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16. Abstract

The North American Free Trade Agreement (NAFTA) calls for harmonization of truck standards among the trade partners. Combined with the desire of U.S. industry to reduce freight costs, this aspect of NAFTA has stimulated interest in how liberalization of truck size and weight limits in the U.S. would affect highway infrastructure and safety. This report distills the findings from the extensive literature on this topic, to which a major recent addition was the Comprehensive Truck Size and Weight study prepared by the U.S. Department of Transportation. Allowing extra weight for a given type of truck can cause substantial pavement damage because of the increase in the weights of the axles. However, the truck size and weight liberalizations that have received most attention in the literature would encourage a switch from the dominant type of heavy truck, the 5-axle tractor semitrailer, to trucks that have higher payloads and additional axles. Such reforms do not necessarily create substantial pavement costs: estimates of their effect on pavement costs are generally modest and sometimes negative. More likely, they will create substantial costs for upgrading bridges to accommodate the increases in gross vehicle weights. The effects on safety are especially hard to predict. Improvements in driver performance and vehicle design can offset the safety drawbacks of larger, heavier trucks. In addition, since higher payloads reduce the number of trips required to transport a given volume of freight, allowing heavier trucks could even reduce the number of accidents. Estimation of the overall effect on safety is not possible with available data on crash rates for heavy trucks.

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EFFECTS OF TRUCK SIZE AND WEIGHTS ON HIGHWAY INFRASTRUCTURE AND OPERATIONS: A SYNTHESIS REPORT

by

David Luskin and C. Michael Walton

Research Report 0-2122-1

Research Project 0-2122
Synthesis Study of the Effects of Overweight/Oversize Trucks

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

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FEDERAL HIGHWAY ADMINISTRATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
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LIST OF ACRONYMS

AC	**Asphaltic concrete**
ALF	**Accelerated Loading Facility**
CTS&W	**Comprehensive Truck Size and Weight**
EDL	**Equivalent Distributed Load Method**
EDTF	**Equivalent Dynamic Filter Technique**
ESAL	**Equivalent single-axle load**
FBF	**Federal Bridge**
FHWA	**Federal Highway Administration**
FM	**Farm-to-Market**
FY	**Fiscal Year**
GVW	**Gross Vehicle Weight**
ITIC	**Intermodal Transportation Inventory Cost (Model)**
LEF	**Load equivalence factor**
LCV	**Longer Combination Vehicle**
MCD	**Motor Carrier Division**
NAFTA	**North American Free Trade Agreement**
OECD	**Organization for Economic Cooperation and Development**
PCC	**Portland Concrete Cement**
PSI	**Present serviceability index**
RMD	**Rocky Mountain Double**
SN	**Structural Number**
STAA	**Surface Transportation Assistance Act of 1991**
TAC	**Texas Administrative Code**
TxDOT	**Texas Department of Transportation**
TTI	**Texas Transportation Institute**
TRB	**Transportation Research Board**
TS&W	**Truck size and weight**
USDOT	**United States Department of Transportation**
VMT	**Vehicle-miles-of-travel**
WIM	**Weigh-in-motion**

PROJECT BACKGROUND

State and federal governments place various limits on the sizes and weights of vehicles on public roads. The primary purpose is to ensure compatibility of vehicle size and weight with roadway design and operations. Of particular concern are the roadway impacts of heavy trucks, which far exceed those of passenger cars.

The North American Free Trade Agreement (NAFTA) may lead to changes in truck size and weight (TS&W) regulations. NAFTA calls for unimpeded movement of trucks across the borders of the treaty partners and for the harmonization of truck standards. Although the agreement was ratified in January 1994, implementation of these provisions has been slow and the harmonization of truck standards has yet to be negotiated. Currently, Mexico and Canada allow heavier trucks than do Texas and many other states.

Even before NAFTA, segments of U.S. industry had been pressing for increased limits on TS&W to save on freight costs. These pressures and those arising from NAFTA led the Texas Department of Transportation (TxDOT) to commission the present study from the Center for Transportation Research. The study involved a review of the literature on the effects of TS&W on highway infrastructure and safety. From this literature, we have distilled certain findings that throw light on the consequences of possible changes to TS&W regulations in Texas. As TxDOT requested, we have focused in particular on possibility of increasing the limit on gross vehicle weight (GVW).

In reporting on this project, we start by describing the truck size and weight limits in place in Texas and then proceed to the lessons learned from our literature review. An annotated bibliography at the back of the report describes the studies reviewed.

WEIGHT REGULATIONS IN TEXAS

FEDERAL REGULATIONS

Weight Limits

The Federal government sets maximum axle weights for vehicles on Interstate highways: 20,000 lb for a single axle and 34,000 lb for a tandem axle. Vehicles on Interstate highways must also conform to the Federal Bridge Formula, which is designed to protect bridges from the catastrophic overloads. The formula defines a maximum weight for each axle group on a vehicle as follows:

$$W= 500 [L N/ (N-1) + 12 N + 36]$$

where

W = maximum weight in pounds carried on any group of two or more consecutive axles.

L = distance in feet between the extremes of the axle group

N= number of axles in the axle group

Federal law specifies the following exceptions to the results given by the above formula:

- The combined weight of the entire set of axles on a vehicle (the "outer bridge" group) cannot exceed 80,000 lb. In other words, gross vehicle weight (GVW) cannot exceed 80,000 lb.
- 68,000 lb may be carried on two sets of tandem axles spaced at least 36 feet apart.
- A single set of tandem axles spread no more than 8 feet is limited to 34,000 lb.

Under the "grandfather rights" accorded by federal law, some states allow vehicles to exceed the above-described weight limits on Interstate Highways. To claim these rights, a state must show that the higher weights would have been allowed under its regulations before the federal limits came into being. Texas would have difficulty making such a claim and has not attempted to do so.

Length Limits

Federal regulation of vehicle size covers the National Network defined by the Surface Transportation Assistance Act of 1982 (STAA). The National Network comprises the Interstate highway system plus designated portions of the Federal-Aid-Primary network, which predates the Interstate highway system.

STAA requires that states allow on the National Network vehicles with certain length dimensions. States are barred from limiting the length of a semitrailer in a semi trailer combination to less than 48 feet. States must also allow trailers of at least 28 feet in a twin-trailer combination; when the trailers are 28 feet, this combination is known as the STAA double (Figure 1).

STAA also restricts vehicles on the National Network to a maximum width of 8.5 feet.

STATE REGULATIONS

Texas applies the Federal limits on vehicle weight and width to all its roads. As well, it restricts tire weight to a maximum of 650 lb per square inch.

In addition, there are the following uniform limits on vehicle size:

Maximum Height	14 feet
Maximum Length:	
Semitrailer	59 feet
Double Trailers	2 x 28.5 feet
Truck and trailer	65 feet

There are no restrictions on the overall length of a tractor-semitrailer combination.

Load Posted Limits

Portions of the road and bridge network in Texas have posted weight limits that are less than the general ones described above. These limits may be imposed where "heavier maximum weight vehicles would rapidly deteriorate or destroy the road or a bridge." [1]

Both the state and county governments in Texas must base load postings on an engineering and traffic investigation that conforms to certain procedures. The procedures for determining the appropriate limits are more complicated for axle weight than for gross vehicle weight (GVW). Partly for this reason, load postings are almost always for GVW rather than axle weight, despite the engineering consensus that pavement deterioration is much less a function of GVW than of axle weight. For bridges, the posted limits on GVW make more sense because the engineering consensus is that deterioration depends mainly on GVW and axle spacing rather than axle weight.

On the state-maintained network, the load-posted stretches lie almost entirely on the network of Farm-to-Market (FM) roads. The FM roads were constructed mainly in the 1940s and 1950s to accommodate gross vehicle weights of up to 58,420 lb, the then-prevailing limit on Texas roads. Although some of these roads have since been upgraded, 58,420 lb restrictions remain on two-fifths of the nearly 41,000 centerline miles of FM roads.

[1] Texas Transportation Code, Sec. 621.102 and Sec. 621.301. See http://capitol.tlc.state.tx.us/statutes/codes.

County roads remain mostly at a standard of 58,420 lb or less, but only some are load-zoned. The establishment of load-zoned limits requires public hearings as well as an engineering study. Some county officials consider the process too troublesome to be worthwhile, particularly with holders of 2060 permits being exempt from load-posted limits (see below). Information on the proportion of county roads that are load-zoned is not readily available. In Panola County, none of the roads are load-zoned, although few can sustain even 60,000 lb trucks with any regularity.

In addition, there are many load-zoned bridges in Texas, including some 4,000 that were built to standards of less than 58,420 lb, and some that were built to a standard of only 5,000 lb. Federal law requires an inspection of each bridge every two years as part of the Bridge Replacement and Rehabilitation Program established in 1970. A bridge that receives a rating of "structurally deficient" is unsafe for legal weights and therefore must be posted and restricted. The Texas Department of Transportation (TxDOT) has advised that some stretches of pavement on the FM system are load-zoned because they lead up to load-zoned bridges, not because the pavement is structurally deficient.

Permits

As in other states, Texas issues special permits for vehicles needing to exceed these limits on portions of the road network. For a "nondivisible" load, disassembly into smaller components, in order to stay within the normal limits on vehicle dimensions, is impracticable. Such a load could be an item for heavy machinery, for example. All states issue permits for nondivisible loads and some, including Texas, issue permits for divisible loads as well.

The large majority of nondivisible-load permits issued in Texas are for single trips, the others being valid for thirty days, ninety days, or a year. To obtain a single-trip permit, an applicant must propose a route for TxDOT to review and possibly modify and pay a fee of $30 or more. The thirty- and ninety-day permits cost $60 and $120 per vehicle and allow increases in width or length only. The annual permits allow trucks up to 12 feet wide, 14 feet high, 110 feet long, and 120,000 lb in gross weight.

Nondivisible-load permits allow travel on neither load-posted stretches nor off the State-maintained network. To haul overweight on local roads, holders of the permits must seek local government approval. On the other hand, the permits may allow travel on Interstate Highways.

Since 1989, Texas has issued an annual "2060" permit that allows an additional 5 percent gross weight and 10 percent axle weight above the maximum allowable weights that would otherwise apply to the vehicle. As interpreted by the Attorney General and later by the courts, the maximum allowable weight should be calculated without regard to load-posted limits. For most vehicles with the permit, the maximum allowable gross weight without a permit would be the general cap of 80,000 lb, rather than a lower limit determined by the Federal Bridge Formula. For these vehicles, the permit allows a gross weight of 84,000 lb (5 percent above 80,000 lb).

