NCHRP 20-07 Task 303

DIRECTORY OF SIGNIFICANT TRUCK SIZE AND WEIGHT RESEARCH

Requested by:

American Association of State Highway
and Transportation Officials (AASHTO)

Standing Committee on Highways,
Subcommittee on Highway Transport

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PREFACE

The body of research related to large truck size and weight is extensive, dating back nearly 80 years. In this context, "large" truck is generally understood to include single unit or combination vehicles in excess of 10,000 lbs, and in particular, vehicles in excess of 26,000 lbs. Early research efforts focused on pavement and bridge infrastructure. Since that time, research efforts have broadened to include large truck size and weight considerations in relation to modal share, enforcement, highway safety, highway geometrics, industry costs, economic impacts, infrastructure financing, highway congestion, the environment, public opinion, and other. Sponsors of large truck size and weight research are equally diverse, including national transportation and research agencies, national coalitions, various State departments of transportation, industry organizations, academic researchers, and international counterparts.

Given the volume of large truck size and weight related research, the breadth of related topic areas, and the diverse interests of the various public and private sponsoring agencies and organizations, decision-makers are challenged to comprehensively identify and utilize the current state of knowledge. As a result, decisions may often lack a substantive basis rooted in sound research simply because access to key findings is onerous.

In response to this need, this *Directory of Significant Truck Size and Weight Research* was developed (under NCHRP 20-07, Task 303) to provide a brief, well organized summary of significant research related to large truck size and weight for use by decision-makers. In particular, this reference document will benefit those involved in considering possible changes in regulations related to truck size and weight limits. This *Directory* is intended to address the breadth of all related topic areas and consider research performed by various sponsoring agencies but is not intended to be inclusive of all related research. Instead, this reference guide will be limited to only that related research that is considered to be relevant, significant, and useful.

From the general body of research identified related to large truck size and weight, researchers distinguished the citations contained herein based on the following criteria:

- Timeliness of the research—recent research presumably builds and improves upon earlier findings. As such, recent publications were favored over older publications in the same topic areas. In general, researchers limited citations to the most recent 20-year time period unless earlier research was thought to be particularly relevant.
- Scope and comprehension of the research—large-scale, broad-based, well-funded research with a national focus were favored over smaller, localized research efforts in the same topic areas. Examples include the U.S. Department of Transportation's *Comprehensive Truck Size and Weight Study* and Federal Motor Carrier Safety Administration's *Large Truck Crash Causation Study*.
- Research conducted in response to an expressed need—the conduct of special reports or synthesis efforts suggests an expressed need for focused information and an inherent usefulness of the information. Examples include the American Association of State Highway and Transportation Official's *Synthesis of Safety Implications for Oversize/Overweight Commercial Vehicles* and Transportation Research Board's *Special Report 225: Truck Weight Limits: Issues and Options*.

This reference document does not include any original research. Further, this *Directory* is intended to be neutral relative to any policy issues.

HOW TO USE THIS DIRECTORY

This *Directory of Significant Truck Size and Weight Research* is organized topically and includes the following subject areas:

- Infrastructure preservation—pavements and bridges
- Modal share
- Enforcement
- Highway safety
- Highway geometrics
- Industry costs
- Infrastructure financing
- Highway congestion
- Environment
- Public opinion

To obtain an overview of findings related a particular subject area, the reader can refer to any topical section of interest. Individual study findings—categorized by domestic experience, State/case studies, and international experience—are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces each topical section in an effort to identify noted trends or differences in research findings.

To explore additional detailed findings from a particular study, the reader can refer to References for a full citation of the publication. Whenever the referenced publication is provided electronically, an embedded link to the full research report (external to the *Directory*) is included. In the event that the electronic publication is removed or the link is otherwise disabled, the reader can still refer to References to locate the publication through traditional means.

To explore additional findings from a single research publication across a broader range of subject areas, embedded cross-references direct readers to additional findings within the *Directory* originating from cross-cutting research publications. Cross-cutting citations are also identified in Table 1 for ease of navigation.

Table 1. Significant Truck Size and Weight Research by Topic Area

AUTHOR	DATE	TOPIC										
		Infrastructure Preservation										
		Pavement	Bridge	Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
INFRASTRUCTURE PRESERVATION—PAVEMENT												
Domestic Experience												
TRB	1989	●	●			●	●	●		●		
TRB	1990	●	●	●	●	●		●		●		
TRB	1990b	●	●	●		●		●		●		
USDOT	2000	●	●	●		●	●	●		●	●	●
FHWA	1996	●	●		●	●						
TRB	2002	●	●		●	●		●		●	●	
Suleiman and Varma	2002	●										
FHWA	2004	●	●	●		●	●	●		●	●	●
USDOT	1997	●	●			●						

Table 1. Significant Truck Size and Weight Research by Topic Area (Continued)

AUTHOR		DATE	TOPIC										
			Infrastructure Preservation		Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
			Pavement	Bridge									
INFRASTRUCTURE PRESERVATION—PAVEMENT (Continued)													
State/Case Studies													
MI	Ervin and Gillespie	1986	●										
CA	Gibby, Kitamura, Zhao	1990	●										
Various	Lee and Peckham	1990	●										
MT	Stephens et al.	1997	●	●									
	Hewitt et al.	1999	●										
LA	Roberts and Djakfar	2000	●										
VA	Freeman and Clark	2002	●										
ME/NH	Wilbur Smith Associates	2004	●	●			●		●				
MN	URS	2005	●										
	Cambridge Systematics, Inc.	2006	●	●			●		●		●		
OH	Ohio Dept. of Transportation	2009	●	●									
WI	Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
TX	Walton et al.	2010	●	●									
International Experience													
OECD		1988	●										
Frith, Mitchell, Newton		1994	●										
INFRASTRUCTURE PRESERVATION—BRIDGE													
Domestic Experience													
TRB		1989	●	●			●	●	●		●		
TRB		1990	●	●	●	●	●		●		●		
TRB		1990b	●	●	●		●		●		●		
Weissman and Harrison		1991		●									
Weissman and Harrison		1998		●									
Weissman and Harrison		1998b		●									
USDOT		2000	●	●	●		●	●	●		●	●	●
FHWA		1996	●	●		●	●						
Khaleel and Itani		1993		●									
Laman and Ashbaugh		2000		●									
Fu et al.		2003		●									
FHWA		2004	●	●	●		●	●	●		●	●	●
Chang and Garvin		2007		●									
TRB		2002	●	●		●	●		●		●	●	
USDOT		1997	●	●			●						
State/Case Studies													
IL	Mohammadi, et al.	1991		●									
WA	Sorenson and Manzo-Robledo	1992		●									
MT	Stephens et al.	1997	●	●									
ME/NH	Wilbur Smith Associates	2004	●	●			●		●				
MN	Cambridge Systematics, Inc.	2006	●	●			●		●		●		
LA	Saber and Roberts	2006		●									
OH	Ohio Dept. of Transportation	2009	●	●									
WI	Adams, Bittner, and Wittwer	2009	●	●	●		●		●		●	●	
TX	Walton et al.	2010	●	●									

Table 1. Significant Truck Size and Weight Research by Topic Area (Continued)

AUTHOR		DATE	TOPIC										
			Infrastructure Preservation		Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
			Pavement	Bridge									
MODAL SHARE													
Domestic Experience													
Hymson		1978			●								
TRB		1990	●	●	●	●	●		●		●		
TRB		1990b	●	●	●		●		●		●		
USDOT		2000	●	●	●		●	●	●		●	●	●
USDOT		2005			●								
FHWA		2004	●	●	●		●	●	●		●	●	●
State/Case Studies													
WI	Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
ENFORCEMENT													
Domestic Experience													
TRB		2002	●	●		●	●		●		●	●	
Grenzeback, Stowers, Boghani		1988				●							
FHWA		1989				●							
OIG		1991				●							
Hajek and Selsneva		2000				●							
Fekpe and Clayton		1994				●							
Fekpe, Clayton, Haas		1995				●							
Strathman		2001				●							
FHWA		1985				●							
Arnold		1991				●							
Cambridge Systematics, Inc.		2009				●							
Cambridge Systematics, Inc.		2009b				●							
Carson		2010				●							
State/Case Studies													
TX	Euritt	1987				●							
VA	Cottrell	1992				●							
WI	Grundmanis	1989				●							
	Cambridge Systematics, Inc.	1994				●							
ID	Parkinson, et al.	1992				●							
OR	Krukar and Evert	1994				●							
FL	Cunagin, Mickler, Wright	1997				●							
Various	Hanscom	1998				●							
Various	Taylor et al.	2000				●							
MT	Stephens et al.	2003				●							
AZ	Semmens and Straus	2006				●							
International Experience													
Wyatt and Hassan		1985				●							
Van Loo and Henny		2005				●							
Honefanger et al.		2007				●							

Table 1. Significant Truck Size and Weight Research by Topic Area (Continued)

AUTHOR	DATE	TOPIC: Infrastructure Preservation: Pavement	Infrastructure Preservation: Bridge	Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
HIGHWAY SAFETY												
Domestic Experience												
TRB	1986					●		●			●	
Glennon	1981					●						
Graf and Archuleta	1985					●						
Sparks and Beilka	1987					●						
Jones and Stein	1989					●						
Mingo, Esterlitz, Mingo	1991					●						
Chirachavala and O'Day	1981					●						
Seiff	1989					●						
Braver et al.	1997					●						
Carsten	1987					●						
Blower, Campbell, Green	1993					●						
Vallette et al.	1981					●						
Polus and Mahalel	1983					●						
Campbell et al.	1988					●						
TRB	1989	●	●			●	●	●		●		
TRB	1990	●	●	●	●	●		●		●		
TRB	1990b	●	●	●		●		●		●		
USDOT	2000	●	●	●		●	●	●		●	●	●
Luskin and Walton	2001					●						
TRB	2002	●	●		●	●		●		●	●	
AASHTO	2009					●						
Scopatz	2001					●						
FHWA	2004	●	●	●		●	●	●		●	●	●
Ticatch et al.	1996					●						
Lemp, Kockelman, Unnikrishnana	2011					●						
State/Case Studies												
MD Fu, Burhouse, Chang	2004					●						
MI Lyles et al.	1991					●						
ME/NH Wilbur Smith Associates	2004	●	●			●		●				
MN Cambridge Systematics, Inc.	2006	●	●			●		●		●		
WI Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
International Experience												
Hartman et al.	2000					●						
Montufar et al.	2007					●						
Walker and Pearson	1987					●						
Edgar, Calvert, and Prem	2001					●						
Woodrooffe et al.	2010					●						
Woodrooffe et al.	2010b					●						
HIGHWAY GEOMETRICS												
Domestic Experience												
TRB	1989	●	●			●	●	●		●		
USDOT	2000	●	●	●		●	●	●		●	●	●
FHWA	2004	●	●	●		●	●	●		●	●	●

Table 1. Significant Truck Size and Weight Research by Topic Area (Continued)

AUTHOR		DATE	TOPIC										
			Infrastructure Preservation		Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
			Pavement	Bridge									
HIGHWAY GEOMETRICS (Continued)													
Domestic Experience (Continued)													
Harwood et al.		1999						●					
Harwood, Glauz, Elefteriadou		1999						●					
Harwood et al.		2003						●					
State/Case Studies													
CA/NJ	Zegeer, Hummer, Hanscom	1990					●	●					
Various	Harkey et al.	1992					●	●					
INDUSTRY COSTS													
Domestic Experience													
Jack Faucett Associates, Inc.		1991							●				
TRB		1989	●	●			●	●	●		●		
TRB		1986					●		●			●	
TRB		1990	●	●	●	●	●		●		●		
TRB		1990b	●	●	●		●		●		●		
USDOT		2000	●	●	●		●	●	●		●	●	●
TRB		2002	●	●		●	●		●		●	●	
FHWA		2004	●	●	●		●	●	●		●	●	●
Woodrooffe et al.		2009							●			●	
State/Case Studies													
MT	Hewitt, Smith, Menuez	1999							●				
ME/NH	Wilbur Smith Associates	2004	●	●			●		●				
MN	Cambridge Systematics, Inc.	2006	●	●			●		●		●		
ND	Upper Great Plains Transportation Institute	2007							●				
WI	Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
INFRASTRUCTURE FINANCING													
Domestic Experience													
Aecom Consult Team		2006								●			
Cambridge Systematics, Inc. et al.		2006								●			
FHWA		2007								●			
AASHTO		2007								●			
AASHTO		2007b								●			
TRB		2009								●			
Samuel, Poole, and Holguin-Veras		2002								●			
Holguin-Veras et al.		2003								●			
Forkenbrock		2004								●			
Conway and Walton		2010								●			
State/Case Studies													
CA	Taylor	2001								●			
CA	Killough	2008								●			
GA	PBQD	2005								●			
TX	Zhou et al.	2009								●			
OR	Rufolo et al.	2000								●			
ID	Balducci et al.	2010								●			
AL	Waid and Sisiopiku	2007								●			

Table 1. Significant Truck Size and Weight Research by Topic Area (Continued)

AUTHOR		DATE	TOPIC: Infrastructure Preservation: Pavement	Infrastructure Preservation: Bridge	Modal Share	Enforcement	Highway Safety	Highway Geometrics	Industry Costs	Infrastructure Financing	Highway Congestion	Environment	Public Opinion
INFRASTRUCTURE FINANCING (Continued)													
International Experience													
Broaddus and Gertz		2008								●			
Dalbert		2001								●			
HIGHWAY CONGESTION													
Domestic Experience													
Schmitt et al.		2008									●		
Cambridge Systematics, Inc.		2008									●		
GAO		2008									●		
AASHTO		2010									●		
Shrank, Lomax, Turner		2010									●		
TRB		1989	●	●			●	●	●		●		
TRB		1990b	●	●	●		●		●		●		
TRB		1990	●	●	●	●	●		●		●		
USDOT		2000	●	●	●		●	●	●		●	●	●
TRB		2002	●	●		●	●		●		●	●	
FHWA		2004	●	●	●		●	●	●		●	●	●
State/Case Studies													
MN	Cambridge Systematics, Inc.	2006	●	●			●		●		●		
WI	Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
ENVIRONMENT													
Domestic Experience													
Hyman, Schiller, Brogan		2010										●	
TRB		1986					●		●			●	
USDOT		2000	●	●	●		●	●	●		●	●	●
TRB		2002	●	●		●	●		●		●	●	
FHWA		2004	●	●	●		●	●	●		●	●	●
Woodrooffe et al.		2009							●			●	
Scora, Boriboonsomsin, Barth		2010										●	
State/Case Studies													
ME	ATRI											●	
WI	Adams, Bittner, Wittwer	2009	●	●	●		●		●		●	●	
International Experience													
Woodrooffe, Glaeser, Nordengen		2010										●	
PUBLIC OPINION													
Domestic Experience													
USDOT		2000	●	●	●		●	●	●		●	●	●
Insurance Research Council		2002											●
Harris et al.		2004											●
Moore et al.		2005											●
International Experience													
Prentice and Hildebrand		1990											●
Synovate, Ltd.		2010											●

BACKGROUND

The Federal government began regulating truck size and weight limits in 1956 to protect the new Interstate Highway System. States historically had regulated the weights and dimensions of vehicles operating on State highways, but Congress believed that the large Federal investment in the Interstate System required more direct Federal controls on the weights of vehicles using the Interstate System. A maximum gross vehicle weight (GVW) limit of 73,280 lb was established along with maximum weights of 18,000 lb on single axles and 32,000 lb on tandem axles. Maximum vehicle width was set at 96 in., but length and height limits were left to State regulation. States having greater weight or width limits in place when Federal limits went into effect were allowed to retain those limits under a grandfather clause.

In 1975, Congress increased allowable GVW and axle weight limits, in part to provide additional cargo carrying capacity for motor carriers faced with large fuel cost increases at the time.

The Surface Transportation Assistance Act (STAA) of 1982 authorized the U.S. Secretary of Transportation to designate a National Network of Interstate and other major highways on which wider (102-in.) and longer tractor semi-trailers (minimum trailer length of 48 ft) and twin trailer (minimum trailer length of 28 ft) approved by the act could travel. Previously, Federal regulations limited vehicle width to 96 in.; individual State regulations were variable. The wider and longer combination vehicles authorized under the 1982 STAA increase vehicle payload capacity and thus, the potential for higher average vehicle weights and axle loads. The 1982 STAA act also required States to provide “reasonable” access from this network to destination terminals and facilities.

The most significant legislative action related to Federal truck size and weight limits since 1982 was the freeze on longer combination vehicle (LCV) operations imposed in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The LCV freeze enacted in the ISTEA prohibited States from allowing any expansion of LCV operations either in terms of routes upon which they may operate or the vehicle weights or dimensions that may be allowed. The subsequent Transportation Equity Act for the 21st Century (TEA-21) did not lift that freeze.

Although basic Federal truck size and weight limits have not changed since 1982 (with the exception of the LCV freeze), the status quo has not been maintained. Several States have been granted exceptions to Federal GVW or axle weight limits in either authorizing or appropriating legislation since 1982. States are granting increasing numbers of oversize and overweight permits, especially for international containers, but also for many other commodities. The cubic capacity of vehicles has also changed, primarily as the result of increasing trailer lengths.

In response to these regulatory, legislative, and administrative changes, as well as continued requests from industry for ever increasing payload capacity, a series of comprehensive studies were undertaken that considered potential impacts to changes in large truck size and weight limits. These comprehensive research studies, as well as smaller, more focused research efforts, were often undertaken to either motivate a change in regulation or policy or demonstrate the impacts as a result of an implemented change. Regardless of intent, research that is considered to be relevant, significant, and useful in the context of truck size and weight decision-making in included in this *Directory*.

INFRASTRUCTURE PRESERVATION

Historical research related to infrastructure preservation has focused on both pavement and bridge structures, often concurrently and often in conjunction with broader considerations related to modal share, highway safety, industry costs, highway congestion, and other. Table 1 presents a list of key citations related to infrastructure preservation, including cross-cutting topic areas.

While select studies have considered the infrastructure effects of large truck *size*—Fu, Burhouse, and Chang (2004) assessed the magnitude of overheight vehicle collisions with highway bridges (described later in this document under Highway Safety)—the majority of research has focused on the the effects of large truck *weight* on pavement and bridge infrasture. Findings from these citations are intended to support truck weight related decision-making—research related to other large truck and infrastructure preservation topic areas (e.g., structure design, tire pressure effects, environmental effects, etc.) are not included here.

Individual study findings related to pavement and bridge structure preservation—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces the Pavements and Bridges sections in an effort to identify noted trends or differences in research findings.

Pavements

General Findings

- Pavement related costs that might be affected by changes in truck weight include costs for (1) new and reconstructed pavements (2) resurfacing and other forms of rehabilitation, (3) routine maintenance, and (4) effects on users caused by changes in pavement condition. Research on this latter effect is limited.
- Axle weight is a more significant determinant in pavement damage and subsequent pavement costs than gross vehicle weight (GVW). Truck weight limits that allow higher axle weights can significantly increase pavement costs. Truck weight limits that allow higher GVWs distributed over more axles (e.g., 6 instead of 5 axles) do not necessarily lead to higher pavement costs and can even produce cost savings.
- An increase in axle weight generally causes an exponential increase in pavement damage. For flexible pavements, the relationship between axle load and pavement deterioration has an exponent power of 4 (recent research suggests it may be closer to 3). For semi-rigid and rigid pavements, this same relationship has an exponent power of between 11 and 33.
- For flexible pavements, tandem axles are generally less damaging to pavements than single axles, tridem axles are less damaging to pavements than tandem axles, and so on. For rigid pavements, the evidence on the relationship between axle grouping and pavement damage is mixed.
- The effects of axle spacing on pavement damage are complex and variable. Increasing the spread of axles within an axle group reduces damage to rigid pavements, but increases fatigue damage to flexible pavements.
- Pavement damage and subsequent pavement costs vary by pavement design/road classification. For example, 5-axle tractor semitrailer that weighs 80,000 lb typically causes about 9 cents in pavement damage per mile of travel on rural Interstate Highways, compared with $5.90 per mile of travel on rural local roads.
- Pavement damage and subsequent pavement costs vary seasonally. The potential for pavement damage is lower during the winter when the ground is frozen and higher during the spring when pavement layers are generally in a saturated and in a weakened state due to partial thaw conditions.

Domestic Experience

In response to changes brought about by the 1982 STAA and with a unique focus on non-Interstate, arterial highway routes, the Transportation Research Board (TRB) initiated a comprehensive study—*Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989)—to consider access implications of wider and longer commercial motor vehicles. More specifically, the study's intent was to better characterize "reasonable" access and diffuse differences among industry representatives seeking uniform standards for access and State and local officials seeking to maintain local decision-making control.

With respect to pavement infrastructure, results of this study indicate pavement life could be reduced by between 10 and 18 percent, and pavement rehabilitation costs would increase by between 7 and 15 percent with the introduction of STAA vehicles, depending on the volume and mix of truck traffic and pavement conditions. The incremental costs for maintenance and new construction were not considered but their effect is likely to be small. Allowing STAA vehicles to travel the 1.35 billion-vehicle miles now traveled by smaller combination vehicles would increase pavement rehabilitation costs on arterials highways from $8.1 million to $20.8 million.

With a focus on Interstate and State highway systems, TRB initiated a second comprehensive study—*Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990)—that considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

Estimated impacts related to pavement infrastructure are summarized in Table 2. The results suggest that truck weight proposals for which the current federal bridge formula remains the controlling factor—including the Uncapped Formula B (Proposal 2) and the Combined Texas Transportation Institute (TTI) HS-20/Formula B (Proposal 8)—would have a negligible effect on pavement costs (± $10 million). As the study explains, such reform would induce a shift from the use of conventional 5-axle tractor-semitrailer toward heavier combinations with more axles. In terms of per ton of freight carried, these combinations generally cause less pavement damage than the conventional 5-axle combinations because of lower per axle weights, irrespective of gross vehicle weight (GVW).

More generally, this study reported that a 10 percent increase in the number of equivalent single axle loads (ESALs, 18,000-lb unit axle) on the nation's highways would increase pavement related costs to highway agencies by about $375 million per year (1988 dollars)—$25 million for new and reconstructed pavements and $350 for the resurface of existing pavements—assuming that pavements were maintained at comparable condition levels. When designing new pavements, the required pavement thickness increases with increased traffic loadings, but in much smaller proportion—a 10 percent increase in ESALs can generally be accommodated by a 1.5 percent increase in pavement thickness.

With a narrowed focus on a series of specific truck configurations—each with lower axle weights but higher GVWs—TRB initiated a comprehensive study to consider potential impacts should industry be allowed to put these proposed vehicle configurations into operation. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).
- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle.

Table 2. Pavement Infrastructure Impact Summary for Various Proposed Truck Weight Limit Modifications (Transportation Research Board 1990)

TRUCK WEIGHT PROPOSALS			PAVEMENT COSTS[1] ($ millions)		
			New and Reconstructed Pavements	Resurfacing of Existing Pavements	Total
1	Grandfather Clause Elimination	No exemptions in federal limits	↓20	↓190	↓210
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	0	↑10	↑10
3	NTWAC	Permit program for specialized hauling	↑20	↑330	↑350
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↑30	↑460	↑490
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA	NA	NA
6	TTI HS-20 Bridge Formula	Higher single-unit/short combination vehicle weights	0	↓50	↓50
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/short combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive for 7+ axle vehicles	↑10	↑130	↑140
8	Combined TTI HS-20/Formula B	Higher single-unit/short combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	0	↓10	↓10
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA	NA	NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA	NA	NA

[1] All costs are in 1988 dollars and were calculated assuming a discount rate of 7 percent.

With respect to pavement infrastructure, study results indicate that a Turner truck would typically be about 40 percent less damaging per truck-mile than the truck configuration currently in use that it would replace. The trucks now carrying freight that would be diverted to Turner trucks are estimated to account for 33 percent of all ESALs. After allowing for the greater capacity of Turner trucks and projected diversion of freight from rail (discussed under Modal Share), the net effect would be a 19 percent reduction in the rate of pavement wear caused by traffic (ESAL-miles of pavement loading). The cost savings to highway agencies—assuming that pavement condition and intervals between resurfacing are the same as if traffic did not change—would be $729 million annually, once Turner trucks had reached their long-run share of truck traffic in an estimated 5 to 10 years.

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network with 42,000 miles for Rocky Mountain/Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher/nationally uniform weight limits.
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to pavement infrastructure, both the North American Trade and LCV Nationwide scenarios were estimated to reduce pavement costs; pavement costs for the Triples Nationwide scenario were estimated to be essentially unaffected. Most significantly, introduction of 51,000 lb tandem axles under the North American Trade scenario—which would increase the average allowable payload per truck and reduce the total truck-miles required for a given volume of freight—was estimated to reduce pavement costs by about $230 million (2000 dollars) per year.

Additional cost savings were attributed to the use of truck configurations with a higher number of axles, effectively reducing pavement damage by spreading the truck’s load over a more axles. According to the study’s estimates for flexible pavements, a 6-axle combination—consisting of a 12,000 lb steer axle, a 34,000 lb tandem axle, a 44,000 lb tridem axle, and a 90,000 GVW—would cause 18 percent less road damage per truck-mile than would a 5-axle combination—consisting of a 12,000 lb steer axle, two 34,000 lb tandem axles, and an 80,000 GVW—despite having a gross weight that is 12 percent greater.

Findings from an earlier domestic and international technology scanning tour focused on highway/commercial vehicle interaction (Federal Highway Administration 1996) also suggest superior performance from alternative truck configurations as compared to the commonly used 5-axle configuration. When the pavement wear per vehicle is assessed against the payload capacity, this study notes that a tractor semitrailer with 6 axles is a more efficient configuration than the 5-axle vehicle.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—concurs with these finding noting that, "If axle weights are not altered, pavement cost per ton-mile of freight will be little affected by a change in the GVW limits."

During the same year, Suleiman and Varma (2002) assessed the impacts of various vehicle configurations and axle weight limits on flexible pavement structures in the context of the North American Free Trade Agreement (NAFTA) and subsequent harmonization efforts between the United States, Canada, and Mexico. Seven different truck configurations were considered in this investigation. The most widely used U.S. configuration—the 5-axle truck (3S2)—was used as the base truck. Alternative truck configurations were compared using each country's governing axle weight limits (see Table 3) and were assessed using three progressive schemes: the truck-factor scheme, the repetition-to-failure scheme, and the tonnage-over-life scheme. Specific configurations and their estimated extent of pavement infrastructure impact in terms of truck factors and repetitions to failure are presented in Table 4.

Table 3. Axle Weight Limits in North American Countries (Suleiman and Varma 2002)

AXLE TYPES	AXLE WEIGHT LIMITS (kips)		
	U.S.	Canada	Mexico
Steering (single tires)	12	12	14
Single (dual tires)	20	20	22
Tandem	34	38	43
Tridem	42	51	50

Table 4. Estimated Relative Pavement Infrastructure Impacts of Various Truck Configurations (Suleiman and Varma 2002)

TRUCK CONFIGURATION		TRUCK-FACTOR (Pavement Damage)			REPETITION-TO-FAILURE (Pavement Life)		
		U.S.	Canada	Mexico	U.S.	Canada	Mexico
3S2	5-axle tractor semitrailer with steer, tandem drive, tandem semitrailer axles	Base	Base	Base	Base	Base	Base
SU3	3-axle single unit truck with steer, tandem axles	↓37–41%	↓21–24%	↑13–25%	↑59–69%	↑27–33%	↑12–20%
2S1-2	5-axle twin trailer with steer, single drive, single semitrailer, two single full trailer axles			↑100–120%		↓23–26%	↓50–55%
3S3	6-axle tractor semitrailer with steer, tandem drive, tridem semitrailer axles	↓8–10%	↑27–38%	↑62–77%	↑9–11%	↓21–28%	↓38–44%
4S3	7-axle tractor semitrailer with steer, tridem drive, tridem semitrailer axles	↓16–19%			↑19–25%	↓20–30%	↓19–28%
3S3-S2	8-axle B-train with double steer, tandem drive, tridem semitrailer, tandem full trailer axles						
3S2-4	9-axle turnpike with double steer, tandem drive, tandem semitrailer, two tandem full trailer axles		↑135–150%	↑275–310%			

Considering payload over a pavement's serviceable life, results indicate that the 7-axle configuration under U.S. axle weight limits, followed closely by the Canadian and Mexican 7-axle truck configurations, performed better than all other truck configurations on the basis of tonnage-over-life. Other configurations with favorable (better than the 3S2 configuration) tonnage-over-life impacts included the 6-axle configuration under either U.S. or Canadian axle weight limits and the B-train and turnpike double configurations under U.S. axle weight limits. The Mexican 5-axle twin trailer truck (all single axles) and the Mexican single-unit truck were worst-ranked in terms of tonnage-over-life, demonstrating the potential for increased infrastructure damage attributable to truck configurations with a greater number of single axles relative to less damaging tandem and tridem axle groups.

With a singular focus on longer combination vehicles (LCVs), the Western Governor's Association (WGA) prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to pavement infrastructure, total pavement costs were estimated to decrease under the Western Uniformity Scenario by approximately 4.2 percent or $138 million (2000 dollars) over base case conditions. This estimated cost savings was attributed to an anticipated reduction in total truck-miles traveled, a traffic shift from lower-order highway systems to the Interstate System that typically has stronger pavements, and the fact that axle load limits are assumed to continue to control loads on individual axle groups. These reported pavement cost savings are substantially lower than impacts of nationwide LCV operations estimated in USDOT's *Comprehensive Truck Size and Weight Study* (2000). Several factors account for these differences—in the Western Uniformity Scenario, a substantially lower volume of traffic would be affected by regional implementation, lower LCV weights and smaller dimensions were assumed, and LCVs were already in operation to some extent in each of the participating States. This latter factor reduces assumed traffic shifts to new LCV operations. Further, potential infrastructure cost savings are tempered in participating States because the higher LCV weights and dimensions have already at least partially been reflected in infrastructure design.

Rather than explore hypothetical impacts of proposed truck configurations that generally include increased weight limits, the *1997 Federal Highway Cost Allocation Study* (U.S. Department of Transportation 1997) assigns transportation system cost responsibilities among existing truck and other vehicle configurations currently in operation.

Costs for pavement reconstruction, rehabilitation, and resurfacing (3R) are allocated to different vehicle classes on the basis of each vehicle's estimated contribution to pavement distresses necessitating the improvements. The overall distribution of pavement 3R cost responsibility among passenger vehicles, single unit trucks, and combination trucks is 23 percent, 18 percent, and 58 percent, respectively. Estimated pavement cost responsibilities for select single and combination truck configurations, expressed in cents per mile, are listed in Table 5. Two trends are of interest. First, as the operating weight for a given configuration increases, the cost responsibility associated with estimated pavement distress, increases exponentially. For example, a 3-axle single unit truck operating at 20,000, 50,000, and 70,000 lb has an estimated cost responsibility of 0.69, 4.81, 31.70 cents per mile, respectively. Second, estimated pavement cost responsibilities generally decrease as the number of axles increases for a given operating weight. For example, associated pavement cost responsibilities for a payload of 50,000 lb transported on a 2-axle single unit truck, a 3-axle single unit truck, a 5-axle tractor semitrailer, and an 8-axle tractor double semitrailer are 32.89, 4.81, 1.19, and 1.06 cents per mile, respectively. Single axles contribute more to 3R pavement costs than tandem axles and tridem axles contribute less than tandem axles for vehicles with comparable weights.

