and Finland
Maximum weight based on static roll threshold		X	New Zealand

Maximum weight/length based on offtracking	X	New Zealand
Maximum weight based on dynamic load transfer	X	New Zealand
Maximum weight based on rearward amplification	X	New Zealand

While it is beyond the scope of this research to determine the reasons that the above countries use more than the average number of infrastructure or safety control measures, some interesting observations can be made. Regulations in Australia, Canada, Denmark, Great Britain, Ireland, Luxembourg, and New Zealand appear in both the infrastructure and safety categories, indicating that these countries use more than the average number of controls in both protective measure categories. Some reasons for this might be that Australia, Canada, and New Zealand have recently experienced truck size and weight reform, resulting in the use of innovative vehicle configurations that require additional size and weight controls. Regulations in Great Britain and Ireland also appear in both categories. This may be attributable to reported extensive congestion and substandard infrastructure conditions.<sup>108</sup>

Norway and Sweden both use more than average infrastructure controls. This may be attributable to the extreme climate conditions or recent investment in bridge repair and replacement.

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<sup>108</sup> A telephone interview with Mr. Ron Rider, Head of Vehicle Engineering, of Great Britain's Freight Transport Association revealed that Great Britain and Ireland had both filed *Derogations*, or exceptions to the E.C. Directive for international freight because these countries have substandard bridges and crowded highways.

## CHAPTER 5: REVIEW OF ENFORCEMENT PRACTICES AMONG STUDY COUNTRIES

The adoption of truck size and weight regulations based on standards of performance has numerous implications for the enforcement community. Some of the enforcement issues and concerns frequently expressed follow (these are summarized from Clarke<sup>109</sup>):

- Will enough testing organizations and tests sites be available to perform vehicle tests and measurements?
- How complex, expensive, and time consuming will it be to run vehicle performance tests?
- How large and sophisticated a technical and administrative organization will have to be put in place in each state to oversee and meaningfully enforce this activity?
- Who will pay for vehicle performance testing? Can it be privatized? How much is it likely to cost?

To address the above issues and concerns, an informal survey was distributed via an international electronic-mail network to an international community of researchers and practitioners working in the area of truck size and weight regulation. The survey asked recipients to respond to a number of open-ended questions relating to truck size and weight enforcement practices. Questions included in the survey were:

- 1) How and where are the European Directive turning circle requirements enforced?
- 2) How are braking efficiency standards (e.g., the E.C. Brake Directive requirement mandating minimum service brake efficiency of 0.5g) enforced in other countries? In the United States, push rod travel is commonly used as a surrogate for braking efficiency. Does any country specifically measure brake efficiency?
- 3) How do Australia and New Zealand enforce the requirements mandating “t” seconds to achieve “x” psi at the rearmost brake chamber of multiple vehicle configurations?
- 4) How is the 0.45g static roll threshold enforced in New Zealand for “A” trains operating at 44 metric tonnes?
- 5) How are the minimum horsepower/weight ratios enforced?
- 6) How are the tire configurations (single tire versus dual tire) monitored at high vehicle speeds in countries such as Australia that frequently use high-speed weigh-in-motion scales for weight enforcement?
- 7) Are inter-axle dimension requirements (bridge formula) routinely checked in other countries?
- 8) How are “maximum tire load per inch of tread width” requirements used by countries such as Canada enforced?
- 9) How are off-tracking requirements monitored?

Using the responses from the above questionnaire, numerous phone interviews, and correspondence as reference, this chapter provides a summary of the truck size and weight

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<sup>109</sup>Robert C. Clarke. *U.S. Heavy Vehicle Size and Weight Policy: Is a Performance-Based Approach in Our Future?* Fourth International Symposium on Heavy Vehicle Size and Weights. Ann Arbor, MI. June 28, 1995.

enforcement practices among the jurisdictions that participated in our survey and phone interviews. These jurisdictions are Australia, Great Britain, New Zealand, and South Africa. Initially, the goal was to include information from at least ten of the study jurisdictions. However, low survey response rates, coupled with greater than expected communication issues, limited the summary to the above four countries.

Enforcement methods among these countries are then categorized and summarized by those that are or could currently be conducted at weigh stations or at random roadside inspections and those that are or could currently be conducted by other agencies such as third-party testing agencies at locations other than the roadside. This section concludes by addressing each of the above enforcement issues related to performance-based size and weight regulations.

## Australia

### Weight Enforcement

Australia reports the extensive use of weigh-in-motion (WIM) systems for the regulation of truck traffic. The WIM systems used can be categorized based upon vehicle speed. Low speed WIM scales monitor truck traffic at speeds less than 15 kilometer/hour (9.3 miles/hour). High speed WIM scales monitor truck traffic at speeds greater than 15 kilometer/hour (9.3 miles/hour). Australia currently has 139 WIM sites for regulating and collecting size and weight data for heavy vehicles. The following table provides a summary of the types of WIM scales currently used in Australia.<sup>110</sup>

**Table 5.1: WIM Scales Used in Australia**

System Name	Sensor Type	Country of Origin	Number of Sites
CULWAY	Strain Gauge	Australia	120.00
HSEMU	Load Cell	Australia	5.00
Golden River Marksman 660	Capacitance Strip	United Kingdom	2.00
Golden River Weighman	Capacitance Pad	South Africa/Great Britain	2.00
PAT DAW	Bending Plate	Germany	10.00

The High Speed Electronic Mass Unit (HSEMU) is the primary WIM system used for truck size and weight enforcement, and is capable of measuring vehicle weight, length, width, and height. Generally, vehicle weight is read directly from the WIM scales by weigh station operators and no evidence of the use of Automatic Vehicle Identification (AVI) equipment was revealed in our research. The Australian National Road Transport Commission has deemed that the HSEMU is not sufficiently accurate for issuing citations or collecting fees (such as road use taxes). However, the system accuracy is sufficient to allow for initial screening of vehicles at scale sites. The system's accuracy is such that 95 percent of the vehicles weighed are recorded within 2.5

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<sup>110</sup>C. Konidisiotis, R. Buckmaster, and P. Fraser. *Australian High Speed Weigh-In-Motion: An Overview*. Fourth International Symposium on Heavy Vehicle Weights and Dimensions. Ann Arbor, MI. June, 1995.

percent of their static weight.<sup>111</sup> Routine weigh station enforcement procedures dictate that any vehicles that do not pass the initial screening are diverted to a static scale for more thorough inspection, while the rest of the vehicles are returned to the mainline.

Although not currently used for enforcement, the most frequently deployed WIM system in Australia is the CULWAY system. This system is based on an array of strain gauges mounted underneath the roadway on the roof of existing box culverts. This unmanned system routinely collects vehicle size, weight, and speed data, and stores it on site or transmits it back to a receiving station. The CULWAY system has been recognized as a powerful tool for data collection. The system's accuracy is such that 95 percent of vehicles weighed are recorded within 10 percent of their static weight. The parameters measured by the system include:

- Vehicle speed
- Number of axles
- Number of axle groups
- Vehicle lane position
- Vehicle width
- Total vehicle length
- Axle spacing
- Axle group weight
- Gross weight

The Australian Road Research Board is responsible for the design and implementation of the WIM systems discussed and is striving to improve their accuracy. Eventually, WIM systems are planned for remote location size and weight enforcement.

## **Roadside Enforcement**

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<sup>111</sup>Konidisiotis, Buckmaster, Fraser. p. 6.

Australia conducts roadside safety inspection of heavy trucks using a system developed and deployed since 1989. The system is based on a device known as the “truckalyzer.” This device tests the braking, steering, and suspension systems of trucks during random roadside inspections. Since initial deployment, the system has demonstrated that the problem of defective brakes, suspension, and steering components is more significant than originally anticipated.<sup>112</sup> The primary purpose of the “truckalyzer” is to increase the effectiveness of random roadside inspections by allowing inspectors to find defects that would not be evident by a simple visual inspection. The self-contained system is mounted on a two-wheel trailer that can be moved from site to site and set up on any relatively flat surface in minutes. The “truckalyzer” contains a roller brake tester that electronically measures the brake force and brake balance at each wheel position. Two shaker plates are then used to check the steering and suspension system tolerances. This process is carried out by lifting the vehicle until the tires are in sliding contact with the shaker plates. The plates are then moved in and out and back and forth, so that the movement of worn steering and suspension components can be observed.

Truckalyzer inspections revealed that brake defects were 10 times greater than the Road Transport Administration (RTA) authorities had originally estimated. Enforcement officials note that the testing criteria are not as strict as European standards and that additional brake defects would be noted if testing were done according to E.C. Braking Directive standards.

### **Annual Inspections**

Australia has a mandatory inspection program that is necessary for vehicle registration. New vehicles must be inspected prior to first registration and all vehicles must then be re-inspected prior to subsequent annual registrations. In the case of “B” train doubles, the entire vehicle combination must be presented for inspection at registration and all dimensions are measured at that time.<sup>113</sup> Vehicle performance measures tested at annual inspections include brake timing, brake balance, and brake efficiency. Low speed off-tracking is also checked at these inspections and the vehicle is then type-classed based on the measured off-tracking, known as “swept path.”

### **Great Britain<sup>114</sup>**

#### **Weight Enforcement**

Great Britain has no fixed weigh stations. Compliance with maximum weight requirements is conducted by the Department of Transport (DOT) or local authority *Trading Standards* officers in cooperation with the local police. Weight enforcement is conducted randomly by uniformed police officers who direct suspected overweight vehicles to authorized *weigh bridges* (certified static scales operated by public and private entities) for close scrutiny.

Great Britain also monitors vehicle weight at the roadside with two portable devices. *Dynamic weighers* are portable scales that are capable of weighing individual axles as vehicles slowly (2.5

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<sup>112</sup>Murray Clifford. *Truckalyzer Brake Testing... "well proven"*. Truck Australia. October 1989. pp. 27-31.

<sup>113</sup>Dr. Peter Sweatman. Response to Vehicle/Roads E-Mail Network questionnaire. October 31, 1995.

<sup>114</sup>The discussion of the current enforcement practices in Great Britain is based on a phone interview and subsequent correspondence with Mr. Ron Rider, Head of Vehicle Engineering, Freight Transport Association, Kent, England. November 30, 1995.

miles/hour) drive over them. The DOT is also testing portable static wheel scales (similar to the “portable scales” used in the United States). However, technical standards, such as the slope of the weighing site, make their use more difficult.

WIM sensors, capable of recording speed, number of axles, axle weight, and vehicle length are also being installed into roadway surfaces as part of an increased effort to monitor traffic. These sensors will be used for detecting potential overload cases upon completion of a testing and approval process.

### **Roadside Enforcement**

Uniformed local police officers regularly conduct random roadside inspections for weight and type approval inspection compliance. Type approval is a process used in the European Community, Great Britain, and Ireland to check and verify the detailed technical standards of vehicles produced and operating on the highways. Type approval requires that manufacturers submit their vehicles for rigorous performance testing by the DOT.

As previously discussed, vehicles suspected of being overweight are directed to authorized weigh bridges (stations) for further inspection. Suspect vehicles may also be directed to Vehicle Inspectorate testing stations for dynamic roller brake testing.