Although the 2060 permit does not require that loads be divisible, the vast majority of loads actually carried appear to be highly divisible, such as shipments of gravel or crude oil. It is, in this respect, a “divisible-load permit.” In FY 1999, nearly 15,000 of the permits were issued at an average annual fee of $238.

Special Allowances and Exemptions

The TS&W regulations in Texas, like those of other states, are replete with allowances and exemptions for special classes of vehicles. Concrete-mixer trucks are allowed tandem axle weights of up to 46,000 lb, whereas the general limit is 34,000 lb. The deal is even better when the gross vehicle weight is less than 69,000 lb; a concrete-mixer truck can then have a tandem axle weighing up to 50,600 lb. Other special tolerances include:

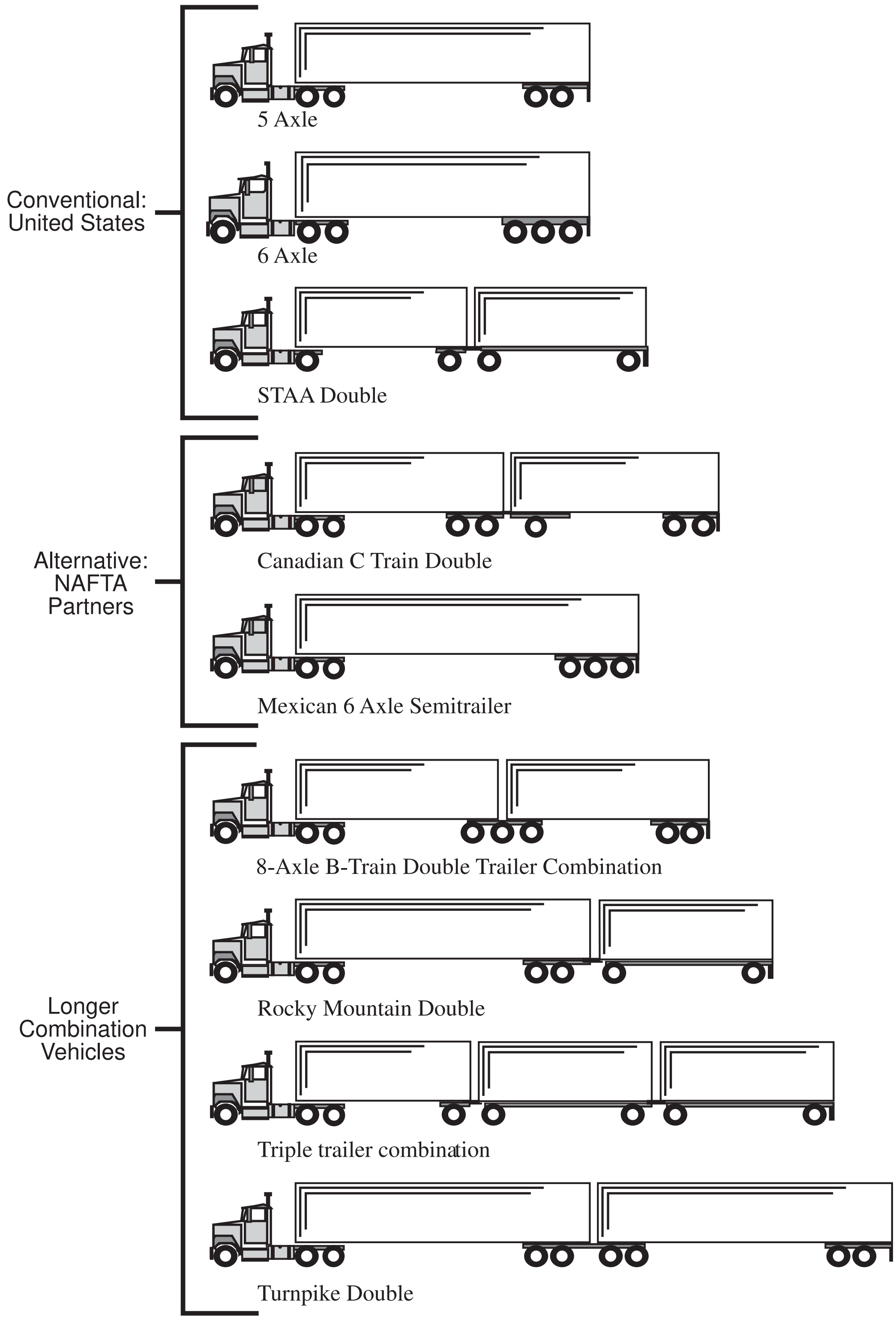
- An exemption from load-posted weight limits on state-maintained roads and bridges for vehicles delivering groceries, farm products, or liquefied petroleum gas.

- An exemption from load-posted weight limits on county roads and bridges for vehicles delivering groceries or farm products, provided that the delivery “requires” use of the road or bridge.

- An exemption from weight limits for vehicles transporting “fixed load oil field service equipment” for servicing an oil and gas well, not more than 50 miles from the equipment’s point of origin.

- A 12 percent tolerance on axle weights for vehicles hauling forestry or agricultural products in their natural state.

Figure 1: Alternative Combination Truck Configurations



REVIEW OF LITERATURE: SYNTHESIS OF FINDINGS

FREIGHT DISTRIBUTION PATTERNS

Finding 1. ***The effects on freight traffic are often hard to predict, in large part because of service quality considerations.***

To understand the effects of truck size and weight (TS&W) regulations on highway infrastructure and safety, one must consider the effects on freight traffic patterns:

- *Choice of route.* For example, in states such as Florida where the weight limits are lower on the Interstate system than on other highways, this differential may cause some rerouting away from Interstate highways. Such rerouting would be likely to increase pavement damage and compromise safety, because the Interstate highways are generally the least vulnerable to damage from heavy trucks and have the lowest rates of accidents.

- *Choice among types of trucks.* To take another example, a reform modeled in the Comprehensive Truck Size and Weight study (USDOT 2000) would supersede the bridge formula by allowing tridem axles up to 51,000 lb. Its adoption would induce shippers to switch toward trucks that use tridem axles. For example, tractor-semitrailer combinations with six axles, including a rear tridem, would replace some of the 5-axle combinations with tandem axles.

- *Choice of transport mode.* In particular, TS&W regulations can affect shipper choices between rail freight and trucking.

- *The amount of freight being shipped.* By reducing the cost of freight shipments, an increase in truck size and weight limits stimulates additional demand for freight shipments. The literature on transportation often refers to this as the "induced demand" effect.

Unfortunately, to estimate the various effects with much confidence is a major challenge, given the limitations of available data. Reflecting the difficulties of this task, each of the attempts that was reviewed for this study featured some omission or simplification that could be significant.

For most reforms to TS&W regulations, the key effects to analyze are on choices among types of trucks. To see how service quality considerations complicate such analysis, consider some reform that would allow a shipper to use trucks with larger payloads. By switching to the larger trucks, the shipper would save on transportation costs—the costs of moving the goods from origin to destination. Whether the shipper actually opts for the larger trucks, however, would also depend on service quality factors such as frequency of delivery.

A potential consequence of using larger trucks is that deliveries become less frequent: with each truck carrying a larger payload, fewer trips are needed to transport a given volume of freight. Less frequent delivery, in turn, causes inventories to accumulate, which means extra costs in tied-up capital. In addition, less frequent delivery can disrupt business operations, as when a business unexpectedly needs a large shipment in a hurry. The maintenance of additional safety stocks can avoid these disruptions for certain types of freight, but will create costs of its own. Moreover, additional safety stocks will not be feasible for some perishable or highly customized items.

Alternatively, a switch to larger trucks could be accompanied by increased consolidation of freight to maintain frequency of delivery. The consolidation of less-than-truckload shipments also entails costs, however, resulting from more circuitous truck routes, additional resources needed to coordinate shipments, and double handling of freight. For the switch to larger trucks to occur, these costs of consolidation must be less than the line-haul savings.

The Comprehensive Truck Size and Weight (CTS&W) modeled the effects on freight traffic of several scenarios for TS&W reforms, using the Intermodal Transportation and Inventory Cost (ITIC) model. The modeling framework was the most elaborate among the studies reviewed, but still had significant limitations The ITIC model assumes that larger payloads lead to less frequent service, and that this results in higher inventory costs. In addition to having this consequence, however, less frequent service can disrupt business operations in various ways (as was noted above). The ITIC model recognizes neither these disruptions nor the possibility of maintaining service frequency through freight consolidation.

The documentation of the ITIC model acknowledges that the model captures service quality considerations only in a "general way." As an example of the omissions, it notes that the freight database on which the model depends used commodity categories that were too broad to factor spoilage into the model. "Food and kindred products" would have included both canned goods and highly perishable goods.

Service quality considerations present similar challenges for modeling choices of transportation mode. Choices between trucking and rail freight services (or rail combined with road) generally present a tradeoff between price and service quality. Rail freight is generally cheaper, but trucking has advantages in flexibility and speed, and often in reliability. It is difficult to quantify the service levels provided by each mode and the values that shippers assign to each service attribute.

Also difficult to estimate are the effects of TS&W limits on the total amount of freight shipped (not just by truck). The estimates in Pickrell and Lee (1998) are highly speculative and are at a national level. A study of possible changes to gross vehicle weight limits in Montana (Hewitt et al. 1999) concluded that the effects on total volume of freight shipped are small enough to ignore, but failed to take account of substitution between truck transportation and other inputs.

Of particular interest is how liberalizations to TS&W limits would affect the total vehicle miles of travel (VMT) among heavy trucks. The Comprehensive Truck Size and Weight Study estimated this effect to be negative in each of three liberalization scenarios it modeled (see finding 9, below). This finding reflects that an increase in TS&W limits allows trucks to carry larger payloads, which reduces the number of trips needed to carry a given freight task. This effect of higher payloads outweighed the increase in truck VMT attributed to diversion from rail. The same pattern emerged from the modeling conducted in an earlier study (TRB 1990).

Finding 2. ***Some reforms to TS&W limits may have large impacts on the types of trucks in use.***

The results of the CTS&W study indicate that some of the reforms modeled would have quite large impacts on the composition of the nation's fleet of heavy trucks. Returning to the scenario where 51,000 lb tridem axles are allowed, the results indicate that such reform would cause a 70 percent decline in the miles traveled by 5 axle tractor-semitrailer combinations and correspondingly large increases in the miles traveled by combinations with tridem axles. Some of the predicted increased use of combinations with tridem axles reflected a diversion away from rail freight.

For some TS&W reforms, however, the effects on the composition of the truck fleet are minor. For example, as discussed below, the introduction in Texas of the "2060" permit for overweight trucks has caused little substitution between truck types. Unlike the reforms modeled in the CTS&W study, the permit allows an increase in weight even for the currently dominant type of combination truck, the 5-axle tractor semitrailer. The permit has simply led to heavier loads on this type of truck rather than switches to trucks with more axles.