State/Case Studies

Michigan. In a study conducted in Michigan, Ervin and Gillespie (1986) considered the impact on pavement deterioration and rehabilitation costs of operating various tractor-semitrailers with trailer lengths ranging from 45 to 53 ft.

Researchers found that a 53-ft trailer—capable of carrying 18 percent more freight of equivalent density than a 45-ft trailer—would increase pavement deterioration by as much as 34 to 45 percent on flexible and rigid pavements, respectively. For each 1 percent of existing 45-ft trailer units replaced with 53-ft trailer units, incremental annual rehabilitation costs would range from $1.8 million to $2.9 million depending on payload weight. Assuming that 53-ft trailers accounted for 20 percent of all combination vehicle travel, incremental pavement costs would represent between 6 and 9 percent of total pavement repair bill attributable to all combination vehicle travel in the State.

Table 5. Estimated Pavement Cost Responsibility of Various Truck Configurations (U.S. Department of Transportation 1997)

OPERATING WEIGHT (lb)	TRUCK CONFIGURATION					
	2-axle Single Unit	3-axle Single Unit	5-axle Tractor Semitrailer	6-axle Tractor Semitrailer	5-axle Tractor Double Semitrailer	8-axle Tractor Double Semitrailer
	SU2	SU3	CS5	CS6	DS5	DS8
0-10,000	0.59					
20,000	0.73	0.69	0.64	0.62	0.65	
30,000	1.67	0.86	0.75	0.76	0.73	
40,000	6.45	1.62	0.89	0.87	0.94	
50,000	32.89	4.81	1.19	1.10	1.32	1.06
60,000		12.03	1.86	1.53	1.92	1.24
70,000		31.70	3.55	2.37	2.90	1.59
80,000			6.37	3.68	4.68	2.51
90,000			11.01	6.40	7.55	3.10
100,000			19.96	10.12	13.55	4.50
110,000			36.53	17.40		6.84
120,000				29.24		10.52
130,000						14.48
140,000						19.87
150,000						34.33

California. With a specific focus on pavement maintenance costs, Gibby, et al. (1990) analyzed more than 1,000 one-mile Sections of California State highways to evaluate the impact of heavy truck traffic. Researchers used traffic, weather, and geometric data to formulate a statistical model of pavement maintenance cost.

Study results indicate that heavy truck traffic has a much larger impact on pavement maintenance cost than light truck or passenger car traffic. On a typical roadway, the average maintenance cost per heavy truck (5+ axles) is $7.60 per mile per year, whereas the cost per passenger car is approximately $0.08 per mile per year. It was further shown that one additional heavy truck per day would cost an additional $3.73 per mile of roadway for pavement maintenance annually. An increase of 50 heavy trucks per day would cost an additional $183.10 per mile per year. The corresponding cost increases due to light truck or passenger car traffic are $0.04 and $2.18 per mile per year, respectively.

New England. The New England States of Massachusetts, New Hampshire, Rhode Island, and Vermont have historically set legal axle weights exceeding those of the federal limits. Single axle weight limits in each of the four States are 22,400 lb compared to the federal limit of 20,000 lb. Tandem axle weight limits are 36,000 lb in Massachusetts and Vermont, 40,000 lb in New Hampshire, and 44,000 lb in Rhode Island—significantly higher than the federal limit of 34,000 lb. Gross vehicle weight limits of 80,000 lb were consistent across all States and at the federal level. Lee and Peckham (1990) used four different pavement design methods or models to assess the potential damage caused to pavements by these heavy trucks in New England as compared to trucks limited by federal axle weight standards—"benchmark trucks."

Study results indicate that the ratio of expected pavement life for trucks meeting federal axle weight limits compared to trucks meeting Rhode Island axle weight limits—the highest among the four states considered—ranged from 0.68 to 0.72, depending on the evaluation method or model used. In all cases, New England heavy trucks were observed to cause more pavement damage than benchmark trucks, and the magnitude of this estimated damage increased as axle weight limits increased.

Montana. With an expansive shared international border, Stephens et al. (1997) considered the impact of adopting Canadian Interprovincial, Canamex, or Canamex Short vehicle weight limits on the Montana State highway system. Canadian Interprovincial truck configurations were developed based on an investigation of safety, economy, and damage to the highway system. Canamex and Canamex Short limits are hybrid weight schemes that couple existing Montana axle weight limits with Canadian GVW limits. All scenarios allow trucks to operate at higher gross weights than are presently allowed in Montana. Maximum allowable axle weight under the Canadian Interprovincial limits are 10 percent on a tandem and 25 percent on a tridem higher than those axle weights currently allowed in Montana. The impact of these configurations on the highway system was determined by (1) developing traffic streams that included these trucks, (2) determining the engineering impact these traffic streams would have on existing infrastructure and on the future designs required to support these trucks, and (3) assigning a cost to these impacts based on the current cost of equivalent work.

With respect to pavement infrastructure, study results indicate that long-term pavement demands under all scenarios increase by less than 5 percent compared to demands under the existing traffic stream. The estimated change in remaining pavement life was typically less than one year in all cases. The estimated average increase in overlay thickness ranged from 0.3 to 1.5 percent (a minimum overlay thickness of 0.25 feet was used). The estimated increase in pavement costs—resulting from the reduction in service life and the cost of subsequent overlays to provide a 20-year life—are $1.38, $1.56, and $1.58 million for the Canada Interprovincial, Canamex, and Canamex Short limits. These values represent increases of 1.4, 1.6, and 1.6 percent over comparable costs under the existing traffic stream. In the short-term, operation under Canadian Interprovincial limits produced the most significant change—a 4.8 percent increase in ESALs and a $1.7 million (1.7 percent) increase in pavement costs. Short-term considerations under Canamex limits produced the smallest predicted change—a $0.38 million (0.4 percent) increase in pavement costs.

In a second study, Hewitt, et al. (1999) considered the overall impacts of changes in truck weight limits on infrastructure and the broader economy in Montana. Four scenarios were considered with different maximum allowable GVWs. Three scenarios, with maximum GVWs of 80,000 lb, 88,000 lb, and 105,500 lb, represented reductions in GVWs. The fourth scenario represented an increase in allowable GVW to 128,000 lb.

Among the study's scenarios, the restriction of GVW to 80,000 lb has the largest estimated impact on pavement costs—an increase of 1.2 percent. Vehicles with lower GVWs and fewer axles would replace the vehicles that currently operate over 80,000 lb. An increased number of trips would be required to transport the same quantity of freight, which, when combined with the reduction in the number of axles, would increase pavement damage. Only marginal increases in pavement infrastructure costs were predicted in the study's liberalization scenario that increases the allowable GVW to 123,000 lb.

Louisiana. In Louisiana, GVW on Interstate routes has typically been restricted to 80,000 lb for 5-axle tractor semitrailer (Louisiana Type 6) vehicles with a maximum tandem axle weight of 32,000 lb. Since 1997, Type 6 trucks hauling the State's essential commodities—sugarcane, rice, timber, and cotton—have been permitted for 100,000 lb GVW and 48,000 lb tandem axle limits during harvest season on non-Interstate (State) highways and for sugarcane commodities on Interstates. Roberts and Djakfar (2000) considered the impacts of these increased weight limits under current operations and considering expanded operation on Interstates. Researchers considered three different scenarios. Of particular interest is the comparison between operations with no overweight permits (Scenario 1) and with overweight permits up to 100,000 lb GVW on non-Interstate (State) highways and for sugarcane commodities on Interstates (Scenario 2) and between operations with no overweight permits (Scenario 1) and with GVW limits up to 100,000 lb on all road systems for Type 6 trucks (Scenario 3).

When moving from no-permit operations (Scenario 1) to the current system of permits on non-Interstate (State) highways (Scenario 2), estimated pavement cost increases range from a low of $34 per lane-mi for timber on Interstates to $8,620 per lane-mi for sugarcane on U.S. highways. Pavement costs were generally higher on Louisiana State and U.S. highways than on Interstate highways. If Type 6 vehicles were allowed to carry up to 100,000 lb on all systems (moving from Scenario 1 to 3), estimated pavement cost increases range from a low of $760 per lane-mi for timber on Interstates to $18,800 per lane-mi for timber on Louisiana State highways.

Virginia. Virginia House Bill 2209 proposed increases in allowable truck weight limits such that a 3-axle single unit or combination truck would have a 60,000 lb gross vehicle, 24,000 single axle, and 45,000 lb tandem axle weight limit; a 4 axle configuration would have a 70,000 lb gross vehicle, 24,000 single axle, and 50,000 lb tridem axle weight limit; and a 5-axle configuration would have a 70,000 to 80,000 lb (depending on axle spacing) gross vehicle, 20,000 single axle, and 40,000 lb tandem axle weight limit. Motivated by these proposed increases in truck weights and subsequently mandated by Virginia's General Assembly, Freeman and Clark (2002) conducted a study to determine if pavements in the southwest region of the State—carrying vehicles operating under higher allowable weight limits—have greater maintenance and rehabilitation requirements than pavements elsewhere in the State bound by lower weight limits. Detailed field surveys were conducted at 18 in-service pavement sites representing the range of roadway and traffic conditions found on Southwest Virginia's primary and secondary highways. Traffic classification and weight surveys, an investigation of subsurface conditions, and comprehensive structural evaluations were conducted at all sites. The results were used to estimate the cost of damage attributed only to the net increase in allowable weight limits.

Results of the study indicate that pavement damage increased significantly with relatively small increases in truck axle weights for all vehicle classes affected by Virginia House Bill 2209. The cost of structural damage to mainline pavements attributable to the net weight increase in the seven affected counties alone was estimated at $28 million over 12 years.

Maine and New Hampshire. The Transportation Equity Act for the 21st Century (TEA-21) provided exemptions from the federal GVW limits on the Maine and New Hampshire Turnpikes. Exempt portions of I-95 and State highways allow a GVW of up to 100,000 lb on 6-axle tractor semitrailer combinations. Certain commodity groups are also allowed a 10 percent GVW tolerance on 5-axle configurations. Individual axle weight limits range from 22,400 to 24,200 lb for a single axle, 36,000 to 44,000 lb for a tandem axle, and 48,000 to 54,000 lb for a tridem axle. Non-exempt Interstates in Maine and New Hampshire remain subject to the federal GVW limit of 80,000 lb. As a result, heavy trucks that would otherwise be through-traffic on I-95 divert to State highways upon reaching non-exempt portions of I-95. Wilbur Smith and Associates (2004) conducted an analysis that compared the current condition of allowing trucks in excess of 80,000 lb GVW on the ME/NH Turnpike to a no-exemption scenario in which State road networks would assume any displaced heavy truck traffic should the weight exemption be rescinded.

With respect to pavement infrastructure, study results indicate that, if the current turnpike exemption were to be rescinded, the State of Maine would experience higher pavement rehabilitation costs each year of between $1.29 million and $2.38 million. For the State of New Hampshire, pavement rehabilitation costs would increase between $41,847 and $49,194.

Minnesota. In an effort to protect the State's highway infrastructure, the Minnesota Department of Transportation and the Minnesota State Patrol cooperatively sponsored development of a *Commercial Vehicle Weight Compliance Strategic Plan* (URS 2005). This effort included a five-step pavement infrastructure damage assessment: (1) determine the weight compliance rate in corresponding ESALS due to overweight vehicles, (2) calculate the remaining expected useful projected life for each roadway feature assuming 100 percent compliance, (3) calculate the remaining expected useful life for each roadway feature accounting for overweight vehicles, (4) calculate the annualized cost for both of the above two life expectancies, and (5) subtract these annualized costs to yield an annualized damage estimate. Using data from existing WIM sites, researchers estimated 1 percent of Interstate ESALs and 9.3 percent of other pavement type ESALs to be attributable to overweight trucks.

Based on this estimate and other assumptions related to replacement costs and pavement service life, annual damage due to overweight trucks was estimated to be in excess of $30 million. A 10 percent reduction in overweight truck ESALs was estimated to result in more that $3 million ($3,111,523) in annual savings for the State of Minnesota.

One year later, Cambridge Systematics, Inc. (2006) conducted a study to assess proposed changes to Minnesota's truck weight laws that would benefit the State's economy while protecting roadway infrastructure and safety. Various vehicle configurations—including a 6-axle tractor semitrailer with a 90,000 lb GVW limit, a 7-axle tractor semitrailer with a 97,000 lb GVW limit, an 8-axle twin trailer truck with a 108,000 lb GVW limit, and a single unit truck with an 80,000 lb GVW limit—were considered, as well as various changes to spring load restrictions.

With respect to pavement infrastructure, pavement costs were estimated based on changes in ESAL-miles for each scenario. For each of the scenarios considered, lower ESALs and fewer truck-miles resulted in lower estimated pavement costs when compared to current conditions. Pavement costs savings ranged from $0.55 million per year for the 80,000-lb single unit truck to $2.24 million per year for the 97,000-lb, 7-axle tractor semitrailer. Estimated pavement cost savings for the 6-axle and 8-axle configurations were $1.27 and $1.25 million per year, respectively. The estimated impacts of relaxed spring load restrictions and increased GVW limits (from 73,280 to 80,000 lb for 5-axle tractor semitrailers) on the 9-ton roadway system were not as favorable. Pavement costs for these two scenarios were estimated to increase by $2.34 million and $8.49 million per year, respectively.

Ohio. The Ohio Department of Transportation (2009) recently considered the impacts of permitted trucking on the State's transportation system and economy, with a focus on infrastructure impacts. A three tiered approach was used in allocating costs among highway users—basic costs are shared by all users, structural costs are shared by all trucks in accordance with their impact, and overweight costs are attributed entirely to permitted vehicles.

With respect to pavement infrastructure, study results indicate a $122 million allocation to overweight vehicles annually for pavement infrastructure. This estimate is conservative in that it does not include all direct costs associated with heavy truck travel on the highway system.

Wisconsin. Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on pavement costs. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

With respect to pavement infrastructure, estimated pavement cost savings are summarized in Table 6. Consistent with prior research, the most "pavement-friendly" configurations are those with the greatest distribution of weight across multiple axles (lowest ESAL impacts), including the 7-axle 97,000 lb tractor semitrailer and the 8-axle single unit. The 6-axle 90,000 lb tractor semitrailer also exhibits high pavement cost savings.

Texas. With an exclusive focus on LCVs, Walton et al. (2010) considered the use of a 97,000-lb tridem configuration, a 138,000-lb 53-ft double configuration, and a 53-ft double configuration that would cube out at 90,000 lb in an effort to meet the State's freight demands.

With respect to pavement infrastructure, the LCV scenario had no impact on pavement life for rigid pavements. For flexible pavements, the use of LCVs extended the pavement life for all but one route. The estimated pavement lives were used in calculating the annualized cost of a thick hot-mix overlay at the end of each cycle. Given the wide variation in overlay costs, a range of $400,000-$1,219,000 per lane-mile was used to calculate the annualized costs. Results showed that between $17.4 million and $53.07 million per year could be saved on overlay cost if LCVs were allowed on the selected Texas routes.

Table 6. Estimated Pavement Costs for Various Truck Configurations (Adams, et al. 2009)

CONFIGURATION	ANNUAL PAVEMENT COSTS (million $)	
	Non-Interstate	Interstate/Non-Interstate
8-axle 108,000 lb double	↓ $3.34	↓ $16.76
7-axle 97,000 lb tractor semitrailer	↓ $3.87	↓ $19.91
7-axle 80,000 lb single unit truck	↓ $0.40	↓ $1.53
6-axle 90,000 lb tractor semitrailer	↓ $2.57	↓ $14.65
6-axle 98,000 lb tractor semitrailer	↓ $1.10	↓ $10.19
6-axle 98,000 lb straight truck-trailer	↓ $0.03	↓ $0.32

International Experience

International experience generally supports the findings reported domestically. In a study conducted by the Organization for Economic Cooperation and Development (OECD), the effects of heavy trucks and climate on pavements were considered, distinguished by pavement type: flexible, semi-rigid, and rigid (Organization for Economic Cooperation and Development 1988). Key findings reported in this study include the following:

- Axle load is a much stronger determinant of pavement damage than GVW.
- For a given load and type of axle, driving axles are more destructive than carrying axles.
- For flexible pavements, axle grouping on a vehicle is beneficial (e.g., the use of a tandem axle in place of single axles reduces pavement damage, as does the use of tridem axles in place of singles and tandems). For rigid pavements, the evidence on the relationship between axle grouping and pavement damage is mixed.

- An increase in axle weight generally causes an exponential increase in pavement damage. For flexible pavements, the relationship between axle load and pavement deterioration has an exponent power of 4 (recent research suggests it may be closer to 3). For semi-rigid and rigid pavements, this same relationship has an exponent power of between 11 and 33.

More recently, Frith et al. (1994) considered the impacts of increased truck weight limits in Europe. In general, researchers noted that GVW could be increased with no additional pavement damage if the weight is spread over a greater number of axles. Estimated pavement damage was highest for 40,000-lb (18-tonne) 2-axle single unit trucks, 84,000-lb (38-tonne) 4-axle tractor semitrailers and 97,000-lb (44-tonne) 5-axle tractor semitrailers.

Bridges

General Findings

- Unlike estimated pavement infrastructure costs that were often predicted to remain the same or decrease, proposed increases to truck size and weight limits are consistently predicted to increase bridge-related infrastructure costs. Bridge-related costs far exceed pavement-related costs attributable to increased truck size and weight limits.
- Bridge-related infrastructure cost estimates may be exaggerated, assuming full replacement of bridges without regard to cost-effective alternatives that offer the same margin of safety—such as strengthening the bridge or restricting select truck configurations indefinitely for bridges along non-essential routes. (Note that strengthening is not a viable option for many bridge types such as reinforced or pre-stressed concrete spans—the cost of strengthening these bridge types approaches the cost of full replacement.)
- Bridge safety concerns under alternative truck loading relate to: (1) overstress—a bridge has inadequate load-bearing capacity to accommodate legal loadings and (2) fatigue—a bridge suffers from a reduction in life attributable to repeated loadings, signaled by cracks developing at points of high stress concentration.
- Much of the historic research related to bridge infrastructure has focused on overstress concerns, noting relatively few fatigue failures that are generally limited to steel structures and bridge decks.
- The number of axles on a truck has little impact on bridges; bridge stress is affected more by the total amount of load than by the number of axles. Bridge stress generally increases with axle group weight and, except on some continuous bridges with long spans, generally decreases with the separating distance. It is possible to have GVWs greater than 80,000 lb without introducing excessive stress.
- The current Federal Bridge Formula—designed to protect bridges from stress levels that would risk bridge failure—has been criticized for setting overly cautious limits on the weights of shorter trucks and for allowing too much extra weight for trucks with additional axles. The Federal Bridge Formula was also based on consideration of stresses on simple-span bridges only and, therefore, allows trucks to operate that could overstress certain continuous spans.

Domestic Experience

In response to changes brought about by the 1982 STAA and with a unique focus on non-Interstate, arterial highway routes, the Transportation Research Board (TRB) initiated a comprehensive study—*Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989)—to consider access implications of wider and longer commercial motor vehicles. More specifically, the study's intent was to better characterize "reasonable" access and diffuse differences among industry representatives seeking uniform standards for access and State and local officials seeking to maintain local decision-making control.

With respect to bridge infrastructure, results of this study indicate that the introduction of STAA vehicles will have little differential effect on the service lives of bridges on access roads. Because of the greater payload capacity of STAA vehicles, a smaller increase in truck traffic is anticipated, mitigating some of the adverse effects of higher truck weights. The most significant impacts will be realized along access routes that previously had little truck traffic. Along such routes, older bridges and bridges designed to lower loading standards might experience accelerated deterioration.

With a focus on Interstate and State highway systems, TRB initiated a second comprehensive study—*Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990)—that considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

Study results related to bridge infrastructure impacts for each of the other truck configurations considered are summarized in Table 7. Researchers considered three types of bridge costs related to upgraded design loads for new bridges, replacement of load deficient bridges, and fatigue. Using operating ratings plus a 5 percent tolerance on the rating factor to represent capacity, 21 percent of the bridges on the primary and Interstate system—above and beyond the bridges deficient to carry current vehicle loads—were inadequate under the proposed configuration scenarios. Using allowable stress-based operating ratings plus zero tolerance on the total stress, 17 percent of the bridges on the primary and Interstate system were found deficient, above and beyond the bridges found to be deficient to carry current vehicle loads.

Bridge costs accounted for the bulk of the infrastructure costs arising from increased truck weight limits. For example, the estimated effects for removing the 80,000 lb cap on GVW (Proposal 2) on annual infrastructure costs were an increase of $10 million for pavements, compared with $680 million for bridges, assuming that all safety-deficient bridges would be replaced. Of the estimated bridge costs, $510 million stemmed from the replacement costs, $150 million from upgrading the design loads for new bridges, and only $20 million were fatigue related costs.

With a narrowed focus on a series of specific truck configurations—each with lower axle weights but higher GVWs—TRB initiated a comprehensive study to consider potential impacts should industry be allowed to put these proposed vehicle configurations into operation. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).

- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle.

Table 7. Bridge Infrastructure Impact Summary for Various Proposed Truck Weight Limit Modifications (Transportation Research Board 1990)

TRUCK WEIGHT PROPOSALS			BRIDGE COSTS[1] ($ millions)				
			Upgraded Design Loads for New Bridges	Replacement of Load-Deficient Bridges		Fatigue-related	Total
				Interstate/ Primary Highways	Non-primary Highways		
1	Grandfather Clause Elimination	No exemptions in federal limits	↓40	↓150	↓90	0	↓280
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	↑150	↑270	↑240	↑20	↑680
3	NTWAC	Permit program for specialized hauling	↑280	↑1,240	↑1,510	↑10	↑3,040
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↑310	↑960	↑1,070	↑70	↑2,410
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA				NA
6	TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights	↑60	↑70	↑200	↑20	↑350
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive when applied to 7+ axle vehicles	↑90	↑100	↑230	↑20	↑440
8	Combined TTI HS-20/Formula B	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	↑150	↑300	↑430	↑20	↑900
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA				NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA				NA

[1] All costs are in 1988 dollars and were calculated assuming a discount rate of 7 percent.

With respect to bridge infrastructure, the major cost of the Turner Proposal that would be incurred by highway agencies related to replacement of load deficient bridges and upgraded design loads for new bridges. Approximately 7,000 (4 percent of the total) Interstate and primary highway bridges and 19,000 (6 percent of the total) bridges on the non-primary system are load deficient. Costs to replace these bridges are estimated to be $2.8 billion and $4.1 billion, respectively. Instead of replacing all of the deficient non-primary highway bridges, many along non-essential freight routes would simply be posted to prohibit Turner trucks. Designing new bridges to carry Turner trucks would add $110 million for new bridge construction. In addition, costs to repair and replace bridges because of increased fatigue damage would be $28 million annually once Turner traffic volume had reached its long-run level. The annualized cost to replace all Interstate and primary system bridges and one-fourth of all bridges on other systems that are deficient to carry Turner trucks, plus the costs of higher design standards for all new bridges and the cost of fatigue damage, would be $403 million, or about a 10 percent increase in bridge capital expenditures.

Nationally, considering pavement savings and added bridge costs, Turner trucks would reduce annual highway agency costs by $326 million. Realized savings following adoption of the Turner Proposal would be less initially because costly bridge improvements are required to support subsequent expansion of Turner truck use.

Looking distinctly at the impact on urban and rural Interstate bridge networks, Weissman and Harrison (1991) performed a study on the impact of adopting Turnpike Doubles (double trailer combination with a 134,000 lb GVW and 108-ft length) and Triple 28s (triple trailer combination with a 115,000-lb GVW and a 95-ft length). Researchers applied the same general bridge infrastructure costing approach as that applied in the prior studies but used a modified bridge rating in calculating bridge replacement costs (based on a survey of representatives in 49 states) and included estimates of user-borne costs attributable to construction delays and including value of time, additional fuel costs, etc. Researchers assumed that all deficient bridges would be replaced rather than strengthened.

Estimates for the total bridge costs on the urban and rural Interstate system using this methodology are on the order of $30 billion (1989 dollars), comprised of $14 billion bridge replacement costs and $16 billion associated user-borne costs.

In a similar study conducted several years later, Weissman and Harrison (1998) considered the impact of a 6-axle 97,000-lb tractor semitrailer truck (including a tridem axle) on bridges on the urban and rural Interstate system. Bridges on the Interstate system that are already deficient at current loads were excluded from this analysis. The authors classified a bridge as deficient using a 5 percent stress tolerance of the inventory rating. The authors noted that *Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990) also used a 5 percent tolerance, but applied this stress tolerance to the operating rating. The authors' justification for using the inventory rating was a survey finding that over 60 percent of states use the inventory rather than the operating rating. After determining how many bridges would be unable to safely accommodate the reference vehicle—an 80,000 lb 5-axle tractor semitrailer—the analysis was repeated for the 6-axle 97,000-lb tractor semitrailer.

The results indicated that the number of deficient bridges on Interstate highways nearly doubles when the 6-axle 97,000 lb tractor semitrailer trucks are considered. The estimated cost of replacing these additional deficient bridges was approximately $30 billion; about $25 billion of this sum consisted of user costs, which would arise from the disruption to traffic while a new bridge is being built. The authors also note substantial differences between States in the estimated cost of bridge reconstruction, ranging from $33 per square foot in Texas to $155 per square foot in Rhode Island.

During the same year, Weissman and Harrison (1998b) assessed the impacts of adopting widely used Mexican and Canadian truck configurations on U.S. bridge structures in the context of the North American Free Trade Agreement (NAFTA) and subsequent harmonization efforts between the United States, Canada, and Mexico. Canadian and Mexican truck weight limits are substantially higher than those permitted on the federal aid system in the United States. The Mexican truck configuration considered in this investigation was a 6-axle, 107,000 lb tractor semitrailer. The Canadian truck configuration was a 128,000 lb C-train short heavy double.

Using a model specifically designed to calculate bridge impacts at the network level, and considering both replacement costs for the deficient structures and the user delay costs incurred when the structures are being reconstructed, the authors estimated that in Texas alone, the introduction of the Canadian truck would require $7.7 billion in expenditures on bridge replacement. Of this amount, about 80 percent consisted of the inconvenience costs to motorists of the traffic delays generated by the bridge work; the costs of the bridge work itself accounted for only 20 percent. Again limited to Texas, the costs of allowing the Mexican-configured trucks were about $6.6 billion, comprising $1 billion in bridge capital costs and $5.6 billion in user delay costs.

In a comprehensive effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to bridge infrastructure, study results indicate that the proposed large truck configuration scenarios would entail large costs for replacing deficient bridges unable to safely accommodate the increased truck weights. Estimated bridge costs, including agency and user-borne costs, is: $254 billion (44,000 lb tridem) and $329 billion (51,000 lb tridem) under the North American Trade scenario; $319 billion under the LCV Nationwide scenario; and $117 billion under the Triples Nationwide scenario. Costs are expressed in 1994 dollars. Recall that these same scenarios were found to either reduce or leave essentially unchanged the costs for pavements.

Costs of bridge fatigue were not considered in this study—fatigue depends on axle weight and most of the vehicles in the study's reform scenarios did not have greater axle loads than vehicles in the current fleet. Bridge fatigue was further considered to be secondary because: (1) it generally affects only steel bridges whose share in the nation's bridge population is decreasing, (2) fatigue damage can generally be repaired inexpensively, and (3) most bridges have been designed with an adequate fatigue code.

Findings from an earlier domestic and international technology scanning tour focused on highway/commercial vehicle interaction (Federal Highway Administration 1996) also suggest that a lesser focus on fatigue is warranted, noting that there are relatively few recognized fatigue failures in bridges and most relate to bridge decks.

A subset of prior research has however focused on identifying fatigue-related impacts attributable to changes in large truck weight. Khaleel and Itani (1993) considered the effects of alternate truck configurations and weights on the fatigue life of partially pre-stressed concrete girder bridges. Data on the fatigue life of concrete, reinforcing bars, and pre-stressing steel show considerable scatter in their service life, due to both the stochastic nature of the imposed loading and the variability in their strengths as determined by the quality control in their manufacture.

The incremental fatigue-related bridge damage caused by each passing truck depends on its gross weight, configuration, axle load distribution, and lateral load distribution on the bridge. The 9-axle B-train double (one of the Turner trucks) was found to be most damaging, whereas the 2-axle single truck was least damaging. The 4-axle tractor semitrailer was found to be less damaging than the 3-axle single truck, even though their average weight is higher.

In a similar study, Laman and Ashbaugh (2000) evaluated 78 distinct truck configurations over a statistically representative sample of steel highway bridges to determine relative fatigue damage potential on a network-wide basis.

Results of the study indicate that weight distribution and axle spacing are the factors responsible for variation in damage potential for a given GVW, and that trucks with heavy, closely spaced axles will induce greater fatigue damage than vehicles with similar GVW, but relatively uniform weight distributions over a longer length. Close spacing of heavy axles results in large stresses at fatigue-prone details when the axle groups pass critical points along the span. A longer vehicle, with a uniform weight-distribution, limits the magnitude of stress induced by spreading the vehicle weight. The study also found that there was a weak (0.65) correlation between GVW and fatigue damage potential and that certain truck configurations would induce significantly lower fatigue damage to bridges for a given GVW. Also, longer vehicles tend to induce an average of 15 percent of the damage induced by shorter vehicles for a given GVW and that short rigid-body or tractor semitrailer trucks induce 6.5 times more damage on average than longer combination vehicles.

Most recently in a study sponsored by the National Cooperative Research Program (NCHRP), Fu, et al. (2003) considered the effect of truck weight on bridge network costs through example applications of the recommended methodology.

Study results indicate that the models for assessing structural material fatigue (for both steel components and reinforced concrete decks) have more uncertainty than the strength assessing models. Essentially it is because fatigue accumulation largely depends on microscopic original discontinuities and acquired damages, which are randomly distributed in location and severity. Predicting failure originating from such sources is inherently involved with notable uncertainty. The study results also indicated that wheel loads have a very significant effect on rigid concrete deck fatigue accumulation. This result has important implications to wheel load limit development and enforcement. More research is recommended to better understand the mechanism of rigid concrete deck deterioration due to combined efforts of load and steel corrosion.

Once again considering broader bridge infrastructure costs with an exclusive focus on longer combination vehicles, the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to bridge infrastructure, study results indicate that regional bridge improvement costs would more than double under the Western Uniformity Scenario. Annualized bridge infrastructure costs—ranging from $116 to $206 million per year (2000 dollars)—were estimated by calculating the difference between total bridge improvement costs over a 20-year period in the scenario States under current weight limits and total bridge infrastructure costs assuming the estimated vehicle miles traveled and weight distributions under the scenario weight limits.