### **Annual Inspections**

Type approval inspections assure that new vehicles conform to the performance criteria of the E.C. Directive. Testing criteria include brake and suspension performance, turning ability, and wheelbase and length measurements. After meeting type approval inspection, the DOT issues the vehicle a plate which supersedes the manufacturers plate for gross weight and axle ratings. Vehicles must be re-inspected annually at government-approved stations to ensure that they continually comply with the E.C. Directives and perform at these standards throughout their service life.

As part of the yearly inspection process, brakes are rigorously inspected for all vehicles over 3,500 kilograms (7,700 pounds). Type approval inspections must occur within 12 months after the vehicle is first put into service at one of the 90 stations owned or controlled by the Vehicle Inspectorate (a branch of the DOT). Yearly re-inspections are conducted at these same locations. Brake tests are conducted by a combination of visual inspection of the components and testing on a roller brake tester that checks the weight of each wheel, brake drum ovality, progressive braking effort up to the vehicle’s maximum, and parking brake efficiency.

The European Directives turning circle requirements are not checked for in-service vehicles. Instead, they are only used to govern the initial design of tractors and trailers. The turning circle requirements only apply to articulated vehicles (tractor-trailer combinations) greater than 15.5 meters (50.8 feet) in length. Since 16.5 meters is the maximum length for a tractor/trailer combination, only vehicles within a one meter window are required to comply with the turning circle requirement. In contrast to those trailers produced in the United States, British trailer manufacturers build trailers with fixed-position tandems and tridem that assure compliance with the E.C. turning circle requirements. The DOT is considering a “deemed-to-comply” proposal

that certifies compliance with turning circle requirements provided the wheelbase of a semi-trailer does not exceed 8.0 meters.

### **New Zealand**

New Zealand enforces its size and weight regulations during routine stops and inspections at weigh stations. As part of the enforcement procedure at these stations, officials monitor axle group and gross weights and paperwork (driver's logbook, payment of Road User Charges, and Certificate of Fitness documents). Sometimes technically qualified staff check height and length and steering, brake, and suspension components during random inspections at weigh stations to ensure that the vehicle is road worthy.<sup>115</sup>

Similar to the E.C. Type Approval process, vehicles must also be presented for Certificate of Fitness (COF) inspections before being granted first registration. Vehicles are also re-inspected at subsequent six-month intervals. Turning circle dimensions are only checked at the first COF inspection. Brakes are rigorously examined at each COF inspection using dynamic roller brake testers.

Certain vehicles ("A" train milk tankers and "B" trains ) are allowed to operate above the 39,000 kilograms (86,000 pounds) weight limits. These vehicles are required to have additional permits that must be carried in the cab at all times.<sup>116</sup> These permits state that the vehicle is safe to operate at these higher weight limits. Stability testing for these vehicles is done using computer simulation programs that are acceptable to the Land Transport Safety Authority.<sup>117</sup> The computer simulations determine if the submitted vehicle design meets the specified target performance levels for static roll threshold, dynamic load transfer ratio, and high speed transient off-tracking. Practical field tests are not recommended due to the difficulty in measuring results accurately and, because under the required test conditions, sudden rollover could occur if a vehicle performs below the standard.<sup>118</sup> The simulations are conducted with the assumption that the vehicle is equipped with new tires, since tests have shown that cornering stiffness is lowest for full tread depth tires. New Zealand officials concluded that a vehicle configuration that meets the above target performance values with new tires would continue to satisfy them for the life of the tire. These configurations may not be modified after receiving state certification.

### **South Africa**

According to responses of local enforcement officials, overloaded trucks are apparently quite prevalent in South Africa. The motor carrier industry has recently been deregulated and

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<sup>115</sup> Questionnaire response from David White, Technical Researcher at the New Zealand Institute for Industrial Research Limited. Auckland, New Zealand. December 6, 1995.

<sup>116</sup> John Edgar. *Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards*. Fourth International Symposium on Heavy Vehicle Weights and Dimensions. Ann Arbor, MI. June, 1995.

<sup>117</sup> John Edgar. p.4.

<sup>118</sup> John Edgar. p.4

enforcement officials believe that many unprofessional truck operators from South Africa and neighboring countries will do anything for a competitive edge.<sup>119</sup> Consequently, the country is investing in the construction of additional weigh stations and enforcement methods that will encourage self-regulation. Currently, all vehicles must enter fixed weigh station sites on established routes. Each time a vehicle enters a station the following items are checked:

- Gross weight and axle weight
- Axle spacing
- Height and length

Brakes are randomly checked using a dynamic roller brake tester at weigh stations. The manufacturer's plate and the Certificate of Fitness (similar to the Type Approval inspections certificate used in Great Britain) are checked at yearly inspections in accordance with the Road Traffic Quality System, to insure that the vehicle meets the specified requirements.

### **Summary of Weigh Station Enforcement Practices**

Our investigation revealed a number of enforcement activities among these four countries that were routinely conducted at weigh stations. Some of the enforcement activities such as weighing and axle spacing measurement protect the highway infrastructure, while others such as roller brake testing protect traffic safety. The following table provides a summary of the reported weigh station enforcement practices and the type of protective measure that is being enforced.

**Table 5.2: Summary of Protective Measures Provided by Weigh Station Enforcement Practices**

<b>Enforcement Practice</b>	<b>Type of Measure</b>	<b>Country Reported</b>
Static weighing	Highway infrastructure	Australia, New Zealand, South Africa
Weigh-in-motion	Highway infrastructure	Australia
Roller brake testing	Traffic safety	Australia, Great Britain, New Zealand, and South Africa
Axle spacing	Highway infrastructure	South Africa
Length and width	Traffic safety	Australia, New Zealand, South Africa
Paperwork	Highway infrastructure and traffic safety	Australia, New Zealand, South Africa

### **Other Enforcement Practices**

The research revealed that numerous enforcement activities were occurring at locations other than weigh stations and by other government agencies and private entities. The following table

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<sup>119</sup>This information was received via fax and e-mail from Paul Nordengen, Director, Division of Roads and Transport Technology, CSIR, Pretoria, South Africa. May 2, 1995.

provides a summary of the enforcement activities, the type of protective measure, and the country practicing the method.

**Table 5.3: Summary of Protective Measures Provided by Other Enforcement Practices**

<b>Enforcement Practice</b>	<b>Type of Measure</b>	<b>Country Reported</b>
Type approval/ initial inspection	Highway infrastructure and traffic safety	Australia, Great Britain, New Zealand, South Africa
Periodic inspection	Highway infrastructure and traffic safety	Australia, Great Britain, New Zealand, South Africa
Static weighing	Highway infrastructure	Great Britain
Stability testing (New Zealand LCVs)	Traffic safety	New Zealand
Truckalyzer random inspections	Traffic safety	Australia

As the above table illustrates, the emphasis of enforcement methods, both at weigh stations and at other locations is generally balanced between protecting both the highway infrastructure and promoting traffic safety.

### **Conclusions**

The review of enforcement practices among these four jurisdictions addressed some of the enforcement issues and concerns listed in the introduction of this chapter while leaving other questions unanswered. The following paragraphs summarize the implications of our findings on these listed enforcement concerns.

#### **Vehicle Performance Testing Organizations and Test Sites**

The experience in the countries that cooperated in this research confirmed that organizations and testing sites must be designated to conduct vehicle performance tests. The four countries cooperating with our research use numerous resources to conduct type approval, certificate of fitness, and periodic inspections. These inspections are keyed to vehicle registration and inspectors are generally certified by some designated oversight agency. Given the experience of these countries, the implementation of performance-based size and weight regulation in the United States may require an investment in vehicle testing and inspection sites. This investment could occur in either the public or private sector for existing or new agencies to establish minimum acceptable performance-based standards and certify testing facilities and procedures.

#### **Complexity of Vehicle Performance Tests**

The complexity of vehicle performance tests is illustrated by the experience of these countries in brake performance testing and vehicle simulation modeling. Each of the four countries that cooperated with our enforcement research use roller brake testing to monitor brake performance. Officials in Great Britain indicated that the roller brake testers in use are computer controlled. These computerized roller brake testers have the specified braking data on over 6,000 vehicle models. The documentation accompanying the vehicle contains a code identifying the vehicle model and brake system specifications. Upon receiving the appropriate brake system code, the computer's visual display unit instructs the operator on the appropriate testing procedure for the particular vehicle being tested. If the United States chooses to adopt brake performance

standards as part of truck size and weight regulation, substantial additional investment would be required to fully implement roller brake testing.

New Zealand's experience with performance testing approval for 44,000 kilogram (97,000 pound) "A" train milk tanker configurations indicates that some performance tests are best suited to computerized testing procedures using simulation programs. At the time that the approval process for these configurations was occurring, the only organization with the ability to do the required simulation test was a government agency entitled the Auckland Industrial Development Division.<sup>120</sup> Officials charged with this process favored computer simulation over actual field tests because of technical and safety concerns with accurately measuring vehicle performance in the field. Similar concerns would exist for U.S. truck size and weight regulators wishing to implement standards for such performance parameters as rollover thresholds or high-speed offtracking. Similar to brake performance tests, a substantial investment in facilities and technologies away from the roadside would be required to conduct these tests.

### **Enforcement and Monitoring of Performance-Based Standards**

With the exception of roller brake testing, the research revealed that current enforcement practices at weigh stations in these four countries are similar to those currently employed in the United States. Current U. S. enforcement practices include monitoring vehicle weights using both static and weigh-in-motion technologies and varied levels of vehicle inspections. The U.S. size and weight enforcement infrastructure includes a comprehensive network of permanent weigh stations and temporary facilities that routinely monitor vehicle size and weight. Additionally, the most current statistics indicate the capacity exists to perform a large number of inspections, as two million safety inspections were conducted in the United States at permanent or random roadside locations during 1994.<sup>121</sup>

Some performance-based standards could be monitored by using technologies such as those currently proposed or being tested as part of the intelligent transportation systems for commercial vehicle operations (ITS/CVO). The goal of the ITS/CVO program is to improve highway safety and motor carrier productivity through the application of advanced technology. The objective of the program is to use cost-effective methods and technologies to streamline current state regulatory and enforcement activities and motor carrier practices.<sup>122</sup> ITS/CVO program planners have identified six CVO user service areas that will benefit from the development and application of advanced technologies. Of the six, the following two areas could be developed to provide information for performance-based standards size and weight regulation.

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<sup>120</sup>John Edgar. *Regulating Heavy Vehicle Safety in New Zealand Using Performance Standards*. Fourth International Symposium on Heavy Vehicle Weights and Dimensions. Ann Arbor, MI. June, 1995.p.5

<sup>121</sup>*Press release number 42-95*. Federal Highway Administration. Washington, D.C. July 14, 1995.

<sup>122</sup>*National ITS Program Plan: Volume II First Edition*. U.S. Department of Transportation. Joint Program Office for ITS. Washington, D.C. March, 1995. p.182.

- Commercial vehicle electronic clearance
- Automated roadside inspection

As envisioned, the commercial vehicle electronic clearance service would allow truck size and weight enforcement personnel to electronically check the credentials, size and weight, and safety records of transponder-equipped vehicles before they enter a weigh station or inspection site. Such credential data could be expanded for performance-based standards to include vehicle type approval or certificate of fitness inspection data. As new technologies are developed and deployed, the size and weight information provided by transponder-equipped vehicles could also include dynamic loading information.