PAVEMENTS

Finding 3. ***The pavement damage from vehicle traffic depends mainly on the number of axle passes over the pavement and axle weights.***

The consensus in engineering literature is that pavement damage is a function of the number of axle passes over the pavement and axle weights. As Crockford (1993) put it:

> The fundamental cause of pavement failure is the application of a *tire contact pressure* that exceeds the *load carrying capacity* of the pavement. The *tire contact pressure* (or the next best indicator, axle load) is important to the minimization of damage. To the trucking industry, this means that the *gross vehicle weight* is almost unlimited by the pavement structure (within reason of course)… The reason gross vehicle weight is almost unlimited by pavement structure is that tire contact pressure can be reduced by increasing the number of axles, the number of tires, or by using low inflation pressure tires.

An increase in the weight of a *given vehicle* will, of course, exacerbate the stresses on pavement by adding to axle weights. If a switch to a vehicle with additional axles accompanies an increase in gross weight, however, the pavement can be neutral or even benign. An example from USDOT (2000) compares two tractor-semitrailer combinations, each with 12,000 lb on the steering axle and with 34,000 lb on one or more tandem axles. One of the combinations has a standard 5-axle arrangement with two tandem axles, making for a gross vehicle weight of 80,000 lb. The other combination has six axles—one tandem plus a tridem loaded to 44,000 lb—and so grosses to 90,000 lb. According to the study's estimates for flexible pavements, the six-axle combination would cause 18 percent less road damage per vehicle-mile than would the 5-axle combination, despite having a gross weight that is 12 percent greater.

Finding 4. ***An increase in axle weight generally causes a more than proportional increase in pavement damage. The relationship appears to approximate an exponential function, and various studies have assumed the power of the exponent to be about 4 as a rule. Estimates of the exponent's power vary substantially, however.***

The "fourth-power" rule emerged from in-situ pavement tests conducted in the 1950s by the organization now known as AASHTO, the American Association of State Highway and Transportation Officials. The tests involved subjecting a large number of pavement structures to alternative axle loads and configurations, and then measuring the resulting damage (see Highway Research Board 1962). For each type of pavement, AASHTO subsequently derived a load equivalence factor that varies by axle configuration and axle weight. The load equivalence factor expresses the pavement damage relative to that from an 18,000 lb single axle. Analysis of the variation in these factors by axle weight led to the fourth-power "rule," which is actually a rough generalization.

Subsequent studies of pavement damage from traffic have used a variety of methods. In addition to full-scale road tests like those conducted by AASHTO—which are time-consuming and expensive—studies have used accelerated pavement testing devices and computer simulations. By passing a vehicle over a short stretch of pavement in rapid succession, an accelerated device enables 20 years of serviceability loss to be obtained in several weeks or months.

The results from these various studies are, in combination, messier than those from the AASHTO study. Even when the measure of pavement condition was the same as in the AASHTO tests (the present serviceability index), some of the findings have diverged substantially from the fourth-power rule. For example, the accelerated pavement tests conducted by Chen and Shiah (2000) indicated an exponential power of about eight versus AASHTO's four. The authors speculated that the difference may have resulted partly from the use of heavier axles in their tests than in the AASHTO tests. Another contributing factor was that the vehicles in their tests traveled at slower speed (21 km/hr) than in the AASHTO tests (see below).

The present serviceability index is based on road user perceptions of ride quality. Although it includes terms for cracking and rutting, the value of the index depends mainly on surface roughness. When a study derives separate load equivalence factors for more than one measure of road damage, the power of the exponent will often be quite sensitive to the choice of measure. OECD (1988) cited a French study in which the exponent turned out to have a power of about 2 in relation to fatigue cracking and about 8 in relation to rutting.

The power of the exponent can also differ between types of pavement. OECD (1988) concluded from its review of international evidence that while the fourth-power rule was a reasonable generalization for flexible pavements, the exponent for rigid pavements was greater than 11.

In addition, because roads designed for light duty are more vulnerable to damage from heavy loads, the exponents tend to have higher powers for these roads than for others (see, for example, Chen and Shiah 2001, p. 16). There may, however, be exceptions to this rule. In one computer simulation, the impact on pavement life of increasing axle load from 27,000 to 32,000 lb was significant for a thick pavement (SN=4.82) but negligible for a thin pavement (SN=2.92). The pavements that were simulated were flexible and their life was measured in terms of cracking (Kilareski 1989).

Finding 5. ***The effects of axle spacing on pavement damage are complex and generalizations elusive.***

The OECD (1988) found from its literature review that bunching of axles has favorable impacts on flexible pavements. For illustration, it presented load equivalence factors from the AASHTO design guide. For a flexible pavement with a PSI of 2.5 and an SN of 4.0, the load equivalence factor for a 36,000 lb tandem axle was 1.38; this means that one pass of the tandem axle over the pavement would cause the same deterioration in pavement condition (as measured by the PSI) as would 1.38 passes of a single 18,000 lb axle. Thus, distributing a 36,000 lb load over a tandem axle instead of two single axles will, according to these numbers, reduce pavement damage per mile traveled by the equivalent of 0.62 passes of a single 18,000 lb axle (0.62= 2 – 1.38). For the tridem axle, the load equivalence factor was 1.66. Kilareski (1989) reported qualitatively similar results.

For rigid pavements, the OECD reported mixed findings. The AASHTO results indicated that bunching of axles into tandems or tridems exacerbated pavement damage, whereas the results of an Italian study indicated the opposite pattern. The OECD concluded that damage to rigid pavements depends much more on load per axle component than on the spacing of components.

TRB (1990) cautioned that the "net effect of changes in axle spacing on pavement deterioration is complex and highly dependent on the nature of the pavement structure." In line with the AASHTO results, it affirmed that increasing the distance between the axles in a tandem pair from 50 to 60 inches will generally increase wear on flexible pavements and reduce it on rigid pavements. The study also explained the ways in which axle spacing affects pavement wear:

> When widely separated loads are brought closer together, the stresses they impart to the pavement structure begin to overlap, and they cease to act as separate entities. While the maximum deflection of the pavement surface continues to increase as axle spacing is reduced, maximum tensile stress at the underside of the surface layer (considered to be the primary cause of fatigue cracking) can actually decrease as axle spacing is reduced. However, effects of overlapping stress contours also include increasing the duration of loading. (USDOT 2000)

Finding 6. ***An increase in truck speed tends to have mixed effects on pavements.***

For a truck moving over a smooth pavement, the load transmitted to the pavement would be static. An increase in the vehicle's speed would not affect the intensity of the stress on the pavement, but would reduce its duration and, hence, the amount of pavement damage. Chatti et al. (1996) conducted tests on an asphalt concrete section of track and found the effects of vehicle speed to be significant. An increase in the speed of the test vehicle (a heavy truck with air suspension) from 2.7 km/hr (1.7 mi/hr) to 64 km/hr (40 mi/hr) caused approximately a 30 to 40 percent reduction in tensile strain at the bottom of the asphalt layer.

The pavements of actual roads are somewhat uneven, however, which causes vehicles traversing them to move up and down. These movements cause the load transmitted to the pavement to vary, increasing as the vehicle moves down and makes greater contact with the pavement, and decreasing as the vehicle is lifted up. Because pavement damage tends to increase more than proportionally with vehicle load (finding 4), these dynamic fluctuations add to pavement damage.

Finding 7. ***The pavement cost per mile traveled by a heavy vehicle varies greatly between pavements, being greater on pavements designed for light duty than on sturdier pavements.***

A 5-axle tractor semitrailer that weighs 80,000 lb can serve as an example. According to estimates in the Comprehensive Truck Size and Weight study, such a vehicle 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. In part, such a variation simply reflects that light-duty roads are more vulnerable to heavy vehicles than are sturdier roads. But it also reflects the major scale economies that exist in designing pavements for greater traffic loadings. TRB (1990) illustrated these scale economies with the AASHTO design manual: as the traffic loading for which a road is designed (as measured by the number of ESALs) increases, the required pavement thickness also increases but in much smaller proportion. "For example, a 10 percent increase in ESALs can be accommodated by 1.5 percent increase in pavement thickness." (TRB 1990, p. 72).

Finding 8. ***Increases in TS&W limits that lead to higher axle weights can have quite large pavement costs.***

Experience with Texas's 2060 permit can serve to illustrate this key finding. The permit is not restricted by type of vehicle or load, and can be used on all public roads except Interstate highways. It allows an additional 5 percent gross weight and 10 percent axle weight above the maximum allowable weights that would otherwise apply to the vehicle. The permit also effectively exempts a vehicle from the limits on gross weights, commonly 58,420 lb, that are posted on many bridges and stretches of pavement. Moreover, the vast majority of vehicles with 2060 permits are 5-axle tractor-semitrailer combinations, for which the maximum gross weight without a permit is normally the general cap of 80,000 lb. So as a rule, vehicles with the permit can legally operate with gross weights of up to 84,000 lb.

According to industry sources, the availability of the permit has not caused significant changes in the types of trucks used for a given freight task. Instead, the result has been that the currently predominant type of heavy truck, the 5-axle tractor-semitrailer combination, carries larger loads than before. The increase in loads has opposing effects on pavement damage. With larger loads, the same freight task can be achieved with fewer vehicle miles of travel, which reduces pavement damage. But the dominant effect, judging by the AASHTO load equivalence factors, is increased strain on pavements due to the additional weight on the load-bearing axles.

The costs of pavement damage from overweight operation under the 2060 permit depend on the types of roads on which such operation occurs. Because detailed data on this question are lacking, a recent study of the permit system (Luskin et al. 2000) considered two hypothetical scenarios. Each scenario pertains to a 5-axle combination truck that has the 2060 permit and a tare weight of 29,000 lb. The truck is loaded to 84,000 lb half the time and empty the rest of the time. Based on responses to the study's survey of permit-holders, annual mileage was assumed to be 80,000.

In the "worst-case" scenario, the truck travels exclusively on roads designed to a 58,420 lb standard, and without a permit would operate at that weight to conform to load postings. In the "best case" scenario, a truck travels exclusively on relatively heavy-duty roads—the state-maintained network other than Farm-to-Market roads—and would operate in the absence of the permit at a loaded gross weight of 80,000 lb. The rough estimates were that overweight operation under permit would cause annual pavement damage equal to $51,160 in worst-case scenario and $493 in the best-case scenario.