With a critical eye toward earlier research, Chang and Garvin (2007) conducted a sensitivity analysis that demonstrates a wide range of costs for the same truck configurations depending upon evaluation assumptions. According to the authors, prior assessments regarding the impact of increased trucks weight on bridge-related costs in the United States have relied on a single, conservative parameter—threshold overstress criterion—that is inconsistent with actual practice, a fact that limits the usefulness of the resultant cost estimates. For various truck configurations previously considered in the research—a 6-axle 97,000-lb tractor semitrailer, a 6-axle, 107,000 lb tractor semitrailer commonly used in Mexico, and a 128,000 lb C-train short heavy double used in Canada—estimated bridge infrastructure sufficiency and subsequent costs varied widely depending on the assumed threshold overstress criterion. For example, in the case of the 6-axle 97,000-lb tractor semitrailer, a 10 percent increase in the inventory rating level results in a 92 percent decrease in bridge replacement costs, from $4.4 billion to $0.52 billion. For the 107,000 lb tractor semitrailer used in Mexico, a 20 percent increase in the inventory rating level reduces estimated bridge replacement costs from $9.9 billion to $0.57 billion. Comparatively, estimated bridge replacement costs for the 128,000 lb C-train short heavy double used in Canada remain significant over a wide range of threshold levels.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—concurs with observations made by Chang and Garvin (2007) regarding the inappropriate reliance on a single, conservative parameter to determine whether bridges require replacement and identified a number of additional shortcomings in prior research methodologies that limits the usefulness of the resultant cost estimates. First, prior research has not taken into account the possibility of "intelligent management of bridge investment and maintenance decisions" by highway agencies, nor the availability of alternative treatments (i.e., strengthening, more intensive inspection and maintenance, or posting) that could produce the same degree of insurance against bridge failure as costly replacement. Second, consideration of costs other than the highway agency's bridge replacement costs has been haphazard. Direct costs related to bridge fatigue, new bridge designs, and remaining useful life of existing bridges, as well as associated costs such as traffic delays and fuel consumption attributable to construction of the new bridge are not consistent components in bridge infrastructure cost estimates.

Rather than explore hypothetical impacts of proposed truck configurations that generally include increased weight limits, the *1997 Federal Highway Cost Allocation Study* (U.S. Department of Transportation 1997) assigns transportation system cost responsibilities among existing truck and other vehicle configurations currently in operation.

Costs of constructing new bridges are allocated to vehicles using an incremental approach in proportion to their passenger car equivalent (PCE)-vehicle-miles traveled (VMT). Incremental costs to provide the additional strength needed to support heavier trucks are assigned to vehicle classes on the basis of the additional strength required on account of their weight and axle spacings. Bridge reconstruction and rehabilitation costs are assigned according to the types of improvements that are made. Some improvements are made because the bridge has become functionally obsolete and can no longer safely and efficiently accommodate traffic because of inadequate capacity, substandard geometrics, or other safety problems. Those costs are allocated on the basis of VMT. Other improvements are required because the bridge has become structurally inadequate to carry the traffic using the facility. Costs to provide additional structural capacity are allocated to those vehicle classes that require the added strength.

Sixty-nine percent of all bridge costs are allocated to passenger vehicles, 10 percent to single unit trucks, and 21 percent to combination trucks. These percentages vary by type of improvement. For example, single unit and combination trucks are allocated 20 and 30 percent of bridge replacement costs, and only 3 and 5 percent of minor bridge rehabilitation costs respectively. Estimated bridge cost responsibilities for select single and combination truck configurations, expressed in cents per mile, are listed in Table 8. Two trends are of interest. First, as the operating weight for a given truck configuration increases, the cost responsibility associated with estimated bridge distress, increases exponentially. For example, a 3-axle single unit truck operating at 20,000, 50,000, and 80,000 lb has an estimated cost responsibility of 0.2, 1.7, 23.9 cents per mile, respectively. Second, estimated bridge cost responsibilities generally decrease as the number of axles increases for a given operating weight. For example, associated bridge cost responsibilities for a payload of 50,000 lb transported on a 2-axle single unit truck, a 3-axle single unit truck, a 5-axle tractor semitrailer, and an 8-axle tractor double semitrailer are 2.4, 1.7, 0.3, and 0.2 cents per mile, respectively.

State/Case Studies

Illinois. Since increasing the state truck weight limits in 1983, from 73,280 lb to 80,000 lb, the Illinois Department of Transportation has reported triennially on the effects of this State legislation change.

In the first triennial report, specific effects on bridges were not included primarily because the increased loading was not expected to produce adverse effects. A more in-depth look at the issue in the second triennial report suggested that the heavier trucks were contributing to a reduction in the service life for some older bridges. An annualized cost of this deterioration was estimated at $9 million. The third triennial report concluded an updated annual cost of $12.3 to $30 million attributable to the increased weight limits, based on a study done by Mohammadi, et al. 1991. Estimates were based on a sample of 15 bridges measured and analyzed under truck loads.

Washington. Sorensen and Manzo-Robledo (1992) estimated the impact of the Turner Proposal on Washington State bridges. In 1989 when this study began, 2,024 of the 3,079 concrete bridges (nearly 66 percent) on the Washington State roadway system were identified to be strength deficient under the Turner truck scenarios.

Table 8. Estimated Bridge Cost Responsibility of Various Truck Configurations (U.S. Department of Transportation 1997)

OPERATING WEIGHT (lb)	TRUCK CONFIGURATION					
	2-axle Single Unit	3-axle Single Unit	5-axle Tractor Semitrailer	6-axle Tractor Semitrailer	5-axle Tractor Double Semitrailer	8-axle Tractor Double Semitrailer
	SU2	SU3	CS5	CS6	DS5	DS8
0-10,000	0.1					
20,000	0.2	0.2	0.2	0.2	0.2	
30,000	0.2	0.2	0.2	0.2	0.2	0.2
40,000	0.7	0.6	0.2	0.2	0.3	0.2
50,000	2.4	1.7	0.3	0.3	0.3	0.2
60,000	4.5	4.3	0.4	0.3	0.3	0.3
70,000		19.1	0.6	0.6	0.4	0.3
80,000		23.9	1.2	0.9	0.7	0.4
90,000			2.1	2.4	1.4	0.8
100,000			4.4	5.5	2.3	1.3
110,000			12.1	13.1		1.8
120,000				21.9		3.1
130,000						7.7
140,000						8.1
150,000						16.5

The various cost estimates were based on the assumption that each bridge in the population had a controlling maximum length simple span which was used in a failure criterion. The largest value of the cost estimate for the replacement of all deficient bridges in the population is $2.643 billion, which resulted from the calculations involving the most severe Turner prototype truck loading, a 75-year design life, and a 0 percent live load overload.

Montana. With an expansive shared international border, Stephens et al. (1997) considered the impact of adopting Canadian Interprovincial, Canamex, or Canamex Short vehicle weight limits on the Montana State highway system. Canadian Interprovincial truck configurations were developed based on an investigation of safety, economy, and damage to the highway system. Canamex and Canamex Short limits are hybrid weight schemes that couple existing Montana axle weight limits with Canadian GVW limits. All scenarios allow trucks to operate at higher gross weights than are presently allowed in Montana. Maximum allowable axle weight under the Canadian Interprovincial limits are 10 percent on a tandem and 25 percent on a tridem higher than those axle weights currently allowed in Montana. The impact of these configurations on the highway system was determined by (1) developing traffic streams that included these trucks, (2) determining the engineering impact these traffic streams would have on existing infrastructure and on the future designs required to support these trucks, and (3) assigning a cost to these impacts based on the current cost of equivalent work.

With respect to bridge infrastructure, study results indicate that 16 to 20 percent of the bridges system-wide are deficient (above and beyond the bridges already deficient under HS-20 loads) to carry Canadian Interprovincial vehicles. Incremental deficiencies under Canamex and Canamex Short vehicles are between 1 and 3 percent of the bridges (above and beyond the bridges already deficient under HS-20 loads) system-wide. Deficiencies were determined using allowable stress based operating ratings and 87 percent of allowable stress based operating ratings. The results were found to be sensitive to the assumed level of bridge capacity and the roadway class (e.g., Interstate, primary). Based on these noted deficiencies, bridge replacement costs were estimated to range from $242.4 to $740.6 million (1996 dollars) for Canadian Interprovincial configurations; from $50.2 to $133.9 million (1996 dollars) for Canamex configurations; and from $51.1 to $215.9 million (1996 dollars) for Canamex Short configurations.

Maine and New Hampshire. The Transportation Equity Act for the 21st Century (TEA-21) provided exemptions from the federal GVW limits on the Maine and New Hampshire Turnpikes. Exempt portions of I-95 and State highways allow a GVW of up to 100,000 lb on 6-axle tractor semitrailer combinations. Certain commodity groups are also allowed a 10 percent GVW tolerance on 5-axle configurations. Individual axle weight limits range from 22,400 to 24,200 lb for a single axle, 36,000 to 44,000 lb for a tandem axle, and 48,000 to 54,000 lb for a tridem axle. Non-exempt Interstates in Maine and New Hampshire remain subject to the federal GVW limit of 80,000 lb. As a result, heavy trucks that would otherwise be through-traffic on I-95 divert to State highways upon reaching non-exempt portions of I-95. Wilbur Smith and Associates (2004) conducted an analysis that compared the current condition of allowing trucks in excess of 80,000 lb GVW on the ME/NH Turnpike to a no-exemption scenario in which State road networks would assume any displaced heavy truck traffic should the weight exemption be rescinded.

Bridge-related cost estimates were developed (in 2003 dollars) for two cost categories: periodic maintenance based on historic cost records and published references and major rehabilitation based on accepted average costs. Because the fatigue analysis indicated that the normal life cycle of the structures would not be significantly affected, replacement costs were not estimated.

Study results indicate that revocation of the federal weight exemption on the Maine Turnpike would result in a net bridge maintenance and rehabilitation cost increase to the State of Maine of $804,683 per year. Bridge maintenance costs are estimated to increase by $519,755 and annualized (25-year time horizon) major rehabilitation costs for bridges along on non-turnpike diversion routes are estimated to be $284,928. Comparatively, revocation of the federal weight exemption on the New Hampshire Turnpike would result in a net bridge maintenance and rehabilitation cost savings to the State of New Hampshire of $376,226 per year. Bridge maintenance costs are estimated to decrease by $581,516 and annualized (25-year time horizon) major rehabilitation costs for bridges along on non-turnpike diversion routes are estimated to be $205,290. Periodic maintenance results for New Hampshire are dominated by a large bridge (470,569 square feet of deck surface) on the Turnpike. The estimated maintenance on this single structure due to the exemption is more than $705,000.

Minnesota. At the request of the Minnesota Department of Transportation (MnDOT), Cambridge Systematics, Inc. (2006) conducted a study to assess proposed changes to Minnesota's truck weight laws that would benefit the State's economy while protecting roadway infrastructure and safety. Various vehicle configurations—including a 6-axle tractor semitrailer with a 90,000 lb GVW limit, a 7-axle tractor semitrailer with a 97,000 lb GVW limit, an 8-axle twin trailer truck with a 108,000 lb GVW limit, and a single unit truck with an 80,000 lb GVW limit—were considered, as well as various changes to spring load restrictions.

With respect to bridge infrastructure, study results indicate that increased bridge costs related to inspection rating and posting ranged from $0.00 for the 80,000-lb single unit truck to $0.05 million for the 90,000-lb 6-axle tractor semitrailer. Similarly, increased bridge costs related to increased design loads ranged from $0.13 million for the 80,000-lb single unit truck to $0.96 million for the 90,000-lb 6-axle tractor semitrailer. A bridge cost savings related to bridge fatigue was estimated, ranging from $0.10 million for the 80,000-lb single unit truck to $0.22 million for the 97,000-lb 7-axle tractor semitrailer. A bridge cost savings of $0.04 million was also estimated as a result of relaxed spring load restrictions. Conversely, increased bridge costs attributable to fatigue were estimated as a result of increased GVW limits (from 73,280 to 80,000 lb for 5-axle tractor semi-trailers) on the 9-ton roadway system.

Louisiana. Motivated again by proposed legislative changes related to truck weight, Saber and Roberts (2006) developed considered the economic impact of a 5-axle tractor semitrailer configuration (3S2) with 12,000 lb steer and 48,000 lb tandem axle limits on State bridges. Most of the bridges in Louisiana are designed for a fatigue life of 50 years or 45.7 million truck crossings, whichever comes first. The estimated average cost per trip across the bridge for the proposed configuration—considering potential fatigue-related damage—was estimated and compared to the current permit fees of $10 per truck per year. For HS-20-44 design loads, the fatigue cost per trip is $5.75 and $8.90 for simple and continuous spans, respectively. For H-15 design loads, the fatigue cost per trip is $8.50. The results of this study indicate that the current $10/truck/year permit fee will not cover the additional maintenance and repair costs for bridges attributable to the proposed new loads. In an effort to assist the forestry product industry in Louisiana and reduce the bridge fatigue damage on the State system, the authors recommend changing the axle configuration to include a tridem instead of tandem axle and the GVW should be limited to 86,600 lb uniformly distributed among these axles.

Ohio. The Ohio Department of Transportation (2009) recently considered the impacts of permitted trucking on the State's transportation system and economy, with a focus on infrastructure impacts. A three tiered approach was used in allocating costs among highway users—basic costs are shared by all users, structural costs are shared by all trucks in accordance with their impact, and overweight costs are attributed entirely to permitted vehicles.

With respect to bridge infrastructure, study results indicate a $22 million allocation to overweight vehicles annually for bridge infrastructure. This estimate was derived using methods consistent with the *1997 Federal Highway Cost Allocation Study* (Federal Highway Administration 1997).

Wisconsin. Most recently, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on pavement costs. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

Bridge infrastructure related costs are summarized in Table 9. These reported costs only reflect incremental bridge costs attributable to these new truck configurations—the total cost to replace all statewide deficient bridges on both State and local routes far exceeds the amounts shown. The most "bridge-friendly" configurations—including the 6-axle 90,000 lb semitrailer, the 7-axle single unit truck, and the 7-axle 97,000 lb semitrailer—offer moderate GVWs distributed across an increased number of axles.

Table 9. Estimated Bridge Costs for Various Truck Configurations (Adams et al. 2009)

CONFIGURATION	ANNUAL BRIDGE COSTS (million $)	
	Non-Interstate	Interstate/Non-Interstate
6-axle 90,000 lb tractor-semitrailer	↑ $2.18	↑ $2.18
7-axle 97,000 lb tractor-semitrailer	↑ $3.08	↑ $3.08
7-axle 80,000 lb single unit truck	↑ $2.26	↑ $2.26
8-axle 108,000 lb double	↑ $6.02	↑ $6.02
6-axle 98,000 lb tractor-semitrailer	↑ $8.48	↑ $8.48
6-axle 98,000 lb straight truck-trailer	↑ $4.22	↑ $4.22

Texas. With an exclusive focus on LCVs, Walton et al. (2010) considered the use of a 97,000-lb tridem configuration, a 138,000-lb 53-ft double configuration, and a 53-ft double configuration that would cube out at 90,000 lb in an effort to meet the State's freight demands.

With respect to bridge infrastructure, 1,713 bridges were analyzed using moment ratios. Research has shown that bridges built post-1980 can support 20 percent overstress, while older bridges can support 10 percent overstress. The 90,000-lb double configuration showed no impact on either type of bridge. Using a 10-20 percent overstress threshold, operation of the 97,000-lb tridem and 138,000-lb double configuration would result in an estimated repair cost of $1.14-$2.8 billion and $1-$1.2 billion, respectively.

Not all bridges would be replaced immediately depending on the overstress level. To incorporate this concept in the analysis, a new fatigue approach was developed during project development with the assumption of a 75-year fatigue design life for a bridge. Results for this analysis approach amount to $1.0 billion and $0.8 billion for the 97,000-lb tridem and 138,000-lb double configuration respectively, with no impacts for the 90,000-lb double configuration.

MODAL SHARE

Historical research related to freight modal share as a result of changing truck size and weight limits has typically focused on the relationship between road and rail transport; air and waterway transport have unique requirements/constraints that preclude ready diversion under changing operating conditions. A number of studies have considered modal share impacts concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, highway safety, industry costs, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to modal share, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research related to other modal share topic areas (e.g., trucking/rail industry logistics, shipper operations, transport fees, etc.) are not included here.

Individual study findings related to freight modal share—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- The proportion of freight transported between rail and truck is determined by complex economic relationships intended to maximize profit for each respective mode. Rail industry revenues are directly related to transport rates established by the trucking industry—and vice versa—for all commodities that can be practicably carried by either mode.
- Increases in maximum allowable truck sizes and weights will predictably lead to lower truck transport costs; industry competition and regulatory pressure will translate these lower costs into lower transport rates. The rail industry has to either match the lower rates or lose traffic to the competing mode—in either instance, rail revenues will decline.

General Findings (Continued)

- The magnitude of revenue loss depends on the extent of trucking industry cost/rate reductions brought about by the increase in capacity, and by the proportion of existing rail traffic that will shift to truck if the relative transport rates of the two modes change.
- Estimates of rail to truck traffic diversion and subsequent losses in rail revenue are highly variable suggesting sensitivity to: (1) regional commodity movement/transportation infrastructure conditions, (2) the extent of truck payload capacity increases, and (3) evaluation assumptions.
- Shippers choosing between truck and rail often consider a trade-off between price and service. In terms of price-per-ton-mile, rail service is almost always less expensive than truck service. In terms of service quality, truck service offers door-to-door delivery and typically faster deliveries.
- For low-value commodities—such as coal, grain, or chemicals—the price of shipping is often a priority over the convenience of door-to-door service, providing rail a formidable advantage over highway movement.
- Intermodal operations that rely upon combined truck and rail transport for different segments of the trip experience the highest level of competition between truck and rail modes. Carload operations that utilize boxcars also experience a high level of competition between these modes.

Domestic Experience

A series of early studies considered the potential for diversion from rail to truck as a result of increased maximum lawful truck sizes and weights. For example, Hymson (1978) estimated that allowable GVW increased from 73,280 lb to 90,000 lb, operation costs and subsequent rates for transport would decline by 16.8 percent. Potential for diversion from rail to truck was estimated by examining market shares of each commodity in each distance grouping. Available market share data suggest that the rail industry and motor carriers compete for freight traffic accounting for approximately 75 percent of rail revenue. Thus, a 16.8 percent decline in motor carrier costs and transport rates would force railroads to make competitive adjustments that would cost the industry up to $2 billion (in 1978 dollars).

More recently, TRB initiated a comprehensive study—*Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990)—that considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

Study results related to modal share impacts are summarized in Table 10. Rail diversion of up to 6.6 percent of current rail traffic is estimated for the Canadian Interprovincial Limits scenario. The three other scenarios that would eliminate the 80,000-lb GVW limit would also result in a diversion from rail, ranging from 2.2 to 2.5 percent. These rail diversion estimates assume that States would not increase their length limits; if length limits are increased, diversion from rail to truck could more than double these estimates. An associated reduction in annual rail revenue, ranging from $310 million to $2.24 billion, is estimated as a result of potential diversion from rail to truck. Implementation of the Canadian Interprovincial Limits scenario would prove most costly for the railroad industry. Only the Grandfather Clause Elimination scenario, which would reduce allowable truck size and weight limits, is estimated to increase the share of freight moved by rail. This predicted increase is rail transport is modest at 0.8 percent, with an associated increase in rail revenue of $230 million.

With a narrowed focus on a series of specific truck configurations—each with lower axle weights but higher GVWs—TRB initiated a comprehensive study to consider potential impacts should industry be allowed to put these proposed vehicle configurations into operation. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

Table 10. Estimated Freight Diversion from Rail to Truck for Various Proposed Truck Size and Weight Limit Modifications (Transportation Research Board 1990)

TRUCK SIZE AND WEIGHT PROPOSALS			RAIL TON-MILES	TRANSPORT COSTS[1, 2] ($ millions)
1	Grandfather Clause Elimination	No exemptions in federal limits	↑0.8%	↑230[3]
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	↓2.2%	↓750[4]
3	NTWAC	Permit program for specialized hauling	↓0.9%	↓310[5]
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↓6.6%	↓2,240[6]
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA	NA
6	TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights	↓0.0%	0
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive when applied to 7+ axle vehicles	↓2.5%	↓850[7]
8	Combined TTI HS-20/ Formula B	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	↓2.5%	↓860[8]
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA	NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA	NA

[1] *All costs are in 1988 dollars and were calculated assuming a discount rate of 7 percent.*

[2] *Competitive railroad rate decreases would reduce shipper costs however, this effect is not included because it represents a redistribution from railroads to shippers rather than a net decrease in costs.*

[3] *Competitive rate decreases by railroads would reduce shipper costs by an additional $50 million.*

[4] *Competitive rate decreases by railroads would reduce shipper costs by an additional $210 million.*

[5] *Competitive rate decreases by railroads would reduce shipper costs by an additional $90 million.*

[6] *Competitive rate decreases by railroads would reduce shipper costs by an additional $620 million.*

[7] *Competitive rate decreases by railroads would reduce shipper costs by an additional $240 million.*

[8] *Competitive rate decreases by railroads would reduce shipper costs by an additional $240 million.*

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).
- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle.

With respect to modal share, study results indicate that Turner trucks—favoring the 9-axle double trailer configuration—would attract freight from rail equivalent to 2 percent of truck ton-miles and 4 percent of rail ton-miles. The rail industry would lose approximately 5 percent of its gross annual revenue as a result of the potential diversion from rail to truck.

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to modal share, study results indicate that a shift to any one of these proposed truck configuration scenarios would divert freight from rail. Both carload and intermodal operations were considered. Carload operations accounts for the majority (86 percent) of freight hauled by rail. Over 10 different equipment types are used to support carload operations, but commodities hauled via the box car body style are most likely to be considered for diversion to truck. Comparatively, intermodal operations utilize containers or trailers placed on a rail flat car or well car—trailer-on-flatcar/container-on-flat-car (TOFC/COFC). Intermodal operations utilize over-the road trucks to move commodities from the shipper to the intermodal rail facility and from the intermodal rail facility to its final destination. If the cost of truck transport were reduced relative to rail intermodal, the entire transport might occur over-the-road.

Under the North American Trade scenario, annual rail car-miles are estimated to decrease between 4.7 percent (5 percent from carload operations and 2 percent from intermodal operations) and 5.8 percent (7 percent from carload operations and 3 percent from intermodal operations), for truck configurations with 44,000-lb and 51,000-lb tridem axles, respectively. Comparatively, under the Triples Nationwide scenario, annual rail car-miles are estimated to decrease by 4.0 percent (5 percent from carload operations and 1 percent from intermodal operations). The LCV Nationwide scenario was estimated to have the most significant effect of rail industry operations—annual rail car-miles are estimated to decrease nearly 20 percent (19.6 percent, 9 percent from carload operations and 31 percent from intermodal operations) under this scenario. Note that the model used to estimate these modal share impacts in USDOT's *Comprehensive Truck Size and Weight Study* (2000) was subsequently updated by the USDOT Federal Railroad Administration. Details of the revised model are contained in the *Intermodal Transportation and Inventory Cost Model—Highway-to-Rail Intermodal User's Manual* (2005).

With a singular focus on longer combination vehicles (LCVs), the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to modal share, study results indicate that the actual diversion from rail to truck is estimated to be small—less than 0.01 percent of rail traffic in the region would divert to LCVs under scenario assumptions. Associated rate reductions that railroads would make to prevent freight traffic from switching to trucks is estimated to be about $26 million per year.

These reported modal share impacts are substantially lower than impacts of nationwide LCV operations estimated in USDOT's *Comprehensive Truck Size and Weight Study* (2000). Several factors account for these differences—in the Western Uniformity Scenario, a substantially lower volume of traffic would be affected by regional implementation, lower LCV weights and smaller dimensions were assumed, and LCVs were already in operation to some extent in each of the participating States. This latter factor reduces assumed traffic shifts to new LCV operations. Most significant—when compared with the *Comprehensive Truck Size and Weight Study*—is the loss in revenues from rail rate discounting relative to revenue losses from traffic diversion. In the *Comprehensive Truck Size and Weight Study*, the loss in revenues from diversion consistently represented a larger share of the revenue losses but under the Western Uniformity Scenario, the results are reversed. It is hypothesized that the geographic boundaries of the Western Uniformity Scenario—are largely responsible. Most of rail traffic and competing truck traffic originates, terminates, (or both) outside of the scenario States studied requiring trans-loading of cargos at State borders to and from conventional configurations and LCVs. Some productivity gains are subsequently eroded—enough that railroads are forced to discount rates, but not so deeply that a large proportion of the affected traffic is diverted to the LCVs.

State/Case Studies

Wisconsin. Most recently, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on pavement costs. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

With respect to modal share, sensitivity analyses were performed to investigate how increasing the amount of freight carried by scenario trucks by 5 percent, 10 percent, and 15 percent would impact diversion from rail and increases in the total amount of freight shipped. Study results indicate that diversion from rail to truck under these truck configuration scenarios would be negligible (especially if increases in truck weight limits are limited to non-Interstates in Wisconsin). The authors note that much of the rail-truck competition exists for long-distance shipments (e.g., over 500 miles).

ENFORCEMENT

In an effort to ensure truck weight and size compliance, existing enforcement efforts rely upon a variety of facilities, equipment, and strategies including but not limited to the following:

- Static scales and weigh station personnel.
- Portable/semi-portable scales and personnel.
- Weigh-in-motion (WIM) and automatic vehicle classification (AVC) equipment.
- Fines, penalties, sanctions.
- Judicial system and culpability for drivers, vehicle owners, and shippers.
- Industry self-certification.

Historical research related to truck size and weight enforcement has typically focused on ensuring compliance with *weight* limits; few studies were identified that considered efforts to enforce legal *size* limits. A number of studies have considered enforcement efforts concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, highway safety, industry costs, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to enforcement, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research related to other enforcement or regulatory actions associated with safety (e.g., driver training, condition, or hours of service; vehicle design or maintenance; cargo securement), fiscal requirements (e.g., vehicle registration, taxation), and other are not included here.

Individual study findings related to truck size and weight enforcement—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Reliable estimates of illegal truck size and weight activity and a wide divergence in enforcement practices across the United States challenges the ability to accurately assess the direct relationship between enforcement activities and truck size and weight compliance.
- Higher levels of enforcement are generally associated with higher truck size and weight compliance. Based on prior studies, estimated violation rates for fixed Interstate weigh stations approximate less than 1 percent when enforcement is present and 15 percent when enforcement is not present. Estimated violation rates along bypass routes and/or determined using mobile enforcement are higher in both frequency (approximately 30 percent) and magnitude.
- A combination of fixed and mobile enforcement has been observed to be most effective in ensuring truck size and weight compliance.
- Recent trends suggest a greater reliance on technology to provide increased spatial and temporal coverage under existing personnel constraints.
- Truck size and weight limit laws and regulations should be uniform in their scope and relatively simple to comprehend, apply, and enforce. Laws or regulations that are complex or that contain numerous exceptions to their application give rise to reduced levels of enforcement and subsequent prosecution.
- Inappropriately directed penalties targeting drivers instead of the shippers/carriers, ineffective penalties, judges and prosecutors who are unaware of the impact of overweight trucks, and low prioritization in a criminal court system all challenge the effectiveness of the current adjudication process.

Domestic Experience

Reliable estimates of the magnitude and frequency of illegal truck size and weight activity are lacking. Further, a wide divergence in enforcement practices across the United States confounds the ability to assess the effects of enforcement on truck size and weight compliance. As such, few evaluations have been performed that directly relate enforcement activities with truck size and weight compliance.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—confirmed these deficiencies, noting that the magnitude of the truck size and weight non-compliance problem and the effectiveness of alternative enforcement strategies are unknown.

In an early attempt to estimate the magnitude and frequency of illegal truck weight activity and, Grenzeback, Stowers, and Boghani (1988)—using State-level data gathered as part of an NCHRP synthesis study—conservatively estimated that 15 percent of large trucks would exceed axle weight or GVW limits along an Interstate highway when enforcement was not taking place. When enforcement was present at fixed facilities, only 0.6 percent of trucks were observed to exceed GVW limits. The authors note that a higher proportion of overweight trucks may routinely avoid these weigh facilities.

Comparatively, annual State certification data compiled by FHWA indicated that, despite increasing efforts to improve truck weight enforcement, truck overloading did not decrease significantly between 1984 and 1987 (Federal Highway Administration 1989). The number of vehicles weighed for enforcement purposes increased by about 16 percent; comparable to the increase in heavy truck traffic during the same period. The number of overweight citations issued and associated fines remained relatively constant during this time period. One factor limiting the effects of enforcement was identified as low fine amounts—in 1987, the minimum fine for operating 20,000 lb over the 80,000 lb GVW limit was $100 or less in six States.

In a follow-on investigation, the U.S. Department of Transportation Office of Inspector General (OIG) concluded that a lack of data was preventing FHWA from accurately assessing the effectiveness of State weight enforcement programs (1991). A need was identified for the development of automatic weight monitoring systems and statistically valid sampling plans for use in determining actual distributions of weights and changes over time.

More recently, using weigh-in-motion (WIM) data from several hundred sites in 18 States, Hajek and Selsneva (2000) estimated that roughly 12 percent of all (loaded and unloaded) tandem axles exceeded the 34,000 lb federal weight limit. This rate equates to 15 percent of tandem axles exceeding federal limits for only loaded trucks.

Considering not only violation rates but also how these rates change under different enforcement levels and strategies, Fekpe and Clayton (1994) developed an innovative upper bound limit (reflecting the finite load carrying capacities of trucks) model to describe the likelihood of traveling overweight based on enforcement activity and other trucking industry parameters. Both fixed and mobile enforcement were considered. Violation rates reported by mobile patrol teams were higher than those at fixed weight stations, indicating that the permanent facilities effectively deterred overweight travel, or caused it to utilize other facilities. Violation rates generally declined as enforcement levels increased.

In a follow-on study, Fekpe, Clayton, and Haas (1995) applied the same mathematical model to estimate the effects of truck weight limits and enforcement levels on pavement infrastructure. The authors assert that enforcement is a critical factor in assessing pavement impacts of alternative weight limits and note that substantial savings are achievable if strict enforcement schedules are implemented.

Assuming an industry perspective, Strathman (2001) considered the economic rationale for exceeding weight limits. In principle, industry is motivated to set load weight levels that will yield maximum profits and as such, will exceed legal weight limits to the point where additional revenues from overloading are just offset by additional costs—including the expected penalty from weight enforcement.

Patterns of weight enforcement practices by States were identified reflecting differences in enforcement levels and the severity of penalties imposed for exceeding weight limits. Four general U.S. weight enforcement regimes were identified:

- High levels of enforcement with low penalties—Louisiana, Colorado, Mississippi, Idaho, Virginia, North Carolina, and West Virginia.
- Low levels of enforcement with high penalties—Minnesota, Pennsylvania, Michigan, Illinois, Rhode Island, and Arkansas.
- High levels of enforcement with high penalties—Arizona, Missouri, Oregon, South Dakota, and Utah, with Oregon taking the most balanced approach.
- Low levels of enforcement with low penalties—Vermont, Maine, Nebraska, and Georgia.