Automated roadside inspection services are envisioned to apply state of the art technologies to provide more rapid and selective inspections through the use of sensors and diagnostics programs. Under performance-based size and weight regulation, these sensors or diagnostic programs could provide such performance criteria as rearward amplification or dynamic load transfer data (e.g., current and peak parameters that occurred over a specified vehicle history period).

### **Cost and Responsibility for Vehicle Performance Tests**

Unfortunately, the research did not reveal sufficient data to adequately address the issue of cost and responsibility for vehicle performance tests. However, the following observations could be used to address these issues.

The responsibility for vehicle certification and vehicle performance tests could be assumed by vehicle manufacturers and operators. Component manufacturers could form partnerships to develop and submit new vehicle configurations for testing and approval. Using a twin-trailer “B” train configuration as an example, tractor manufacturers could form partnerships with trailer manufacturers and coupling vendors to cooperatively develop and submit a complete vehicle to a designated agency or facility for testing and approval. The cost of this cooperative development and submittal would be shared by all parties (e.g., truck and trailer manufacturers and component vendors) involved. The designated testing agency could either assume the cost of vehicle type approval tests or request reimbursement of costs from the partnership that developed and submitted the configuration.

Under this scenario, vehicle operators would likely bear the responsibility of purchasing the approved vehicle components and submitting the “whole vehicle” for inspection and approval. Once again using a “B” train configuration as an example, vehicle operators would be responsible for purchasing approved tractors (e.g., specified with appropriate wheelbase, suspensions, tire size and type, and horsepower) and trailers (e.g., also specified with appropriate wheelbase, suspensions, tire type and size and approved coupling devices). Vehicle operators would then submit the entire “B” train configuration for testing and approval by certified agencies or organizations. The cost of initial testing and approval would be assumed by these vehicle operators. Vehicle operators would also be responsible for periodic re-inspections.

Similar to current enforcement practices, the public sector would likely bear the cost of enforcing

performance-based standards. For example, the development and deployment of vehicle testing devices such as roller brake testers or devices similar to the “Truckalyzer” used in Australia would be borne by the public sector. The public sector would likely also bear the cost of training for enforcement officials charged with monitoring vehicle performance.

## **CHAPTER 6: POTENTIAL OF NOTED PERFORMANCE-BASED STANDARDS FOR U.S. SIZE AND WEIGHT REGULATION**

The review of size and weight regulations revealed 24 standards used to directly or indirectly control truck size and weight which are based on the interaction between the vehicle and the infrastructure and/or traffic safety environment. The purpose of this chapter is to investigate the potential of these standards for U.S. truck size and weight regulation.

This section first arranges the 24 noted standards according to their fundamental governing objective and then groups them corresponding to the feasibility of integrating them in the U.S. truck size and weight framework. This approach illustrates the importance of assessing the potential of these standards as systems based on how they interact with and complement one another rather than assessing them individually. For example, if truck size and weight policy makers were to implement standards to govern highway network usage by specifying maximum vehicle weight by roadway class, they would also likely implement standards defining maximum length by roadway class. The chapter concludes with a comparison of the benefits versus the enforcement issues associated with integrating each of the identified groups of standards into U.S. size and weight regulations.

### **Fundamental Governing Objectives**

Six categories, shown below were first developed to describe the fundamental governing objective of the standards noted.

- **Group One:** Maximum axle load
- **Group Two:** Maximum gross weight
- **Group Three:** Maneuverability and length control
- **Group Four:** Suspension and axle set performance
- **Group Five:** Braking efficiency and overhang requirements
- **Group Six:** Highway network restrictions

Table 6.1 summarizes each of the 24 noted standards by group and then designates whether they are performance-based or pure performance. As the table illustrates, 21 of the 24 noted standards are parametric performance-based. Additionally, the majority of these standards (13 of 24) are used to govern maximum gross weight and maximum axle weight.

**Table 6.1: Summary and Classification of Performance Standards**

Governing Group and Standard Name	Standard Type	
	Parametric	Pure Performance
<i>Group One: Maximum axle load</i>		
• Maximum weight limits for steering axles	X	
• Maximum axle weight based on number of tires	X	
• Maximum tire load based on tread width	X	
• Maximum tandem/tridem weight based on axle spacing	X	
<i>Group Two: Maximum gross weight</i>		
• Maximum vehicle weight based on number of axles	X	
• Maximum vehicle weight based on wheelbase	X	
• Maximum bridge weight based on axle spacing	X	
• Maximum weight based on engine horsepower	X	
• Maximum weight based on static roll threshold	X	
• Maximum weight based on dynamic load transfer	X	
• Maximum weight based on rearward amplification	X	
• Maximum trailer weight based on configuration type	X	
• Load distribution requirements	X	
<i>Group Three: Maneuverability and length controls</i>		
• Turning circle requirements		X
• Maximum length/weight based on offtracking	X	
<i>Group Four: Suspension and axle set performance</i>		
• Static load sharing requirements	X	
• Maximum axle weight based on suspension type	X	
• Maximum vehicle weight based on suspension type	X	
<i>Group Five: General performance controls</i>		
• Braking efficiency standards		X
• Rear overhang requirements	X	
• Maximum speed limits	X	
<i>Group Six: Highway network restrictions</i>		
• Maximum vehicle weight based on roadway class	X	
• Maximum length based on roadway class	X	
• Maximum height based on obstruction clearance		X

**Feasibility of Standards for U.S. Truck Size and Weight Regulation**

Four categories, as shown below were identified to judge the feasibility of the 24 noted performance standards for U.S. truck size and weight regulation.

- Standards capable of enhancing existing size and weight regulations
- Standards readily implemented in a broadened size and weight regulation set
- Standards requiring investments in enforcement and/or equipment technologies
- Standards requiring policy reform.

For each of the above categories, the following paragraphs define and identify the standards included, discuss the benefits and enforcement issues, and summarize the potential role of these standards in the U.S. truck size and weight regulations.

### **Standards Capable of Enhancing Existing Size and Weight Regulations**

The performance standards included in this group are either currently utilized or could be used to enhance the existing set of size and weight regulations. The underlying assumption in integrating this group of standards is that no significant revisions in existing size and weight regulations would be required. Rather, these standards could be used to place equitable constraints on those vehicles permitted to operate at existing maximums. As a result, certain existing practices that are known to overstress the highway infrastructure would be reduced and thus result in less infrastructure wear and improved traffic safety with little or no cost to highway users. As noted in the paragraphs below, some of these standards, such as maximum bridge weight, currently exist in U.S. size and weight regulations.

**Performance Standards Included** The performance standards included in this group are shown below: Key words in the each of the noted standards are italicized and used in subsequent paragraphs discussing the benefits, enforcement issues, potential role of these standards in U.S. truck size and weight regulations.

- Maximum weight limits for *steering axles*: Under this performance standard, steering axles could be limited to different maximum weights than other single axles.
- Maximum axle weight based on the *number of tires*: This standard could establish lower axle weights for those axles equipped with single tires at each wheel position than for those axles equipped with dual tires at each wheel position. As at present, the load rating of the tires would have to be adequate for the maximum axle weight.
- Maximum tire load based on *tread width*: This standard could prescribe load limits for each tire of a given vehicle based on tread width. Tires with wider treads would be allowed greater loads.
- Maximum *bridge weight* based on axle spacing: As currently applied, this standard bases the maximum weight of any group of two or more axles on the distance between the most widely spaced axles, with greater weight allowed for those axle groups spaced farther apart.
- *Load distribution requirements*: For tractor-trailer or truck-trailer combinations, this requirement could place restrictions on the percent of total vehicle weight that could be carried by the power unit or the trailer. For example, some jurisdictions using this criterion specify that trailer weight cannot exceed 150 percent of tractor weight.
- *Static load sharing requirements*: Quite simply, a requirement such as this could mandate that individual axles of any axle group share loads equally.

- *Braking efficiency standards:* Braking efficiency is currently governed using either or both of two criteria: A performance-based standard that establishes minimum braking forces at each wheel position or a pure performance standard that prescribes maximum stopping distances from a given speed.
- *Rear overhang requirements:* This criterion could limit the distance from the last axle to the rear of the vehicle.
- *Maximum speed limits:* This criterion could be used to place lower maximum speed limits on those vehicles with poorer handling characteristics.

**Potential Benefits** The benefits of integrating this group of standards, as shown below, include reduced pavement rutting, and improved vehicle handling.

- *Steering axle:* Pavements and bridges would benefit from reduced wear and rutting. Safety benefits would accrue to motor carriers through reduced tire failure on steering axles.
- *Number of tires:* This standard could reduce wear on pavements and is based on proven research that illustrates that single tires cause more pavement stress per pound of load than dual tires.
  - *Tread width:* Pavements (primarily flexible pavements) would benefit by ensuring that wheel loads were spread over an acceptable contact patch width.
- *Bridge weight:* Benefits accrue to bridges because allowable bridge weights are based on overstress criteria that are designed to protect weak bridge spans.
- *Load distribution requirements:* The benefits of such a requirement would be to the traffic safety environment. This is based on principles of vehicle design that demonstrate the poor handling qualities of vehicles with too great a portion of total weight on the rear of the vehicle.
- *Static load sharing requirements:* Pavements would benefit from such a standard because it would prevent the additional fatigue caused by overloaded individual axles.
- *Braking efficiency standards:* The traffic safety environment benefits from specified minimum braking performance.
- *Rear overhang requirements:* The traffic safety environment would benefit by limiting the hazards caused by “reverse swing” during tight turning maneuvers at the rear of long vehicles with a short wheelbase.
- *Maximum speed limits:* The traffic safety environment would benefit by limiting the speed of those vehicles with known handling deficiencies.

**Enforcement Issues** Generally, few enforcement issues are associated with integrating this group since many of the standards included are currently employed. The following paragraphs summarize the issues with each of standards.

- *Steering axle:* This could be readily enforced using visual checks or technology to assist officials in determining axle configurations and monitoring allowable weight.
- *Number of tires per axle:* This would be a simple standard to enforce as weigh station officials could use technology or visual checks to quickly determine the number of tires per axle. However, the activity of monitoring tire configurations would add to the workload of those personnel.
- *Tread width:* Enforcement officials would be required to determine the tire size and tread width as part of the process of monitoring vehicle weight. Unfortunately, tire size and tread width cannot be quickly checked by visual methods. Because tire sizes are branded in the tire sidewall with small-sized numbers, visual identification of tires would have to be done from a short distance. This would require more time and effort than visually monitoring other standards (e.g., axle spacing). Additionally, personnel charged with monitoring vehicle weight using this requirement would need to either observe tire size and use a chart or formula to convert tire size to tread width or obtain measurements of tread width using a mechanical device (e.g., calipers), in-pavement sensors, or in-tire sensors (e.g., transponders). Either of the monitoring methods would increase the complexity of size and weight enforcement.
- *Bridge weight:* Minimum enforcement issues, as this practice of controlling axle weight has been in use since the 1972.
- *Load distribution requirements:* This standard would be complex to enforce because load transfer would make it difficult to determine the portion of load that is carried by the trailer. Most likely, a proxy for load distribution that would provide load distribution percentages based on steering axle, tractor tandem, and trailer tandem weight would have to be developed to quickly enforce such a standard.
- *Static load sharing requirements:* This standard is readily enforceable as part of the vehicle weighing process. It would require enforcement personnel to measure the individual axle weights within an axle group and determine that axles within the group were equally loaded.
- *Braking efficiency standards:* Braking efficiency standards are currently part of the Federal Motor Carrier Safety Regulations and enforced using surrogate measures such as brake pushrod travel as indicators of brake performance. Keying these standards to size and weight regulations (e.g., pure performance standards in which the vehicle would be required to demonstrate stopping distance from a defined speed at maximum allowable weight) could increase the complexity of enforcement.