Although the range between these estimates is vast, reality appears to contain a significant element of the worst-case scenario. Responses to the study's survey of permit-holders indicated that trucks with 2060 permits would travel about a quarter of their miles on local roads, few of which are built to a standard exceeding 58,420 lb. Another 19 percent of the miles traveled were estimated to occur on Farm-to-Market roads, many of which were built to the 58,420 lb standard and have not been upgraded. The responses to the survey further indicate that a third of the permitted trucks are in companies that travel load-zoned roads on at least 20 percent of their trips. Such usage of load-zoned roads may not sound particularly high, but the proportion of county roads that are load-zoned would likely be higher in the absence of the 2060 permit. At present, the permit's exemption from the load-zone restrictions discourages county governments from undertaking the time-consuming process for establishing load-zone limits.

Finding 9. ***Increases to TS&W limits that encourage the use of trucks with more axles do not necessarily lead to higher pavement costs; they can even produce savings in pavement costs.***

The Comprehensive Truck Size and Weight study modeled five scenarios for reform to TS&W limits, including three scenarios that involved liberalization:

The *North American Trade scenario* would allow heavier tridem axles, up to either 44,000 or 51,000 lb, to facilitate trade between the U.S. and its NAFTA partners. Such reform would allow the eight-axle B-train combinations used in Canada to appear on U.S. highways. It would also increase the use on U.S. highways of six-axle tractor-semitrailer combinations, which are currently much more common in Canada and particularly in Mexico.

The *Longer Combination Vehicles Nationwide* scenario would establish a national network over which these vehicles could operate. The network would comprise 42,000 miles for Rocky Mountain Doubles and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for eight-axle B-train doubles. The study noted that only 21 states (not including Texas) allow Longer Combination Vehicles (LCVs), and that some of the Eastern states only allow them on their turnpike facilities. The scenario for LCVs would set nationally uniform weight limits by vehicle type—for example, 120,000 lb for a seven-axle Rocky Mountain Double—limits described as being higher than those now prevailing.

The *Triples Nationwide Scenario* would establish a national 65,000-mile network for seven-axle triple combinations weighing up to 132,000 lb.

The modeling of each scenario made use of a pavement deterioration model, NAPCOM, which has evolved since 1992. For the triples scenario, pavement restoration costs were estimated to be essentially unaffected. For the other liberalization scenarios, the modeled reform was estimated to reduce these costs. Pavement costs were measured in all cases at prices prevailing in 1994. The largest estimate pertained to the introduction of 51,000 lb tandem axles under the North American Trade scenario. This reform would reduce pavement costs over the study's 20-year planning horizon by the equivalent of a one-off reduction of $3.1 billion. At current prices, this equates to a saving of about $230 million per year for each of 20 years.[2] In the study's simulations, one source of this cost saving is

[2] The FHWA index of road construction prices increased by 19.4 percent between 1994 and the third quarter of 2000, the most recent quarter for which the index is available (FHWA 2000). Thus, $3.1 billion in pavement costs at 1994 prices equates to about $3.7 billion at near-current prices. The annualized equivalent of this amount depends on the real interest rate. The annual yield on 30-year U.S. Treasury

the reduction in total truck-miles traveled due to the increase in payload per truck. The other source of the cost saving is the switch toward using trucks with additional axles, especially, with 6 or 8 axles rather than the more conventional 5: this reduces pavement damage by spreading the truck's load over a larger number of axles.

BRIDGES

Finding 10. *The Federal Bridge Formula is in need of revision.*

The Federal Bridge Formula (FBF) was designed to protect bridges from stress levels that would risk bridge failure. The Federal government requires that vehicles on Interstate highways conform to the formula, and some states, including Texas, require exactly the same of vehicles on all public roads.

The Comprehensive Truck Size and Weight study reaffirmed the criticisms of the Federal Bridge Formula levied in TRB (1990). The study noted that formula grants additional weight to vehicles that have more axles, even though "bridge stress is affected more by the total amount of load than by the number of axles." The formula allows long combination trucks to exceed 80,000 lb even though the resulting stresses on bridges exceed the levels that the formula was meant to allow. On the other hand, the formula is unnecessarily restrictive when applied to some short trucks.

Finding 11. *The infrastructure costs of increasing truck size and weight limits tend to consist mainly of costs for bridges.*

The Comprehensive Truck Size and Weight study estimated that the modeled increases to TS&W limits would either reduce or leave essentially unchanged the costs for pavements. In contrast, the study found that these reforms would entail large costs for replacing bridges that would be unable to safely accommodate the increased vehicle weights. For example, the estimated increase in bridge cost that would result under the North American Trade Scenario was $254 billion with a 44,000 lb tridem, and $329 billion with a 51,000 lb tridem. These are one-off rather than annual costs, measured at 1994 prices. At current prices, the annualized equivalents over 20 years would be almost $19 million and about $24 million, respectively.

The simulations of TS&W reform scenarios in TRB (1990) show a similar predominance of bridge over pavement costs, with all costs measured at 1988 prices. The estimates for removing the 80,000 lb cap on gross vehicle weight can serve to illustrate. The estimated effects 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 bridge costs, $510 million stemmed from the replacement costs, $150 million from upgrading the design loads for new bridges, and only $20 million from

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bonds is about 5 percent at the time of writing, while inflation has recently been running at about 3 percent (as measured by the percent increase in the consumer price index during the year ending February 2001). The real long-term interest rate is therefore about 2 percent at present. At this rate, a one-off savings of $3.7 billion at present would equate to a savings of about $230 million for each of the next 20 years.

fatigue costs for existing bridges that would not be replaced. In comparison, the estimated savings in transportation costs were over $2 billion annually.

The evidence also suggests that the costs to society of bridge replacement are mainly in disruption of traffic while work is underway. Weissmann and Harrison (1998a, 1998b) considered the costs for bridge replacement that would be needed for U.S. highways to accommodate the types of trucks that Canada and Mexico allow. The Mexican truck was a 107,000 lb tractor-semitrailer with six axles; the Canadian truck was a 128,000 lb "C-train" short heavy double. 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. In the findings of the CTS&W study as well, the delay costs to motorists were the main costs of bridge replacement.

Possibly, these studies have exaggerated the bridge costs of increases to TS&W limits by assuming that bridges have to be replaced when they cannot safely accommodate the increases in weights. An alternative that warrants further investigation is that the bridges could be strengthened.

SAFETY

Finding 12. ***A switch toward heavier or larger trucks need not increase the rate of accidents per vehicle mile of travel. Changes in vehicle and roadway design can offset the safety drawbacks of some heavier or larger vehicles; so can improvements in the performance and selection of drivers.***

In addition to human factors, the safety performance of a truck depends on engineering factors such as resistance to rolling over and capabilities for accelerating and maintaining speed.

Static rollovers

Trucks sometimes roll over when negotiating curves ("static rollover"), but the risk is not necessarily greater for larger, heavier trucks. Indeed, an STAA double tends to be more stable on curves than a conventional 5-axle tractor semitrailer because of its additional length. Spreading a given payload over a greater length reduces the height of the vehicle's center of gravity, which reduces the risk of static rollover. Other vehicle design factors that influence this risk are track width, the suspension, and tire properties.

Other controllable influences on the risk of static rollover include roadway design and driver performance. The risk increases with the sharpness of the curve, which highway designers can control, and with vehicle speed.

Rearward amplification

Alternatively, rollovers can occur when a multi-trailer truck travels at high speed (generally above 50 mph), and the driver abruptly maneuvers the truck either left then right, or right then left. Such maneuvers may occur when the driver encounters an unexpected obstacle in the truck's path. The result is "rearward amplification" of the vehicle, which can cause the rearmost trailer to skid sideways into adjacent lanes or even to rollover. The relationship between truck size and weight and the propensity toward rearward amplification is complex. Importantly from a regulation perspective, an increase in trailer length tends to reduce this propensity—to improve "dynamic stability." In addition, dynamic stability improves with a reduction in the number of articulation points connecting the components of a combination vehicle. Substitution of B-train and C-dolly connections for the more-widely used A-dollies would effectively eliminate an articulation point.

Acceleration and speed maintenance capabilities

The acceleration and speed maintenance capabilities of heavy trucks are also important safety factors. For example, accidents can occur when a truck, particularly a long truck, crosses a non-signalized intersection after slowing or coming to a stop. With better acceleration capabilities, the truck can clear the intersection more clearly, reducing its exposure to opposing traffic. Other accident situations can result from heavy trucks accelerating more slowly than do light vehicles. In particular, when an upward grade lacks a climbing lane for slow-accelerating trucks, accidents can result when lighter vehicles that attempt to pass these trucks.

A concern about liberalization of TS&W limits is that it will increase the rate of these sorts of accidents per mile of truck travel. Indeed, without changes in other factors such as driver performance, the heavier or larger trucks that become legal will need to match or even surpass the acceleration and speed maintenance capabilities of existing trucks, if this outcome is to be avoided. However, with suitable powertrains and braking systems, as well as higher horsepower engines, this should be largely achievable. Moreover, to the extent that such changes in vehicle design do not suffice, changes in roadway design, such as provision of climbing lanes for trucks, can compensate.

Human factors

Better selection and training of drivers can counteract the potential safety risks of larger and heavier vehicles. According to the CTS&W study, improvements in these factors contributed to the decline that occurred between 1985 and 1995 in the rate of fatal accidents involving medium-to-heavy trucks. (The rate was measured per mile of truck travel.) The study referred to the introduction of nationally uniform licensing of truck drivers, tracking of drivers' traffic violations and accident experiences, and improved industry programs for driver training.

An argument can also be made that people tend to drive more cautiously in dangerous situations—the "risk compensation" hypothesis. So even when a heavier or larger truck has features that, other things equal, would increase the rate of accidents, the driver response to this situation may offset much of the added risk. Unfortunately, reliable evidence on risk compensation behavior among drivers is lacking (Levy and Miller 2000).

Finding 13. ***Analyses of crash statistics do not allow firm conclusions about differences in crash rates among classes of heavy trucks.***

Many studies have attempted to estimate the differences in crash rates among classes of heavy trucks, often with a focus on double-trailer combinations and, in particular, on longer combination vehicles. As the CTS&W study has noted, findings from this literature do not yield a clear picture. Depending on the study, the LCVs or double-trailer combinations may have crash rates that are slightly lower, slightly higher, or the same as the crash rates for other heavy trucks.

The murkiness of this picture owes to the limitations of available data related to truck crashes. Scopatz (2000) examined the quality of data collected in five states on crashes involving large trucks, with a focus on LCVs. Indicative of the problems uncovered are those he found in Oregon and Utah. The audits performed in those states 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.

In addition to the data problems with the numerator of the crash rates—the number of crashes per year—there are also data problems with the denominator, that is, the vehicle miles of travel. 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 (Mingo, Esterlitz, and Mingo 1991). In addition, they provide no breakdown of double-trailer combination traffic between LCVs and other trucks.