A regression model was estimated relating overweight citations issued in the 48 participating States to enforcement levels, overweight penalties, and industry revenue potential from overloading. The results indicated that the effects of increasing enforcement levels or overweight penalties are comparable in their ability to deter overloading activity, with the latter likely being more cost-effective. Overweight fine structures have been observed to be well below both the marginal industry revenues and cost of road damage from overloading. Enforcement efforts utilizing portable/semi-portable scales were found to be most effective but accounted for less than 2 percent of vehicle weight measurements reported by the subject States in 1999.

A number of studies have focused exclusively on the adjudication process subsequent to truck size and weight violation detection and citation issuance. In an early investigation, the Federal Highway Administration (1985) examined the process by which truck weight violations are adjudicated and identified five broad-based shortcomings:

- *Judges:* Many judges view truck size and weight offenses as benign and insignificant, failing to understand the nature and extent of infrastructure damage caused by overweight vehicles and the profitability of illegal weight operations to the truckers. They sometimes dismiss truck overweight cases or find the defendant not guilty without good reason, suspend all or most of the fine, or simply refuse to impose the statutory fine.
- *Prosecutors:* Like the judges, prosecutors generally have little understanding of the truck overweight problem and often fail to effectively prosecute these cases. Prosecutors sometimes plea bargain the case away, simply decline to prosecute, prosecute without preparation or zeal, or simply default to the enforcement officer.
- *Wrong Defendant:* The defendant in the adjudication is generally the truck driver, rather than the owner or the shipper. The enforcement action is directed against the driver, but drivers often have little control over the load they are carrying. Also, drivers are not the persons most likely to profit from the overweight operation.
- *Ineffective Penalties:* The penalties imposed in following adjudication in many States have no appreciable deterrent value.
- *Criminal Courts:* Most States still define overweight truck operation as a crime and adjudicate the o offense within the criminal courts, which are often backlogged with cases. In criminal courts, truck overweight cases are given a low priority.

In response to these shortcomings, Arnold (1991) proposed a three-step strategy for deterring overloading practices when a State's criminal statutes prove ineffective:

Step 1 *Temporary Restraining Order:* To accelerate the adjudication process, the first step is to request a temporary restraining order (TRO), which must typically be heard within 20 days. When requesting a TRO, the judge should be presented with evidence demonstrating the number of citations issued to the subject carrier and their apparent disregard for truck size and weight laws.

Step 2 *Temporary Injunction:* After the TRO is issued, the next and most important step is to attempt to convert the TRO into a temporary injunction. Under a temporary injunction, a carrier is ordered by the court to not violate the law (to not drive overloaded vehicles on the State highways) until the case is heard and disposed of by a court of law. If the defendant receives just one citation during the temporary injunction, the carrier is considered to be in contempt of court. As such, the carrier is motivated to accelerate the trial process. Without the temporary injunction, the carrier may continue to violate the law and pay any associated fines until the case is heard in court, which may be 1 to 2 years from the date of citation. When requesting a temporary injunction, the State should provide convincing evidence of the infrastructure damage attributable to even a single overweight truck.

Step 3 *Trial:* During the trial, witnesses for the prosecution should include: (1) a member of the State transportation agency who testifies that the State is responsible for the cost of maintaining the State and Federal highways and identify the source of road maintenance and repair funds, (2) a member of law enforcement who testifies regarding the frequency and magnitude of defendant violations during the subject time period, and (3) the State's expert witness who will relate the illegal activity with resultant infrastructure damage and associated costs to the State.

Special Report 225: Truck Weight Limits: Issues and Options (Transportation Research Board 1990) included several recommendations for Congressional action, including a targeted outreach effort for judges and prosecutors regarding truck size and weight violations. The study recommended that FHWA be tasked to develop and disseminate materials describing the damage to the highways and bridges caused by illegally overloaded trucks and the costs to taxpayers and other highway users. The materials should highlight the adverse safety effects of overweight operations and unfair competitive advantages gained by those who operated over legal weight limits. The study estimated that the expected transport costs for a carrier traveling 12,500 miles with a 20,000 lb overload is $15,350 whereas the costs of carrying the same amount of freight legally is $19,950—a $4,600 costs savings under illegal operation. This study also recommended that Congress consider the imposition of stiff federal or mandatory State penalties for violations of federal weight limits on Interstate highways and promoted forced offloading of illegally overweight trucks as an effective method for ensuring compliance by shippers and operators.

Shifting focus from truck size and weight compliance outcomes to enforcement tools and strategies, a series of recent documents have been developed to guide States in deploying technologies intended to improve enforcement efficiency and effectiveness. These recent guidance documents build upon findings from an earlier domestic and international technology scanning tour (Federal Highway Administration 1996) that point to significant potential enforcement benefits through the use of technology.

As part of the broader *Truck Size and Weight Enforcement Technology Project* sponsored by the FHWA, Cambridge Systematics, Inc. (2009) identified the state of the practice and "best practices" regarding the use of roadside technologies to support truck size and weight enforcement in participating States. Key technologies and applications considered in this study included high-speed WIM used in fixed weigh station operations; low-speed WIM used for ramp sorting; and screening at WIM sites using any of a number of automatic vehicle identification (AVI) methods, including license plate and USDOT number readers. Virtual weigh stations are featured in the report.

In a companion document, Cambridge Systematics, Inc. (2009b) recommended implementation strategies for the deployment of virtual weigh stations and other roadside enforcement operations. The *Implementation Plan* includes a two-page *Reference Guide to Deploying Roadside Technologies* that summarizes the important steps that can be taken by States to incorporate new roadside technologies into their enforcement programs. States are encouraged to tailor or modify the guide to suit their particular circumstances and needs.

In a similar effort sponsored by NCHRP, Carson (2010) conducted an outreach effort targeting decision-makers at State transportation and law enforcement agencies across the Nation that encouraged implementation of notable technology-based European policies and procedures for truck size and weight enforcement observed during a 2006 *Commercial Motor Vehicle Size and Weight Enforcement Scan Tour*. The development and dissemination of various outreach products, combined with in-person outreach events, was intended to accelerate an understanding of related issues and lead to better programmatic direction for truck size and weight enforcement. Outreach products developed as part of this project are available for download from TRB's website, http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2335.

State/Case Studies

Texas. An early study conducted in Texas showed that a typical truck on a Texas highway could travel approximately 12,500 miles before encountering a weigh station (Euritt 1987). A truck carrying 20,000 lb in excess weight over this distance would generate $3,700 more profit as compared to operating legally. A vehicle averaging 75,000 miles per year might come in contact with enforcement only six times per year.

Virginia. With a focus on weigh station bypass activity, Cottrell (1992) examined data from two sites along Interstate 81 in Virginia and found that 11 and 14 percent of trucks were found to be overweight on bypass routes proximate to these sites. Weight measurements captured using WIM systems in the absence of enforcement were 30 to 60 percent higher than weight measurements captured by enforcement personnel using static scales. The study also observed the practice of weigh station "running" or "plugging," where drivers purposely convoy large numbers of trucks in order to exceed the approach ramp capacity. Overloaded and heavier vehicles travel at the rear of the convoys, with the intent of bypassing when the station is temporarily closed. Over 38 percent of the vehicles that were running by the station as a result of these convoys were shown to be overloaded.

Wisconsin. In a similar study, Grundmanis (1989) examined weigh station bypass activity by overweight trucks in Wisconsin and found that 20.3 percent of trucks on bypass routes were in violation of size and weight laws, and 69.7 percent of trucks/drivers on bypass routes were in violation of additional motor carrier safety and driver regulations.

In a second study conducted in Wisconsin, Cambridge Systematics, Inc. (1994) considered the benefits and costs to industry and the State regarding overweight travel and enforcement. Researchers considered a range of scenarios using fixed weigh stations in isolation, mobile enforcement in isolation, and a combined fixed/mobile enforcement approach, with variations in supplemental technology use. Results of the study indicated that the combined fixed/mobile enforcement approach was the most cost-effective strategy for the State, with the fully mobile approach offering the least cost.

Idaho. In Idaho, Parkinson et al. (1992) developed a methodology to quantify the economic benefit of the State's Ports of Entry (POEs) in terms of infrastructure preservation and applied this methodology to the Bliss POE. Weigh-in-motion data was used to determine the percentage of overloaded trucks. The cost of reduced pavement life was based on construction and rehabilitation costs of a typical asphalt highway section with an assumed life of 36 years. The economic benefit of increased pavement life resulting from the Bliss POE ranges from $175,000 to $407,000, depending on the assumed influence of the POE.

Oregon. In 1987, the Oregon Department of Transportation—as part of a demonstration project jointly funded by ODOT and FHWA—automated the new Woodburn POE, located along Interstate 5. Compelling reasons were to minimize personnel tasks; improve weight, size, and safety enforcement; provide more data for planning and design purposes; maximize resources; improve tax collection and audit capabilities; and save time for the trucking industry. Automation of the Woodburn POE interfaced six components including WIM and AVI systems, electronic static scales, supervisory computer, various software interfaces, and a carrier database.

The estimated savings to the State and industry from the automation system are significant. Savings to the State are $470,300 annually and $1,181,900 for the 5 years of operation (1988 to 1993). Private industry savings are $286,300 annually, amounting to $1,431,500 during the 5-year period. Average annual facility costs over the 5-year period amounted to $88,500 (Krukar and Evert 1994).

Florida. In a study sponsored by the Florida Department of Transportation (FDOT), Cunagin, Mickler, and Wright (1997) estimated the magnitude of weigh station avoidance by overweight trucks along the Interstate 95 (I-95) corridor. Two permanent weigh stations and four bypass routes were used as traffic monitoring sites. Truck weight enforcement officers followed four enforcement strategies during the study:

Strategy A: Scales open with no overweight citations issued or bypass patrols.

Strategy B: Scales open with no enforcement teams patrolling the bypass routes. Citations were issued at the weigh scales.

Strategy C: Scales open with some enforcement teams patrolling the bypass routes. Citations were issued at the weigh scales and on the bypass routes.

Strategy D: Scales open for a shorter time period with as many enforcement teams as possible patrolling the major and secondary bypass routes and selected rest areas. Citations were issued at the scales and on the bypass routes.

The magnitude of the overweight-truck problem was assessed by computing both the number and percent of overweight violations for FHWA Type 9 vehicles on each route during each enforcement scenario.

Under Strategy A (no enforcement), 12.9 percent (or 5,843*)* of the FHWA Type 9 trucks passing through the study corridor weighed in excess of the legal limits. Under Strategy D (intense enforcement), the percentage fell to 1.4 (or 583 trucks). With increasing enforcement, the volume of FHWA Type 9 trucks decreased at the permanent weigh station on I-95. A total of 0.8 percent of the trucks were overweight at the fixed scales, whereas 19 percent were in violation on the bypass routes during the study. Trucks cited on bypass routes weighed an average of 992 lb more than those cited on fixed scales.

The results of the study indicate that the numbers of overweight vehicles decrease with increasing enforcement activity, but that vehicles attempt to bypass permanent truck weigh stations. In general, the violations at the permanent weigh stations were minor, whereas those on the bypass routes were much more severe. These results, when considered with the WIM data and the experience of weight enforcement officers, suggest that only intensive enforcement activity can reduce violations to low levels.

Based on this study's results, the authors recommended that WIM systems be used to monitor traffic and direct enforcement along bypass routes and that a reporting requirement for compliance under Title 23 (23 USC Sec. 127, Vehicle Weight Limitations, Interstate System) be considered related to weigh station bypass enforcement (e.g., bypass routes should be identified and monitored for 7 days each calendar quarter to identify evasion patterns and adjust random officer deployments).

California, Georgia, Idaho, and Minnesota. Noting that traditional measures of enforcement effectiveness provide indications of enforcement *activity* (such as numbers of trucks weighed and citations issued) rather than *objectives* (such as deterring overweight trucks and minimizing pavement wear and tear), Hanscom (1998) developed a software tool to better estimate the effectiveness of truck weight enforcement efforts. Five distinct measures of effectiveness (MOEs)—including the severity of overweight violation, the proportion of overweight trucks in a sample, ESALs, excess ESALs, and bridge formula violations—were established on the basis of their enhanced ability to demonstrate truck weight enforcement effects.

These MOEs were subsequently validated in a comprehensive four-State field evaluation. Matched WIM data sets, collected under controlled baseline and enforcement conditions, were analyzed to determine the sensitivity of candidate MOEs to actual enforcement activity. Findings observed in each state are summarized below:

- *California.* An analysis of 3,678 truck combinations exhibited lower gross weights, with a smaller proportion of overweight axles, during the time when the weigh station was open. A subsample of 2,370 tractor-semitrailer combinations demonstrated lower rear-tandem weights with fewer instances of excess ESALs when the weigh station was open.
- *Georgia.* Under conditions of visible mobile enforcement operations, the observed sample exhibited lower steering-axle weights, lower rear-axle weights, and lower rear-tandem weights. Moreover, less severe excess ESAL violations were observed during the enforcement period. During an unexpected enforcement operation, a number of overweight trucks were observed to either park alongside the roadway or divert to alternate routes.
- *Idaho.* Each of the proposed MOEs was shown to be sensitive to enforcement activity. The MOEs most consistently demonstrating sensitivity were: (1) truck proportion exceeding 80,000 lb, (2) truck proportion with overweight tandems, (3) rear-tandem

weight violation severity, and (4) truck proportion that exhibited excess ESALs. While less frequently associated with enforcement activity, the following measures were also validated in the Idaho data: (1) higher average ESALs, (2) bridge formula violations, and (3) the truck proportion exhibiting bridge formula violations.

- *Minnesota.* Analyzed data sets suggest enforcement leads to reduced bridge formula violations, a smaller proportion of overweight trucks, and reduced average ESALs.

Arizona, Florida, Idaho, Maryland, Montana, Virginia, and Wisconsin. Using information reported in seven States, Taylor et al. (2000) refuted the argument that—based on low violation rates observed at isolated weigh stations on primary highway systems (typically around 1 percent for continuously operated weigh stations on the U.S. Interstate System)—enforcement efforts to control truck weights are unnecessary. Evidence suggests that the low rates of overweight violations currently being observed on many primary highway systems are indicative of the impact of an effective weigh enforcement program. In addition, recent observations of accelerated damage on many secondary and country road systems may be indicative of the impact of low or non-existent weight enforcement on the performance of the road network. Violation rates under low levels of enforcement have been reported to range from 12 to 34 percent in participating States.

Montana. The Montana Department of Transportation (MDT) recently completed a pilot project in which data from a statewide network of WIM systems was used to assist in scheduling mobile weight enforcement activities (Stephens et al. 2003). The purpose of this project was to determine if one of the Division's objectives—reducing infrastructure damage from overweight vehicles—could be better realized by using WIM data in dispatching officers. Data from the State Truck Activities Reporting System (STARS) was processed to determine the pavement damage caused by overweight vehicles each month during the baseline year. The trends identified from this analysis were used in the subsequent year to direct patrol efforts each month to the five sites that had historically experienced the greatest pavement damage from overweight vehicles. Officers were directed to the specific vehicle configurations historically responsible for the damage, as well as to their direction of travel and time of operation.

During this year of WIM-directed enforcement, pavement damage from overweight vehicles decreased by 4.5 million ESAL-miles and the percentage of vehicles operating overweight decreased by 20 percent across all STARS sites (both enforced and unenforced). While changes in loading patterns were observed during the enforcement activities (fewer overweight and more weight compliant vehicles), the effectiveness of the focused enforcement in producing long term changes in loading behaviors was uncertain.

Arizona. Arizona currently budgets about $5.8 million per year for mobile enforcement efforts aimed at penalizing and deterring overweight vehicle operations, among other things. Semmens and Straus (2006) estimated, that if this investment in mobile enforcement were to increase, the savings from reduced pavement damage would range from $6 million to $27 million per year. At the lower figure, the expansion of mobile enforcement would be a little better than a "break-even" proposition; the savings from avoided pavement damage would slightly exceed the cost of the program. At the higher figure, the expansion of mobile enforcement would have about a four- or five-to-one benefit/cost ratio. That is, for every dollar invested in truck size and weight enforcement efforts, $4.50 in pavement damage would be avoided.

International Experience

As part of an early study conducted in Saskatchewan, Wyatt and Hassan (1985) investigated the relationship between enforcement effort and weight compliance at permanent and mobile weigh stations. Results are expressed as a percentage of loaded trucks and were obtained from violation rate records (static weighing), number of loaded trucks checked, and average percent time the scale is open.

Study results indicate that at permanent weigh stations, zero enforcement results in violation rates that exceed 15 percent for all types of loaded trucks. The violation rate is reduced to about 3 percent when the probability of apprehension exceeds 10 percent. For mobile weight enforcement operations, zero enforcement corresponds to violation rates of about 30 percent, with the violation rate reducing to 9 percent as inspections increase. In both situations, once low violation rates are achieved, additional enforcement effort results in little improvement.

A similar analysis was performed for short-haul trucks. Under routine enforcement (20 hr/wk), 31.2 percent of 3S2 trucks (26 percent of all trucks) exceeded legal GVW. Violation rates increased to 34.5 percent of 3S2 trucks (33.2 percent of all trucks) under zero enforcement,

More recently, Van Loo and Henny (2005) considered the enforcement of overloaded vehicles in Europe. *The Requirements for Enforcement of Overloaded Vehicles in Europe (REMOVE) Project*—led by a consortium of enforcement agencies, transportation agencies, technical experts from the research community, and transport industry from 15 countries—departed from previous studies by focusing on technology application instead of performance. The objective of the *REMOVE Project* was to provide a legal framework in which new and existing WIM systems and technologies could operate at strategic and tactical levels across the European community, with the intention of reducing the danger and damage caused by overloaded trucks.

The project recognized an evolution in the use of technology in truck size and weight enforcement, beginning with manual selection and limited use of data for planning and statistical purposes and evolving toward a more extensive use of data to support “intelligent” and ultimately direct enforcement efforts. Under current enforcement conditions, researchers estimated controlling less than 5 percent of trucks, noted only incidental use of WIM technology, and observed an exclusive focus on enforcement. Near full evolution, anticipated enforcement efforts are estimated to control 95 percent of the trucks, use an intelligent enforcement mix of technology and personnel, and focus on both prevention and enforcement. This evolutionary process is challenged by various legal, technical, operational, and cost-benefit issues.

Incorporating findings from the *REMOVE Project*, a broader European scanning study (Honefanger et al. 2006) considered the application of contemporary European procedures and technologies for enforcing truck size and weight laws and regulations in the United States. Key findings and observations related to truck size and weight enforcement resulting from the six-country scanning study are summarized below:

- In general, the use of technology in enforcing both truck size and weight is viewed as beneficial in enhancing effectiveness and efficiency.
- Two of the six countries visited use technology for truck size enforcement; the Swiss use an automated profile measuring device in low-speed applications suitable for direct enforcement and the Germans use a gantry laser system in high-speed applications suitable for pre-selection.
- The extent and use of technology to support truck weight enforcement varies among the countries visited. A general consistency, however, was noted in the type of WIM sensor (i.e., piezoquartz or piezoceramic) used for roadway applications. Previously observed challenges with accuracy and maintenance are being addressed in the countries visited.
- A bridge WIM system is being used successfully and extensively in Slovenia, is undergoing tests on several bridges in France, and is generating interest in several other countries visited. Primary applications include preselection for mobile enforcement activities; data support for planning, design, and structure analysis; overweight permit application processes; and monitoring of alternate routes (i.e., bypass detection).
- Weigh-in-motion technology, commonly used with video technology, is used to support truck weight enforcement through (1) real-time preselection for mobile enforcement, (2) scheduling time and location (to the extent possible) of enforcement activities, and (3) directing carrier/company advisory notices of noncompliance (i.e., warning letter) and preventive visits (this information is shared with enforcement personnel).
- In general, the accuracy levels attained by WIM systems are sufficient for preselection of vehicles to weigh on static or low-speed scales for enforcement, for infrastructure design and maintenance, and for planning and statistical purposes, but are not sufficient for direct/automated enforcement. France is nearing use of low-speed WIM for legal enforcement (i.e., issuing citations based directly on the low-speed WIM measurements).
- A greater use of mobile enforcement activities and few fixed roadside weigh facilities were consistently observed. This strategy results in a lower volume of trucks being processed and geographically and geometrically constrained inspection and offloading areas, but provides more flexibility to respond to industry loading/routing patterns and more efficient and effective enforcement action. For example, the use of WIM and vehicle identification technologies in The Netherlands has been credited with increasing officer efficiency (i.e., the number of citations issued compared to the number of vehicles stopped) from about 40 percent to more than 80 percent.
- A high level of collaboration in truck size and weight enforcement activities was observed in several of the countries visited between similar agencies of different jurisdictional levels (e.g., national and regional law enforcement agencies) and between different agencies (e.g., transportation and law enforcement agencies). For example, to ensure that truck size and weight enforcement is a continued priority among police agencies, the Dutch Ministry of Transport funds additional police officers who focus 40 percent of their time on weight enforcement and 60 percent on congestion and incident management activities

HIGHWAY SAFETY

Truck-related highway safety—often characterized in terms of observable crash rates, frequencies, or severities or implied through estimated crash risk—has shown a marked improvement over time. Much of this improvement has been attributed to several significant and national initiatives outside of any changes to truck size or weight regulation or compliance including but not limited to increased safety technology in truck designs, audits and inspections performed under the Motor Carrier Safety Assistance Program, and introduction of a nationally uniform truck driver licensing system. In fact, the safety performance of large trucks depends upon a myriad of interrelated driver, vehicle, cargo, carrier, and operating environment characteristics.

Although the subject of truck-related highway safety has been extensively studied, few studies were found that directly addressed the effect of truck size and weight on safety. Changes in truck size and weight limits can affect highway safety by:

- Increasing or decreasing the amount of truck traffic.
- Causing or requiring changes in vehicle design and vehicle performance that may affect crash rates and severity.
- Causing trucks to shift to highways with higher or lower crash rates.

Much of the historical literature considered the safety effects of vehicle configuration and observable vehicle handling and performance characteristics (e.g., rollover resistance, acceleration) that can only be indirectly related to truck size and weight conditions.

A number of studies have considered truck-related highway safety concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, enforcement, industry costs, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to truck-related highway safety, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research related to other truck-related highway safety topics associated with driver condition or qualifications, vehicle condition or maintenance, road or environmental factors, or other are not included here. Further, comparisons of safety levels between large trucks and other types of vehicles, such as passenger cars, are not included. Safety-related comparisons among large truck classes and configurations, however, are thought to be relevant to truck size and weight related decision-making and hence, are included here.

Individual study findings related to truck-related highway safety—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Changes in truck size and weight limits can affect highway safety by: (1) increasing or decreasing truck traffic; (2) causing or requiring changes in vehicle design and performance that may affect crash rates and severity; or (3) causing trucks to shift to highways with higher or lower crash rates.
- Limitations in available crash and exposure data challenge the ability to definitively relate truck size and weight conditions to highway safety levels.
- Operating environment—particularly road class—has consistently been observed to significantly influence truck-related highway safety, with Turnpikes/Interstates being generally safer irrespective of truck size or weight.
- With some consistency, heavier trucks (higher GVWs) were associated with lower crash rates (attributable to fewer required truck trips to haul a given amount of freight) but higher crash severities.
- With some consistency, larger, heavier trucks were observed to have the same or slightly higher crash risk based on vehicle handling and stability characteristics:
  - Double trailer trucks are prone to rearward amplification that can have a detrimental safety effect.
  - Higher centers of gravity increase potential for rollover or ramp-related crashes.
- Results relating truck configuration and safety are inconsistent:
  - Double trailer trucks have been estimated to have higher, lower, and the same crash rates and severities when compared to single trailer/tractor-semitrailer configurations.
  - LCVs have been estimated to have higher and lower crash rates and severities when compared to other truck configurations, although recent research suggests superior safety performance.
- Changes in driver qualifications and vehicle/roadway design can potentially offset the safety drawbacks of some larger, heavier vehicles.
- International efforts have defined safety performance measures—based on vehicle stability and control characteristics—to help assess the safety-related impacts of changes in truck size and weight limits.

Domestic Experience

Much of the prior truck-related highway safety research in the United States was motivated by the changes brought about by the 1982 STAA. Many of these early studies were critically reviewed in *Special Report 211 Truck Weight Limits* and *Twin Trailer Trucks* (Transportation Research Board 1986). Of the 14 different historical studies related to crash experience of singles and doubles, only 5 were considered to be valid. Others suffered from methodological flaws, data insufficiencies, or obscuring effects of the operating environment. Key findings from these early studies, as well as supporting or contradictory findings from external studies performed during the same time period are described below. When appropriate, methodological shortcomings that may invalidate research results are noted.

Purporting conclusive evidence, Glennon (1981) and Graf and Archuleta (1985) reported a 6 percent and 12 percent higher overall crash rate for doubles than singles, respectively. Sparks and Beilka (1987) found that the percent of doubles within the truck fleet has the greatest influence on the estimated crash rates. Using a case-control methodology, Jones and Stein (1989) found that doubles were consistently over-involved in crashes by a factor of 2 or 3, independent of driver age, hours of driving, cargo weight, or type of fleet. Similarly, Mingo et al. (1991) found that multi-trailers, single trailers, and single-unit trucks have fatal crash involvement rates of 9.96, 6.01, and 3.00 per 100 million mi traveled, respectively. The ratio of fatal crash involvement rates for multi-trailers to single trailers and single-unit trucks is 1.66 and 3.32, respectively. Earlier efforts estimated the ratio of the total crash involvement rate of doubles to that of singles between 0.8 and 2.3, with most in the range of 0.9 to 1.1 (Transportation Research Board 1986).

Contrary to these findings, Chirachavala and O'Day (1981) reported a 2 percent lower overall crash rate for doubles than singles. Seiff (1989) also found double trailer combinations to be underrepresented in crashes, while bobtail tractors are overrepresented.

More recently, Braver et al. (1997) observed no overall increase in crash risk between doubles and singles but noted that a lack of control of potential confounding factors, such as driver age and work operation attributes, limits these conclusions.

Turning attention to crash severity, historical studies that considered the distribution of crash types by severity level suggest that a larger proportion of double-involved crashes result in death, and conversely, a larger proportion of single-involved crashes result in non-fatal injury (Transportation Research Board 1986). These findings were deemed inconclusive, citing the aforementioned shortcomings related to methodological flaws, data insufficiencies, or obscuring effects of the operating environment. In studies in which crash severity was expressed by deaths or by fatal crash involvements, crashes involving doubles have usually been found to be more severe than those of singles. Comparable early studies found that doubles have fatality crash rates ranging from 7 percent lower to 5 to 20 percent higher than single-unit trucks (Transportation Research Board 1986).

Contrary to these general observations, a higher fatal or injury crash involvement rate for doubles was not observed by Carsten (1987), however, researchers note that doubles are used in safer operating environments and double drivers may be compensating for different vehicle handling characteristics. Similarly, Blower et al. (1993) found differences between single- and multiple-trailer vehicle involvement in injury and property damage crashes to be non-significant after adjusting for road type, time of day, and urban/rural locations, though there was some evidence of doubles having increased injury crash risk on lower class roads.

With respect to the direct effects of truck weight on highway safety (no early studies were identified that considered the effects of truck size independent of vehicle configuration), Vallette et al. (1981) concluded that truck crash rates varied inversely with GVW for both double and single trailer combinations, but based these findings on unreliable exposure estimates. Similarly, Polus and Mahalel (1983) observed a decreasing trend in crash rate and truck driver injury with increasing GVW.

Conversely, Campbell et al. (1988) noted a moderate increase in single-unit and combination truck crash rates for higher GVW, although the relatively small number of data points and the high degree of scatter make conclusions questionable.

A similar review of prior safety studies was conducted as part of TRB's *Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989) to consider implications of wider and longer commercial motor vehicles along non-Interstate and access routes. This study reiterated issues with widespread conflicting findings but noted some general consistency in the relationships between GVW and highway safety levels; a higher GVW results in lower crash rates but a higher crash severity.

With a focus again on Interstate and State highway systems, TRB initiated a comprehensive study—*Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990)—that considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

With regard to truck-related highway safety, key findings of this study are as follows:

- Without changing truck dimensions, number of axles, or vehicle/component designs, increased truck weights would increase crash risk, particularly for rollover and ramp-related crashes for all trucks and in rearward amplification related crashes for multiple-trailer combinations.
- Unlike tractor semitrailers, 5-axle doubles may experience rearward amplification which could negatively impact safety in obstacle avoidance or sudden lane changing maneuvers at highway speeds.
- The rates of fatal involvements in crashes on curves or crashes in which trucks rear-end other vehicles may also be adversely affected.
- Existing 5-axle doubles have fatal involvement rates 10 percent higher than tractor semitrailers when both are operated under similar conditions.

This study noted that although larger, heavier vehicles have slightly higher crash risk (and in some instances, crash rates), the increased payload for trucks may result in fewer trips, lower crash exposure, and an overall improvement in safety levels. On the other hand, the associated reduction in trucking costs that result from these reforms may stimulate additional demand for trucking, which would lead to more crashes overall.

With a narrowed focus on a series of specific truck configurations—each with lower axle weights but higher GVWs—TRB initiated a comprehensive study to consider potential impacts should industry be allowed to put these proposed vehicle configurations into operation. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).
- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle.

With respect to truck-related highway safety, potential impacts attributable to these proposed configurations were estimated using a synthesis of evidence from three sources: vehicle handling a stability properties, traffic operations effects, and estimates of crash rates. The authors prefaced their findings by noting several shortcomings in methodology:

- There is uncertainty regarding the accuracy of the estimated crash rates because of the limitation in the crash and travel data used.
- The investigation of vehicle-handling and stability properties of prototype Turner trucks was based on vehicle simulation, a fully controlled experiment that assumed ideal conditions of vehicle components.
- The inferences about the traffic operations of Turner trucks were obtained through extrapolation of evidence associated with existing combination vehicles, because the prototype trucks are not in common use in the United States at this time.

Nevertheless, findings from these three sources considered as a whole reinforce the conclusions that 9-axle Turner doubles would have crash involvement rates no worse than those of existing 5-axle twins but slightly higher than those of existing tractor semitrailers and that 7-axle Turner tractor semitrailers would have crash involvement rates no worse than those of existing tractor semitrailers, when these trucks are operated under identical conditions. If Turner trucks were adopted, annual miles of travel by combination vehicles would be reduced by 3.4 percent after accounting for rail diversions. On the basis of this truck travel projection, the system-wide annual number of truck crashes could be reduced by 2.6 percent.

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

The authors reiterated several challenges in estimating crash rates for these scenario vehicles:

- Weights and dimensions of trucks involved in crashes often are not known or recorded on crash reports.
- Even if the number of crashes for certain types of trucks are known, the exposure (vehicle-miles traveled) for those trucks is often not known.
- Crash rates for larger trucks currently in use in certain regions of the country or on turnpike facilities may not be transferrable to other parts of the country where traffic volumes are higher and the operating environment is less safe.