- *Rear overhang requirements:* Similar to the procedure used to enforce wheelbase or bridge dimensions, this requirement could be quickly monitored using visual checks or sensing devices.
- *Maximum speed limits:* This standard would require enforcement personnel to be aware of and monitor of those vehicle configurations with speed limit restrictions.

**Potential Role** Many of these standards are currently or could be feasibly adapted to the existing size and weight regulation set.

- *Steering axle:* Although easy to enforce, this standard could adversely affect the productivity of some vehicle configurations. Vehicle manufacturers and operators have specified wider and stronger tires for vehicles with heavily loaded steering axles. Establishing and implementing this standard would therefore require input from vehicle, tire, and pavement designers to achieve steering axle weight limits that best promote pavement and tire life.
- *Number of tires:* Relatively easy to enforce and deploy, this standard offers potential for U.S. size and weight regulations. Motor carriers not constrained by heavy axle loads would be permitted to operate vehicles with single tire axles and potentially lower their cost of operation. Highways and bridges could benefit from reduced wear and rutting.
- *Tread width:* Although enforcement of such a standard would be complex, the benefits to pavements are great. Additionally, vehicle and tire manufacturers would be provided with the initiative to develop innovative tire designs that conformed to, or even surpassed, prescribed standards.
- *Bridge weight:* Currently, this standard is a major component of U.S. size and weight regulations.
- *Load distribution requirements:* Providing that a method could be developed for quickly determining load distribution from axle weight, this standard could assure certain levels of vehicle performance and be easily integrated into U.S. size and weight regulations.
- *Static load sharing requirements:* This requirement would be readily enforced, create less pavement wear, and not dramatically affect the existing U.S. heavy vehicle fleet.
- *Braking efficiency standards:* Braking efficiency standards are presently a component of the Federal Motor Carrier Safety Regulations.
- *Rear overhang requirements:* This requirement could be readily enforced and the benefits to the traffic safety environment are quite apparent. However, limiting rear overhang may have an adverse effect on segments of the motor carrier industry that frequently use sliding trailer tandems to assist maneuverability in urban areas or areas where turning space is constricted.

- *Maximum speed limits*: This standard is currently used in many areas by placing blanket speed restrictions on all commercial vehicles. However, significant issues must be resolved prior to implementing such a standard on a subfleet of commercial vehicles. For example, what procedures would be used to test and certify the handling properties of vehicle configurations? How would such a standard be effectively monitored at the roadside?

### **Standards Readily Implementable**

Standards included in this group could be readily integrated into an expanded set of truck size and weight regulations. These standards could be used to assure that increased size and weight limits would be rationally applied using proven pavement and vehicle handling research results. Truck size and weight regulators could either apply these standards uniformly to all commercial vehicles or to just a subfleet of trucks operating under a more stringent specification set. The primary difference between this group of standards and the next group is that it would not require a significant change in existing enforcement practices. Quite simply, vehicle operators would make an investment in more productive equipment in exchange for operating under a more stringent set of requirements.

**Performance Standards Included** The performance standards included in this group are shown below: Key words in the each of the noted standards are italicized and used in subsequent paragraphs discussing the benefits, enforcement issues, and potential role of these standards in U.S. truck size and weight regulations.

- *Maximum tandem/tridem weight based on axle spacing*: Using this standard, jurisdictions base maximum tandem or tridem-axle weight on the distance between the first and last axles of the group, and tandem or tridem-axles with greater axle spacing are allowed higher maximum weight
- *Maximum vehicle weight based on number of axles*: This measure would base maximum vehicle weight on the number of axles. Quite simply, vehicles with more axles (say six instead of five) would be allowed higher gross weights.
- *Maximum vehicle weight based on wheelbase*: This criterion would govern maximum vehicle weight based on the distance between the first and last axles of a given vehicle. Vehicles with greater wheelbase would be granted higher maximum weight.

**Potential Benefits** The benefits of this group, as shown below, primarily include reduced infrastructure wear.

- *Tandem/tridem based on axle spacing*: The benefits of increased axle spacing are based on pavement and bridge design principles. For example, research has shown that increased axle spacing on rigid pavements prevents the stress cones under each axle from overlapping each other, thereby reducing total pavement stress. Some research has even shown that appropriately spaced tandem-axles can cause less pavement wear than the wear caused by two single axles carrying the same load.

- *Number of axles:* Chapter two of this report discussed the engineering principles of limiting axle loads and distributing weight over more axles. As proven by extensive research, the major determinant of pavement wear is axle load. Additionally, a recent study investigating the safety implications of various vehicle configurations revealed that a six-axle, tractor-semitrailer with tridem-axles on the trailer could be a vehicle with reasonable levels of intrinsic safety at gross weights of 39,000 kilograms (86,000 pounds).<sup>123</sup> Motor carriers making investments in vehicles with more axles would be rewarded with higher payload capacities.
- *Wheelbase:* Primarily, bridges would benefit from the engineering principles of spreading loads over greater distances. Secondary traffic safety benefits would accrue because longer wheelbase vehicles have exhibited less tendency to tip, sway, or wander at given gross weights.

**Enforcement Issues** Primarily, the enforcement issues associated with integrating this group of standards, as shown below, are attributable to routinely determining the axle spacing and wheelbase of vehicles.

- *Tandem/tridem weight based on axle spacing:* This standard would require enforcement personnel to determine axle spacing as part of routine weight enforcement procedures. This could be accomplished by visual checks or with equipment that could measure axle spacing as the vehicle passed a sensing device. Visual checks are not as difficult as one would first assume because the difference between the axle spacing categories used in other countries are quite apparent (e.g., the three tandem-axle spacing categories used in the European Directive are 1.0 meters [3.3 feet], 1.3 meters [4.3 feet], and 1.8 meters [5.9 feet]) and reference points could be used to quickly assess the axle spacing of the vehicle in question. For example, the most common tandem-axle spacing for vehicles in the United States is 1.3 meters (4.3 feet). At those spacings the gap between the tires on the adjacent axles is less than one foot. If the tandem-axle spacing is increased to 1.8 meters (5.9 feet), the gap between the tires would increase to about two and one-half feet. This difference would be very apparent to most observers.
- *Number of axles:* Few enforcement issues are associated with a criterion such as this. Size and weight enforcers would only need to determine the number of axles to establish maximum allowable weight. This could be quickly accomplished by visual checks or sensors to tabulate the number of axles for the vehicle in question.
- *Wheelbase:* Currently enforced as part of bridge weight laws and easily measured by visual or electronic methods.

**Potential Role** These standards could play a significant role and be readily implemented in any size and weight reforms that provided increased truck size and weight limits.

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<sup>123</sup>Paul S. Fancher and Arvind Mathew. *Safety Implications of Various Vehicle Configurations - Vol. III: Summary Report*. Report No. FHWA-RD-89-085. Turner-Fairbank Highway Research Center, Federal Highway Administration. McClean, VA. January, 1990. p 61.

- *Tandem/Tridem weight based on axle spacing*: This standard may have a role in U.S. size and weight regulation because the benefits are based on proven engineering principles and the standard could be enforced with very little effort. Using this standard, motor carriers making the investment in equipment with appropriately spaced axle groups would be rewarded with higher payloads.
- *Number of axles*: If the goal of truck size and weight reform is to provide more productive vehicles with equal or better levels of safety and pavement wear than vehicles currently operating under prescriptive size and weight regulations, this standard has the capability to quickly accomplish such a goal. Many jurisdictions in our study have used this type of governing technique to provide more productive vehicles, while simultaneously protecting the infrastructure and the traffic safety.
- *Wheelbase*: Currently exists in the U.S. truck size and weight regulations as part of the bridge weight standards.

### **Standards Requiring Significant Investment**

Standards included in this group are more complex than previous groups. They are generally based on vehicle handling properties that would require sophisticated instrumentation to measure. As shown below, the traffic safety environment benefits of implementing these standard are significant. However, a fundamental change in current truck size and weight enforcement equipment and methods would be required prior to implementing these standards.

**Performance Standards Included** The performance standards included in this group are shown below: Key words in the each of the noted standards are italicized and used in subsequent paragraphs discussing the benefits, enforcement issues, potential role of these standards in U.S. truck size and weight regulations.

- Maximum weight based on *engine horsepower*: This criterion would limit maximum vehicle weight on the basis of engine horsepower. Vehicles with higher horsepower would be allowed greater maximum weight.
- Maximum weight based on *static roll threshold, off-tracking, dynamic load transfer, or rearward amplification ratio*: Similar to the standards employed in New Zealand, these requirements would base maximum weight on attributes of vehicle handling. Vehicles demonstrating improved handling (e.g., higher static roll thresholds, or lower off-tracking) would be permitted higher maximum weight.
- Maximum *trailer weight based on configuration type*: This standard would apply to multiple trailer configurations. Under this scenario, the lead and rear trailers of a multiple trailer configuration would be allowed different maximum weights based on the coupling method. For example the M.O.U. for interprovincial travel in Canada sets lower maximum rear trailer weight for “A” train configurations than for “B” train configurations.
- *Turning circle requirements*: This would require that vehicle configurations be able to

complete a 360 degree turn within a prescribed wall-to-wall distance.

- **Maximum axle weight or maximum vehicle weight based on *suspension type*:** This standard would establish different axle weight limits for different suspension types. The standard could either set a norm for axles with leaf spring suspension and grant extra weight for axles equipped with proven “road friendly” suspensions or prescribe different axle weight limits for each of the commonly used suspension types.

**Potential Benefits** The benefits of implementing this group, as shown below include improved vehicle handling and reduced pavement wear.

- ***Engine Horsepower:*** The traffic safety environment would benefit in mountainous terrain because such a standard could indirectly regulate minimum road speed.
- ***Static roll threshold, off-tracking, dynamic load transfer, or rearward amplification ratio:*** The traffic safety environment would benefit from standards such as these because minimum prescribed levels of vehicle handling would be ensured while simultaneously providing for greater vehicle productivity
- ***Trailer configuration:*** The primary benefit of limiting trailer weight is the traffic safety environment. Vehicle design principles have demonstrated that rearward amplification, high-speed transient off-tracking, and static roll threshold (all of which determine the extent of trailer sway and wander) are affected by factors such as the method of coupling multiple trailer configurations.
- ***Turning circle requirements:*** Benefits would accrue to the traffic safety environment by ensuring the ability of vehicles to negotiate tight turns without striking any obstructions.
- ***Vehicle/Axle weight based on suspension Type:*** Pavements and bridges would receive the greatest benefits from this type of standard. Research has suggested that some suspensions (e.g., air-ride) have lower dynamic loads than others (walking beam or leaf spring). Although initial findings suggest that the benefits to pavements are greatest if all axles are air-ride equipped, much additional research needs to be done before pavement and vehicle designers can accurately assess the extent of these benefits and the nature of the benefits when only one axle group is air-ride equipped.