Another caveat about the literature under discussion is that only certain states, particularly in the West (but not including Texas), allow much use of LCVs. To generalize from evidence on the relative safety performance of LCVs in these states would be risky because the highway-system characteristics of other states may be quite different.

Finding 14. ***How an increase in TS&W limits affects safety overall depends partly on how it affects the traffic volume of heavy trucks.***

Recall that an increase in TS&W limits may reduce the volume of heavy truck traffic (because with larger payloads, the same volume of freight can be moved with fewer miles of travel). Largely for this reason, it is possible that such reform will improve road safety overall, as TRB (1990) predicted for the reforms it modeled. On the other hand, the reduction in trucking costs that result from these reforms will stimulate additional demand for trucking, which would lead to more accidents. The problems in estimating this increase in demand, which were discussed at the start of this section, will often make it unclear whether a reform would increase or reduce heavy truck traffic.

REFERENCES

ABBREVIATIONS

AASHO	American Association of State Highway Officials
FHWA	Federal Highway Administration
OECD	Organization for Economic Cooperation and Development
TRB	Transportation Research Board
USDOT	United States Department of Transportation

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APPENDIX: ANNOTATED BIBLIOGRAPHY

TRAFFIC PATTERNS

USDOT 2000, *Comprehensive Truck Size and Weight Study*, *Vol. III*: *Scenario Analysis*, Publication FHWA-PL-00-029 (Volume II), USDOT.

The Comprehensive Truck Size and Weight (CTS&W) study analyzed several scenarios for reforms to truck size and weight limits. To model the effects of these nation-wide reforms, the study divided freight traffic between short haul—operations within 200 miles — and long haul. The analysis omitted trucks with only two axles, since their dimensions are seldom constrained by the legal limits. Single-unit trucks with more than two axles were assigned to the short-haul category, since their trips are generally shorter than 200 miles. The framework for the modeling was the Intermodal Transportation and Inventory Cost (ITIC) model, which is documented in USDOT (1999).

Analysis of long-haul shipments

The CTS&W study classified combination trucks according to number of axles and number of trailers. Reforms to limits on TS&W affect shippers' choices among these truck classes and each class's vehicle-miles of travel (VMT). The CTS&W study used the ITIC model to estimate these various effects for long-haul shipments. In each reform scenario, the effects on shippers' choices among truck classes mainly took the form of substitution to, or away from, five-axle tractor semitrailers. For TS&W liberalizations, the modeling also incorporated the effects on shippers' choice of mode. By reducing the costs of trucking, increases to limits on TS&W induce shippers to divert some of their freight from rail modes to truck-only mode. The rail modes in the analysis were intermodal—containers or trailers go by rail for only part of their journey—and rail carload.

The framework for modeling long-haul shipments, the ITIC model, recognizes that choices among shipment options can entail tradeoffs between transportation and inventory costs. The assumption is that for any shipment, the shipper chooses the option that minimizes the sum of these costs.

The model adopts the conventional categorization of inventory stock as safety, cycle, or in-transit. For the calculation of safety stock, the model includes parameter values that measure the reliability of lead time for delivery. These values indicate lower reliability for rail carload than for other shipment options. However, the documentation of the model does not explain how these values were derived.

The ITIC model specifies that the amount of cycle inventory increases proportionally with the payload of the freight-moving unit. This means, for example, when a shipper switches to a truck with 20 percent more payload than a truck used previously, the amount of cycle inventory increases by 20 percent. The underlying assumption is that the frequency of delivery declines by the same proportion by which payload increases: with delivery less frequent, companies must hold higher levels of inventory to tide them over between deliveries.

The documentation of the ITIC model acknowledges that the model only “generally captures” considerations of service quality, and omits some of them. As an example of the omissions, the study noted that the freight database on which it depended used commodity categories that were too broad to factor spoilage into the model. “Food and kindred products” would have included both canned goods and highly perishable goods.

Another limitation of the ITIC model is that it takes the total volume of freight that is shipped as given. The model only explains the distribution of this total across types of trucks and modes. In reality, a change in TS&W limits could affect the total volume of freight by changing the cost of freight. In the case of increased TS&W limits, for example, the resulting gain in truck freight volume would consist partly of a net increase in the total volume of freight (all modes) rather than diversion from other modes. Based on Pickrell and Lee (1998), the CTS&W study concluded that this component of the induced increase in truck freight traffic would be small enough to ignore without much loss of realism. (See below for description of Pickrell and Lee’s paper.)

Analysis of short-haul shipments

For short-haul shipments, the study notes that rail is not competitive with truck and considers only truck-to-truck substitution. For single unit trucks, the ITIC model represents substitution between three and four-axle trucks as a function of the change in their relative operating costs (induced by changes in TS&W limits). Short-haul combination trucks are assumed to have diversion that mirrors the diversion of long-haul combination trucks.

Estimated effects on heavy truck VMT

Of the reform scenarios that the CTS&W study modeled, three involved increases to TS&W limits. These liberalization scenarios are described below in the section under **BRIDGES**. For each one, the ITIC modeling indicated that liberalization would reduce heavy truck VMT: the easing of the limits allows trucks to carry larger payloads, which means that fewer trips are needed to carry a given volume of freight. The effect of higher payloads outweighed the increase in truck VMT attributed to diversion from rail. The estimated reduction in heavy truck VMT among the liberalization scenarios varied between 10 and 23 percent.

Pickrell, D.H., and Lee, D.B. "Induced Demand for Truck Services from Relaxed Truck Size and Weight," Draft working paper prepared for the U.S. Federal Highway Administration. (The authors' affiliation is listed as the U.S. Department of Transportation, Volpe National Transportation Center, Cambridge, MA.)

Abstract from paper: "To the extent that truck operators are constrained by regulations to operate differently from what they would choose to do without restrictions, the relaxation of truck size and weight regulations would allow truckers to carry more cargo at less cost. If it is assumed that trucking is a competitive industry, these savings will be passed on to shippers. Lower prices to shippers will induce some additional amount of freight movement, more so in the long run as producers and consumers respond directly and indirectly to the relatively lower prices. The question addressed here is how much additional truck freight?"

Additional description: This working paper was prepared as an input to the CTS&W study described above; hence, the focus is on effects at the national level. In addressing the question posed in their abstract, the authors distinguish two ways in which a reduction in truck freight costs could stimulate an increase in total freight shipments:

(1) *Changes in the composition of national output.* "Prices for goods whose production and distribution costs include a significant trucking cost component would decline, and demand for these goods would increase in response. Producing and distributing the larger volumes of these goods demanded at their reduced prices would require an increase in the use of trucking services."

(2) *Substitution of trucking for other inputs to production*. "Suppliers of goods would attempt to substitute trucking services for non-transportation inputs in their production and distribution processes, further increasing the number of ton-miles carried by truck. This could occur, for example, as suppliers relocated production or warehousing facilities to take advantage of lower shipping rates by distribution networks or even reorganized production processes to substitute transportation for other inputs in response to reduced costs for truck shipping."

For a hypothetical 10 percent reduction in trucking costs, the authors estimated the increase in truck shipping that would result through each of these two channels. The choice of 10 percent was for comparability with the reductions in trucking costs of between 5 and 12 percent that the CTS&W study estimated for its truck size and weight liberalization scenarios.

The authors concluded that output compositional effects (the first of the channels identified above) would cause only a slight increase in truck freight, less than 0.3 percent. Although uncertainties about the parameter values underlying this estimate make it rather illustrative, the authors' conclusion appears sound. As the authors explain, trucking costs account for only a small share of production costs for most commodities; among the 48 commodity groups in their calculations, that share is less than 5 percent in all cases, and typically less than 2 percent. Therefore, a 10 percent reduction in trucking costs would produce only very small changes in the relative output prices of these commodities.

Regarding the effects of input substitution (the second of the above-identified channels), the authors estimated that they would cause about a 2.5 percent increase in truck freight. However, this estimate is based on a highly conjectural value (0.25) for the elasticity of substitution between trucking and other inputs (a parameter that measures the extent to which these inputs are substitutable).

BRIDGES

TRB 1990, *Truck Weight Limits: Issues and Options*, Special Report 225, TRB (National Research Council), Washington, D.C.

The report discusses basic concepts in bridge design and analyzes the impacts on bridges of potential changes to TS&W policies. The discussion of bridge design includes the following points:

Overstress: The costs associated with overstress are incurred once a bridge has been found to have inadequate load-bearing capacity to accommodate legal loadings, in which case, the owner of the bridge has three options: a) replace the bridge, b) strengthen the bridge, or c) restrict the bridge indefinitely to lighter traffic by posting a special weight limit. The report asserts that strengthening is not a viable option for many bridge types such as reinforced or prestressed concrete spans—the cost is close to the cost of replacing the bridge.

Fatigue: Bridge fatigue results from repeated loadings, and is signaled by cracks developing at points of high stress concentration. The costs associated with fatigue are due to the reduction in bridge life. “Generally, only steel bridges are susceptible to fatigue, although some studies suggest that commonly used prestressed concrete spans, if overloaded, are also susceptible to fatigue damage.”

Bridge Formula and Ratings: The report faults the Federal Bridge Formula for setting overly cautious limits on the weights of shorter trucks and for allowing too much extra weight for trucks with additional axles. The number of axles on a truck has little impact on bridges. The report also discusses alternatives to the bridge formula. Recommended are new methods for bridge rating that would make better use of remaining bridge capacity. Suggested approaches are LRFD, autostress, bridge testing, and finite-element analysis.

The scenarios for nationwide reform that are analyzed include adoption of alternative bridge formulae, retention of the current FBF but without any limit on GVW, importation of the higher TS&W limits from Canada, and the introduction of special overweight permits for special hauling vehicles.

The impacts of reforms on bridge costs had three components. The dominant component was the costs of replacing existing bridges that would be made deficient by the reform. A bridge was judged deficient if the inventory stress level (75 percent of the yield level) would be exceeded by more than 5 percent. The costs of replacement were estimated assuming that all deficient bridges would be replaced and, alternatively, that only bridges on primary highways would be replaced. Following bridge replacement costs in importance were the added costs for new bridges, due to the change in design standards that the reforms would necessitate. The fatigue impacts on existing bridges that would not need to be replaced were also costed, but were only a small component of the total estimated bridge costs. The results indicated that bridges accounted for the bulk of the infrastructure costs arising from more liberal TS&W limits. Generally, the additional infrastructure costs were much less than the estimated savings in transportation costs that the liberalization would produce.