Given limitations in existing crash data, this study relied instead on the evidence from tests of vehicle handling and stability to indirectly estimate truck-related crash potential. Handling and stability characteristics considered included low-speed and high-speed off-tracking, acceleration and speed maintenance, braking performance, and sight distance. Results suggest that multi-trailer combinations—without compensating design features—have inferior performance capabilities compared to single-trailer combinations. These differences, especially if frequently challenged in traffic conflict situations, result in incrementally higher crash likelihoods.

As part of a synthesis effort, Luskin and Walton (2001) echoed the findings the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000). The authors reported additional findings related to static rollover, noting that an STAA double tends to be more stable on curves than a conventional 5-axle tractor semitrailer because of its additional length—spreading the payload over a greater length reduces the height of the vehicle's center of gravity, which reduces the risk of static rollover. The authors also noted that although multi-trailer truck combinations may suffer from rearward amplification, their dynamic stability may be improved through substitution of B-train and C-dolly connections for the more-widely used A-dollies, effectively reducing an articulation point.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—noted that prior studies have failed to relate these observable truck handling and stability properties (e.g., speed maintenance, rollover threshold) with crash risk. Instead, previous studies tend to correlate increases with truck size and weight to reductions in vehicle miles of travel (VMT), lowering the inherent risk due to exposure and hence reduce the overall potential for truck crashes.

Most recently, AASHTO sponsored a synthesis study to determine the current state-of-knowledge regarding the safety of oversize/overweight trucks (American Association of State Highway and Transportation Officials 2009). Consistent with prior reviews, the authors noted few substantiated findings relating truck size and weight conditions to highway safety and instead, identified a number of data-related shortcomings that challenge determination of such a relationship. Existing data often lacks sufficient information regarding crash exposure (VMT) and confounding factors (e.g., road system, driver characteristics, etc.) to effectively estimate and isolate the effects of truck size and weight influences on safety. With some consistency, prior studies do suggest that as trucks become larger and heavier, crash rates decrease but crash severity increases.

Similar concerns over the adequacy of crash data were expressed Scopatz (2001) who examined the quality of crash data collected in five States (Florida, Idaho, Nevada, Oregon, and Utah) with an exclusive focus on LCVs. Two of the states (Oregon and Utah) also participated in an audit of completed crash reports for crashes involving specifically doubles and triples.

Scopatz (2001) concluded that, at the time of the study, none of the five States had a crash reporting system that adequately supported analysis of LCV safety. In general, there is a lack of reliable data on the exact configuration of vehicles involved in crashes, and a lack of specific measures of exposure for LCVs. The audits performed in Oregon and Utah showed that many officers do not know how to recognize and/or code the various configurations of vehicles. Oregon is unable to require officers to complete the crash reports and so relies to a significant extent on self-reports from drivers and motor carriers. A large proportion of the audited reports in both States had information in the vehicle configuration boxes that appeared to be incorrect—the remainder of the information in the report clearly pointed to a different vehicle configuration. With respect to exposure, a common source of data on VMT by truck class is the Highway Performance Monitoring System. These data tend to overstate combination truck travel, especially that of double-trailer combinations. In addition, they provide no breakdown of double-trailer combination traffic between LCVs and other trucks. Without good data on configuration and exposure, the main question about LCV safety relative to other large truck configurations cannot be answered empirically.

With a continued focus on LCVs, the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to truck-related highway safety, study results echo previously expressed concerns related to data adequacy. Data on the number of fatal crashes involving LCVs are available from the National Highway Traffic Safety Administration's Fatality Analysis Reporting System and the University of Michigan Transportation Research Institute's Trucks Involved in Fatal Accidents databases. However, even in States where LCVs currently operate, estimating LCV crash rates is difficult because most States do not collect data on LCV travel.

Without data on crash rates, it is difficult to quantify safety impacts of allowing more widespread LCV operations in Western States. One set of safety-related factors that can be quantified are stability and control properties of different vehicle configurations. Three specific performance measures were evaluated as part of this investigation: static rollover stability, rearward amplification, and load transfer ratio. Stability and control performance of most LCVs currently used in the Western States is as good or better than the performance of STAA doubles (twin 28-ft trailers) that are widely operated in all States. Performance for some configurations is comparable to that of a standard tractor-semitrailer. There are exceptions, however. Conventional triple trailer combinations, in particular, have poorer rearward amplification and load transfer ratios than other vehicles, which makes them more prone to trailer sway and rollover if they have to make a sudden turning movement. Offsetting the relatively good stability and control properties of LCVs are the greater time required to pass an LCV, the greater off-tracking of longer double trailer combinations, the heavier weight of the vehicles which places greater demands on braking systems, and operational problems that longer vehicles create in urban areas where many weaving and merging maneuvers are required.

In an earlier study and in the absence of adequate datasets for crash data, Ticatch et al. (1996) used survey-based crash and travel data to estimated crash rates for LCV and non-LCV configurations. Expressed as crash rates per million VMT the following rates were determined: 1.79 for non-LCV combinations (tractor-semi-trailers and short doubles under 80,000 lb), 1.02 for Turnpike doubles, 0.83 for triples, and 0.79 for Rocky Mountain doubles. The difference between the non-LCV and LCV crash rates was statistically significant; the differences among the different LCV configurations were not. Fatal crash rates for LCVs and non-LCVs were found to be equal. This study was however deemed inconclusive because the survey-based data could not be verified and because confounding factors were not adequately controlled for.

Most recently, Lemp, Kockelman, and Unnikrishnan (2011) used standard and heteroskedastic ordered probit models, along with the United States' Large Truck Crash Causation Study, General Estimates System, and Vehicle Inventory and Use Survey datasets, to study the impact of vehicle, occupant, driver, and environmental characteristics on injury outcomes for those involved in crashes with heavy trucks, with a particular focus on LCVs. Results suggest that the likelihood of fatalities and severe injury is estimated to rise with the number of trailers, but fall with the truck length and gross vehicle weight rating (GVWR). While findings suggest that fatality likelihood for two trailer LCVs is higher than that of single-trailer non-LCVs and other trucks, controlling for exposure risk suggest that total crash costs of LCVs are lower (per vehicle-mile traveled) than those of other trucks.

State/Case Studies

Maryland. In a unique study focused on the safety impacts of vehicle height, Fu, Burhouse, and Chang (2004) assessed the magnitude of overheight vehicle collisions with highway bridges that caused structural damage, injuries, and sometimes even fatalities in Maryland and at the national level. The seriousness of the collisions was exemplified by a case in 1999 in which a truck hauling an overheight excavator struck and collapsed a pedestrian bridge over the Baltimore Beltway, killing one motorist and injuring three others. Statistics on overheight collisions in Maryland were collected from overheight vehicle detector records, the statewide crash database, and bridge inspection reports.

Data analysis revealed that the frequency of overheight accidents reported in Maryland increased by 81 percent between 1995 and 2000. Of the 1,496 bridges susceptible to impact by overheight vehicles statewide, 309 (20 percent) have been struck, with 58 (4 percent) requiring repairs. No nationwide databases on overheight collisions exist, so a survey was sent to each state to collect national statistics. Of the 29 states responding, 18 (62 percent) indicated that they consider overheight collisions to be a significant problem, but few were able to provide hard data.

Michigan. In response to the 1982 STAA that allowed the use of double-trailer combinations nationwide on Interstate highways, Lyles et al. (1991) undertook a study to determine the potential impacts to highway safety. Specifically, study objectives were to calculate disaggregate truck crash rates by road class, day or night, and urban or rural operating conditions for tractors without trailers (bobtails) and in single- and double-trailer configurations.

Lyles et al. (1991) found no consistent difference between safety for singles and doubles. The findings indicated that differences in truck safety by roadway class are more important than those between singles and doubles. Crash and casualty rates for single and double configurations were similar to one another; bobtails consistently had the highest crash rates.

Maine and New Hampshire. The Transportation Equity Act for the 21st Century (TEA-21) provided exemptions from the federal GVW limits on the Maine and New Hampshire Turnpikes. Exempt portions of I-95 and State highways allow a GVW of up to 100,000 lb on 6-axle tractor semitrailer combinations. Certain commodity groups are also allowed a 10 percent GVW tolerance on 5-axle configurations. Individual axle weight limits range from 22,400 to 24,200 lb for a single axle, 36,000 to 44,000 lb for a tandem axle, and 48,000 to 54,000 lb for a tridem axle. Non-exempt Interstates in Maine and New Hampshire remain subject to the federal GVW limit of 80,000 lb. As a result, heavy trucks that would otherwise be through-traffic on I-95 divert to State highways upon reaching non-exempt portions of I-95. Wilbur Smith and Associates (2004) conducted an analysis that compared the current condition of allowing trucks in excess of 80,000 lb GVW on the ME/NH Turnpike to a no-exemption scenario in which State road networks would assume any displaced heavy truck traffic should the weight exemption be rescinded.

With respect to truck-related highway safety, the analysis: (1) provided a detailed examination for three years of geo-coded crash records looking specifically at 5- and 6-axle tractor semitrailers in Maine; (2) examined national trends for fatal crashes involving large trucks; (3) conducted a comparative analysis of truck crash statistics for Maine and New Hampshire as compared to other States and national averages; and (4) constructed fatal and non-fatal truck crash profiles for three years of crash data for Maine and New Hampshire. The most prominent findings from this investigation are as follows:

- Nationally, the safety of large trucks (and combination trucks in particular) has shown dramatic improvements in safety as measured by fatal crash rates.
- The crash rates of 5- and 6-axle tractor semitrailers registered to carry commodities at the subject weights are 7 to 10 times higher on non-Interstate facilities in Maine, than on the Maine Turnpike. These findings are consistent with national studies that have found a strong relationship between road class and crash risk.
- Comparative analysis found no correlation between States that allow GVW in excess of 80,000 lb in normal operations on State networks and high crash rates. In fact, regression analysis suggests a positive correlation between low crash rates and high load factors.
- The crash rate for 5- and 6-axle tractor semitrailers in Maine was slightly below the national average.

- If the current weight exemption on the Maine and New Hampshire Turnpike were discontinued, these States combined would experience six additional crashes each year having an economic impact of more than $540,000.

Minnesota. At the request of the Minnesota Department of Transportation (MnDOT), Cambridge Systematics, Inc. (2006) conducted a study to assess proposed changes to Minnesota's truck size and weight laws that would benefit the State's economy while protecting roadway infrastructure and safety. Various vehicle configurations—including a 6-axle tractor semitrailer with a 90,000 lb GVW limit, a 7-axle tractor semitrailer with a 97,000 lb GVW limit, an 8-axle twin trailer truck with a 108,000 lb GVW limit, and a single unit truck with an 80,000 lb GVW limit—were considered, as well as various changes to spring load restrictions.

With respect to truck-related highway safety, safety-related costs savings ranged from $0.05 million per year for the 108,000-lb 8-axle twin truck to $0.23 million per year for the 97,000-lb 7-axle tractor semitrailer. Estimated cost savings for the 6-axle and single unit configurations were $0.15 and $0.06 million per year, respectively. The estimated impacts of relaxed spring load restrictions and increased GVW limits (from 73,280 to 80,000 lb for 5-axle tractor semitrailers) on the 9-ton roadway system produced more significant safety-related cost savings—estimated to decrease by $0.44 million and $1.65 million per year, respectively.

Wisconsin. Most recently, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on highway safety. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

With respect to highway safety, estimated safety cost savings are summarized in Table 11. Configurations that offer the greatest safety cost savings, when compared to the base case 5-axle tractor semitrailer include the 6-axle 98,000-lb tractor semitrailer, the 7-axle 97,000-lb tractor semi-trailer, and the 6-axle 90,000-lb tractor semitrailer. The 6-axle 98,000-lb straight truck trailer and the 7-axle 80,000-lb single unit truck offer the lowest safety cost savings.

Table 11. Estimated Safety Costs for Various Truck Configurations (Adams, et al. 2009)

CONFIGURATION	ANNUAL SAFETY COSTS (million $)	
	Non-Interstate	Interstate/Non-Interstate
8-axle 108,000 lb double	↓ $0.46	↓ $2.90
7-axle 97,000 lb tractor semitrailer	↓ $0.70	↓ $4.43
7-axle 80,000 lb single unit truck	↓ $0.11	↓ $0.53
6-axle 90,000 lb tractor semitrailer	↓ $0.46	↓ $3.48
6-axle 98,000 lb tractor semitrailer	↓ $1.52	↓ $9.40
6-axle 98,000 lb straight truck-trailer	↓ $0.09	↓ $0.68

International Experience

The U.S. and countries of the European Union share many of the same concerns and face similar challenges regarding large truck safety. Hartman et al. (2000) documented the results of a 1998 technology transfer tour to four European countries to learn how these countries are addressing their own safety issues.

In 1997, the European Commission (EC) promulgated a "modular concept" rule for vehicle length in the EU. Operators are allowed to couple their standard vehicles (26-ft straight truck, 45-ft semitrailer, and fifth-wheel dolly) in a number of ways to extend the maximum length. This directive allows larger vehicles previously not permitted under earlier EC directives to operate in Sweden and Finland, which restricted maximum lengths to 54 ft (semitrailer combination) and 62 ft (2-unit road train). Analysis conducted prior to advancing the modular concept hypothesized the elimination of every third truck trip and deployment of smart logistic solutions. Results showed a positive effect on traffic safety.

More recently, Montufar et al. (2007) analyzed the safety performance of LCVs operating in Alberta, Canada, relative to the safety performance of other vehicle types operating on the same roadway network. Three types of LCVs—Rocky Mountain doubles (RMDs), Turnpike doubles (TPDs), and triple trailer combinations (triples)—operate in Alberta and other provinces and States under special permit.

Key findings from this study are as follows:

- LCV-involved crashes accounted for 0.02 percent of all collisions in the study area (106 of 490,956)—60 percent of these (65 of 106) occurred on the LCV network and 40 percent (41 of 106) occurred in urban areas.
- Driver action, environmental condition, and adverse road surface conditions (wet, slush, snow, or ice) were primary contributing factors listed for LCVs involved in collisions on the LCV network and in urban areas.
- The severity of LCV collisions on the LCV network was lower than that of other vehicle types. LCVs accounted for one percent of all trucks (articulated and non-articulated) in fatal, in injury, and in property damage only (PDO) collisions. Tractor semitrailers and legal-length tractor double trailers accounted for nearly two-thirds of trucks in fatal collisions, 57 percent of trucks in injury collisions, and 43 percent of trucks in PDO collisions. Accounting for traffic exposure, LCVs have a lower fatality, injury, and PDO rate per 100 million vehicle kilometers travelled (VKT) than other vehicle types.
- From a collision rate perspective, LCVs as a group had the best safety performance of all vehicle types with 25 collisions per 100 million VKT on the LCV network. The collision rates for other vehicle types in descending order of performance were: tractor semitrailers (42 collisions per 100 million VKT), legal-length tractor doubles (44 collisions per 100 million VKT), passenger vehicles (83 collisions per 100 million VKT), and straight trucks and bobtails (123 collisions per 100 million VKT).

- Turnpike doubles had the lowest collision rate of all individual vehicle types (16 collisions per 100 million VKT), followed by Rocky Mountain doubles (32 collisions per 100 million VKT) and triple trailer combinations (62 collisions per 100 million VKT).
- LCVs were under-represented in terms of collision frequency with respect to traffic exposure, accounting for 0.1 percent of all collisions on the LCV network, and for 0.4 percent of all traffic exposure. Other vehicle types that were also under-represented were tractor-semitrailers and legal-length tractor doubles. Straight trucks and bobtails were over-represented in terms of collision frequency with respect to traffic exposure.
- A sensitivity analysis revealed that a 10 percent decrease in LCV VKT, combined with a 10 percent increase in non-LCV articulated truck VKT, still results in a lower collision rate for all LCVs than for all non-LCV articulated trucks.

With a broader focus on achieving uniformity in truck size and weight through regulatory reform, earlier efforts in Canada resulted in the development of various safety performance measures—based on vehicle stability and control characteristics—to help assess the safety-related impacts of changes in truck size and weight limits (Walker and Pearson 1987). Seven distinct stability and control measures were defined—static rollover threshold, dynamic load transfer ratio, friction demand in tight turns, braking efficiency, low-speed offtracking, high-speed offtracking, and transient high-speed offtracking—each with respective targets for performance. Vehicles that meet or exceed performance targets are recommended for interprovincial transport. The authors acknowledge that the desired performance targets cannot be achieved soley through the application of size and weight limits. However, the influence of truck size and weight on vehicle stability was carefully considered in this development effort.

Building upon the earlier work performed in Canada, the National Road Transport Commission (NRTC) and Austroads initiated a major joint project to develop Performance Based Standards (PBS) for heavy vehicle regulation in Australia and New Zealand. Under existing regulations, vehicles that meet certain requirements are allowed generally unrestricted access to the entire road network. Under PBS, the vehicle's capabilities and relevant road standards and traffic conditions can be examined jointly to decide whether the vehicle can be granted access. A set of 25 proposed performance standards was developed against which the Australian heavy vehicle fleet was tested. Sixteen of these performance standards targeted safety issues, while the remainder provided scope for productivity improvement. Edgar, Calvert, and Prem (2001) provide a general discussion of the policy principles, performance standards, and computer simulation models used; readers are referred to a number of other reports published by the NRTC (www.nrtc.gov.au) for more in-depth technical background.

These fundamental performance based efforts are referenced in contemporary research. Documented in *NCHRP Report 671: Review of Canadian Experience with Regulation of Large Commercial Motor Vehicles*, Woodrooffe et al. (2010) considered the process used in Canada to harmonize heavy truck size and weight regulations across the country and provided insights on how lessons learned from the Canadian experience might be applied in a U.S. context. Consistent with earlier efforts in both Canada and Australia, Woodrooffe et al. (2010b) concluded—in a study sponsored by the OECD and the International Transport Forum—that regulatory systems could reliably promote safer and more efficient vehicles by using performance measures to guide policy decisions.

HIGHWAY GEOMETRICS

Historical research related to the effects of truck size and weight on highway geometrics has primarily focused on horizontal curvature and ramp/interchange design in the context of safety and maneuverability. A number of studies have considered truck-related highway geometrics concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, highway safety, industry costs, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to truck-related highway geometrics, including cross-cutting topic areas.

This review is generally limited to Interstate/highway geometric design considerations under increased truck size and weight limits—research related to non-highway geometric design considerations (intersections, railroad grade crossings, lane widths, etc.) is limited in discussion.

Individual study findings related to highway geometrics—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Geometric design features most affected by increased truck size and weight include horizontal curves, intersection turning radii, passing sight distance, sight distance at intersections and railroad grade crossings, and ramp interchanges.
- Increases in trailer lengths are most problematic in terms of current highway geometric designs—the longer the trailer, the greater the vehicle's off-tracking.
- Estimated costs to upgrade existing geometric features to accommodate larger, heaver trucks are significant but highly variable depending on truck configuration and the extent of roadway network to be redesigned.
- Wider trucks operating on rural two-lane highways have been observed to elicit undesirable/unsafe actions by oncoming drivers.

Domestic Experience

In response to changes brought about by the 1982 STAA and with a unique focus on non-Interstate, arterial highway routes, the Transportation Research Board (TRB) initiated a comprehensive study—*Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989)—to consider access implications of wider and longer commercial motor vehicles. More specifically, the study's intent was to better characterize "reasonable" access and diffuse differences among industry representatives seeking uniform standards for access and State and local officials seeking to maintain local decision-making control.

With respect to highway geometrics, results of this study indicate the increased width of STAA vehicles does not have a substantially effect on geometric design—the modest increase of 6 in. is already accounted for in AASHTO's geometric design policies and was shown to have only a minor effect on such features as passing sight distance requirements and lateral separation/placement of vehicles on two-lane roads.

The increased STAA vehicle length, however, poses several challenges related the following:

- Horizontal curves on narrow two-lane roads—the off-tracking problems of longer-wheelbase tractor semitrailers make it difficult to negotiate turns without encroaching into oncoming traffic lane or running off the road.
- Turning radii at intersections with restrictive geometry—the longer-wheelbase STAA tractor semitrailers may off-track, encroach onto adjacent lanes, or ride up on the curb when negotiating turns, even at intersections built to current AASHTO design standards.
- Passing sight distance on two-lane roads—vehicles passing an STAA or any other long combination vehicle will spend significantly longer in the passing lane, than is provided by current practices for signing and marking no-passing zones.
- Sight distance at intersections and railroad grade crossings—current AASHTO guidelines may not accommodate sight distance requirements for most large combination vehicles.
- Existing ramp and interchange designs—the stability and control characteristics of STAA vehicles are likely to adversely affect their performance on many interchanges and ramps.

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to highway geometrics, the study identified interchanges and intersections that cannot accommodate the turning radii of some scenario vehicles as the primary deficiencies in the highway network. The extent of geometric deficiencies for different scenario vehicles was estimated based on a survey of interchange and intersection design in nine States representing different regions of the country. For purposes of estimating improvement needs it was assumed that no encroachment on shoulders or adjacent lanes would be allowed except for at-grade interchanges where vehicles would be allowed to encroach on one lane in the same direction of travel. No costs are assumed for improvements needed to accommodate existing vehicle configurations. Related to these geometric costs is the requirement that certain LCVs assemble and disassemble at staging areas rather than being allowed to travel off the designated networks.

Under these assumptions, the LCV Nationwide scenario would require a significant investment in upgraded highway geometrics, with estimated costs 965 percent higher than the base case. The North American Trade scenario was also estimated to increase highway geometric costs over the base case, but by just 13.3 percent. The Triples Nationwide scenario was estimated to have negligible effects on highway geometrics.

With a singular focus on longer combination vehicles (LCVs), the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to highway geometrics, base costs to improve horizontal curves, intersections, and interchanges that are presently deficient in accommodating in-service truck configurations are estimated to be $864 million, $713 million of which is on the Interstate System. Under assumptions of the Western Uniformity Scenario, geometric improvement costs would nearly double to $1,640 million. These geometric improvements would not all have to be made before longer vehicles could operate, but in certain locations, safety could be compromised if geometric improvements were delayed.

Using interchange ramp and at-grade intersection data from a sample of States including California and two States in each of four U.S. regions (west, midwest, northeast, and southeast), Harwood et al. (1999) evaluated the adequacy of the current roadway system for its ability to accommodate large trucks. The geometric design elements examined were horizontal curves and grades on mainline roadways, horizontal curves on interchange ramps, and curb return radii for at-grade ramp terminals and intersections.

Study results indicated a relatively low incidence of steep mainline grades and of mainline and ramp curves with sharp radii. Much more common, however, are curb return radii of 39 ft or less that would cause trucks to encroach on other lanes. Urban areas have a greater number of curb returns with sharp radii than rural areas and are more often found at intersections than at ramp terminals.

As part of the same study sponsored by FHWA, Harwood, Glauz, and Elefteriadou (1999) estimated the associated costs of widening existing roads to accommodate larger trucks. Low-speed off-tracking was the criterion for judging where widening would be needed. The authors demonstrated that the substantial costs that could be required to accommodate potential future trucks on the existing roadway system. These costs are sensitive to the size of the truck and the extent of the roadway system considered.

The costs for upgrading the extended network—comprising 56,000 mi of both freeway and non-freeway facilities throughout all regions of the United States—can be summarized as follows:

- Accommodation of the baseline 48-ft tractor-semitrailer on the network would require an expenditure of approximately $653 million.
- The B-train double with two 33-ft trailers and the Triple with three 30-ft trailers would require only limited expenditures beyond that required for the baseline truck for the extended network.
- The 3-S3 tractor-semitrailer with a 53-ft trailer can be accommodated for an additional expenditure of $87 million beyond that for the baseline vehicle.
- Six study trucks—the 3-S2 tractor-semitrailer with a 53-ft trailer, the 3-S2 tractor-semitrailer with a 57.5-ft trailer, the 3-S3 tractor-semitrailer with a 57.5-ft trailer, the Rocky Mountain Double with a 48-ft and a 28-ft trailer, the Rocky Mountain Double with a 53-ft and a 28-ft trailer, and the Turnpike Double with two 42-ft trailers—can all be accommodated on the extended network for an additional expenditure of between $610 and $820 million.
- Accommodating the Turnpike Double with two 48-ft trailers on the extended network would require an expenditure of $1.8 billion, and accommodating a Turnpike Double with two 53-ft trailers would require an expenditure of $3.2 billion, beyond the expenditure to accommodate the baseline truck.

Additional costs would be incurred in the development of staging areas. Nationwide, the extended network would potentially require 2,480 rural staging areas at a total cost of $744 million. It is assumed that the cost of providing staging areas at individual interchanges in urban areas would be prohibitive and would, in all likelihood, be physically infeasible without disrupting existing development. However, staging areas could be provided at the urban fringe on each roadway of a particular truck network where it enters or leaves a major urban area. The cost of providing staging areas at the urban fringe of selected metropolitan areas is estimated to be $1.2 billion for the extended network.

A recent and comprehensive review of truck characteristics as factors in roadway design, documented in *NCHRP Report 505* (Harwood et al. 2003), provides guidance for roadway geometric designers on how best to accommodate large trucks on the U.S. highway system. This effort focused primarily on the characteristics of the current truck population. In anticipation of potential increases in allowable truck size and weight, however, authors identified four proposed design vehicles for inclusion in AASHTO's *Policy on Geometric Design of Highways and Streets* (American Association of State Highway and Transportation Officials 2001). These four design vehicle—each larger than similar trucks currently on the road—include a combination truck with a single 53-ft semitrailer, a combination truck with two 33-ft trailers, a Turnpike double combination truck, with two 53-ft trailers, and a B-Train double combination with one 28-ft trailer and one 31.5-ft trailer. Each of the various design criteria contained in AASHTO's *Policy on Geometric Design of Highways and Streets* (American Association of State Highway and Transportation Officials 2001) would subsequently be reviewed for adequacy under specific vehicle dimension, handling, and stability characteristics.

State/Case Studies

California and New Jersey. With a unique focus on rural roads, Zegeer, Hummer, and Hanscom (1990) examined the ability of various truck configurations to negotiate rural roads with restrictive geometry. Truck sizes included tractor semitrailers with trailer lengths of 40, 45, and 48 ft and twin-trailer combinations with 28-ft trailers. Test sites consisted of approximately 60 mi of rural, two-lane roads in California and New Jersey with a variety of lane widths, shoulder widths, and horizontal and vertical alignment. Photographic and radar equipment were used in a field data collection caravan to measure the effects of the trucks on oncoming vehicles in terms of speed changes and lateral placement changes. Statistical testing was used to compare operational differences between various truck types for specific geometric conditions.

Results showed that 48-ft tractor semitrailers and twin-trailer combinations caused some changes in operation of oncoming vehicles, particularly on narrow roadways. However, careful driving by drivers of larger trucks may have partially compensated for operational differences in oncoming vehicles between truck types. Overall, truck driving behavior and site differences had more of an effect on vehicle operations than the effects of the different truck types. Potential safety problems as evidenced by extreme maneuvers were observed for a few oncoming motorists in reaction to the longer tractor semitrailers and twin trailer configurations. The authors make a good case for restricting these vehicles to wide, well-maintained roads (i.e., the National Network).

Arkansas, North Carolina, and Virginia. With a continued focus on rural roads, Harkey et al. (1992) conducted a study to determine the differences in performance based on truck width (102-in. and 96-in.) and the impact that these trucks have on other traffic. Trucks that were studied primarily included random trucks in the traffic stream, although some control truck data were also collected to account for driver differences. Truck data were collected on rural two-lane and multi-lane roads that included curve and tangent sections and a variety of roadway widths and traffic conditions. The data collection effort resulted in approximately 100 hr of videotape and 9,000 slides from which various measures of effectiveness (MOEs) were extracted. Such measures included lateral placement of the truck and the opposing or passing vehicle, lane encroachments by the truck or opposing vehicle, and edgeline encroachments by the truck or opposing vehicle. Analysis of variance and regression analysis techniques were used to determine the significance of and the relationship among the variables used.

The results revealed that the wider trucks had significantly higher rates of edgeline encroachments and tended to drive closer to the centerline than the narrower trucks. The authors recommended the use of 12-ft lanes and a minimum of 3-ft paved shoulders on rural roadways having severe horizontal or vertical alignment based on the sample of trucks observed but noted that a 3-ft paved shoulder may be insufficient to accommodate alternative truck configurations such as triples, Rocky Mountain doubles, or Turnpike doubles that were not observed as part of this study.

INDUSTRY COSTS

Increases in allowable truck size and weight could reduce the costs of shipping freight, thereby increasing productivity. The benefits of improved productivity extend well beyond the carrier—affecting truck drivers, shippers, producers, and broader consumers of goods. The extent of the benefit realized by each of these groups would depend upon the nature of changes in truck size and weight regulations and responses by States, different segments of the trucking industry, and shippers to such changes.

Not every shipment would benefit from increases in either the allowable size (cubic capacity) or weight of a truck. Time sensitive shipments that are becoming increasingly important with just-in-time and other advanced logistics systems might not benefit from larger trucks. Likewise, short-distance moves that have either an origin or destination away from roads on which larger vehicles are allowed to operate might not benefit. Shippers may also incur higher inventory costs to store larger quantities of goods that can be shipped in the larger trucks, and the shipper's customers might also incur higher inventory costs to store goods at the destination.

Historical research has typically quantified industry costs in terms of aggregate annual shipping costs or per mile/per ton-mile vehicle operating unit costs. A number of studies have considered industry costs concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, modal share, enforcement, highway safety, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to industry costs, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research related to trucking industry costs independent of truck size, weight, or configuration; as a function of broader infrastructure investment; as a function of improved transport logistics; and other are not included here.

Individual study findings related to industry costs—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Increased truck size and weight limits consistently result in industry cost savings.
- The magnitude of industry cost savings varies by carrier type, the nature of transportation services offered, and typical commodities transported.
  - Truckload carriers and low density cargoes (cargos that will fill available cargo space before reaching the legal weight limit) benefit most from larger truck sizes.
- Industry cost savings are expressed in terms of per mile or per ton-mile vehicle operating unit costs or more commonly, as aggregate annual shipping or transport costs.
- Estimated industry cost savings—attributable to increased truck size and weight limits and subsequent use of alternative configurations—generally range from 1.4 to 11.4 percent of annual transport costs in the United States.

Domestic Experience

Select historical studies have expressed the impacts of increased truck size and weight limits in terms of per mile or per ton-mile vehicle operating unit costs.

In an early study, Jack Faucett Associates, Inc. (1991) considered the costs of operating various truck configurations—including LCVs—under a range of GVW limits. In this analysis, researchers considered six distinct cost categories: labor, fixed vehicle costs, fuel, tires, repair and servicing, and indirect and overhead. Individual cost component estimates were combined to provide overall estimates of total cost per vehicle- and ton-mile. Specific truck configurations considered in this investigation are listed in Table 12, along with their estimated change in costs relative to the base truck configuration—a 5-axle truck semitrailer, 48 ft in length.