**Enforcement Issues** Significant enforcement issues, primarily attributable to vehicle performance testing, associated with this group are noted below.

- ***Engine horsepower:*** This standard would be relatively simple to enforce. Officials would need to determine engine horsepower ratings as part of vehicle weight enforcement using visual methods (e.g., observing placards) or an element of the registration tag that signified an engine power rating class) or electronic methods (e.g., transponders).
- ***Static roll threshold, off-tracking, dynamic load transfer, or rearward amplification***

*ratio*: These are the most vexing standards to enforce as the parameters of such standards are difficult, if not nearly impossible, to measure in the field. One possible enforcement method would be to verify that vehicle designs meet with the prescribed standards using computer simulations and then certify that “as-built” vehicles met with the approved designs. Certified vehicles could then be placarded as meeting specified performance requirements. However, these placards could be inaccurate in situations where one tractor was coupled to many different trailers.

- *Trailer configuration*: Truck size and weight officials would be required to determine both the type of configuration and the trailer weight to appropriately enforce this rule. Given that total trailer weight may be masked in some multiple trailer configurations (e.g., “B” trains), this would be a problematic standard to enforce.
- *Turning circle requirements*: The turning ability of vehicle configurations could be demonstrated to enforcement officials at inspection facilities with adequate open space. Alternatively, vehicle placards could certify the turning circle capabilities of a given vehicle configuration. However, vehicle placards could be inaccurate in situations where one tractor was coupled to many different trailers.
- *Suspension type*: Several enforcement issues exist for a standard such as this. First, the standard would require enforcers to quickly assess the type of suspension for the vehicle in question. While this process could be assisted through training of enforcement personnel, it would still be quite cumbersome and potentially time consuming. Most likely, a means of suspension identification, (e.g., a placard or plate) would be required to make this a workable standard.

**Potential Role** The potential role of this group of standards is summarized below.

- *Engine horsepower*: Although used in several of our study jurisdictions (Chile and Finland), better methods of ensuring minimum vehicle speed on upgrades exist. Perhaps, the most efficient means of preventing slow moving vehicles on upgrades is through minimum speed limits. The task of enforcement would be simple, as slow-moving vehicles would be ticketed. Such standards currently exist in some U.S. locations.
- *Static roll threshold, off-tracking, dynamic load transfer, or rearward amplification ratio*: Much discussion has occurred in regard to the implementation of standards such as these. The primary goal of these standards is to reduce traffic accidents or the sudden loss of vehicle control during severe maneuvers. However, the relationship of traffic accidents or loss of control to measures such a static roll threshold or dynamic load transfer rates is difficult to judge. Additionally, the enforcement of such standards is difficult to establish.
- *Trailer configuration*: Currently, most multiple trailer configurations being operated in the United States are five-axle “A” train, twin-trailer combinations, that are used

predominantly in the less-than-truckload motor carrier sector. Limiting the rear trailer weight of these combinations would be feasible because the weight of these trailers is not masked by load transferring hitches. However, a standard such as this would become quite complex to enforce when and if a greater mix of multiple trailer combinations (e.g., “B” trains) are used in the United States.

- *Turning circle requirements:* A requirement such as this would be more important in urban and industrialized areas or mountainous terrain with narrow or twisting roadways. However, implementing such a standard could have dramatic effects on the current U.S. heavy vehicle fleet because of the extensive use of sliding fifth wheels and trailer tandems. Turning circle requirements may result in devices to limit the slide length of fifth wheels or trailer tandems.
- *Vehicle/Axle weight based on suspension type:* The issues related to this standard are quite complex because it is based on the principle of dynamic, rather than static loads and is based on research illustrating that some suspensions transmit lower dynamic loads to the pavement structure. As noted in chapter two of this report, current pavement design methodology is insensitive to dynamic loads. Further, this standard would require training or technological assistance to be effectively monitored by enforcement personnel.

### **Standards Requiring Policy Reform**

This group of standards could be used to place restrictions on highway access. Under existing truck size and weight policy, the majority of the U.S. commercial truck fleet is provided uniform access to the national highway network through legislation such as the STAA of 1982.

However, standards such as those listed below could limit commercial vehicle travel based on vehicle size and/or weight.

**Performance Standards Included** The performance standards included in this group are shown below: Key words in the each of the noted standards are italicized and used in subsequent paragraphs discussing the benefits, enforcement issues, potential role of these standards in U.S. truck size and weight regulations.

- Maximum *weight* based on roadway class: This requirement would base maximum vehicle weight on the load bearing ability of the roadway. Vehicles would be allowed higher maximum weight on roads constructed to accommodate greater loads.
- Maximum *length* based on roadway class: This standard would allow longer vehicles on roadways with the appropriate length class. Non-articulated trucks, truck trailers, and tractor-trailers would have different length limits for each roadway class.
- Maximum height based on *obstruction clearance*: This standard would allow higher vehicles to operate on roadways with fewer height obstructions, and place the responsibility for obstruction clearance with the vehicle operator

**Potential Benefits** The benefits of this group, as shown below, primarily include reduced infrastructure wear.

- *Weight*: Roadways with low bearing capacity would be protected from excessive pavement fatigue and rutting since more productive vehicles would be limited to those roadways with higher load bearing capacity.
- *Length*: The traffic safety environment would benefit because excessively long vehicles would be prohibited from operating on narrow or twisting highways.
- *Obstruction clearance*: The primary benefit would accrue to motor carriers or individuals wishing to operate high profile vehicles on a limited regional basis.

**Enforcement Issues** Significant enforcement issues are attributable to this group of standards.

- *Weight*: Size and weight enforcement officials would again be required to quickly determine the roadway bearing class and vehicle weight to adequately enforce this rule. This would be more difficult for random roadside enforcement than at fixed location weigh stations.
- *Length*: This would be a more cumbersome standard to enforce at the roadside than at fixed weigh stations, as officials would be required to quickly determine both vehicle

length and roadway class.

- *Obstruction clearance:* This would also be a cumbersome standard to enforce because officials would be required to know the vertical clearance of bridges and tunnels. Enforcement would be further compounded by construction or resurfacing activities that could affect vertical clearance.

**Potential Role** The potential role of this group may be limited given current uniform access polices.

- *Weight:* Three issues could impede the implementation of a roadway bearing classification system. First, motor carriers would be required to have information on the roadway bearing class for their area of operations. Given the vast size of the U.S. roadway network, this would be a considerable task. Second, shippers located on roadways with a lower bearing class would be at a competitive disadvantage. Third, motor carriers would be required to limit vehicle loads to the lowest roadway bearing class for a given journey or travel circuitous routes to avoid such roads.
- *Length:* In addition to the enforcement issues noted above, this standard would require motor carriers to know the class of each roadway traveled and operate vehicles configured appropriate to the roadway class. The size of the U.S. roadway network would make this a difficult standard to put into use.
- *Obstruction clearance:* This standard would require that both enforcement officials and motor carriers be equipped with an inventory of up-to-date obstruction clearance information for their area of operations. This information could be updated using technologies such as global positioning systems. However, the size of the U.S. roadway network and the issues associated with communicating changes in vertical clearance would make this a difficult standard to implement.

## Conclusions

The potential U.S. role in the 24 noted standards could be evaluated individually or in groups by using a two by two matrix in which enforcement issues and benefits are compared. This matrix is shown in Figure 6.1. The vertical axis of the matrix in Figure 6.1 represents enforcement issues and the horizontal axis of the matrix represents benefits. Each of the 24 noted standards has been plotted in Figure 6.1 on the basis of the enforcement issues and benefits associated with them. Those standards with greater enforcement issues are plotted higher on the vertical axis and those standards with greater benefits are plotted further to the right on the horizontal axis. The magnitude of enforcement issues and benefits for this exercise are based on the authors' judgment. A more accurate assessment of benefits and enforcement issues could be completed using a procedure in which members of the enforcement community, and truck size and weight policy officials would assess the benefits and issues associated with each of the noted standards. Using the above procedure, maximum weight based on number of axles has been plotted in the lower right quadrant of the matrix because it has many benefits and few enforcement issues. Similarly, maximum height based on obstruction clearance has been plotted

in the upper left quadrant of the matrix because it has many enforcement issues and few benefits. The following paragraphs first summarize the comparison of benefits versus issues for each of the standards individually then as previously identified groups according to feasibility of implementation.

### **Individual Assessment of Benefits and Enforcement Issues**

Figure 6.1 illustrates that some of the noted standards have been plotted in or near the lower right quadrant of the matrix, indicating that the benefits are likely to be equal to or greater than the enforcement issues. Interestingly, four of the standards within this quadrant are among those previously designed as controlling the interaction between the vehicle and the highway infrastructure. Two of the standards are among those previously designed as controlling the interaction between the vehicle and the traffic safety environment. Two of the standards (braking efficiency standards and maximum bridge weight based on axle spacing) exist in the current U.S. regulations.

These standards could be used as a starting point for the implementation of performance-based U.S. size and weight regulations because, based on the authors' judgment, the benefits likely outweigh the enforcement issues for motor carriers, the public infrastructure investment, and the traffic safety environment. Motor carriers making an investment in appropriately equipped vehicles would be rewarded with greater productivity through standards such as maximum weight based on number of axles. The public infrastructure investment would be protected through standards such as maximum tandem/tridem axle weight based on axle spacing and static load sharing requirements. The traffic safety environment would benefit from improved heavy vehicle handling and maneuverability through braking efficiency standards and turning circle requirements. In addition, the enforcement of nearly all of these standards could occur at existing weigh stations, or during random roadside inspections.

Seven of the standards have been plotted within the upper left quadrant of the matrix. This indicates that the enforcement issues associated with such standards potentially exceed their benefits. Some of these standards such as maximum height based on obstruction clearance and maximum weight based on roadway bearing classification may not have significant potential for U.S. truck size and weight regulation. This is primarily attributable to the vast size of the U.S. highway network. However, some of the other standards in this quadrant may have a role in regulating the size and weight of heavy trucks, but additional research and technology would have to be developed to fully realize their potential. For example, the enforcement issues associated with standards such as maximum tire load based on tread width and load distribution requirements could be mitigated by technology designed to aid enforcement officials in quickly determining vehicle parameters such as tread width or load transfer. Standards such as allowing additional weight for "road friendly" suspensions may need more research to fully understand the benefits and to set parameters equivalent to the infrastructure benefits.

Four standards (maximum weight based on static roll threshold, off-tracking, dynamic load transfer, and rearward amplification) have been plotted within the upper right quadrant and are the most perplexing. These standards offer potential benefits in vehicle productivity and improved safety. However, they cannot be readily enforced in the field. The potential role of these standards may reside in a subfleet of specialized or highly productive vehicles such as

those found in Australia, Canada, or New Zealand. Those countries have focused efforts on improving the safety-related performance parameters of LCVs using standards such as these. Longer combination vehicles enhance the productivity of their sparsely distributed economic base, which has a substantial portion of economic activity focusing on agriculture and natural resources. This is not unlike the western United States, where similar issues have promoted the adoption of LCVs and LCV highway networks.

### **Group Assessment of Benefits Versus Enforcement Issues**

Figure 6.1 also illustrates that each of the 24 noted standards has been plotted according to the previously identified feasibility groups based on the following legend.