These patterns can be illustrated with the scenario in which the Federal Bridge Formula governs without the 80,000 lb cap on GVW. The estimated increase in pavement costs was a mere $10 million per year, compared with $680 million per year assuming replacement of all deficient bridges. Of the bridge costs, $510 million stemmed from the replacement costs, $150 million from upgrading design loads for new bridges, and only $20 million from fatigue costs for existing bridges that would not be replaced. In comparison, the estimated savings in transportation costs were over $2 billion annually. (All the dollar estimates were at 1988 prices.)

USDOT 2000, *Comprehensive Truck Size and Weight Study: Volume II, Issues and Background*, Publication FHWA-PL-00-029 (Volume II), USDOT,

USDOT 2000, *Comprehensive Truck Size and Weight Study*, *Vol. III*: *Scenario Analysis*, Publication FHWA-PL-00-029 (Volume II), USDOT.

The study repeats statistics from the 1997 *Status of the Nation's Surface Transportation System*: that 11.7 percent of bridges on the nation's arterial systems are structurally deficient and 15.2 percent are functionally obsolete. The report also places the annual cost of maintaining current bridge structural and functional conditions at $5.6 billion (1995 dollars).

The study reaffirms the proposition that the impact of trucks on bridges varies primarily with the weight on each group of axles and with the distance between axle groups. The impact increases with axle group weight and, except on some continuous bridges with long spans, generally decreases with the separating distance.

The significance of distinguishing between simple and continuous-span bridges is discussed. The Federal Bridge Formula (FBF) was based on consideration of stresses on simple-span bridges only and, therefore, allows trucks to operate that could overstress certain continuous spans.

The FBF is also faulted for granting additional gross weight to trucks with more axles, even though the bridge stress depends more on the total amount of load than the number of axles. To further evaluate the formula's adequacy, the study calculated the critical weights above which the stress tolerances on which the FBF is based would be exceeded. (The tolerances are 5 percent above the design stress for HS-20 bridges, which predominate on the Interstates, and 30 percent for H-15 bridges, which are geared toward somewhat lighter loads.) These critical weights were compared with the weights actually allowed by the FBF and, alternatively, by the bridge formula developed by the Texas Transportation Institute (TTI). For semitrailer combinations with five or six axles and for Rocky Mountain doubles, the critical weights generally exceeded the allowances in the FBF and the TTI formula; that is, both of these formulas appeared to be too conservative. For multi-axle short, straight trucks, the FBF was again found to be too conservative. But for some of the larger of the Longer Combination Vehicles (LCVs), such as the nine-axle turnpike doubles, the FBF was found to allow too much weight and the TTI formula too little. The study concludes that the FBF "is not effective in modeling the actual physical phenomenon." (Much the same deficiencies in the FBF had been previously identified by TRB 1990.)

To estimate the bridge costs that would result from certain potential changes to TS&W regulations, the study developed a model that took input data from the National Bridge Inventory. For each reform scenario, the model was used to identify bridges that would be structurally deficient and to estimate the cost of replacing them. (Structurally deficient meant exceeding the stress tolerances that underlie FBF.) Importantly, the study's estimates of bridge replacement costs include the inconvenience costs to bridge users while the work is underway. Costs of bridge fatigue, on the other hand, were not considered. In part, this was because 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.[3] Overall, the study considered bridge fatigue costs to have minor relevance to the reform scenarios. The study was less dismissive of the bias in estimates that resulted from the assumption that deficient bridges would need to be replaced rather than strengthened or load-posted; this would have exaggerated the impact of reforms on bridge costs.

Three of the reform scenarios involved increases to TS&W limits:

The *North American Trade scenario* would allow heavier tridem axles, up to either 44,000 or 51,000 lb, to facilitate trade between the U.S. and its NAFTA partners. Such reform would allow the eight-axle B-train combinations used in Canada to appear on U.S. highways. It would also increase the use on U.S. highways of six-axle tractor-semitrailer combinations, which are currently much more common in Canada and particularly Mexico. The estimated increase in bridge cost that would result under the North American Trade Scenario was $254 billion with a 44,000 lb tridem, and $329 billion with a 51,000 lb tridem. These are one-off, rather than annual, costs and are measured at 1994 prices.

[3] The study also asserted that the fatigue damage is generally inexpensive to repair. Yet another reason for the study's omission of fatigue costs was that existing evidence was deemed inadequate to quantify them. Further research was called for to determine relationships between truck traffic, axle loads, and bridge (fatigue) deterioration.

The *Longer Combination Vehicles Nationwide scenario* would establish a national network over which these vehicles could operate. The network would comprise 42,000 miles for Rocky Mountain Doubles and Turnpike Doubles, 60,000 miles for triples, and the existing National Network for eight-axle B-train doubles. The study noted that only 21 states (not including Texas) allow LCVs, and that some of the Eastern states only allow them on their turnpike facilities. The scenario for LCVs would set nationally uniform weight limits by vehicle type—for example, 120,000 lb for a seven-axle Rocky Mountain Double—limits described as being higher than those now prevailing. The estimated cost of bridge replacement to accommodate the more numerous and heavier LCVs under this scenario was $319 billion.

The *Triples Nationwide scenario* would establish a national 65,000-mile network for seven-axle triple combinations weighing up to 132,000 lb. The estimated cost of bridge replacement that would result from this reform was $117 billion.

For all these scenarios, the estimates underscored the significance of the disruption to traffic from replacing a bridge. The estimated costs of the inconvenience to bridge users were much more than the capital costs entailed in bridge replacement. For example, in the LCVs Nationwide scenario, the inconvenience costs were $266 billion compared to capital costs of $53 billion.

Another finding common to the scenarios was that costs for bridges were the main infrastructure cost of implementing the reforms. The costs for pavement restoration were found to be either reduced by the reforms or, in the Nationwide Triple Scenario, virtually unaffected. The other infrastructure cost would be for upgrading roadway geometry to deal with the increased traffic from larger vehicles that have relatively poor offtracking performance. According to the study estimates, however, these costs would be quite small compared to the bridge replacement costs.

Weissmann, J., and Harrison, R. 1998a, "Impact of 44,000-kg (97,000-lb) Six-Axle Semitrailer Trucks on Bridges on Rural and Urban U.S. Interstate System," *Transportation Research Record*, no. 1624, pp. 180–183.

Abstract from article: "The impact of a 44,000-kg (97,000-lb) tridem semitrailer truck on bridges on the urban and rural U.S. Interstate system is examined. The impacts are determined using a suite of models developed for Federal Highway Administration (FHWA) policy use, and both agency and user costs are estimated. Bridges on the Interstate system that are already deficient at current loads are excluded from this analysis, which utilizes the National Bridge Inventory database and reports results for the rural and urban Interstate systems."

Additional description: The authors classified a bridge as deficient if the reference vehicle would produce stress exceeding 5 percent of the inventory rating. The authors noted that the TRB (1990), in analyzing which bridges that would become deficient as a result of reforms, also used a 5 percent tolerance, but applied this tolerance to the operating rating level of stress. The authors' justification for using the inventory rating was a survey finding that over 60 percent of states use this rating rather than the operating rating.

The reference vehicle for the base case was an 80,000 lb five-axle semitrailer truck. After determining how many bridges would be unable to safely accommodate these vehicles, the analysis was repeated for the 97,000 lb semitrailer truck with six axles (including a tridem axle). The results indicated that the number of deficient bridges on Interstate highways nearly doubles when the 97,000 lb, semitrailer trucks are allowed. The estimated cost of replacing the additional deficient bridges was about $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.

Corresponding estimates at the state level were offered in the article upon request. Substantial differences between states were noted in the estimated cost of bridge reconstruction, ranging from $33 per square foot in Texas to $155 per square foot in Rhode Island.

Weissmann, J., and Harrison, R. 1998b, "Increasing Truck Size and Weight Regulations under NAFTA: The Bridge Dimension," ***Journal of the Transportation Research Forum*****, vol. 37, no. 1, pp. 1–14.**

Abstract from article: "In the North American Free Trade Agreement (NAFTA) nations, Canadian and Mexican truck size and weight limits are substantially higher than those permitted on the Federal aid system of the United States. Currently, a NAFTA Land Transportation Standards subcommittee is considering a variety of truck related issues, including size and weight harmonization. If this process selects a typical Canadian or Mexican heavy truck as the NAFTA configuration, productivity gains will need to be balanced against the marginal increase in infrastructure costs. This paper evaluates the impacts of adopting two of the most widely used truck types—one Mexican, one Canadian—on the bridge system of the U.S. Interstate highway network. It uses a model specifically designed to calculate bridge impacts at the network level, and reports both replacement costs for the deficient structures and the user delay costs incurred when the structures are being reconstructed."

Additional description: The Mexican truck was a 107,000 lb tractor-semitrailer with six axles; the Canadian truck was a 128,000 lb "C-train" short heavy double. The methodology for estimating the additional bridge costs associated with these vehicles was the same as Weissmann and Harrison (1998a). Results were presented at national and state levels. For 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. For the Texas bridges to accommodate the Canadian-configured trucks, the total cost was an estimated $7.7 billion.

Laman, J. A., and Ahsbaugh, J.R. 2000, "Highway Network Bridge Fatigue Damage Potential of Special Truck Configurations," ***Transportation Research Record*****, no. 1696, February.**

The objectives of this study were to: (1) evaluate several special truck configurations over a statistically representative sample of steel highway bridges to determine relative fatigue damage potential on a network-wide basis; (2) develop a methodology and algorithm to accurately quantify relative fatigue damage to bridges resulting from all types of vehicles, and (3) evaluate the influence of impact (IM) values and endurance limits specified in bridge codes for fatigue analysis. The paper provides a detailed evaluation of the relative fatigue damage potential for 78 vehicle configurations. It also purportedly incorporated significant improvements to previous studies in that it was able to more accurately determine fatigue damage resulting from changes in legal and permit loading.

The study used the stress life method (S-N diagram) and developed an analytical tool to determine the fatigue damage induced by each of the study vehicle configurations. It simulated vehicle crossings over analytical bridge models. The analysis then determined stress range histories at each identified AASHTO fatigue-prone detail on the bridge. Fatigue damage factors were determined by relating the calculated stress ranges to the appropriate AASHTO classifications using rainflow counting, a modified AASHTO S-N relationship, and the "Palmgren-Miner hypothesis."

The paper states that weight distribution and axle spacing are the factors responsible for variation in vehicle damage potential for a given gross vehicle weight (GVW), and that vehicles 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 for the 78 special vehicles studied and that certain vehicle axle configurations would induce significantly lower fatigue damage to bridges for a given GVW. The paper concludes that 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 vehicles, or tractor semitrailer vehicles, induce on average, 6.5 times more damage than longer combination vehicles.