Although the estimated change in industry costs relative to the base 5-axle, 48-ft tractor semitrailer configuration are highly variable across proposed configurations and GVW limits, industry costs are consistently higher for each of the proposed configurations at the 80,000-lb GVW limit. If higher GVWs were allowed, industry could realize significant savings utilizing alternative truck configurations designed to support the increased loads. Many more historical studies have expressed the impacts of increased truck size and weight limits in terms of aggregate annual shipping costs.

In response to changes brought about by the 1982 STAA and with a unique focus on non-Interstate, arterial highway routes, TRB initiated a second comprehensive study—*Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989)—to consider access implications of wider and longer commercial motor vehicles. More specifically, the study's intent was to better characterize "reasonable" access and diffuse differences among industry representatives seeking uniform standards for access and State and local officials seeking to maintain local decision-making control.

With respect to industry costs, information gathered through in-depth telephone interviews of selected carriers and shippers suggests potential efficiency gains as a result of STAA vehicles. For example, participating shippers estimated that the shift from 45-ft trailers to the moderately more spacious 48-ft trailers reduced line-haul trucking costs by 5 to 13 percent (8 percent on average). These transport cost savings are tempered by select State and local access regulations including but not limited to an inability to access some terminals, circuitous routing and hours of service limitations, time and administrative costs associate with access applications, and uncertainty about access regulations and enforcement. For shippers and carriers most likely to use STAA vehicles, the cost of access regulation is estimated to be approximately $125 million per year or one fourth of one percent of their operating revenues per year.

With a focus on Interstate and State highway systems, *Special Report 211 Truck Weight Limits* and *Twin Trailer Trucks* (Transportation Research Board 1986) considered the impacts to industry costs attributable to improved line haul and handling efficiencies. The use of twin trailer trucks was estimated to lower less-than-truckload, general freight common carrier costs by approximately 2 percent or $500 million per year.

Table 12. Minimum and Maximum Percent Change in Truck Operating Costs for Select Configurations and Gross Vehicle Weights (Jack Faucett Associates, Inc. 1991)

CONFIGURATION	PERCENT CHANGE IN COST PER TON-MILE													
	Dry Van				Refrigerated Van		Flatbed		Tank		Hopper		Dump	
	Truckload		Less-than-truckload											
	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW
5-axle, 36-ft semi													-14.63%	78,000
5-axle, 48-ft semi	Base		Base		Base		Base		Base		Base		Base	
6-axle, 40-ft semi													-12.62%	81,000
													-5.86%	77,000
6-axle, 48-ft semi	-8.47%	86,500			-9.33%	86,500	-8.36%	86,500	-6.12%	86,500				
	3.54%	54,000			1.71%	80,000	3.16%	79,500	4.72%	80,000				
5-axle, twin 28-ft	-10.46%	59,800	-8.21%	63,200	16.55%	80,000					5.34%	80,000		
	6.09%	80,000												
9-axle, twin 28-ft	-15.33%	108,000			-9.53%	108,000	-14.60%	108,000	-13.01%	108,000	-10.98%	108,000	-21.48%	108,000
	35.51%	80,000			52.81%	80,000	37.43%	80,000	37.95%	80,000	41.53%	80,000	30.04%	80,000
9-axle, twin 33-ft	-19.34%	113,500	-11.20%	77,200	-14.12%	113,500	-18.97%	113,500	-17.85%	113,500	-16.49%	113,500	-25.34%	113,500
	40.83%	80,000			59.86%	80,000	42.37%	80,000	40.80%	80,000	43.49%	80,000	35.62%	80,000
9-axle, twin 36-ft, 42-ft, or 48-ft	-36.65%	95,200			-19.88%	129,000	-24.90%	129,000	-23.67%	129,000	-25.91%	129,000	-26.79%	117,000
	-22.06%	127,400			98.82%	80,000	70.11%	80,000	65.00%	80,000	57.94%	80,000	40.90%	80,000
7-axle, Rocky Mountain Double	-27.93%	76,400			-11.22%	105,500	-17.27%	105,500	-15.84%	105,500	-13.56%	80,000		
	29.34%	80,000			42.06%	80,000	26.67%	80,000	27.01%	80,000	22.86%	102,000		
7-axle, triple	-29.75%	83,400	-30.32%	93,000	-4.40%	116,000	-21.56%	116,000	-18.62%	116,000	-20.92%	116,000		
	48.13%	80,000	-14.07%	80,000	96.97%	80,000	40.21%	80,000	42.70%	80,000	39.14%	80,000		

TRB initiated a second comprehensive study focused on Interstate and State highway systems—*Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990)—that considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

Study results related industry transport costs are summarized in Table 13. Industry transport costs would decrease for six of the seven scenarios because only the first scenario—Grandfather Clause Elimination—would reduce weight limits from their current levels. The largest transport cost savings—nearly $12 billion per year—would result from the elimination of the current bridge formula and 80,000 lb GVW limit and the alternate adoption of the Canadian minimum axle spacing and GVW limits. This reduction accounts for approximately 6 percent of the prior costs of all truck freight transportation.

With a narrowed focus on a series of specific truck configurations—each with lower axle weights but higher GVWs—TRB initiated a comprehensive study to consider potential impacts should industry be allowed to put these proposed vehicle configurations into operation. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

Table 13. Transport Cost Impact Summary for Various Proposed Truck Size and Weight Limit Modifications (Transportation Research Board 1990)

TRUCK SIZE AND WEIGHT PROPOSALS			TRANSPORT COSTS[1] ($ billions/year)
1	Grandfather Clause Elimination	No exemptions in federal limits	↑7.8
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	↓2.1
3	NTWAC	Permit program for specialized hauling	↓5.4
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↓11.7
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA
6	TTI HS-20 Bridge Formula	Higher single-unit/short combination vehicle weights	↓2.7
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/short combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive for 7+ axle vehicles	↓5.1
8	Combined TTI HS-20/Formula B	Higher single-unit/short combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	↓5.2
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA

[1] All costs are in 1988 dollars and were calculated assuming a discount rate of 7 percent.

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).
- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle.

With respect to industry costs, study results indicate an annual cost savings of $2.3 billion in the cost of freight transportation if all Turner trucks utilize cargo capacity at the same rate as the trucks they replace (see Table 14). Allowing for the cost of the logistical inefficiencies of Turner doubles would reduce the savings to $2.0 billion, assuming that Turner doubles that carry freight shifting from single-trailer combinations have reduced utilization rates. The savings of $2.0 billion is 1.4 percent of the total annual cost of truck freight in the United States. This estimate is based on 1988 prices and 1987 freight volumes; aggregate savings at 1990 prices and volumes would be somewhat higher.

The authors note the considerable uncertainty associated with these estimates, because they rest on a series of assumptions about costs and acceptability of Turner trucks in various applications. Nonetheless, the estimates are purported to be a plausible indication of the magnitude of productivity gains that could be achieved with Turner trucks.

Table 14. Estimated Transport Savings for Various Assumed Shifts in Carrier Operation (Transportation Research Board 1990b)

CARRIER OPERATION SHIFTS		TRANSPORT SAVINGS[1] ($ millions/yr)	
From	**To**	**Same Capacity Utilization Rate**	**Accounting for Logistical Inefficiencies**
High-density truckload semitrailer	9-axle Turner double	$919	$713
Tank or bulk semitrailer	9-axle Turner double	$548	$474
Low-density truckload semitrailer	9-axle Turner double	$141	$101
High-density truckload semitrailer	7-axle Turner double	$221	$221
Tank or bulk semitrailer	7-axle Turner double	$104	$104
Twin	9-axle Turner double	$283	$283
Rail	Any Turner configuration	$111	$95
Total		**$2,327**	**$1,991**

[1] All costs are in 1988 dollars.

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to industry costs, projected annual shipper costs are estimated to decrease for each of the truck configuration scenarios considered. The LCV Nationwide scenario would results in the greatest cost savings for shippers—with estimated costs 11.4 percent lower than the base case. The Triples Nationwide scenario was estimated to result in shipper costs 8.65 percent lower than the base case. Shipper costs for the North American Trade scenario were also estimated to decrease when compared to the base case—by 5.1 and7.0 percent for 44,000 and 51,000 lb tridem axle limits, respectively.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—concurs with this and earlier findings, noting significant potential for industry cost savings and public benefit.

With a singular focus on LCVs, the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

Of all potential benefits considered in the Western Uniformity Scenario, shipper cost savings were most significant. For shipments currently moving by truck, the expanded availability of various types of LCVs could reduce shipper costs by as much as $2 billion per year or approximately 4 percent of total shipper costs in and through the region. Savings would be lower if some States chose not to allow LCVs to operate as widely as is assumed in the scenario. Shippers that currently use railroads also would realize savings. The actual switch from rail to truck is estimated to be small, producing savings of about $3 million annually. A greater savings to rail users would come from rate reductions that railroads would make to keep traffic from switching to trucks. These savings would be about $26 million per year.

Working with the National Private Truck Council (NPTC), Woodrooffe et al. (2009) estimated the change in industry transport costs—attributable solely to fuel cost savings—if the existing federal limitations were to be lifted, allowing increased GVW limits and the use of LCVs among private fleets. Specifically, the study considered the following scenarios: (1) an 8,000 lb and 14,000 lb increase in GVW limits for a 53-ft tractor semitrailer and (2) the use of two 53-ft. trailers (Turnpike doubles) with maximum GVW limited by the bridge formula. Of the companies surveyed for this study, five indicated that they would benefit from the increased GVW limit and three indicated that they would benefit from the expanded use of LCVs.

Study results indicate that the number of truck loads could be reduced by 10 percent if the allowable GVW was increased and 6 percent if LCVs were permitted. Based on these truck load reductions, annual fuel cost savings was estimated to total $27.8 million and $40.3 million across the five affected companies for the 8,000 lb and 14,000 lb increase in GVW limits, respectively. Annual fuel cost savings was estimated to total $88.2 million across the three affected companies under an expanded use of LCVs. The authors note that these direct industry cost savings would be offset to some degree by costs associated with supplemental driver training, vehicle modifications (additional axles, potential increased tire/trailer wear, required redesign of receiving structures/processes and other. These ancillary costs are thought to be modest relative to the potential for cost savings attributable to the use of larger, heavier trucks.

State/Case Studies

Montana. In an earlier study, Hewitt et al. (1999) considered the overall impacts of changes in truck weight limits on the economy in Montana. Four scenarios were considered with different maximum allowable GVWs. Three scenarios, with maximum GVWs of 80,000 lb, 88,000 lb, and 105,500 lb, represented reductions in GVWs. The fourth scenario represented an increase in allowable GVW to 128,000 lb.

Only nominal changes in infrastructure demands were observed across all scenarios (maximum of $1.5 million). Case studies of the impacts expected on selected industries within the state were conducted. Changes in transportation costs of 4 to 54 percent were predicted under the 80,000 lb scenario, which were estimated to be 0.2 to 4.1 percent of the value of the goods produced. Changes in transportation costs typically were at least an order of magnitude larger than changes in infrastructure costs. Statewide economic impacts in terms of forgone gross state product amounted to -0.4 percent and, in the first year alone, were 2 to 20 times the infrastructure impacts, depending on the scenario.

Maine and New Hampshire. The Transportation Equity Act for the 21st Century (TEA-21) provided exemptions from the federal GVW limits on the Maine and New Hampshire Turnpikes. Exempt portions of I-95 and State highways allow a GVW of up to 100,000 lb on 6-axle tractor semitrailer combinations. Certain commodity groups are also allowed a 10 percent GVW tolerance on 5-axle configurations. Individual axle weight limits range from 22,400 to 24,200 lb for a single axle, 36,000 to 44,000 lb for a tandem axle, and 48,000 to 54,000 lb for a tridem axle. Non-exempt Interstates in Maine and New Hampshire remain subject to the federal GVW limit of 80,000 lb. As a result, heavy trucks that would otherwise be through-traffic on I-95 divert to State highways upon reaching non-exempt portions of I-95. Wilbur Smith and Associates (2004) conducted an analysis that compared the current condition of allowing trucks in excess of 80,000 lb GVW on the ME/NH Turnpike to a no-exemption scenario in which State road networks would assume any displaced heavy truck traffic should the weight exemption be rescinded.

To estimate the impacts of discontinuing the exemption in terms of industry costs, researchers interviewed 15 companies in Maine and 9 companies in New Hampshire that ship or haul heavy commodities—primarily timber, bulk liquids, stone and aggregates, garbage and heavy equipment. Nearly all participants (88 percent) indicated that the current weight limit exemption was either "essential" or "very important" to their businesses. Should the exemption be discontinued, participants predicted having to:

- Add new equipment (22 percent).
- Add additional drivers/shifts (30 percent).
- Reroute existing equipment (45 percent).
- Outsource transportation (3 percent).

One company with ten heavy haul vehicles estimated that it would have to expand its fleet by one-third, which would also require one-third more drivers and total at least $300,000 to $400,000 in additional costs each year.

Minnesota. At the request of the Minnesota Department of Transportation (MnDOT), Cambridge Systematics, Inc. (2006) conducted a study to assess proposed changes to Minnesota's truck size and weight laws that would benefit the State's economy while protecting roadway infrastructure and safety. Various vehicle configurations—including a 6-axle tractor semitrailer with a 90,000 lb GVW limit, a 7-axle tractor semitrailer with a 97,000 lb GVW limit, an 8-axle twin trailer truck with a 108,000 lb GVW limit, and a single unit truck with an 80,000 lb GVW limit—were considered, as well as various changes to spring load restrictions.

Study results indicate that potential cost savings for industry attributable to these alternate vehicle configurations ranged from $2.01 million per year for the 108,000-lb 8-axle twin truck to $6.27 million per year for the 80,000-lb single unit truck. Estimated pavement cost savings for the 6-axle, 90,000-lb and 7-axle, 97,000-lb truck semitrailer configurations were $3.68 and $4.00 million per year, respectively. The estimated impacts of relaxed spring load restrictions and increased GVW limits (from 73,280 to 80,000 lb for 5-axle tractor semitrailers) on the 9-ton roadway system were more significant. Industry cost savings for these two scenarios were estimated as $8.82 million and $24.82 million per year, respectively.

North Dakota. With a similar focus on the impact of seasonal load restrictions—as well as annual load limits—on industry costs, the North Dakota Department of Transportation commissioned a study to consider Statewide truck size and weight issues(Upper Great Plains Transportation Institute 2007). Researchers developed an economic costing model to analyze industry costs under various GVW limit scenarios and for two different types of operation: farm and commercial. Farm operations benefit from lower equipment, insurance, license, and tax costs. Gross vehicle weight limit scenarios included Class A (8-ton), No. 1 (7-ton), and No. 2 (6-ton) with maximum GVWs of 105,500 lb, 80,000 lb, and 65,000 lb, respectively.

Estimated incremental industry costs for various farm truck configurations and GVW limit scenarios are summarized in Table 15. The farm operations analysis shows that the smallest truck is the most costly to use, and the 5-axle semi provides the lower cost for producers for all GVW limits. The Rocky Mountain Double is least costly for non-restricted legal weight and theClass A (8-ton) GVW scenario. Comparably, industry costs for commercial trucks under the various GVW limit scenarios are presented in Table 16 in terms of costs per ton-mile and total costs to haul 300,000 barrels of crude oil 190 miles. Note that commercial truck costs under the No. 2 (6-ton) GVW limit scenario is nearly double the costs under the Class A (8-ton) GVW limit scenario ($779,313 as compared to $374,160). Based on these analysis results, the authors state that load restrictions could significantly increase total transportation costs and reduce profitability of companies, which could subsequently have negative effects on the efficiency of freight flows and competitiveness of the region.

Wisconsin. Most recently, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on pavement costs. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

Estimated industry cost savings are summarized in Table 17. For non-Interstate operations, annual transport cost savings range from $2.19 million per year for the 6-axle, 98,000-lb straight truck-trailer configuration to $19.19 million per year for the 6-axle, 98,000-lb tractor semitrailer configuration. Assuming Interstate operation is available, industry cost savings for these same configurations increase to $14.61 million per year and $127.94 million per year, respectively.

Table 15. Estimated Incremental Farm Industry Costs for Various Truck Configurations and GVW Limit Scenarios (Upper Great Plains Institute 2007)

CONFIGURATION	GVW LIMIT SCENARIOS			
	Legal Weight	Class A (8-ton)	No. 1 (7-ton)	No. 2 (6-ton)
Single	$0.097	$0.107	$0.125	$0.150
Tandem	$0.077	$0.082	$0.089	$0.115
Tridem	$0.055	$0.064	$0.076	$0.094
5-axle	$0.048	$0.051	$0.055	$0.071
Rocky Mountain Double	$0.041	$0.041	$0.060	$0.086

Table 16. Estimated Commercial Industry Costs to Haul 300,000 Barrels 190 Miles under Various GVW Limit Scenarios (Upper Great Plains Institute 2007)

CONFIGURATION	GVW LIMIT SCENARIOS		
	Class A (8-ton)	No. 1 (7-ton)	No. 2 (6-ton)
Ton-mile Cost	$0.055	$0.093	$0.162
Total Cost	$374,160	$549,213	$779,313

Table 17. Estimated Industry Costs for Various Truck Configurations (Adams et al. 2009)

CONFIGURATION	ANNUAL TRANSPORT COSTS (million $)	
	Non-Interstate	Interstate/Non-Interstate
8-axle 108,000 lb double	↓ $3.42	↓ $22.77
7-axle 97,000 lb tractor semitrailer	↓ $6.27	↓ $41.83
7-axle 80,000 lb single unit truck	↓ $2.46	↓ $9.83
6-axle 90,000 lb tractor semitrailer	↓ $5.50	↓ $36.64
6-axle 98,000 lb tractor semitrailer	↓ $19.19	↓ $127.94
6-axle 98,000 lb straight truck-trailer	↓ $2.19	↓ $14.61

INFRASTRUCTURE FINANCING

The primary source of federal and State funding for highways comes from a combination of motor fuel and vehicle taxes. Revenues from motor fuel taxes have not kept pace with highway program needs for several reasons:

- Inflation has eroded the value of revenue developed from motor fuel taxes over time.
- The reluctance of national and state elected officials to increase motor fuel tax rates or index them to account for the diminishing value effects of inflation over the years.
- Increases in vehicle fuel efficiency due to improved engine designs and advanced technology, such as hybrid vehicles powered by a gasoline engine and electric motor;
- The advent of alternative fuels taxed at lower rates or exempt from taxation.
- Significant increases in the price of construction resulting from global shifts in the supply and demand for critical highway materials, such as steel, petroleum-based asphalt, and concrete (Aecom Consult Team 2006).

In fact, a 2006 study sponsored by NCHRP estimated an annual shortfall of $58 billion and $119 billion in the Federal Highway Trust Fund to maintain and to improve the system, respectively (Cambridge Systematics, Inc. et al. 2006). The inability of the motor fuel taxes to provide adequate funding has prompted transportation policymakers to consider alternative financing and revenue sources concurrent with traditional funding streams.

Recent research has supported transportation agency efforts to pursue alternative financing and revenue sources, most commonly in the form of road pricing and direct user fees. The introduction of road pricing and user or "impact" fees provides an opportunity for direct collection at either State or Federal levels although these collection mechanisms are not fully explored in the research. Table 1, provided earlier, presents a list of key citations related to infrastructure financing.

Findings from these citations are intended to support truck size and weight related decision-making—research related to broader infrastructure financing strategies that apply uniformly to all types of vehicles or are primarily intended to alter driving behavior (e.g., congestion pricing) are not detailed here. Instead, the reader is referred to a series of recent and comprehensive publications that detail a broader set of long- and short-term infrastructure financing strategies including but not limited to the following: *NCHRP Web-only Document 102: Future Financing Options to Meet Highway and Transit Needs* (Cambridge Systematics, Inc. et al. 2006), *Financing Freight Improvements* (Federal Highway Administration 2007), *Revenue Sources to Fund Transportation Needs* (American Association of State Highway and Transportation Officials 2007), *Report of Long-term Financing Needs for Surface Transportation* (American Association of State Highway and Transportation Officials 2007b), and *Funding Options for Freight Transportation Projects* (Transportation Research Board 2009).

In addition, this Directory does not consider the equity issues associated with special oversize/overweight permits. While adjustments to existing permit fees may indeed provide a State or jurisdiction with additional revenue, the variability in existing fee structures and special transport characteristics by locale were thought to limit its utility in directing decision-making for broader truck size and weight regulations.

Individual study findings related to infrastructure financing—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- The primary source of federal and State funding for infrastructure comes from a combination of motor fuel and vehicle taxes. Revenues from motor fuel taxes have not kept pace with infrastructure needs because of inflation, a reluctance of elected officials to raise taxes, improved vehicle fuel efficiency, alternative fuel subsidies and other.
- To supplement traditional funding sources, predominant alternative financing strategies with a focus on large trucks include tolled facilities, weight-distance based road user fees, and to a lesser extent, container and/or U.S Customs and Border Protection fees.
- The trucking industry is highly fragmented—any alternative financing strategy initiative is likely to evoke varied reactions from different segments of the industry.
- With some consistency, the truck industry favors truck-only tolled facilities or shared facilities that provide a significant operational advantage such as increased allowable size or weight limits—shared toll facilities that offer benefits related only to congestion avoidance are insufficient in overcoming the increased operating costs attributable to the tolls.
- Weight-distance based road user fees are most commonly levied based on registered GVW rather than actual vehicle weight.
  - Levies based on registered GVW may promote a higher logistical efficiency by discouraging trips with empty trailers although this effect has not been considered or reported in the literature.
  - Current technology (WIM systems) allows capture of actual weight, making fees more equitable in terms of potential infrastructure damage.
  - In a study conducted in Idaho, weight-distance based road user fees were demonstrated to generate more revenue than the current mileage-based registration fee system (Balducci et al. 2010).

Domestic Experience

In the United States, recent research has focused almost exclusively on the potential for "road pricing" as a supplemental source of revenue to support highway infrastructure maintenance or improvement. Road pricing—an economic concept regarding the various direct charges applied for the use of roads—is not new. Traditional road charges include fuel taxes, license and registration fees, and parking taxes. More recent and direct road charges include tolls and congestion charges, which may vary by time of day, by the specific road, or by the specific vehicle type being used. Road pricing has two distinct objectives: (1) revenue generation to support infrastructure financing and (2) congestion pricing for demand management purposes.

Considering the first of these two objectives—revenue generation—two predominant alternative financing strategies with a focus on large trucks have emerged: (1) tolled facilities and (2) weight-distance based road user fees. A third freight-specific strategy for revenue generation—container and/or U.S Customs and Border Protection fees—has demonstrated potential but has received less focus.

Beginning in 2002, a series of studies conducted by the Reason Foundation considered the potential for truck-only tolled facilities. As envisioned, "toll truckways" (TTW) would consist of one or more dedicated barrier-separated lanes in each direction, be self-financed, and would be designed and built for use by heavier and longer vehicles. By allowing only large tractor trailer combinations of three or more axles to operate on those dedicated lanes, weight and size limitations could be relaxed allowing the use of LCVs on a much larger network of roads. The increased use of LCVs would in turn increase the trucking industry's productivity, thereby lowering the costs of operation. This is an important prerequisite for motor carrier support of road pricing initiative. In exchange for productivity increases, trucks would be charged tolls to use the TTWs. The resulting toll revenues would be used to pay debt associated with the construction and maintenance of dedicated truck toll lanes. Since trucks using the truckways would pay tolls to cover the costs of building and operating the lanes, those trucks should not be charged ordinary State or federal fuel taxes or other truck user taxes for the miles they actually drive on TTWs (Samuel et al. 2002).

In 2003, Holguin Veras et al. analyzed the economic and financial feasibility of TTWs along an existing Interstate with three mixed-flow lanes in each direction and a single TTW lane in each direction. Assuming that the TTW attracts 25, 50, 75, or 100 percent of the heavy trucks away from the mixed-flow lanes, Table 18 shows the annualized net impact to State Departments of Transportation (DOT). The addition of a self-supporting TTW in such a corridor would benefit the state DOT in two ways: (1) it would provide new lane capacity at little or no cost to the DOT and (2) by attracting between 25 and 100 percent of heavy truck traffic off the existing lanes, the TTW would lead to significant reductions in the DOT's maintenance and rehabilitation expenditures. The loss of fuel-tax revenue from those trucks that shift to the TTW must be weighed against these two benefits. The difference between the fuel tax loss (calculated as 16 cents/mile for the federal plus State fuel tax paid by heavy trucks) and the operations and maintenance (O&M) savings is the net cost to the DOT of having the TTW added to the Interstate.

As shown in Table 18, the annual cost *avoided* by the DOT is significantly greater than the net cost of its fuel tax loss under any of the assumed usage scenarios. Several policy changes are required before TTW could be implemented. The most important of these changes include: (1) providing a right-of-way along existing highway corridors on the federal-aid system; (2) easing current federal truck size and weight regulations for trucks using the TTWs; and (3) providing a rebate of federal and State truck user taxes for miles driven on toll-supported truckways.

Table 18. Annualized Impact on State Departments of Transportation (DOTs)

TTW		Fuel Tax Loss	O&M Savings	Net Cost	Avoided Cost of New Lane[1]	
					1:1 Case	1:1.5 Case
Truck %	Truck ADT	$/lane-mile of TTW	$/lane-mile of TTW	$/lane-mile of TTW	$/lane-mile of TTW	$/lane-mile of TTW
25%	1,000	$58,400	$6,090	$52,310	$352,428	$340,468
50%	2,000	$116,800	$13,298	$103,502	$366,250	$358,132
75%	3,000	$175,200	$37,558	$137,642	$381,478	$366,252
100%	4,000	$233,600	$47,101	$186,499	$389,788	$376,198

[1]Annualized TTW costs were calculated in detail for the baseline capital cost case of $1 million per lane-mile and extrapolated to the $2 million/lane-mile and $3 million/lane-mile cases. The figures shown in the table are for the $2 million/lane-mile case.

In terms of shared toll facilities, toll agencies have traditionally focused their facilities planning, design, and operations on motorists—the largest category of toll road customers. The needs of commercial motor carriers have received less attention, in part because the trucking industry has been among the staunchest opponents of the introduction or increase in tolls on the nation's highways. To make tolling and road pricing more palatable to the trucking industry, the Aecom Consult Team (2006) recommend the following strategies:

- Provide improved service in return for the toll that results in productivity gains greater than the cost of the toll (e.g., ability to operate at highest safe speed, with gross weight limits over 48 tons, and truck combination lengths over 53 ft).
- Do not put tolls or congestion pricing on currently non-tolled lanes by limiting tolling to new capacity paid for by the tolls.
- Limit tolling to state and federal highways, not local roads.
- Dedicate toll revenues to operation, maintenance, and construction costs of the highway facility or system being tolled.
- Provide a rebate for motor fuel taxes paid for truck travel on tolled facilities through an adjustment of the truck toll rate (e.g., on a vehicle-mile basis).
- Make the toll cost predictable so it can be planned for as part of shipping contracts.
- Provide advanced notification of toll rate changes to allow for shipping contracts to be adjusted (e.g., at least six months prior to effective date of change).
- Limit duration of tolling on any facility so it is not perpetual.

In response to industry opposition, researchers note that along some tolled facilities—including the Ohio Turnpike and the New York State Thruway—toll rates for large trucks have been reduced in an attempt to thwart facility avoidance and diversion to local parallel routes.

In addition to tolled facilities, distance based (VMT) road user fees are being promoted as a potential substitute for the weakening motor fuel tax. In the case of large trucks, a weight component is often included in the fee schedule to account for the increasing infrastructure damage attributable to higher vehicle weights. In many cases, weight-distance fees are determined using a carrier's self-reported registered GVW per vehicle. Technological advances now make it possible to determine weight-distance fees using the real-time weight of the truck.

As part of a pooled fund investigation involving 16 States, Forkenbrock (2004) developed a system that would allow for the collection of broader distance based road user fees and weight-distance fees specific to large trucks. Key to this approach is a simple onboard computer that stores a record of actual road use charges. Periodically this record is uploaded and transmitted to a data processing center, referred to as the collection center. The center bills a vehicle owner and reimburses the States, counties, and cities operating the roads on which the vehicle has traveled. The onboard system is simple, secure, and capable of protecting the user's privacy. Importantly, the onboard system enables a variety of user charge conventions. In its simplest form, this approach can be used to assess a VMT user charge. With a VMT user charge, the computer can calculate road mileage actually traversed and compare this mileage with that obtained through an odometer feed. It then applies appropriate user charges to mileage traveled in each jurisdiction.

In the case of large trucks, simple per mile user charges could be instituted in a manner similar to that for autos. Optionally, a rather basic weight indicator—a simple strain gauge attached to the trailer's suspension—could be activated each time the cargo doors are closed. The weight indicator would transmit information to the onboard computer, indicating the current weight. A code would inform the computer about the configuration of the trailer, especially the number of axles. The computer then would take into account vehicle weight and configuration, along with type of road being traveled (a State may choose to levy a lower per mile charge for travel by heavy vehicles on Interstate highways and other facilities that are capable of withstanding high axle loads without being damaged) in calculating the road use charges that are due.

More recently, Conway and Walton (2010) developed a theoretical framework for future distance based (vehicle-miles traveled) road user fees for large trucks using real-time vehicle weight and configuration information collected using weigh-in-motion (WIM) systems. Under this system, researchers propose an "Axle-Load" based tolling structure that recovers costs for heavy vehicle consumption more equitably than a commonly employed "Number-of-Axle (n-1)" structure. Under the unfavorable "Number-of-Axle" toll structure, vehicles pay a higher toll for each additional axle despite the fact that the addition of an axle can potentially reduce pavement and bridge impacts by lessening the load being applied at a given point. The results of this research indicate that employing WIM systems for real-time load classification would allow system operators to better measure and recover the costs of infrastructure consumption from individual users.

A third strategy—container and/or U.S Customs and Border Protection fees—has received less focus in the historic literature but may prove to be a significant source of revenue. As reported in *Revenue Sources to Fund Transportation Needs*, AASHTO (2007) estimates that dedicating just 5 percent of customs fees to port intermodal connections via rail and highways would bring in $1.8 billion per year. Customs revenues are derived from duties on imported goods passing through international gateways. The transportation of these goods imposes significant costs on ports, intermodal facilities, and the surrounding communities. Over the next 15 years the number of international containers expected to cross U.S. docks and border crossings is expected to grow from 40 million units to 110 million units. With growth rates like these, sharing only 5 percent of this rapidly growing resource should prove reasonable.

A second revenue generation opportunity proposed by AASHTO (2007) is the imposition of a container fee of $30 on every 20-ft cargo container, which would be placed in a trust fund dedicated to freight-related improvements nationwide. If applied at all U.S. ports, it is estimated that this could generate in the range of $2 billion per year.

The Alameda corridor freight rail project in California was the first to institute container fees to help pay for transportation infrastructure improvements. Up to $30 fees are paid on each container that use, or could have used, the corridor. The terminal operators in the ports of Los Angeles and Long Beach have also recently imposed daytime surcharge fees on container movements to encourage shifts to night time operation. California State Senator Lowenthal recently proposed the implementation of a $30 fee on every 20-ft cargo container moving through the ports of Los Angeles and Long Beach to help fund port and intermodal improvements to serve this commerce. This bill was passed by the state legislature in the summer of 2006 but vetoed by the Governor.