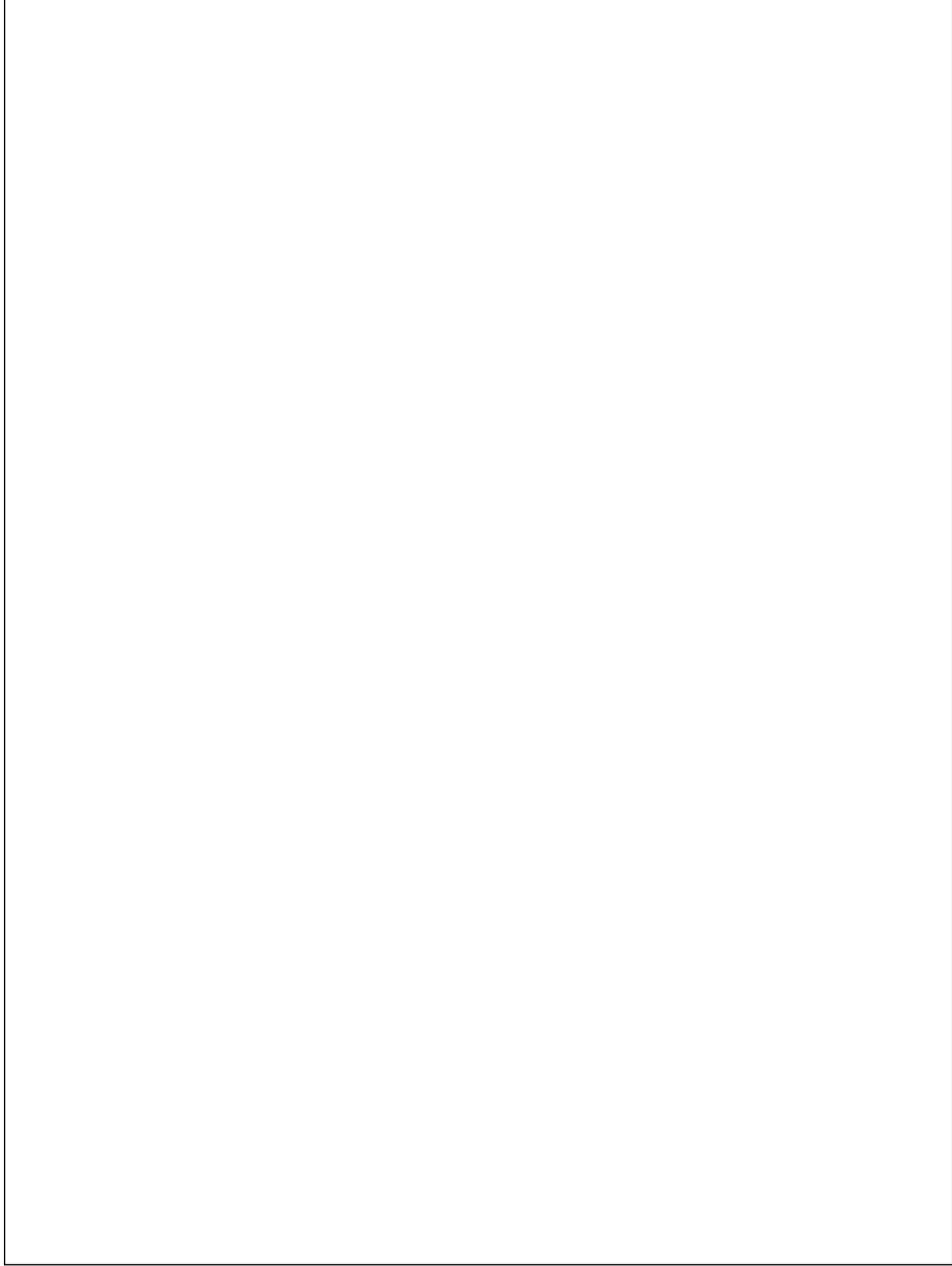


Similar to the individual comparison of benefits versus enforcement issues, Figure 6.1 illustrates that some of the feasibility groups may be more easily implemented in the U.S. size and weight regulations than others. For example, those standards requiring policy reform are plotted in the upper left quadrant of the matrix, indicating that, for the purposes of this exercise, the enforcement costs likely exceed the potential benefits. Alternatively, integrating those standards that are readily implementable in a broadened set of size and weight regulations would result in benefits that likely exceeded the enforcement costs as they are plotted in lower right quadrant of Figure 6.1.

It should be emphasized that the comparison of enforcement issues and benefits attributable to each of the noted standards was based on the judgment of the authors. A more thorough analysis could be conducted using the above procedure should policy makers consider implementing performance-based standards in the U.S. size and weight regulations. In that analysis, policy makers could choose from among the above noted standards and feasibility groups those that are best suited for existing and future conditions.

Even though adopting some performance-based standards may be difficult, the concepts underlying them offer too many advantages not to move forward and use a performance-based framework as a foundation for future size and weight reform.

**Figure 6.1: Comparison of Noted Standards**



## **CHAPTER 7: ASSESSING THE BENEFITS OF PERFORMANCE-BASED REGULATIONS**

A shift from prescriptive to performance-based size and weight regulations could produce benefits for the following three groups of highway stakeholders.

- Personal travel: Those individuals and entities engaged in travel for recreation, shopping, and work.
- Freight and goods movement: Those individuals and entities engaged in the movement of freight and other goods.
- Public infrastructure investment: Organizations such as state, federal, and local transportation departments charged with building and maintaining highway networks.

Benefits to individuals engaged in personal travel include fewer traffic casualties and less congestion, and air pollution resulting from a decrease in vehicle miles traveled. Benefits to those engaged in freight movement include more productive vehicles as a result of increased payload capacity and fewer vehicle miles traveled (VMT) because fewer trips should be required to haul the same amount of freight. Benefits to the public infrastructure investment include less wear on highways and bridges. Some of the benefits, such as more productive vehicles and reduced infrastructure wear, are a primary result of the more benevolent vehicles operating under a performance-based standards regime. Other benefits, such as reduced traffic casualties result from a combination of improved vehicle handling characteristics and a reduction in VMT.

The purpose of this chapter is to cite the potential benefits of a shift from prescriptive to performance-based size and weight regulations and to discuss how these benefits might be assessed. The potential benefits of such a shift are first compiled and reviewed. Several methods of assessing transportation productivity improvements, from general to specific terms, are then reviewed to determine how well they may assess the potential improvements resulting from performance-based regulations.

### **Potential Benefits of Performance-Based Size and Weight Regulations**

The following paragraphs provide the potential benefits of performance-based size and weight regulations for personal travel, freight movement, and the public infrastructure investment.

#### **Personal Travel Benefits**

Motorists will benefit from the increased stability and control provided by vehicles operating under performance-based standards regulations. For example, vehicles that meet or exceed performance criteria for rearward amplification or friction demand may be less likely to jackknife or collide with other motorists while negotiating tight turns or completing sudden evasive maneuvers.

#### **Freight and Goods Movement Benefits**

The freight and goods movement benefits of performance-based regulations include:

- More productive vehicles

- Fewer VMT
- Fewer accidents (e.g., savings in terms of property damage and lost productivity)
- Improved reliability and longevity of equipment

Improved vehicle productivity will be a primary benefit of performance-based regulations because innovative vehicle designs will be permitted to operate at higher allowable weights. Productivity is generally expressed as the comparison of outputs with inputs and is measured by examining these input/output relationships over time and across firms and industries.<sup>124</sup>

Research studies generally define vehicle productivity in terms of payload capacity because it is the one major variable to which truck productivity is most sensitive.<sup>125</sup> A recent congressionally mandated study of the potential impact of four possible size and weight policy scenarios also defines vehicle productivity in terms of payload capacity.<sup>126</sup>

Fewer VMT will be an indirect benefit of increased payload capacity. Assuming a fixed quantity of freight, the increased vehicle payloads will result in fewer trips and thus fewer miles traveled. The reduction in miles traveled will also create other indirect benefits such as decreased fuel consumption, fewer traffic casualties, and reduced emissions.

Performance-based standards should also result in improved equipment longevity and reliability because vehicles that are more benevolent to highway infrastructures will likely save wear and tear on the vehicles themselves. For example, equipping vehicles with air-ride suspensions improves the quality of the vehicle ride by reducing road shock and thus reduces wear and tear on the vehicle components.

### **Public Infrastructure Investment and Other Public Sector Benefits**

The potential public infrastructure benefits of performance-based regulations include:

- Less deterioration of pavements and bridges
- Fewer accidents (e.g., savings in terms of loss of life, medical expenses, pain and suffering)
- Reduced transportation costs
- Cleaner air

A primary public infrastructure benefit of performance-based size and weight regulations will be a reduction in the deterioration of pavements and bridges. Research has shown that modifications to vehicle design such as increasing the number of axles or increasing the spacing of axles within axle groups can reduce pavement wear.

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<sup>124</sup>Tae H. Oum, Michael W. Trethway, and W.G. Waters II. "Concepts, Methods and Purposes of Productivity Measurement in Transportation." *Transportation Research*. Vol. 26A, No. 6. Great Britain. 1992. pp. 494.

<sup>125</sup>Edward S. Fekpe, John Woodroffe, and Peter Sweatman. *Efficiency Characteristics of Tractor-Semitrailers*. Fourth International Symposium on Heavy Vehicle Weights and Dimensions. Ann Arbor, MI. June, 1995. p.4.

<sup>126</sup>*Truck Weight Limits: Issues and Options*. Transportation Research Board. National Research Council. Washington, D.C. 1990. Appendix G. p.295.

The indirect benefits of performance-based regulations include fewer accidents and a reduction in transportation costs. These benefits will be accrued all or in part by a reduction in truck miles traveled.

### **Methods of Assessing the Benefits of Performance-Based Regulations**

Regardless of the method chosen, measuring the benefits of performance-based standards will be a difficult task due to many issues. First, many factors affect productivity, making it difficult to identify the source of the productivity improvement. For example, a vehicle productivity measure of payload capacity is cost per ton-mile, which can be expressed in the following form:

Cost per ton mile =

The components of cost per vehicle mile that have been selected by other studies to assess size and weight policy changes include:<sup>127</sup>

- Driver cost as affected by vehicle size and number of trailers
- Fuel costs affected by vehicle configuration, gross vehicle weight, and trailer type
- Tire costs affected by number of tires and gross vehicle weight
- Indirect and overhead costs

The above vehicle cost components are also affected by many other factors such as the nature of the shipment, method of driver pay (mileage rate versus hourly pay), and vehicle route. Even if the variability in the above cost components could be controlled, typical cost accounting methods currently used by motor carriers are deficient in attributing these cost components to their source.<sup>128</sup>

Second, difficulties exist in distinguishing those productivity improvements that occur as a result of the size and policy changes from those that occur as a result of general economic or industry trends. For example, many motor carrier innovations that have improved motor carrier productivity occurred due to increased competition since economic regulation of the industry was relaxed in 1980. These innovations include improved carrier/shipper relationships and improved communications capabilities. The productivity improvements attributable to performance-based standards would be difficult to separate from those that are a result of competition-drive/driven innovations.

Third, some of the likely benefits of performance-based standards are indirect and complex. For example, the twin-trailer “A” trains currently operating under performance-based standards in New Zealand have a lower center of gravity than other vehicles. This lower center of gravity may result in fewer traffic accidents. However, it would be a difficult task to measure the reduction in traffic accidents that were attributable to these vehicles with lower centers of gravity.