Mohammadi, J., S. A. Guralnick, and R. Polepeddi. 1998, "Bridge Fatigue Life Estimation from Field Data," ***Practice Periodical on Structural Design and Construction*****, vol. 3, no. 3, August, pp. 128–133.**

The paper presents the results of an Illinois study that investigated the effects of traffic growth and gross vehicle weight (GVW) on bridge fatigue. The study estimated the remaining life of several highway bridges by compiling strain data that were used together with roadway traffic data. The results were then used to investigate the significance of truck weight increase and traffic growth on fatigue life of the studied bridges. The paper considers a 10 percent increase in GVW (72,000 lb to 80,000 lb) and the effect of a 5 percent traffic growth factor. The authors conclude that "weight increase alone does not dramatically affect" the bridges analyzed.

The paper acknowledges that it is costly to collect comprehensive stress data and as such, used strain data to estimate remaining life. "Stress spectrum" was developed using "cycle counting" methods; in particular the "rainflow" technique was employed. The paper suggests that the methods described may be used in practice to estimate remaining fatigue life of existing bridges and to assess bridges for various conditions of truck weight and/or traffic volume.

Thater, G., P. Chang, D. R. Schelling, and C. C. Fu. 1998, "Estimation of Bridge Static Response and Vehicle Weights by Frequency Response Analysis," *Canadian Journal of Civil Engineering*, vol. 25, pp. 631-639, NRC Canada.

The paper asserts that determining truck weights and their dynamic effect are integral parts of bridge life estimation and bridge ratings, a task that has traditionally been done using weigh stations. The authors state that the use of weigh stations is "inconvenient, and that they can neither be operated continuously, nor can they provide a good estimate of the dynamic effects (of trucks on bridges)." The paper notes that more recently, weigh in motion (WIM) techniques have been employed. Weighing trucks in motion is preferable to the use of weigh stations. The paper reports that lighter and more flexible bridges, which have more significant dynamic effects, have resulted from the use of sophisticated materials and analysis techniques used in the last few decades. It states furthermore that more frequent fatigue failures of bridge components and connections indicate the need for more accurate predictions of dynamic effects. The paper proposes use of the equivalent dynamic filter technique (EDFT), which determines the dynamic and pseudo static responses. The proposed method "determines the dynamic and pseudo static responses using the Fast Fourier Transform. The reported advantage of EDFT over WIM techniques is that the EDFT predicts truck weights up to 5 percent of the actual weight, compared to 10 percent errors by WIM techniques.

The paper next gives an overview of past studies, which are judged inadequate because they gave "poor approximations to the correct static curves." The past studies also negate the assumption that static responses occurred at low frequencies and dynamic responses at high frequencies. The paper describes methods currently in use and proposes a method to distinguish static and dynamic responses. Application of the EDFT to the actual WIM data has the claimed benefit of including all of the parameters that influence bridge response, such as vehicle configuration, vehicle springing, bridge stiffness, and road surface roughness. The paper purports that the proposed method is highly accurate in estimating static vehicle weight on dynamic response untainted by other miscellaneous vibrations. It acknowledges, however, the need for further analysis before practical application of the proposed method.

TRUCK ROUTING

Osegueda, R., Garcia-Diaz, A., Ashur, S., Melchor, O., Chang, S.H., Carrasco, C., and Kuyumcu, A. 1999, "GIS-Based Network Routing Procedures for Overweight and Oversized Vehicles," ***Journal of Transportation Engineering,*** **vol. 125, no. 4 (July/August), pp. 324–331.**

This article proposes a computerized support methodology for automated routing of overweight vehicles with vertical and horizontal clearance requirements. The suggested procedure would automatically identify all bridges on a route and evaluate the adequacy of each bridge structure for a given vehicle. The procedure, which is based on a geographic information system (GIS), could be tailored to meet the requirements of the permitting agency, either to minimize travel distance or to maximize the margin of safety (in terms of bridge stress). The article also suggests the use of BRINSAP—the Texas bridge database.

The article's analysis is geared toward the administrative task of the Motor Carrier Division (MCD) of the Texas Department of Transportation, which processes over 35,000 permits each month for oversize and/or overweight vehicles. The process for finding feasible routes consists of (1) establishing a tentative route with adequate width and height clearances; (2) manually identifying all of the bridges along the route; (3) retrieving the files for each bridge; (4) analyzing each bridge to evaluate the adequacy of the structure; and (5) identifying an alternate route when at least one requirement is not satisfied.

The MCD evaluates most overweight permit requests by following the Texas Administrative Code, which limits the gross weight on each axle group as well as the load on each tire. If either the axle group weight or the tire load exceeds the specified limit, a procedure known as the Equivalent Distributed Load (EDL) method is employed. The EDL method converts the total weight of any axle group to a distributed load per linear foot. The suggested method would improve on the current procedures by incorporating bridge information, such as bridge geometry and bridge type, that the current procedures ignore. In addition, it would save considerable time in the issuance of permits.

Osegueda, R.A., Gourabathina, S., Noel, J.S. 1992, University of Texas at El Paso Research Report 1266-2, ***Towards the Implementation of an Overload Permit Formula using Network Models and BRINSAP*****, National Technical Information Service, Springfield, VA.**

The aim of this research was to improve the process for issuing overload permits in Texas by incorporating more information on bridges. The result was a conceptual methodology that uses simple network models to determine the route of travel given in general directions. The methodology also identifies bridges along the route and retrieves information about these bridges from the BRINSAP database, which it links to maps (control section and digitized geographic).

REGULATORY

Fu, G., and O. Hag-Elsafi. 2000, "Vehicular Overloads: Load Model, Bridge Safety, and Permit Checking," ***Journal of Bridge Engineering*****, vol. 5, no. 1 (February), pp. 49–57.**

Abstract from article: "All states in the U.S. issue special permits for nondivisible and/or divisible truck overloads exceeding the weight limit of the highway jurisdiction. This causes stress levels higher than those induced by normal truck traffic. The rationality of such overstress levels has not been documented. This paper addresses several aspects of this issue. It presents: 1) a method to develop live load models including overloaded trucks; 2) associated reliability models for assessing structural safety of highway bridges; and 3) proposed permit-load factors for overload checking in the load and resistance factor format. It shows that the proposed overload checking procedure leads to relatively uniform reliability of bridge structures. A sensitivity analysis is also presented here to assure that possible variations of the input data used to prescribe the proposed load factors will not adversely affect bridge safety. The proposed procedure is intended to be used by engineers responsible for checking overload permits. It may be included in evaluation specifications for highway bridges."

Keating, P.B., Litchfield, F.C., and Zhou, M. 1995, ***Overweight Permit Rules,*** **Texas Transportation Institute Report 1443-1F, National Technical Information Service, Springfield, VA.**

Abstract from article: "This document defines standards for issuing permits for overweight vehicles crossing standard H-type and HS-type Texas highway bridges. A general formula and a bridge specific formula were developed for simple spans of both bridge types. Several reinforced concrete continuous-span slab bridges were then evaluated according to the proposed criteria to ensure the validity of the proposed formulae for continuous spans as well as simple spans. The general formula limits the axle-group weight according to only the 'X' rating and the vehicle dimensions, while the bridge specific formulae also include the span length. Currently, the vehicle dimensions are the only criteria used by the Texas Department of Transportation (TxDOT) to determine whether or not an overweight permit will be issued. The proposed restrictions allow only one permit vehicle on the bridge at a time and ensure that the maximum stress does not exceed the operational stress level. In addition to determining the maximum weight, which may be safely carried by a given axle configuration over a specific bridge or an unknown bridge, the proposed formulae may also yield the 'X' rating for any specific truck. Being able to quickly convert any truck to an equivalent HX or HSX rating will greatly simplify and increase the accuracy of the permitting process."

Additional description: As of the report writing, the Central Permit Office for TxDOT was issuing more than 20,000 oversize/overweight permits each month, some of which were for superheavy vehicles requiring an engineering analysis for each bridge along the proposed route.

The study explains that Texas regulations limit the axle weights by two methods: (1) basing the limits on the number of axles in any subgroup; or (2) converting total weight of any axle group to a distributed load per linear foot, which may then be modified by additional factors for wider than average axle widths, and more than four tires per axle. The study faulted the current methods for being based on limited data regarding the overweight vehicles and for not taking into account bridge design.

The general formula proposed by the study bore some similarities to the existing Texas rules, but was significantly more restrictive. The bridge-specific formula would allow safe higher permit weights without additional engineering analysis. Its advantage over the general formula is the accuracy achieved in permitting the greatest allowable load for a particular bridge – the general formula would tend to be conservative.

Moreover, as the study points out, there is negative bending at the interior supports of continuous span bridges; a vehicle with axles near the center of the spans, adjacent to the support, would maximize the stress at this point. Thus, the assumption that a distributed load may approximate the critical axle configurations would not hold for continuous span bridges. Furthermore, the study infers that some reinforced concrete slab bridges with short spans and narrow widths, which were designed for H-type rather than HS-type live loads, may be critical, in that the H-type loading used in design would result in lower negative bending moment capacity.

The study concludes that the proposed formulae are much more versatile than those currently used and that by considering bridge design type and the span length, greater loads may be allowed without a detailed engineering analysis.

PAVEMENTS

Chatti, K., Kim, H.B., Kyong, K.Y., Mahoney, J.P., and Monismith, C.L. 1996, "Field Investigation into effects of vehicle speed and tire pressure on asphalt concrete pavement strains," ***Transportation Research Record*****, vol. 1539, pp. 66–71.**

Abstract from article: "An asphalt concrete section on a test track in the PACCAR Technical Center in Mount Vernon, Washington, was fitted with strain gauges at the surface and in pavement cores and tested using an instrumented truck operated at different speeds and with different tire pressures. The field test results are presented. The results indicate that the effects of both vehicle speed and tire pressure-contact area on pavement strains are significant. Increasing vehicle speed from 2.7 km/hr (1.7 mi/hr) to 64 km/hr (40 mi/hr) caused a decrease of approximately 30 to 40 percent in longitudinal strains at the bottom of the asphalt concrete layer, which was 137 mm (5.4 in.) thick. The speed effect on transverse strains is lower, causing only a 15 to 30 percent decrease. Reducing tire pressure from 620 kPa (90 psi) to 214 kPa (30 psi) caused a decrease of approximately 20 to 45 percent in the horizontal strains at the bottom of the asphalt concrete layer. The pressure effect on surface strains was significantly lower, causing only a 5 to 20 percent decrease. The speed effect was somewhat reduced at lower pressures, and the pressure effect was reduced at higher speeds."