State/Case Studies

California. As means to more efficiently keep goods movement flowing smoothly, improve overall mobility along the freeway, and improve traffic safety and air quality issues, Taylor (2001) considered the feasibility of exclusive lanes for large trucks along State Route 60 (SR-60), from I-710 to I-15, a distance of approximately 38 miles. This freeway, serving intermodal freight yards and bridging between the Ports of Long Beach/Los Angeles and inland areas, currently carries a daily truck volume of more than 20,000 in some locations, projected to more than double by 2020. SR-60 is identified in the association's adopted 2001 Regional Transportation Plan as one of four highways planned to include exclusive truck lanes by 2025.

As part of this study, researchers evaluated opportunities for revenue collection through tolling. At a capital development cost of approximately $16.5 billion, the study showed that a per-mile toll ranging from $0.38 to $0.80 and averaging $0.56 over a 30-year financing period would be sufficient to totally fund the development and operation of this system.

More recently, Killough (2008) advanced the concept of a truck-only tolled facility in Southern California at the request of the Goods Movement Roundtable—a consortium of government, economic development, shipping, logistics, and port agencies and companies interested in building a consensus in support of public and private financing for the project. The analysis examined the Return-On-Investment for truck operators during the morning peak comparing truck toll lane time savings to the projected toll fees. The unique aspect of this analysis was an assessment of the truck toll lane contribution to improved travel time reliability and how consideration of reliability enhanced the ROI analysis.

The results of this analysis are presented in Table 19. With the assumed value-of-time for heavy-duty trucks of $73 per hour used in this analysis, time savings would amount to $103 for trips to downtown Los Angeles, $233 for trips to Ontario, and $345 for trips to Victorville. These savings more than offset the assumed $0.86 per mile toll cost for using the freeway truck toll lanes that total $17 to downtown Los Angeles, $32 to Ontario, and $64 to Victorville to use the lanes. The ROI ratio ranges from $5 to $11 for every $1 of toll cost. This ROI does not consider the added benefit that would accrue from trucks being able to make 1-2 additional trips during the day. The Truck operator return on investment that includes reliability is considerable, but will vary by facility and by time of day. A combination of truck toll lanes and additional funds will be required to cover facility capital costs and environmental mitigation that have been estimated at $36 billion. While this analysis suggests that the tolls charged to truck operators to use the truck lanes can be increased, it is unlikely that tolls can be set at a level that will retire the total investment needed to provide the facilities.

Table 19. 2030 Truck Toll Lane Return on Investment (Killough 2008)

WAREHOUSE DISTRICT	VALUE OF TIME $73/hour		TOLL COST 86¢/mile	TIME VALUE SAVINGS		ROI RATIO	
	To	From		To	From	To	From
Downtown	$103	$118	$17	$86	$101	6:1	7:1
Ontario	$233	$361	$32	$201	$329	7:1	11:1
Victorville	$345	$490	$64	$281	$336	5:1	8:1

Georgia. In a similar effort, Parsons, Brinkerhoff, Quade, and Douglas (PBQD 2005) completed a feasibility study in Atlanta that considers both high-occupancy toll and truck-only toll (TOT) lanes. With respect to TOT lanes, the stated facility objectives are to improve safety, improve efficiency, and generate revenue. The project study area included all limited-access facilities in the 13-county Atlanta region. This study examined three TOT lane alternative scenarios:

- *A1 Major Truck Corridors.* Along two of the most promising corridors in the region, two TOT lanes would be constructed in each direction, in addition to HOV lanes.
- *A2 Service to Deliveries.* In addition to A1, current HOV lanes would additionally be reserved for light-duty commercial vehicles willing to pay a fee during the midday.
- *A3 Regional TOT Network.* All existing and proposed HOV lanes would be converted into TOT lanes, with no need to construct separate TOT lanes.

With respect to revenue generation, the study found that under any of the three scenarios, respectable amounts of revenue can be generated to cover operating and maintenance costs (see Table 20).

Texas. With a focus on truck use of shared toll facilities, Zhou et al. (2009) researched the possibility of using innovative pricing incentives as a means to encourage truck carriers to use the State Highway 130 (SH 130) toll road in Austin, Texas, as an alternative route to congested Interstate 35. The researchers developed and administered both an online and a paper survey of which a total of 2,023 valid responses were obtained. The survey focused on classification of type of operation, delivery flexibility, travel behavior, and perceptions of proposed incentives and travel scenarios.

Results showed that drivers plan to avoid congestion and that the incentives that were most favored were those that directly impact costs, such as reduced fuel price and off-peak discounts. The researchers subsequently analyzed the potential costs and benefits for the truck companies associated with the preferred incentives using SH 130 and the added cost of the incentive to the toll road operator. These costs were estimated for the year 2015 when congestion on Interstate 35 is predicted to reach its peak. From the survey the research team obtained a value of time of $34.49/hour and time savings for the completed SH 130 were estimated to be between 11.6 minutes in off-peak hours, between 33.6 and 47.7 minutes in the AM peak hour and between 13.9 and 19 minutes Southbound and between 36.9 and 51.7 Northbound in the PM peak hour. The estimated benefit cost ratio was 1.36, suggesting that although offering incentives to shift truck traffic to the toll road could have a positive impact, the overall implementation costs could ultimately result in the costs outweighing the benefits.

Table 20. 2030 Regional Revenue Estimates for TOT Lane Alternatives (PBQD 2005).

TOT ALTERNATIVE SCENARIO	WEEKDAY REVENUE (K)				PROJECTED ANNUAL REVENUE (K)
	Light-Duty Truck	Heavy-Duty Truck	Total	Per TOT Lane-mile	
A1: Major Truck Corridors	$186	$142	$327	$694	$89,400
A2: Service to Deliveries	$219	$153	$372	$614	$101,000
A3: Regional TOT Network	$429	$296	$724	$554	$198,000

Oregon. As an alternative to truck-only or shared toll facilities, Oregon imparts a weight-distance tax based on a cost-responsibility approach to road financing. Because trucks require higher standards of road construction and generate substantial road damage, the tax is intended to accurately reflect the costs of the higher road standards and the damage done by trucks traveling on State roads. This form of road user fee has been in place for more than 40 years.

For the fiscal year ending July 1, 2000, Oregon collected $225 million in weight-distance taxes on trucks. In the same year $14.5 million in truck registration fees were collected. Weight-mile taxes represented about 30 percent of State Highway Fund revenue. The tax is levied on the basis of the distance driven in the State and the declared weight.

Whereas cost-responsibility is the primary reason for the tax, it is also expected to influence behavior. Higher taxes for trucks that do more damage to the roads should lead to less frequent usage of such trucks relative to trucks that damage roads less often. In 2000, Rufolo et al. considered the effects of a 1990 amendment to Oregon's weight-distance tax that provided for a lower tax rate for trucks weighing more than 80,000 lb to which axles were added. The tax break was largely based on equity considerations, since trucks within a weight class tend to do less road damage if they have more axles. However, the tax reductions also created an economic incentive to add axles and thus reduce road damage. Whether the tax break actually led to an increase in the number of axles within weight classes and a reduction in the amount of road damage was investigated.

Study results suggest some evidence that the weight-distance tax does seem to influence behavior in a manner consistent with reduced road damage; however, the data are not complete enough to allow for a definitive conclusion. Statistical data indicate that a small increase occurred in the number of axles in most weight classes and a large increase occurred in mileage by the heaviest trucks with the most axles. These increases reduced the damage per ton shipped on trucks subject to the axle incentive, but to determine if this was due to the weight-mile tax is not possible. A series of structured interviews supplemented the statistical analysis and indicates that the tax incentive is not a major determinant of truck configuration. One reason for this is that regulatory constraints, particularly weight limits, limit the effectiveness of the tax incentives.

Idaho. Idaho also utilized a weight-distance tax approach to road financing. This tax generated $37.3 million in Fiscal Year 2000, or about 12 percent of State highway user taxes and fees. Trucks in excess of 60,000 lb GVW paid a registration fee of $120 and a weight-distance tax ranging from 22.45 mills a mile for farm and non-commercial registrations (limited rate) to 44.9 mills a mile for 80,000-lb GVW trucks (regular rate). In 1999, the American Trucking Association (ATA) filed suit against Idaho's two-tiered weight-distance tax structure, which imposed a separate mileage fee schedule for vehicles hauling selected commodities (e.g., logs, pulp wood, ores, livestock, sand, and gravel). The Limited Commodity Rate schedule was found unconstitutional by the Fourth Judicial District Court of Idaho and the alternative fee schedule was ordered to be discontinued as of April 1, 2000. In 2001, the weight-distance tax in Idaho was replaced entirely by a mileage-based registration fee system.

Figure 1 demonstrates the revenue impact of this change over the 1991 to 2009 time period. As shown, revenues grew from $29.0 million in 1991 to $45.5 million in 2000. Had the weight-distance tax not been repealed, revenues were forecast to grow to $60.4 million based on analysis of historical trends. Comparatively, following an initial surge in 2001, revenues from the mileage-based registration fee system declined. In 2008, registration fee revenues amounted to $48.8 million; approximately $11.6 million less than the forecasted revenues from the weight-distance tax (Balducci et al. 2010).

Alabama. Despite the repeal of the weight-distance tax in Idaho, other States continue to investigate similar road user strategies. In 2007, Waid and Sisiopiku evaluated a "heavy truck road user fee" (HTRUF) as a potential funding source for transportation financing. The assessment was based on HTRUF's revenue potential, equity, efficiency, and political acceptability to the taxpayers and decision makers in Alabama. The proposed HTRUF system would charge trucks based on their vehicle-miles traveled (VMT) in the entire State. The fee schedule would either be a flat fee per mile across all truck classes, or would vary based on emissions class and/or weight and axles.

The study confirms that this innovative revenue source is an excellent way to generate income for transportation investments. The projected revenues from the HTRUF system implementation were based on the number of truck miles driven in the State of Alabama in 2002. For simplicity, the projected revenues were based on a flat fee across all vehicle emissions, weight, and axle classes. At a rate of $0.25 per mile, the gross revenue for State is estimated as $643 million.

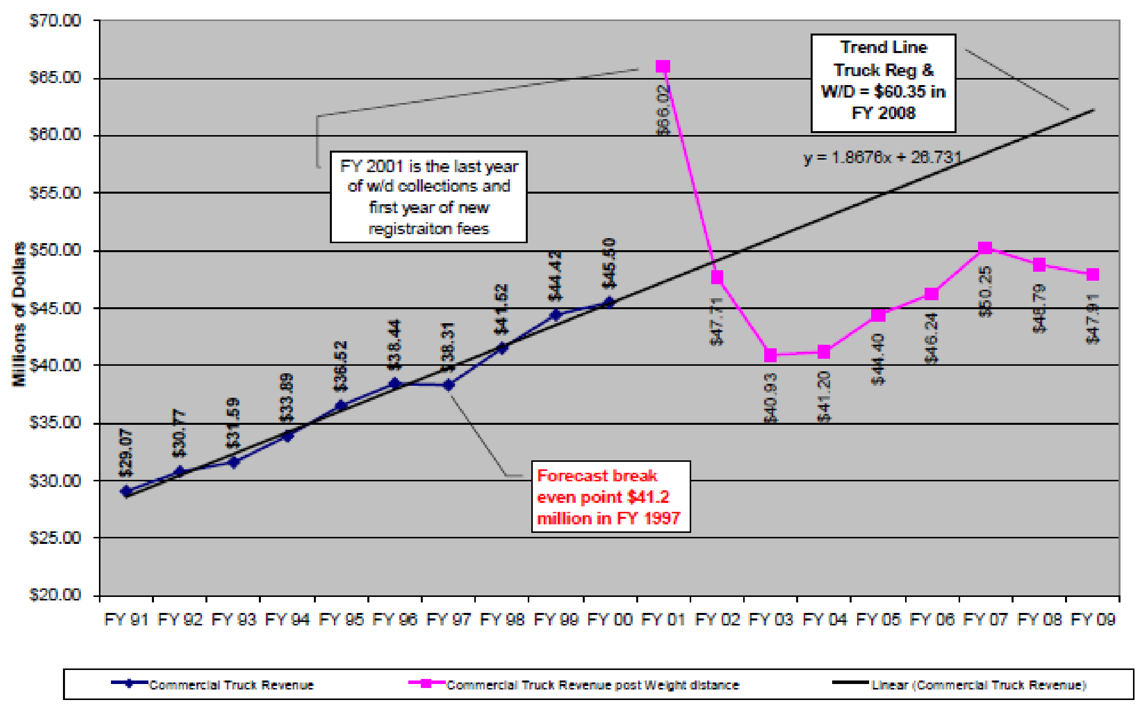

Figure 1. Revenue Impact of Weight Distance Tax Repeal in Idaho (Balducci et al. 2010)

International Experience

Many European countries have charged tolls on their national roadway systems for decades, but an emerging trend is targeted tolls on heavy goods vehicles (HGVs). With the expansion of the European Union (EU) since the 1990s, goods movements have significantly increased, particularly along east–west axes. Since 1995 more than 20 European countries have instituted tolls for HGVs using their national motorways. The motivations are similar: expanding sources of revenue beyond the gas tax, managing demand for road space, encouraging efficient operations, leveling the tax burden on haulers registered in different countries, and reducing CO_2 emissions.

In 1999, the European Commission adopted a directive which set common rules for the charging of heavy vehicles for member states. A specific provision of that directive encouraged member states to introduce a common system of user charges. In response Belgium, Denmark, Luxembourg, Germany, the Netherlands, and Sweden initially agreed to the introduction of a common tolling system called the "Eurovignette." Under that system, charges are levied on all heavy trucks above 26,500 lb that use highways in participating countries. Heavy vehicles must obtain a sticker to travel on the highways of participating countries for a specified period of time.

In August 2003, Germany withdrew from the Eurovignette agreement to introduce "Toll Collect"—a high-tech electronic tolling scheme using Global Positioning System onboard units with mobile communications technology. Resulting distance-based revenues are intended to replace the motor fuel taxes formerly paid by trucks operating on the Autobahn in Germany. Broaddus and Gertz (2008) propose the German system as a potential model for the United States. In its 2005 launch year, Germany collected $72.87 billion which will be spent on road building and maintenance (50 percent), upgrading the federal railway network (38 percent), and inland waterways (12 percent).

In 2001, Switzerland—who does not participate as a member of the European Union—launched the "distance-based heavy vehicles fee" levied on all vehicles greater than 7,700 lb. The system charges commercial motor carriers the equivalent of between $0.21 and $0.86 per mile. The fee is calculated on the basis of the weight threshold, vehicle emission class, and distance driven each month (Dalbert 2001).

The Swiss system relies upon dedicated short range communication (DSRC) beacons located at the country's borders that activate and deactivate each truck's on-board unit (OBU) using microwave or infrared signals as it enters or leaves the country. The OBU consists of an odometer and a global positioning system (GPS) unit, used as an auditing tool to verify the accuracy of the data from the odometer. The readings are stored on a smart card and can be transmitted to authorities or downloaded online.

Installation of the system cost $22.5 million in development and $71 million for roadside and back-office installations. Annual operating expenditures are estimated at $14 million, and the system is expected to generate revenues of up to $880 million per annum in the short term, for investment in road and rail infrastructure.

HIGHWAY CONGESTION

Congestion occurs when the volume of traffic using a highway at a particular time approaches or exceeds the capacity of the highway. Increases in allowable truck size and weight could impact highway congestion through resultant changes in either truck volumes or highway capacity:

(1) The volume of truck traffic–expressed as annual heavy truck vehicle-miles traveled (VMT)—may either decrease as a result of increased truck capacity or increase in response to lower trucking transport costs.

(2) Larger, heavier trucks may be less maneuverable and have less horsepower in relation to their weight, effectively reducing highway capacity. The effects of trucks on capacity—measured in terms of their "passenger-car equivalents" (PCEs)—depend on their length and their weight-to-horsepower ratio, as well as their operating environment (e.g., steep grades vs. flat terrain, two-lane roads with limited sight distance for passing).

A number of studies have considered highway congestion concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, modal share, enforcement, highway safety, the environment, and other. Table 1, provided earlier, presents a list of key citations related to highway congestion, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making. A series of recent studies have characterized and quantified the effects of highway congestion on existing freight transport. Select studies have also identified various strategies to reduce congestion through increased highway capacity and/or improved system efficiency. None of these studies explicitly consider the effects of increased allowable truck size and weight on highway congestion and as such, are not detailed here. Instead, the reader is referred to these general highway congestion studies including but not limited to the following: *Freight Story 2008* (Schmitt et al. 2008); *Estimated Cost of Freight Involved in Highway Bottlenecks* (Cambridge Systematics, Inc. 2008); *Freight Transportation: National Policy and Strategies can Help Improve Freight Mobility* (United States Government Accountability Office 2008); *Transportation Reboot: Unlocking Freight* (American Association of State Highway and Transportation Officials 2010); and *TTI's 2010 Urban Mobility Report* (Schrank, Lomax, and Turner 2010).

Individual study findings related to highway congestion in the context of truck size and weight decision-making—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Increases in allowable truck size and weight could impact highway congestion through resultant changes in either truck volumes or highway capacity:
  - Heavy truck VMT may either decrease as a result of increased truck capacity or increase in response to lower trucking transport costs.
  - Larger, heavier trucks may be less maneuverable and have less horsepower in relation to their weight, effectively reducing highway capacity.
- With some consistency, increases in allowable truck size and weight were predicted to result in a modest degradation in traffic flow and associated capacity however, anticipated corresponding reductions in heavy truck VMT were predicted to offset these negative impacts in the broader context of highway congestion.
  - Larger, heavier trucks would have inferior capabilities related to speed maintenance on upgrades; traction; and freeway merging, weaving, and lane changing and require increased intersection and passing sight distance.
- Prior studies have been criticized for oversimplifying the complex interactions between trucks and other vehicles in the traffic stream. Changing truck volumes, dimensions, and acceleration abilities will affect other vehicles' driving, acceleration, and braking patterns.

Domestic Experience

In response to changes brought about by the 1982 STAA and with a unique focus on non-Interstate, arterial highway routes, the Transportation Research Board (TRB) initiated a comprehensive study—*Special Report 223: Providing Access for Large Trucks* (Transportation Research Board 1989)—to consider access implications of wider and longer commercial motor vehicles. More specifically, the study's intent was to better characterize "reasonable" access and diffuse differences among industry representatives seeking uniform standards for access and State and local officials seeking to maintain local decision-making control.

With respect to highway congestion, results of this study indicate a modest degradation in traffic flow and associated capacity attributable to larger, heavier trucks. Two characteristics of STAA vehicles are largely responsible for the adverse effects: (1) higher average truck weights that may increase the vehicle weight-to-horsepower ratio, reducing speed and acceleration capabilities and (2) added truck length that challenges passing on two-lane roads and causes delays at intersections as trucks make turning maneuvers. The magnitude of these adverse impacts depends on the volume of larger, heavier trucks in the traffic stream. The authors note that improved engine technology enhancing weight-to-horsepower ratios and historically low observed increases in truck traffic following the introduction of increased allowable truck size and weight limits will likely lead to a small net adverse impact on highway congestion.

Considering again the potential impacts of higher average truck weights and added truck length on traffic flow, TRB initiated a second comprehensive study that considered a series of specific truck configurations—each with lower axle weights but higher GVWs—intended for operation on Interstate and State highway systems. Findings are documented in *Special Report 227: New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal* (Transportation Research Board 1990b).

The many possible vehicle configurations that fit the Turner concept were condensed into four prototypes:

- 7-axle tractor-semitrailer with a 91,000-lb GVW limit and 60-ft length.
- 9-axle double trailer with a 114,000-lb GVW limit and 81-ft length (two 33-ft trailers).
- 9-axle B-train double with similar dimensions as above but with a different coupling arrangement between the two trailers.
- 11-axle double trailer with a 141,000-lb GVW limit.

In comparison, the most common large truck configuration in use currently is a 5-axle tractor-semitrailer with a 80,000-lb GVW limit and 50- to 65-ft length. The most common multi-trailer combination is a 5-axle double trailer with an 80,000-lb GVW limit and 70-ft length (two 28-ft trailers). On the prototypes, a single axle would weigh a maximum of 15,000 lb and a tandem axle would weigh a maximum of 25,000 lb compared with the current federal limit of 20,000 lb for a single axle and 34,000 lb for a tandem axle. With respect to highway congestion, study results indicate variable impacts from the use of Turner Trucks across a wide range of traffic flow and capacity characteristics (see Table 21).

Table 21. Traffic Operations Characteristics of Turner Trucks Relative to Trucks Replaced (Transportation Research Board 1990b)

CHARACTERISTIC	COMPARISON BETWEEN TURNER TRUCKS AND TRUCKS REPLACED
Speed on upgrade	Turner trucks, if operated by existing range of engine power, would have lower hill-climbing speed than existing combination vehicles.
Traction ability	Nine-axle Turner double would be similar to exist in twin 28-ft trailer truck, whereas the 11- axle Turner double would be slightly poorer. Both Turner trucks would have considerably poorer traction ability than existing tractor semitrailers.
Passing on two-lane highways	Because of their extra length, prototype nine-axle Turner double would increase passing sight distance for cars passing heavy trucks by up to 7 percent relative to existing tractor-semitrailers.
Freeway merging, weaving, and lane changing	Relative to existing configurations, it would be more difficult for Turner trucks operate by the existing range of engine power to merge, weave, or change lanes. Extra length of Turner trucks would add to the difficulty of these maneuvers.
Freeway exiting maneuvers	Turner trucks, relative to existing combination vehicles, would not affect the ease or the safety of such maneuvers.
Unsignalized intersection sight distance for trucks to cross	Prototype Turner doubles would increase sight distance required by up to 10 percent relative to existing 28-ft twins.
Unsignalized intersection sight distance for trucks to turn	Prototype Turner trucks, if operated by the existing range of engine power, would increase sight distance required because of their lower acceleration capability.
Signal timing	The yellow-phase of traffic signals is already inadequate for existing combination vehicles; the extra length of Turner vehicles would worsen the problem.
Downhill operations	Prototype Turner trucks are not expected to be less safe than existing combination vehicles. Use of retarders and antilock brake systems that modulate foundation and auxiliary brakes would further enhance safety of downhill operations.
Longitudinal barriers	Existing barriers to restrain/redirect vehicles are inadequate for all heavy trucks.
Splash and spray	Extra length of Turner vehicles would increase the duration in which motorists' vision is impaired by the spray; it would not affect the spray intensity, however.
Truck blind spots	Turner trucks would be no worse than trucks they would replace.
Blockage of view	
Aerodynamic buffeting	

According to this study's results, Turner trucks would have inferior capabilities related to speed maintenance on upgrades; traction; and freeway merging, weaving, and lane changing. In addition, Turner trucks would require increased intersection sight distance for trucks to cross and turn at unsignalized intersections and yellow-phase duration in signal timing plans. Other vehicles attempting to pass Turner trucks on two-lane highways would require increased passing sight distance and would be subjected to an increased duration of splash and spray. Other operational characteristics—including freeway exiting maneuvers, downhill operations, the effectiveness of longitudinal barriers, truck blind spots, blockage of view, and aerodynamic buffeting—were predicted to be no different for Turner trucks than other truck configurations currently in use. This study also estimates that the predicted use of Turner trucks would reduce heavy truck VMT by 3.4 percent, potentially offsetting the negative impacts to traffic flow and operations.

During the same year, *Special Report 225: Truck Weight Limits: Issues and Options* (Transportation Research Board 1990) considered 10 different scenarios for changes in truck weight regulations. For seven of these proposals, detailed scenario analyses were conducted to quantify potential impacts resulting from these proposed regulatory changes.

Study results related to highway congestion—expressed in terms of the estimated percent change in heavy truck vehicle-miles traveled (VMT)—are summarized in Table 22. Heavy truck VMT is estimated to decline by up to 6.3 percent for the Canadian Interprovincial Limits scenario. The three other scenarios that would eliminate the 80,000-lb GVW limit would also result in a reduction in heavy truck VMT, ranging from 0.5 to 2.5 percent. Only the Grandfather Clause Elimination scenario—which would reduce allowable truck size and weight limits—is estimated to increase heavy truck VMT. This increase is estimated to be 3.2 percent.

Table 22. Estimated Percent Change in Vehicle-Miles Traveled for Various Proposed Truck Size and Weight Limit Modifications (Transportation Research Board 1990)

TRUCK SIZE AND WEIGHT PROPOSALS			HEAVY TRUCK VMT
1	Grandfather Clause Elimination	No exemptions in federal limits	↑3.2%
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	↓2.2%
3	NTWAC	Permit program for specialized hauling	↓1.1%
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↓6.3%
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA
6	TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights	↓0.5%
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive when applied to 7+ axle vehicles	↓2.2%
8	Combined TTI HS-20/Formula B	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	↓2.5%
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA

In a similar effort sponsored by the U.S. Department of Transportation (USDOT), the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With an initial focus on highway capacity, this study estimated a series of PCEs by evaluating the relative effects of many different types of trucks. In both rural and urban areas, truck length was found to have only a minor effect on PCEs, limited to the fact that the longer vehicle occupies more physical space. On very congested roads with many closely spaced interchanges and high volumes of long trucks, the effect of longer trucks on traffic flow would likely be greater because of interference with merging movements at the on- and off-ramps. The weight-to-horsepower ratio has a greater effect on traffic flow, especially in rural areas. The most significant variable affecting estimated PCEs is the degree of highway grade. On a four-lane rural Interstate, PCEs for 80-ft trucks can range from 2.6 to over 14 depending on the grade and weight-to-horsepower ratio. On two-lane highways, PCEs can be even higher.

The change in annual hours of delay was computed from the projected changes in PCEs, with delay valued at $13 per vehicle-hour. Expressed as the percent change in associated costs relative to the base case, highway congestion costs are estimated to decrease for each of the truck configuration scenarios considered. The Triples Nationwide scenario would results in the greatest cost savings—with estimated congestion costs 7.6 percent lower than the base case. The LCV Nationwide scenario was estimated to result in congestion costs 2.9 percent lower than the base case. Highway congestion costs for the North American Trade scenario were also estimated to decrease when compared to the base case—by 1.2 percent for both 44,000 and 51,000 lb tridem axle limits.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—notes a primary shortcoming in the determination of congestion costs, such as those presented in *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000). According to the expert panel, prior studies have oversimplified the treatment of the complex interactions between trucks and other vehicles in the traffic stream. Changing the traffic volume, dimensions, and acceleration abilities of trucks will change how motorists drive around them, affecting other vehicles' patterns of acceleration and braking.

With a singular focus on longer combination vehicles (LCVs), the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to highway congestion, study results indicate an overall estimated reduction in heavy truck VMT of 25 percent (from 18,823 to 14,028 million) as a result of LCV use in the 13 western States. The predicted change in VMT is highly variable across truck configurations (see Table 23). Estimates of base case LCV travel rely on State-reported traffic counts and vehicle classification/WIM data that are not designed to provide statistically reliable estimates of total LCV travel. Other data sources—including the Census Bureau's Vehicle Inventory and Use Survey—have been used to supplement the State reported data, but there is considerable uncertainty about the amount of LCV traffic in the scenario States. Benefits from predicted reductions in congestion and delay could be offset by decreased passing opportunities, increased delay if LCVs cannot maintain their speeds on steep grades, increased difficulty merging and weaving in urban areas because of the greater vehicle lengths, and potential delays at intersections and other locations caused by the larger off-tracking of LCVs.

Rather than explore hypothetical impacts of proposed truck configurations that generally include increased size and weight limits, the *1997 Federal Highway Cost Allocation Study* (U.S. Department of Transportation 1997) assigns transportation system cost responsibilities among existing truck and other vehicle configurations currently in operation.

Table 23. Estimated Base Case and Western Uniformity VMT by Vehicle Configuration (Federal Highway Administration 2004)

VEHICLE CONFIGURATION	VMT (Millions)		PERCENT CHANGE
	Base Case	Scenario	
5-axle Tractor Semitrailer	14,476	3,442	↓76%
5-axle Tractor Semitrailer	1,924	938	↓51%
5- or 6-axle Double	1,351	750	↓44%
6-axle Truck Trailer	626	607	↓3%
7-axle Double	188	2,190	↑1,065%
8- or more axle Double	213	5,626	↑2,541%
Triple	45	473	↑951%
Total	**18,823**	**14,028**	**↓25%**

State/Case Studies

Minnesota. At the request of the Minnesota Department of Transportation (MnDOT), Cambridge Systematics, Inc. (2006) conducted a study to assess proposed changes to Minnesota's truck size and weight laws that would benefit the State's economy while protecting roadway infrastructure and safety. Various vehicle configurations—including a 6-axle tractor semitrailer with a 90,000 lb GVW limit, a 7-axle tractor semitrailer with a 97,000 lb GVW limit, an 8-axle twin trailer truck with a 108,000 lb GVW limit, and a single unit truck with an 80,000 lb GVW limit—were considered, as well as various changes to spring load restrictions.

With respect to highway congestion, costs savings ranged from $0.05 million per year for the single unit truck up to 80,000-lb to $0.23 million per year for the 97,000-lb, 7-axle tractor semitrailer. Estimated cost savings for the 6-axle tractor semitrailer and 8-axle twin configurations were $0.18 and $0.08 million per year, respectively. The estimated cost savings from relaxed spring load restrictions were comparable at $0.17 per year, while the increased GVW limits (from 73,280 to 80,000 lb for 5-axle tractor semitrailers) on the 9-ton roadway system produced more significant highway congestion cost savings—estimated to decrease by $0.72 million per year.

Wisconsin. Most recently, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight—on highway congestion. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. Researchers considered impacts of operation along non-Interstate highways and Interstate and non-Interstate highways combined (should national laws change to allow these configurations on Interstate highways in Wisconsin).

With respect to highway congestion, estimated congestion cost savings are summarized in Table 24. Configurations that offer the greatest highway congestion cost savings, when compared to the base case 5-axle tractor semitrailer, include the 6-axle 98,000-lb tractor semitrailer, the 7-axle 97,000-lb tractor semi-trailer, and the 6-axle 90,000-lb tractor semitrailer. The 6-axle 98,000-lb straight truck trailer and the 7-axle 80,000-lb single unit truck offer the lowest highway congestion cost savings.