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<sup>127</sup> *Truck Weight Limits: Issues and Options*. Appendix G. p.296.

<sup>128</sup> James S. York. *Measuring Motor Carriers' Use of Innovative Cost Accounting Methods*. A thesis submitted to the Graduate College of the Iowa State University in partial fulfillment for the degree of Master of Business Administration. Ames, Iowa. 1995. p.67.

Given the above limitations, the following paragraphs review several methods of assessing changes in motor carrier productivity.

### **General Productivity Assessments**

U.S. physical distribution costs as a percent of gross domestic product (GDP) are often used to assess general trends in motor carrier productivity. For example, one third-party logistics firm has compiled and tracked these costs for 23 years and has noted that U.S. physical distribution costs have declined from 14.5 percent GDP in the early 1980s to 9.8 percent GDP in 1994.<sup>129</sup>

Theoretically, the productivity and safety improvements attributable to the benefits of performance-based size and weight regulations would be reflected in lower freight rates because motor carriers could pass lower operating and insurance costs on to shippers. However, measuring these changes in the form of U.S. physical distribution costs would be difficult because it is likely that marginal increases in productivity would be masked among the many inputs to these distribution costs. Additionally, changes in these costs fail to quantify such benefits as increased safety that are likely to occur because of innovations in vehicle design.

### **Focused Productivity Assessments**

Two recent studies that assessed the potential impacts of changes in size and weight policy are discussed below because a similar framework could be used to assess the effects of a shift from prescriptive to performance-based regulations.

A recently commissioned study by the Dutch Ministry of Transport, Public Works, and Water Management examined the possible productivity enhancements resulting from several size and weight policy revisions being considered in the European Community.<sup>130</sup> The goal of the research was to determine the likely implications of adopting any of three proposed uniform size and weight limit scenarios for all E.C. member countries (e.g., uniform weight limits of 40,000 kilograms, 44,000 kilograms, or 48,000 kilograms). The consequences of the proposed scenarios were expressed in terms of changes in:

- The number of trips
- The number of vehicle kilometers traveled
- Fuel consumption
- Emission of carbon dioxide and nitrous oxide
- The number of traffic casualties

The researchers based the changes in the above factors on many assumptions and thus avoided the issue of accurately measuring changes in vehicle productivity. Some of the assumptions used by the researchers included:

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<sup>129</sup>These costs are compiled and reported annually by Cass Logistics, Inc. of St. Louis, MO. Thomas, Foster A., *It's about Time and Inventory*. Distribution. Chilton Publications. Radnor, PA. July 1994. pp. 6-10.

<sup>130</sup>*Consequences of Harmonising the Maximum Weight Limit Within the European Union*. Directorate-General for Energy, Ministry of Transport, The Netherlands. July, 1994.

- A specific percentage of freight would be moved by various vehicle configurations (e.g., 90 percent of freight moved by five-or six-axle truck-trailer combinations), and this percentage would not change with any of the proposed scenarios.
- No modal freight shifts would occur in any of the proposed scenarios.
- A constant relationship between the number of miles traveled and the number of traffic-related injuries.

The effects of the proposed size and weight scenarios were determined by first establishing changes in the number of trips with each of the size and weight scenarios. Using the assumed changes in number of trips, the shift in the number of kilometers traveled, amount of fuel consumed, and quantity of vehicle emissions was then computed. As a result, the study determined that uniform E.C. weight limits of 48,000 kilograms would result in 43.2 million fewer trips than present weight limits of 40,000 kilograms.<sup>131</sup> This method could be used to determine the net effects of a shift from prescriptive to performance-based size and weight regulations because the increased vehicle productivity would also result in fewer trips to haul an assumed quantity of freight. However, many of the potential effects of a shift such as motor carrier response to the proposed size and weight regulations were not evaluated in this study.

A similar but more detailed method of assessing size and weight policy changes was used in a 1990 U.S. congressionally mandated study that assessed the potential impacts of the following four proposed size and weight limit options:<sup>132</sup>

- Eliminating the grandfather clause
- Determining gross weight and axle weight limits by alternative methods
- Analyzing the current bridge formula
- Appropriately treating specialized hauling vehicles (refuse hauling vehicles and cement mixers)

The study identified the impacts of the above changes and made recommendations to Congress based on the net assessment of benefits. The net impacts were identified using the following method:

- The net change in transportation costs was determined using region-based estimates of changes in cost per ton-mile and motor carrier responses to the proposed size and weight policy changes.
- Estimates of modal diversion were made to determine the extent that rail freight would be attracted to truck traffic and the possible rate reductions by rail to retain the freight.
- The cost of repairing or replacing bridges that would become load deficient under the proposed scenarios was computed.
- Carrier responses to proposed size and weight regulations were determined based on interviews with 32 motor carriers to determine regional changes in vehicle miles traveled

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<sup>131</sup>These fewer trips resulted in 7.6 billion fewer kilometers traveled, 1,655 million liters fuel saved, 62.2 million fewer kilograms of NO<sub>x</sub> emissions, and 311 fewer traffic fatalities.

<sup>132</sup>*Truck Weight Limits: Issues and Options*. Transportation Research Board. National Research Council. Special Report Number 225. Washington, D.C. 1990

- (VMT).
- Reductions in traffic accidents were then computed based on predicted changes in vehicle miles traveled.

Quite apart from the study conducted in the E.C. that estimated the effects of various uniform size and weight limits for all E.C. member countries, the above U.S. study estimated the effect of size and weight policy changes that could result in larger and more productive vehicles. However, the above U.S. study has several deficiencies in evaluating the effect of implementing performance-based regulations. First, it will be more difficult to determine motor carrier responses to the implementation of performance-based regulations because the size and weight limits imposed under this method of regulation have yet to be defined and will be dependent on vehicle performance. For example, motor carrier expectations of the effect on VMT will be difficult to determine because of uncertainties in the cost of new and innovative vehicle configurations that will be developed to comply with performance-based standards. Second, the link between VMT and traffic accidents will be more complex because vehicles meeting performance-based standards could have less accidents than the current vehicle fleet due to improved handling characteristics.

### **Conclusions**

The implementation of performance-based size and weight regulations could result in such positive benefits as increased safety and reduced infrastructure wear. Some of the negative outcomes of such an implementation include the need to develop a technical vehicle inspection and certification infrastructure at locations other than the roadside. Assessing the varied outcomes of performance-based standards regulations will be a difficult task. Currently, the complexity of the task is further compounded because a proposal that defines size and weight limits and vehicle performance parameters has yet to be developed.

## CHAPTER 8: SUMMARY AND CONCLUSION

The purpose of this research project was to determine the extent and nature of the application of performance-based standards for regulating the size and weight of vehicles in other countries. The goal of the research was to describe an alternative method of truck size and weight regulation based on vehicles' measured effect on the highway infrastructure and traffic safety environment.

The standards that are the framework for current U.S. truck size and weight regulation do not fully recognize the effects of vehicles on the highway infrastructure and traffic or how those effects vary among different vehicles. Recent research investigating the effects of heavy vehicle characteristics on the highways indicates that numerous negative effects can occur under the current regulatory framework. For example, the National Cooperative Highway Research Program (NCHRP) report that examined vehicle/highway interaction using computer simulations noted that vehicles with different tandem-axle spacing can have different impacts on pavement life. That research noted that a single pass of a 36,000 pound tandem-axle group with axles spaced 4.25 feet apart caused the same pavement wear as 1.4 passes of a single axle weighing 18,000 pounds.<sup>133</sup> However, increasing the axle spacing of that same tandem-axle group to 6.75 feet reduced the pavement wear to the equivalent of 1.0 passes of a single axle weighing 18,000 pounds. Because current standards do not recognize these differences, the safety and longevity of the U.S. highway infrastructure may not be fully maximized.

This chapter first summarizes the findings of an extensive literature review of pavement and vehicle design principles that provided an understanding of issues related to size and weight regulations that are tied to vehicle performance. Second, the existing applications of performance-based standards and enforcement of these standards are summarized. The purpose of this summary is to illustrate the extent and nature of the application of performance-based standards in size and weight regulations. Third, a summary of those noted standards that are feasible for a performance-based U.S. size and weight regulation framework is provided. Fourth, due to the likely complexity of incorporating performance-based standards into size and weight regulations, the role of advanced technologies, such as those used in intelligent transportation systems (ITS), in monitoring a complex set of size and weight regulations is discussed. Finally, this chapter suggests areas for further research that are beyond the scope of this project yet are important to the implementation of performance-based truck size and weight regulations.

### **Pavement and Vehicle Design Principles Related to Performance-Based Standards**

The road wear performance of vehicles depends partially on the vehicle design. For example, to a large degree, vehicle dynamic loadings can be reduced through "road friendly" suspensions. It may be possible to increase the gross vehicle weight limits on vehicles with more benevolent suspensions and at the same time reduce road wear. The review of pavement and bridge design principles revealed:

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<sup>133</sup>T.D. Gillespie, et. al. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance*. Transportation Research Board, National Research Council. NCHRP Report 353. 1993. p 17.

- Current pavement design methods are insensitive to dynamic loading conditions.
- The most commonly used pavement design methods in the U.S. was developed by the American Association of State Highway and Transportation Officials (AASHTO). This method predominately focused on designing pavements with adequate strength to prevent failure due to fatigue resulting from repetitive vehicular axle loadings forecasted to occur over the projected life of the pavement. However, recent research findings of the Strategic Highway Research Program (SHRP) have shown that factors other than axle loadings, predominately attributable to the effects of the environment, significantly impact the useful life of pavements and pavement's decline in condition over time. This result clearly indicates that commonly used models of the relationship between axle loadings and pavement life do not account for the complex interaction between road use, pavement life, pavement performance, the pavement's interaction with the environment and aggregate materials, and other variables. Although AASHTO methods are based on good research and engineering practice, clearly much research remains to be conducted before the science is robust enough to account for the exact pavement life implications of changes in vehicle designs.
- The current federal bridge formula may need to be evaluated to ensure that limits are the most efficient and properly apportion the costs of highway users and the costs to build and maintain bridges. Implied weight limits of the current bridge formula were set arbitrarily without attempting to design limits which minimize transportation system costs.

With respect to vehicle design principles, the literature review indicated that many complex factors interact to determine vehicle performance. Some of the issues of vehicle performance that should be considered when developing performance-based standards include the following:

- Vehicle performance should be measured in the context of the entire vehicle (e.g., a tractor-trailer combination) because changes in vehicle design to improve one handling property could adversely affect other aspects of vehicle performance.
- Tires dictate many of a vehicle's handling properties. However, many elements of tire performance, such as tire loading, road surface, and tread depth, are controlled by factors beyond the scope of practical enforcement techniques. As a result, vehicle performance should be evaluated under the realm of conditions that could be encountered during routine operations.
  - Many target performance levels can be ensured by controlling such vehicle parameters as wheelbase and rear overhang.
- The complexity of vehicle performance measurement suggests the need for the development of a testing and inspection infrastructure away from the roadside and the need for a multiple-tier inspection process.

### **Existing Application and Enforcement of Performance-Based Size and Weight Regulation**

This study revealed that some countries have begun to account for differences in vehicle performance in their size and weight regulations. Based on the experiences of these countries, the following observations could assist size and weight policy makers in considering size and weight regulations that are tied to vehicle performance:

- Single-axle weight limits among the 32 study jurisdictions are generally consistent and range from 5,500 kilograms (12,100 pounds) to 13,000 kilograms (25,600 pounds). Much of the variation in these weight limits can be attributed to the fact that many jurisdictions have developed subcategories of single-axle weight for steering axles, single-tire axles and drive/driven axles.
- Tandem-axle weight limits vary significantly among jurisdictions with a range from 10,000 kilograms (22,000 pounds) to 21,000 kilograms (46,300 pounds). This is primarily attributable to axle spacing requirements prescribed to limit the weight of closely-spaced tandem-axles.
- Twenty-two jurisdictions have separate categories for and allow higher weight on tridem-axles than on tandem-axles. The weight limit of tridem-axles among these jurisdictions ranges from 15,500 kilograms (34,200 pounds) to 30,000 kilograms (66,100 pounds) and is also controlled by axle spacing requirements.
- A wide discrepancy exists among jurisdictions' maximum vehicle weight. The discrepancy appears to be linked to the complexity of the vehicle. For example, the range in maximum weight for three-axle, non-articulated trucks is 7,000 kilograms (15,400 pounds). However, the range in the maximum weight for five-axle tractor trailer combinations is 34,000 kilograms (75,000 pounds).
- Countries have adopted widely different bridge formulas. The differences in these formulas result in significant variation in maximum allowable bridge weight.
- Eleven jurisdictions recognize and grant higher weight limits for vehicles equipped with "road friendly" or air-ride suspensions.
- Jurisdictions are using other standards related to scientific and engineering principles to control the interaction of vehicles on the highway infrastructure and on traffic safety. These criteria include:
  - » Turning circle requirements
  - » Static load sharing requirements
  - » Braking efficiency standards
  - » Load distribution requirements
  - » Rear overhang requirements
  - » Traction requirements
  - » Maximum tire loads
  - » Minimum horsepower/weight ratios

The enforcement methods used for performance-based and pure performance standards are more complex than those used to enforce prescriptive standards. A review of the enforcement methods of selected countries revealed that:

- The development of a vehicle type approval and annual inspection infrastructure appears to be crucial to the implementation of some parametric performance-based standards.
- The complexity of vehicle performance tests requires that these tests be conducted away from the roadside.
- The existing U.S. investment in inspection facilities, mobile inspection equipment, and enforcement personnel could provide an adequate platform for monitoring many performance-based standards (such as wheelbase, axle weight and spacing, and load

distribution) at fixed weigh stations or random roadside locations. Additionally, this existing infrastructure could provide the nucleus for certifying additional test stations and monitoring the credentials of vehicles tested at these additional locations.

### **Standards That Are Feasible for Performance-Based U.S. Size and Weight Regulations**

The potential U.S. role of 24 noted performance-based and pure performance standards was examined by using a two by two evaluative matrix for comparing enforcement issues versus the benefits associated with each noted standard and groups of standards. Based on the judgment of the authors, this matrix revealed that the benefits attributable to 12 of the noted standards may be equal to or greater than their enforcement issues. Those 12 standards are listed below:

- Maximum vehicle weight based on number of axles
- Maximum axle weight based on number of tires
- Maximum bridge weight based on axle spacing
- Static load sharing requirements
- Braking efficiency standards
- Maximum vehicle weight based on wheelbase
- Maximum tandem/tridem weight based on axle spacing
- Rear overhang requirements
- Maximum weight limits for steering axles
- Maximum trailer weight based on configuration type
- Turning circle requirements
- Maximum weight based on engine horsepower

Should truck size and weight policy makers decide to embrace performance-based regulations, they could choose from among the above 12 standards based on the goal of such an action. For example, standards such maximum weight based on number of tires, maximum steering axle weight, and load distribution requirements could be integrated within existing size and weight limits and result in less infrastructure wear, and improved traffic safety at little or no cost to highway users.

Similarly, standards such as maximum weight based on number of axles and maximum tandem/tridem weight based on axle spacing could be implemented should policy makers decide to expand U.S. size and weight regulations. Under such a scenario, motor carriers willing to invest in equipment conforming to these standards would be rewarded with greater vehicle productivity. The public infrastructure investment would be protected through standards which seek to reduce pavement loads through suspension designs that allow for a more even distribution of loads across axles. The traffic safety environment would benefit from improved heavy vehicle handling and maneuverability.

The enforcement of nearly all of these 12 standards could occur at existing weigh stations, or during random roadside inspections. Most importantly, these standards are based on proven principles of pavement and vehicle design and the experience of other countries has demonstrated that they can be successfully implemented.

The role of the three following performance-based standards in U.S. size and weight regulations is less clear.

- Maximum weight based on static roll threshold
- Maximum weight/length based on offtracking
- Maximum weight based on dynamic load transfer

These standards offer potential benefits in vehicle productivity and improved safety, yet the international experience revealed that these standards cannot be readily enforced at the roadside. The potential role of these standards may be most applicable for a subfleet of specialized or highly productive vehicles such as those found in Australia, Canada, or New Zealand. These countries have focused efforts on improving the safety-related performance parameters of Longer Combination Vehicles (LCVs) using standards such as these. These vehicles offer enhanced productivity and are primarily used in regions with a sparsely distributed economic base. This is not unlike the western United States, where similar issues have promoted the adoption of LCVs and LCV highway networks.

Even though adopting some performance-based and or pure performance standards may be difficult, the concepts underlying them offer too many advantages not to move forward and use a performance-based framework as a foundation for future size and weight reform.

### **Role of Intelligent Transportation Systems (ITS) in Performance-Based Standards**

ITS technologies could be used to assist the enforcement of performance-based standards. Technology including on-board computers and automated vehicle identification devices could provide dynamic vehicle performance information to equipment operators and enforcement personnel through digital display units or transponders and roadside readers. The vehicles operating under a performance-based set of size and weight regulations could use the technologies to report their vehicle class, axle weight, axle spacing, and inspection data to truck size and weight enforcers at weigh stations or at random roadside locations. The enforcement community could also use weigh-in-motion classifiers similar to those currently used and transponders to discern those vehicles that are operating under the performance-based size and weight regulations.

For example, tire-mounted transponders could relay tire inflation pressures to the driver and provide an audible or visual warning if tire inflation pressures were outside prescribed limits. Truck-mounted transponders could be used to provide type approval inspection information to members of the enforcement community. Vehicles equipped with sophisticated on-board weighing devices could report their axle loads and gross weight to roadside readers to truck weight enforcement personnel. In addition to current registration and identification data, the transmitted information set could also include such vehicle specifications as axle type (single, tandem, or tridem-axles), axle spacing, and brake efficiency criteria. The nature and type of the most recent inspection could also be included in this information set. As technologies are further developed and deployed, the information set could be expanded to include any or all of the dynamic vehicle parameters such as tire inflation pressures, suspension rebound frequencies, and dynamic wheel loads.

As with current ITS technologies, motor carriers operating under a performance-based standards regulation set would submit to higher levels of scrutiny in exchange for certain benefits. The motor carrier benefits of performance-based standards would be more productive and safer vehicles.

### **Issues Requiring Further Study**

This research revealed some issues that are significant to size and weight regulation reform but that are beyond the scope of this project. These issues include the weight-bearing classification of highways, a reevaluation of bridge formula B, additional pavement design research, and the potential impacts of performance-based standards implementation on the current U.S. heavy vehicle fleet.

#### **Highway Classification System**

Some countries in our study have implemented highway classification systems that specify maximum allowable size and weight limits based on existing highway conditions. For example, Norway has developed three vehicle length roadway classes (i.e., 18.5 meters [60.7 feet], 15 meters [49.2 feet], and 12.4 meters [40.7 feet]) that specify different maximum truck lengths for each roadway class. Using this system, the maximum tractor-trailer length is 17 meters (55.8 feet) on an 18.5 meter class road and 12.4 meters (40.7 feet) on a 12.5 meter class road. Sweden has developed a three-tiered highway classification system based on the bearing capacity of the roadway. Sweden's system, consisting of roadway bearing classes BK-1, BK-2, and BK-3, provides different maximum allowable weights for each roadway bearing class. The greatest maximum allowable weight is permitted on BK-1 highways. Recent investments in bridge repair and replacement have been made on these primary highways to upgrade their bearing capacity. Maximum allowable weights are reduced by approximately 10 percent on BK-2 class highways and an additional 30 percent on BK-3 class highways. A similar system could be implemented in the United States that would provide the greatest maximum allowable weight on such primary highway systems as the recently designated National Highway System (NHS). Although this issue involves more subjects than just performance-based standards, it is an issue that is relevant to any examination of truck size and weight policy.

#### **Reevaluation of Bridge Formula B**

The examination of study country size and weight limits revealed a wide disparity in maximum bridge (multiple axle group) weight. Using the provided bridge formulas and bridge weight tables from 13 countries, maximum bridge weight was found to vary by as much as 6,700 kilograms (14,800 pounds) for identical vehicle configurations with identical axle spacing. For example, Finland allows a maximum bridge weight of 43,000 kilograms (94,800 pounds) for a five-axle group consisting of one steering axle and two tandem-axles that are spaced 15.5 meters (51.0 feet) apart. The identical configuration is allowed 37,000 kilograms (81,600 pounds) in New Zealand and 36,300 kilograms (80,000 pounds) in the United States. These differences may be attributable to existing bridge conditions or accepted overstress criteria. This issue involves more subjects than those included in this project, but is relevant to any size and weight investigation.

### **Additional Pavement Design Research**

The research efforts that are being undertaken by the Strategic Highway Research Program and the DIVINE project begin to address the issue of pavement wear attributable to environmental factors and dynamic vehicle loads. Additional efforts will be needed to incorporate these factors into new pavement designs because the science of pavement design needs to be further developed to fully understand all of the factors that affect pavement life. Clearly, the public investment in infrastructure will receive the primary benefits of new highway designs which include environmental factors and dynamic vehicle loads as input parameters. Motor carriers will also receive such benefits as more productive vehicles and less equipment wear as a result of smoother, longer-lived roadways. To expedite the realization of these benefits, the motor carrier industry should participate in supporting more pavement design research.

### **Impacts on the Current U.S. Heavy Vehicle Fleet**

The implementation of performance-based size and weight standards has the potential to impact the current U.S. heavy vehicle fleet. Even if these standards were implemented incrementally, significant investment in equipment would be required. At the most basic level, performance-based standards could recognize that such axle configurations as tridem-axle groups and appropriately spaced tandem-axles are more friendly to the highway infrastructure. Since the current heavy vehicle fleet is generally equipped with one or more tandems with axles spaced 4.25 feet apart, significant potential changes are likely if performance-based size and weight regulations would allow additional weight for tridems or tandems spaced at distances to reduce pavement stress.

The implementation of performance-based truck size and weight regulations may result in other recommended vehicle specifications that are different than the existing U.S. heavy vehicle fleet. Possible changes in vehicle configurations might include limitations on the use of sliding tandem-axle groups (sliding trailer tandems), wide scale integration of air-ride suspension on tractors and trailers, and mandated brake performance measures. The motor carrier industry needs to understand the potential impacts of performance-based size and weight regulations on the current U.S. heavy vehicle fleet.

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