Table 24. Estimated Highway Congestion Costs for Various Truck Configurations (Adams, et al. 2009)

CONFIGURATION	ANNUAL CONGESTION COSTS (million $)	
	Non-Interstate	Interstate/Non-Interstate
8-axle 108,000 lb double	↓ $0.49	↓ $1.65
7-axle 97,000 lb tractor semitrailer	↓ $0.85	↓ $4.08
7-axle 80,000 lb single unit truck	↓ $0.08	↓ $0.09
6-axle 90,000 lb tractor semitrailer	↓ $0.92	↓ $3.44
6-axle 98,000 lb tractor semitrailer	↓ $1.89	↓ $11.03
6-axle 98,000 lb straight truck-trailer	↓ $0.06	↓ $0.26

ENVIRONMENT

The impacts of increased allowable truck size and weight on the environment—typically characterized in terms of energy consumption; harmful emissions (nitrogen oxides, particulate matter, volatile organic compounds, and sulfur oxides); and noise levels—are closely related to highway congestion. Increased highway congestion leads to increased fuel consumption and harmful emissions. Truck noise levels—originating from the exhaust, the engine, and the tires—are more a function of vehicle design, although frequent accelerating and decelerating can contribute to increased noise levels. Estimates of fuel consumption, harmful emissions and subsequent air quality, and noise levels are often derived based on changes in VMT and do not directly differentiate between truck configurations or size and weight classes.

A number of studies have considered the environment concurrently and often in conjunction with broader considerations related to pavement and bridge infrastructure, modal share, enforcement, highway safety, highway congestion, and other. Table 1, provided earlier, presents a list of key citations related to industry costs, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research that characterizes impacts to the environment: based on existing truck size and weight limits and configurations; comparatively across existing freight modes and modal shares; or attributable to advances in vehicle or roadside technologies is not included here. Similarly, strategies for controlling truck emissions—including standards which provide bounds on the amount of each pollutant emitted per unit of energy, carbon taxes and cap-and trade systems, and traffic control measures such as emissions based road user charging, high occupancy toll lanes and truck only toll lanes—are often uniformly applied to a broad class of "large or heavy trucks" with no refinement by truck size and weight limits. Such strategies may prove useful to control environmental impacts resulting from increased allowable truck size and weight limits, but contemporary research does not address this option. For a comprehensive general description of how freight contributes to air quality issues, strategies to mitigate those freight-related pollutant emissions and improve air quality, and funding and financing tools available for freight-related air quality projects, the reader is referred to the Freight and Air Quality Handbook recently published by FHWA (Hyman, Schiller, and Brogan 2010).

Individual study findings related to the environment—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- The impacts of increased truck size and weight limits on the environment are typically characterized in terms of energy consumption, harmful emissions, and noise levels.
  - Estimates are often derived from anticipated reductions in heavy truck VMT and do not directly differentiate between truck configurations or size and weight classes.
- With some consistency, fuel consumption is estimated to decrease with increased truck size and weight limits, attributable to anticipated reductions in heavy truck VMT.

General Findings (Continued)

- Harmful emissions impacts are largely inestimable for specific truck configurations or size and weight classes using contemporary models with the exception of CO_2—CO_2 production is directly proportional to diesel fuel use. As such, CO_2 production is also consistently estimated to decrease with increased truck size and weight limits, attributable to anticipated reductions in heavy truck VMT.
- Results relating increased truck size and weight limits and noise levels are inconsistent—noise levels have been shown to both increase and decrease with increased allowed truck size and weight.

Domestic Experience

As part of an early comprehensive study focused on the use of twin trailer trucks on Interstate and State highway systems, the estimated impacts to the environment were considered in *Twin Trailer Trucks* (Transportation Research Board 1986). In brief, the study reports that the use of twins, 48-ft semitrailers, and 102-in wide trucks (compared to 45-ft semitrailers and 96-in wide trucks) will each reduce exposure to noise and harmful emissions nationwide because of the expected reductions in VMT.

More recently, the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to the environment, the study's intent was to comprehensively consider differences and associated costs in energy consumption, harmful emissions, and noise levels attributable to the use of the proposed large truck configurations. Limitations in existing air quality models prevented estimation of harmful emissions costs across the various truck configurations. As such, quantitative study results were limited to consideration of energy consumption and noise levels; both were derived as a function of estimated changes in heavy truck VMT (see Table 25).

Expressed as the percent change in associated costs relative to the base case, energy consumption costs are estimated to decrease for each of the truck configuration scenarios considered. The LCV Nationwide scenario would results in the greatest cost savings—with estimated energy consumption costs 13.8 percent lower than the base case. The Triples Nationwide scenario was estimated to result in energy consumption costs 12.8 percent lower than the base case. Energy consumption costs for the North American Trade scenario were also estimated to decrease when compared to the base case—by 6.3 percent and 6.2 percent for the 44,000 and 51,000 lb tridem axle limits, respectively.

Table 25. Estimated Environmental Impacts for Various Truck Configurations Relative to Base Case (U.S. Department of Transportation 2000)

CONFIGURATION		HEAVY TRUCK VMT		ENVIRONMENTAL IMPACT			
				Energy Consumption		Noise	
		(millions)	(percent)	(million gallons)	(percent)	(million $)	(percent)
North American Trade	44,000 lb	↓13,617	↓10.6	↓1,889	↓6.3	↑281	↑6.5
	51,000 lb	↓13,656	↓10.6	↓1,870	↓6.2	↑255	↑5.9
LCV Nationwide		↓29,726	↓23.2	↓4,129	↓13.8	↑21	↑0.5
Triples Nationwide		↓25,888	↓20.2	↓3,819	↓12.8	↓7	↓0.2

Conversely, noise-related costs are estimated to increase by between 0.5 percent and 6.5 percent for each of the truck configuration scenarios considered, except the Triples Nationwide scenario which is estimated to result in a modest decrease in noise-related costs of 0.2 percent. The estimated decrease in heavy truck VMT attributable to the use of these larger, heavier truck configurations may be offset by the associated increase in the number of tires in use on the roads and engine noise.

The Transportation Research Board's *Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (2002)—which presents previous study findings of significance and opinions of an expert panel—reiterates the challenges in estimating harmful emissions across various truck size and weight classes identified in the *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000), noting that "basic data on in-use emissions of heavy trucks are extremely limited" and additional research is needed "on how truck traffic volume, the performance characteristics of trucks, and the effect of trucks on the behavior of other drivers affect emissions of all vehicles on a road."

With a singular focus on longer combination vehicles (LCVs), the Western Governor's Association prompted FHWA to assess the impacts of lifting the existing LCV freeze and allowing harmonized LCV weights, dimensions, and routes—limited only by federal axle load limits and the federal bridge formula, with a maximum gross vehicle weight of 129,000 lb and trailer lengths of 48 ft—among only those Western States that currently allow such vehicle configurations. Participating states included Washington, Oregon, Nevada, Idaho, Utah, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma. Findings are documented *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested By the Western Governors' Association* (Federal Highway Administration 2004).

With respect to the environment, study results indicate that reductions in VMT associated with the Western Uniformity Scenario could reduce fuel consumption associated with freight transportation and could also reduce emissions and highway noise. The 25 percent reduction in truck VMT associated with the scenario is estimated to result in a 12 percent reduction in fuel consumption. Fuel savings are not directly proportional to VMT reductions because fuel economy decreases as vehicle weight increases. Reductions in heavy truck travel estimated under the scenario could also reduce noise and emissions. LCVs generally are noisier than conventional trucks, primarily because they have more tires. However the lower volume of truck travel associated with the scenario would result in about a 10 percent reduction in noise-related costs compared to the base case.

As in prior studies, estimation of air quality impacts caused by changes in freight transportation under the Western Uniformity Scenario was challenged. Changes in overall truck volumes under the scenario are not likely to cause significant changes in speeds or other traffic characteristics that affect emissions rates. The primary factor that would cause emissions to change is the change in total truck volumes and the change in traffic composition with more LCVs and fewer conventional trucks. Since other environmental, technological, and geographical factors that might affect emissions are assumed to be the same for the base case and the scenario, it was assumed—consistent with methods used by the Environmental Protection Agency to estimate heavy truck emissions in its Mobile 6 model—that total emissions vary directly with changes in fuel consumption. Therefore, emissions under the Western Uniformity Scenario are estimated to decrease approximately 12 percent from the base case.

Working with the National Private Truck Council (NPTC), Woodrooffe et al. (2009) estimated the change in environmental impact if the existing federal limitations were to be lifted, allowing increased GVW limits and the use of LCVs among private fleets. Specifically, the study considered the following scenarios: (1) an 8,000 lb and 14,000 lb increase in GVW limits for a 53-ft tractor semitrailer and (2) the use of two 53-ft trailers (Turnpike doubles) with maximum GVW limited by the bridge formula. Of the companies surveyed for this study, five indicated that they would benefit from the increased GVW limit and 3 indicated that they would benefit from the expanded use of LCVs.

Study results indicate that the number of truck loads could be reduced by 10 percent if the allowable GVW was increased and 6 percent if LCVs were permitted. If both strategies were implemented, the estimated reduction in truck loads from the NPTC members surveyed is 16 percent. Extrapolating the findings from the companies surveyed as part of this study to reflect environmental impacts at the national level, Woodrooffe et al. (2009) estimates the following:

- Under the 97,000-lb GVW limit scenario, the national annual diesel fuel reduction would be nearly 3 billion gallons and the amount of CO_2 produced would be reduced by over 65.3 billion lb (32.6 million tons).
- Under the LCV scenario with an assumed 91,000 lb GVW limit, the national annual diesel fuel reduction would be 2.6 billion gallons and amount of CO_2 produced would be reduced by 58.6 billion lb (29.3 million tons).

Looking to specifically address previous shortcomings related to the estimation of harmful emissions for trucks, Scora, Boriboonsomsin, and Barth (2010) recently considered the impact of operational variability associated with heavy truck use on carbon dioxide (CO_2) emissions. Operational factors considered included vehicle weight, as well as vehicle speed, road grade, and roadway facility type. To examine how CO_2 emissions vary with weight, an emissions model developed by the authors— Comprehensive Modal Emission Model (CMEM)—was run with varying vehicle weight and speed thresholds. The results are presented in Figure 2.

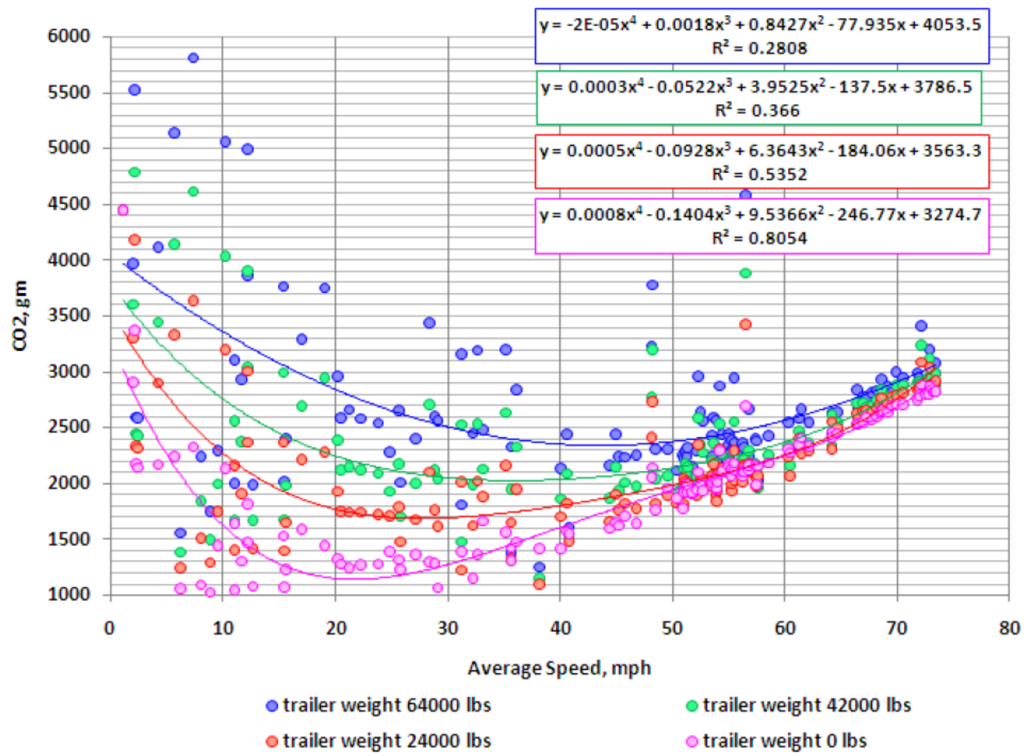

Figure 2. Modeled CO_2 Emissions as a Function of Vehicle Speed and Vehicle Weight (Scora et al. 2010)

The data suggests that the effect of vehicle weight is greater at moderate speeds with the effect decreasing at very low and very high speeds. This is consistent with the idea that at low speeds road friction plays a large role and that at higher speeds aerodynamic drag becomes an increasingly more important factor. Figure 2 also shows that as truck weight increases, the range in CO_2 emissions across all speeds for that weight decreases and that across all weights, CO_2 emissions are lowest at moderate speeds and highest at low and high speeds. The optimal driving speed at which CO_2 emissions are minimized increases with increasing vehicle weight. For the modeled vehicle, the speed at which CO_2 emissions are minimized is close to 23 mph when there is no additional trailer weight and approaches 45 mph with a large trailer weight of 64,000 lb.

State/Case Studies

Maine. The Transportation Equity Act for the 21st Century (TEA-21) provided exemptions from the federal GVW limits on the Maine and New Hampshire Turnpikes. Exempt portions of I-95 and State highways allow a GVW of up to 100,000 lb on 6-axle tractor semitrailer combinations. Certain commodity groups are also allowed a 10 percent GVW tolerance on 5-axle configurations. Individual axle weight limits range from 22,400 to 24,200 lb for a single axle, 36,000 to 44,000 lb for a tandem axle, and 48,000 to 54,000 lb for a tridem axle. Non-exempt Interstates in Maine and New Hampshire remain subject to the federal GVW limit of 80,000 lb. As a result, heavy trucks that would otherwise be through-traffic on I-95 divert to State highways upon reaching non-exempt portions of I-95.

With a focus on the environment, the American Transportation Research Institute (ATRI 2009) investigated the potential energy and emissions impacts of expanding the Federal GVW exemption to additional portions of Maine's Interstate system. Simulation methods were used to compare the environmental impacts of traditional 80,000 GVW truck configurations operating along Route 9 with the exempted 6-axle, 100,000 lb truck configurations operating along I-95 under various free flow and stop-and-go conditions.

Despite longer travel distances along the simulation route, an overall fuel savings of approximately 1 to 2 gallons was estimated when traveling the I-95 route compared to Route 9. To account for differences in trip lengths, a measurement of efficiency, miles per gallon (mpg) of fuel consumed, was used to compare the vehicle's performance over the two routes. Fuel economy improved from 14 to 21 percent over the 1-95 route compared to Route 9. The impact of stopping at all the traffic signals along Route 9 was responsible for nearly a gallon of additional fuel consumption. Carbon dioxide emissions ranged from 6 to 11 percent lower for the longer 1-95 route compared to Route 9. The impact of stopping at all the traffic signals along Route 9 increased CO_2 emissions by as much as 6 percent. Particulate matter and NOx + NMHC emissions were from 3 to 8 percent less over the 1-95 route. Assuming these findings are representative of system-wide impacts, an expansion of the GVW exemption could result in daily fuel savings of 194 gallons, CO_2 emission reductions of 2 metric tons, PM emission reductions of 12 grams, and NOx + NMHC emission reductions of 60 lbs.

Wisconsin. During the same year, Adams, et al. (2009) considered the impacts of various vehicle configurations—each with an increased allowable weight. Vehicle configurations included a 6-axle 90,000 lb tractor semitrailer, 7-axle 97,000 lb tractor semitrailer, 7-axle 80,000 lb single unit truck, and 8-axle 108,000 lb double. In addition to these four configurations, the analysis considered a 6-axle 98,000 lb tractor semitrailer and 6-axle 98,000 lb straight truck and trailer which do not meet the Federal Bridge Formula but are both currently in use through exceptions in Wisconsin law. To determine the potential impacts to the environment, researchers considered operation along non-Interstate highways only.

With respect to the environment, estimated impacts—in terms of fuel consumption and emissions of CO_2, particulate matter (PM), and nitrogen oxides (NO_x)—resulting from the proposed truck configurations are summarized in Table 26. The 6-axle 98,000 lb semitrailer has the highest fuel and emissions reductions because it diverts the most payload ton-miles from the base case truck (5-axle 80,000 lb semitrailer). Other trucks with high energy and emissions benefits include the 7-axle 97,000 lb semitrailer and the 6-axle 90,000 lb semitrailer combinations.

Table 26. Estimated Environmental Impacts for Various Truck Configurations (Adams, et al. 2009)

CONFIGURATION	DIVERTED PAYLOAD (million ton-miles)	FUEL AND EMISSIONS REDUCTIONS			
		Fuel (million gallons)	CO_2 (million lb)	PM (million grams)	NO_x (million grams)
8-axle 108,000 lb double	300	0.24	5.26	0.03	5.45
7-axle 97,000 lb tractor semitrailer	450	0.54	11.97	0.06	12.40
7-axle 80,000 lb single unit truck	25	0.04	0.92	0.00	0.96
6-axle 90,000 lb tractor semitrailer	540	0.45	9.94	0.05	10.29
6-axle 98,000 lb tractor semitrailer	900	1.42	31.62	0.16	32.76
6-axle 98,000 lb straight truck-trailer	15	0.06	1.22	0.01	1.27

International Experience

In a study sponsored by the Joint Transport Research Center of the Organization for Economic Cooperation and Development (OECD) and the International Transport Forum, Woodrooffe, Glaeser, and Nordengen (2010) considered the productivity, efficiency, and environmental impact of 40 vehicles from 10 countries. All vehicles considered were designed for longer-haul applications and were classified in three separate categories:

- Workhorse vehicles were defined in this study as having a GVW of less than 110,230 lb and a length of less than 72 ft.
- High-capacity vehicles typically operated under restricted access conditions that depend on the suitability of the road network with a GVW of up to 132,280 lb and a maximum length of 98 ft.
- Very high-capacity vehicles typically operates under permit conditions and often in rural or remote areas with a GVW of more than 110,230 lb and a length of at least 98 ft.

The metrics considered in the analysis include maximum cargo weight (mass) and volume capacity, optimum cargo density, fuel consumption, and CO_2 output.

With respect to the environment and for the vehicles examined in this study, using fuel efficiency and CO_2 produced relative to the product of cargo mass and volume was found to be the performance measure most effective at differentiating vehicle efficiency performance. The variations are significant within each vehicle class, and the performance measure results show improvement in both fuel efficiency and CO_2 produced with each increasing vehicle capacity category (see Figures 3 and 4, respectively). Because CO_2 production is directly proportional to diesel fuel use, the emissions characteristics relative to each vehicle are the same as those related to fuel consumption. Based on these results, the authors conclude that truck size and weight regulations have a significant effect on fuel consumption and vehicle emissions per unit of cargo transported and noted the importance of considering the freight transport task when evaluating environmental impacts attributable to large trucks.

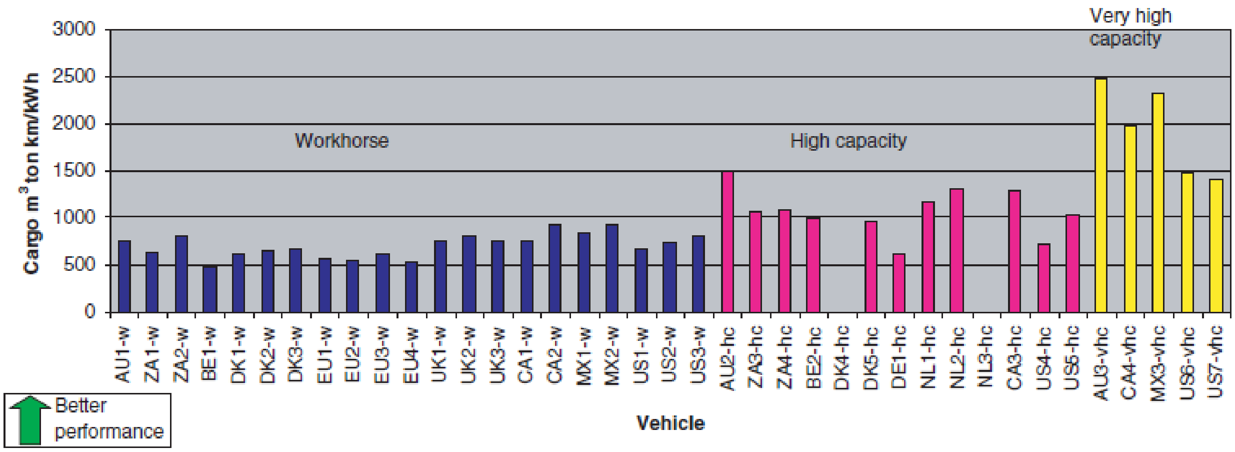

Figure 3. Comparison of Cargo Mass Volume by Fuel Consumption (Woodrooffe, Glaeser, and Nordengen 2010)

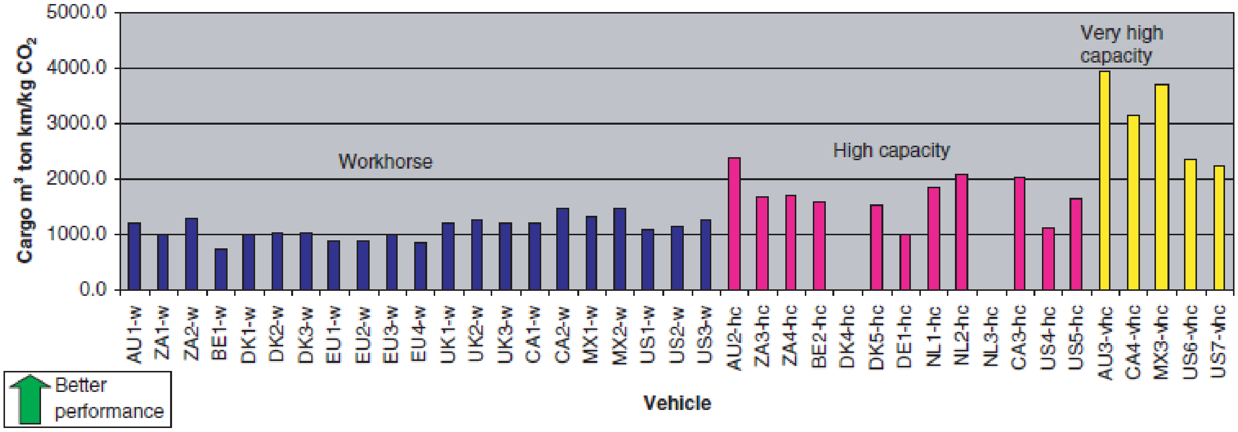

Figure 4. Comparison of Cargo Mass Volume by CO_2 Produced (Woodrooffe, Glaeser, and Nordengen 2010)

PUBLIC OPINION

Public opinion regarding increases in allowable truck size and weight has been largely shaped by media campaigns focused on safety, despite demonstrated trends in truck-related highway safety that show a marked improvement over time. Such campaigns are often sponsored by various advocacy groups including but not limited to the Advocates for Highway and Auto Safety and the Coalition Against Bigger Trucks. Few formal research studies have been conducted to accurately assess the extent of public support or opposition.

Of the studies conducted, public opinion regarding increases in allowable truck size and weight has most often been considered in isolation however, select studies have considered public opinion concurrent with other considerations related to pavement and bridge infrastructure, modal share, enforcement, highway safety, highway congestion, the environment, and other. Table 1, provided earlier, presents a list of key citations related to industry costs, including cross-cutting topic areas.

Findings from these citations are intended to support truck size and weight related decision-making—research related to public opinion associated with truck driver condition or qualifications, vehicle condition or maintenance, vehicle operating speeds, or other are not included here. In addition, this Directory does not address changes in motorists' driving behavior around trucks attributable to recent media and education campaigns (e.g., Share the Road) designed to improve safety independent of changes in truck size and weight.

Individual study findings related to public opinion—categorized by domestic experience, State/case studies, and international experience—are described distinctly below. Findings are generally presented in chronological order to demonstrate the evolving state of knowledge. A summary prefaces this section in an effort to identify noted trends or differences in research findings.

General Findings

- Public opinion regarding increases in allowable truck size and weight has been largely shaped by media campaigns focused on safety.
- Despite demonstrated trends in truck-related highway safety that show a marked improvement over time, the majority of drivers express safety concerns regarding large trucks.
- Few formal research studies have been conducted to accurately assess the extent of public support or opposition to increases in allowable truck size and weight.
- Based on a limited number of studies, increases in truck size rather than truck weight are of more concern to drivers.
  - Increased truck size—particularly length—is more visible to the public and perceived to affect safe passing maneuvers and truck driver visibility.
  - Increased truck weight is perceived to have little effect on safety—incremental changes in truck weight will likely not affect survivability in a collision.
- The majority of public respondents prefer the status quo on Federal truck size and weight limits—or a return to more restrictive limits if any changes are to be made (U.S. Department of Transportation 2000).
- Enforcement of existing truck size and weight regulations was perceived to be inadequate, undermining public confidence that increases to allowable truck size and weight limits could be controlled.

Domestic Experience

The *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) considered potential impacts of five large truck configuration scenarios, including three that involved increased truck size and weight limits:

- North American Trade: 6-axle tractor semitrailer combinations, 8-axle B-train combinations, tridem axle limits of either 44,000 or 51,000 lb.
- Longer Combination Vehicles (LCV) Nationwide: national network that would comprise 42,000 miles for Rocky Mountain and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for 8-axle B-train doubles; higher and nationally uniform weight limits by vehicle type (e.g., 120,000 lb for a 7-axle Rocky Mountain Double).
- Triples Nationwide: 65,000-mile national network for 7-axle triple combinations weighing up to 132,000 lb.

With respect to public opinion regarding the associated increases in allowable truck size and weight afforded by these configurations, the most recent *Comprehensive Truck Size and Weight Study* (U.S. Department of Transportation 2000) reiterated findings from the prior study conducted in 1996. As part of this earlier study, FHWA held twelve focus group meetings intended to assess, in part, the perceptions, concerns, and reactions of the auto driving public to possible changes in truck size and weight limits.

Study results indicated that auto drivers constantly worry about their safety when they are on the highway and perceive the greatest threat to come from other auto drivers—people who are impatient, aggressive, reckless, intoxicated or simply inattentive—although large trucks are consistently cited among their top three or four highway safety concerns. Many auto drivers indicated that they feel outmatched by the size and weight of large trucks. They indicated having seen or experienced dangerous and frightening interactions with large trucks on the highway, as well as news media reports of fatal truck crashes that stuck in their minds and reinforced their safety concerns.

The vast majority of participants said they preferred the status quo on Federal truck size and weight standards, and a return to greater restrictions if any changes were actually made. At the same time, motorists suggested that it made little difference whether truck weights were increased or decreased because, in either case, they were not likely to survive a collision with a truck. Participants said they were opposed to allowing longer trucks and trailers because they perceive longer trucks to be less safe and harder to see or maneuver around. They commented that truck length is visible and therefore they can observe its impact on safety. With respect to LCVs, many participants said that they would not believe that doubles or triples can be operated safely. Others said doubles and triples should be used, but only under very strict limits and conditions. Finally, the respondent auto drivers doubted they would realize any economic benefits from increased truck dimensions and felt that policy decisions would be based on narrow political or economic pressures and would undermine highway safety. Further, they indicated that they saw little evidence to suggest that current regulations were being adequately enforced; noting that they rarely saw trucks being inspected or pulled over for speeding.

In the same year, the Insurance Research Council (2002) released a summary of public attitudes toward trucks and highway safety. As part of a broader survey, respondents were asked whether bigger trucks should be allowed in order to increase efficiency. Only 15 percent agreed (either "strongly" or "somewhat") that bigger tractor-trailers should be allowed in order to increase the trucking industry's efficiency. Difference in opinion were noted across age ranges: 22 percent of respondents aged 34 and younger agreed that bigger trailers should be allowed, compared to only 11 percent among those 35 and older. Safety was cited as the primary reason for opposition even though 39 percent reported "rarely" or "never" observing truckers driving unsafely.

A similar survey was conducted in 2004 under sponsorship of the Advocates for Highway and Auto Safety (Harris et al. 2004). A total of 1,003 interviews were completed by telephone with randomly selected adults aged 18 years and older. Survey results indicated that a large majority (77 percent) of the public opposes increases in truck size and weight limits. When asked whether trucks pulling two or more trailers are as safe as trucks pulling one trailer, 80 percent of the respondents felt that trucks with two or more trailers are less safe.

Reflecting a third survey effort, the Social Science Research Center (SSRC) at Mississippi State University, conducts an annual national survey of drivers' attitudes and opinions. To assess public opinion concerning large trucks, Moore et al. (2005) were able to include six questions intended to assess motorists' perceptions of trucks. Survey results are based on 1,392 responses.

Based on the results of the national sample, the authors conclude that the overall perception of truck behavior on the highways is negative. The results show that the majority of respondents agree with the perception that trucks represent a safety hazard on the highway. Additionally, truck drivers are perceived to speed and create dangerous conditions for others when passing and during rainstorms. These perceptions perhaps contribute to the overall nervousness of drivers in the presence of trucks. Individual perceptions were found to be correlated, suggesting motorists have an embedded overall image of trucks, supported by our single factor solution. For example, those who perceive trucks are driving too fast are likely to perceive that trucks represent a safety hazard on the highways. Similarly, those who do not get nervous driving near trucks do not believe that trucks passing each other represent a dangerous condition. Regression analysis was used to confirm the hypothesis that motorists' perceptions of truck driving behavior influences support concerning regulations.

International Experience

Truck size and weight limits have been gradually liberalized in Canada. Allowable trailer lengths have increased from 40 ft to 45 ft, 48 ft, and now 58 ft through much of Canada. At the same time, the size of personal automobiles has continued to decrease. While safety has been closely monitored, the general public has not been consulted directly regarding these changes. Prentice and Hildebrand (1990) noted this shortcoming and attempted to introduce public opinion into the decision-making process regarding truck size and weight limits.

Results from a national telephone survey indicate that a significant portion of Canadian drivers are concerned about their safety when sharing the highways with large trucks. The level of concern varies with the characteristics of the individual, location, and road environment. Truck weight was not explicitly addressed in the survey, but concern about the size of trucks was the second most important safety concern identified by drivers (16.7 percent of responses). Most of these concerns related to the problems of visibility (not being able to pass safely or fears that the truck driver may not see them).

Most recently, the Australian National Transport Commission (NTC) sponsored an effort to enhance understanding of public perceptions regarding large trucks—shaped through the media and direct encounters on the road (Synovate, Ltd. 2010).

Study results indicate that the size of vehicle, including length and configuration, affect driver opinion when driving beside or behind these trucks. General driver behavior and attitude is based on fear for one's own safety and is not influenced by the size or type of vehicle the public owns or drives (i.e., drivers of small to medium sedans exhibit the same concerns as drivers of larger vehicles). There is a strong belief that truck driver behavior is likely to be reinforced by the type of vehicle a truck driver chooses to drive. The public perceives that aggressive looking freight vehicles are likely to be driven by 'cowboys' with little regard for others on the road. This perception then strengthens the apprehension felt when passing or being passed by trucks. Attitudes concerning the freight vehicle and freight driver are closely linked in public perception; attention to one without the other would produce little change in public concern.

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