Chen, J., and Shiah, M. 2001, "Development of Load Equivalence Factors for Accelerated Loading Facility (ALF) and Full-Scale Test Road," paper presented to the 80th annual meeting of the Transportation Research Board, January 7–11, 2001, Washington, D.C.

Abstract from paper: "The Accelerated Loading Facility (ALF), located at the Federal Highway Administration Turner-Fairbank Research Center, was used to simulate the effect of traffic on pavement performance. Data from two full-scale test roads (i.e., the AASHO Road Test and one conducted in Taiwan) were also compared with these from the ALF. The purpose of this study was twofold: (1) to investigate the difference between ALF and in-service pavements, and (2) to evaluate the effect of heavy traffic loading on pavement distress. An enhanced procedure was developed in this study to calculate the load equivalence factors (LEF). Results indicated that this procedure is feasible to evaluate the effect of heavy axle loadings on pavement performance under an accelerated rate. ALF pavement performance followed the trend observed on full-scale test roads. Based on present serviceability index (PSI) loss of the ALF pavement performance data, it was found that an eighth power law existed for the ALF in contrast to the fourth-power law in full-scale test roads. This implied that the LEF for ALF single-axle load of the same configuration was equal to the ratio of the axle weights raised to the eighth power. This finding explained why pavements tested by the ALF failed much faster than regulated loading. Critical loads, however, appeared to be present for pavements tested by the ALF. Pavements tested beyond the critical load might fail predominantly by traffic loading."

Additional description: The authors speculated that the difference between the eighth-power relationship suggested by their results and the AASHTO fourth-power relationship may have resulted partly from the use of heavier axles in their tests than in the AASHTO tests. Another contributing factor was that the vehicles in their tests traveled at slower speed (21 km/hr) than in the AASHTO tests. The ALF tests were performed on both thin and thick flexible pavements. The pavements had an asphalt concrete surface of either 12 cm or 18 cm, and a crushed aggregate of either 18 cm or 30 cm. When pavement damage was measured by rutting, the exponential relationship between damage and axle load had a power of about eight for the thin pavement versus about three for the thick pavement. This difference simply reflects that pavements designed for light-duty are more vulnerable to damage from heavy loads.

Crockford, W. 1993, *Weight Tolerance Permits*, Report to the Texas Department of Transportation, Texas Transportation Institute, National Technical Information Service, Springfield, VA.

Abstract from report: "The Texas legislature has authorized the issuance of annual permits allowing commercial motor vehicle operators to operate nonagricultural vehicles exceeding the legislative mandated axle weight by 10 percent and the allowable gross vehicle weight by 5 percent, with heavier loads allowed for agriculture. The $75 permit (and $15,000 bond) allows operation on state and county roads except the interstate system. The interpretation has been that this effectively allows 84,000 lb vehicles on roads designed for 58,420 lb vehicles. The movement of goods on Texas surface transportation infrastructure is an important factor in the economic health of the state; truck shipping productivity is a key element in this movement. There is often a trade-off between vehicle weight management policies and pavement management policies in the maximization of productivity. AASHTO pavement design procedures indicate that the effect of the Texas legislation should be accompanied by a permit costing significantly more than $75. The study included a full-scale truck loading experiment on two county roads and one state highway. General agreement with AASHTO damage models was found. Surveys of state and county agencies as well as the trucking industry were conducted. In general, the trucking industry showed substantial cost savings with the increase in load. Government agencies responsible for pavement and bridge management did not obtain receipts from the permit fee sufficient to offset maintenance and enforcement costs associated with this management activity."

Additional description: The survey of the trucking industry yielded a sample of only nine responding companies. However, the conclusion that the permit yields substantial savings to industry accords with the anecdotal evidence reported in a subsequent evaluation of the permit that is described below (Luskin et al. 2000).

Crockford notes that damage to pavements he considered is mainly caused by the synergistic effect of rainfall and heavy loads. Field experiments conducted for the study produced estimates of pavement damage from a 5-axle tractor semitrailer, loaded to a gross weight of either 84,000 lb or 58,420 lb. The experiments took place on light-duty rural roads. The ratios of the damage from the heavier truck to that from the lighter truck spanned from a low of 1.8 to the AASHTO-based prediction of 5.57. The study also reports that the rut depth produced by the heavier vehicle should be approximately 2.8 times that produced by a 58,420 lb vehicle.

Kilareski, W.P. 1989, "Heavy Vehicle Evaluation for Overload Permits, Rigid and Flexible Pavement Design and Analysis, Unbound Granular Materials, Tire Pressures, Backcalculation, and Design Methods," *Transportation Research Record*, no. 1227, pp. 194-204.

Abstract from article: "Highway agencies often receive requests for permits to allow the movement of overloaded machinery, structures, and other commodities. Many highway departments issue permits up to a standard-axle loading of approximately 27,000 lb; however, they do not have sufficient data to respond to requests for other loads and axle configurations. A study for the Pennsylvania Department of Transportation analyzed the expected pavement damage resulting from overloaded axle configurations, in particular, four- and five-axle configurations with loads up to 34,000 lb. A computer simulation approach was used to model both flexible and rigid pavements. Flexible pavements were analyzed with structural numbers of 2.92 and 4.82 representing a low and high structural capacity, respectively. Rigid pavement was analyzed as a 10-inch slab on 6 inches of crushed aggregate base. Calculated strains and deflections were compared to limiting tensile and vertical strains (flexible pavements) and stress ratios (rigid pavements). The remaining life of each pavement was evaluated. It was found that four- and five-axle configurations developed the same tensile stresses as the single and tandem-axle configurations for a thin flexible pavement, but the strains were lower for the thick pavement cross section. The stress ratios for the rigid pavement for all axle loads and configurations were below 50 percent, which implies that an unlimited number of repetitions can be applied."

Additional description: The author estimated the number of axle passes that could occur before the pavement started to crack. Axle passes were measured in 18 kip single-axle equivalents. For the thick flexible pavement (SN=4.82), his estimates indicated that single axles are worse for pavement than tandem axles, which, in turn, are worse than four- or five-axle configurations. (Tridem axles were not studied.) "For example, a single-axle load of 22 kips will cause cracking after 880,000 passes. A tandem axle causes cracking after 1.15 million passes. The four- and five-axle configurations cause cracking after 1.25 million passes."

Luskin, D., Harrison, R., Walton, C.M., Zhang, Z., and Jamieson Jr., J. L. 2000, "Texas Weight Tolerance Permits: Current Practice and Options," Report to the Texas Department of Transportation, National Technical Information Service, Springfield, VA.

This report evaluates the "2060" permit in Texas, which allows a 5 percent tolerance on gross vehicle weight and a 10 percent tolerance on axle weight. Although not limited to divisible loads, the freight that is carried under these permits is overwhelmingly of a divisible nature. A survey of permit-holders was conducted for the study and yielded over 300 responses indicated that the commodities carried are mainly aggregates (sand, gravel and the like), followed by agricultural and food products; forestry-related products; and chemicals, petroleum, or petroleum-related products.

After describing the regulations of truck weights in Texas, the report sketches a simplified theoretical framework for determining the optimal fee for an overweight permit. The optimality criterion is economic efficiency. In a completely efficient system, the report notes, the amount charged for each road trip would equal the costs of the externalities that the trip generates. These externalities include pollution, congestion and damage to road infrastructure (The costs of road accidents are only partly external.) To allow for the political obstacles to comprehensive reform, the framework focuses on the optimal permit fee and takes as given the provisions of other taxes and charges on road users (which consist mainly of fuel taxes and registration fees). As the analysis shows, the optimal permit fee can be very difficult to determine when other taxes and charges on road users remain economically inefficient.

The report also notes that insufficient information is available to pin down the costs of pavement damage that result from overweight operation under permit. In view of the uncertainties, it provides only "best-case" and "worst-case" estimates of the annual damage: \$493 and \$51,160. The authors note that even the smaller of these estimates exceeds the average permit fee of \$238 in FY 1999. From a survey of permit-holders that was conducted for the study, and to which 239 companies responded, the authors found that reality contains a significant element of the worst-case scenario. The conclusion drawn from this is that fees for the permit are probably below the economically efficient levels. In addition to recommending a fee increase to more fully recover the costs of pavement damage, the report offers other recommendations for the permit system.

Meyburg A., Saphores J., and Schuler, R. 1988, "The Economic Impacts of a Divisible-Load Permit System for Heavy Vehicles," ***Transportation Research A*****, vol. 32, no.2, pp.115–127.**

Abstract from article: "A methodology is demonstrated for analyzing the economic impacts of various weight limits for heavy vehicles through an application to New York State. Truck usage data were gathered from truck operators in 1990-1991 through three seasonal mail surveys, which allowed the collection of sensitive truck usage data while guaranteeing anonymity to the respondents. The benefits of this permit system are primarily lower business costs for those operators who hold permits; in the long-run, part of the savings realized by the truck operators flow to most sectors of the state's economy. On the cost side, increased infrastructure damage is assumed to result primarily from increased pavement damage. The authors find that direct benefits of the permit system (to the transportation industry and its users) exceed its costs (to society) by a factor of 17 to 1. An important finding of this study is the surprising level of non-compliance with permitted weight limits that was reported voluntarily. This may be due to the complexity of the New York state permit system and to the enforcement levels of the weight limits by state and local authorities."

Additional description: The permit system operating at the time of the surveys allowed generous weight tolerances: for example, gross weights of up to 120,000 lb and tandem axles up to 69,000 lb. The mail surveys conducted for the study requested permit-holders to provide detailed information on the characteristics of a specific truck and its usage on a randomly chosen day of the week. Other questions elicited information on the characteristics of the respondent's company. Only about one-third of the companies receiving the surveys responded

To estimate pavement costs per ESAL-mile, the authors conducted a literature review and held discussions with state highway officials. The figures they settled on were 2 cents for federal (i.e., Interstate) highways, 6 cents for state highways, and 40 cents for local highways. (These estimates are in 1987 prices, and road construction costs have since increased to the tune of 38 percent, as measured by the FHWA's road construction price index; FHWA 2000b.) In New York and other states with freeze-thaw cycles, the vulnerability of pavement damage to heavy trucks varies across seasons, variation that the study did not factor into its estimates. The study also omitted the costs of bridge deterioration and, apparently, the costs of administering the permit system. Yet, as the study noted, these costs would have to be many times the pavement damage costs to overturn the study's finding of a high benefit-cost ratio for the permit system.

OECD Scientific Experts Group. 1988, "Heavy Trucks, Climate, and Pavement Damage," *Road Transportation Research*, OECD, Paris.

This study examines the effects of heavy trucks and climate on pavements distinguished by type: flexible, semi-rigid, and rigid. A key conclusion is that axle load is a much stronger determinant of pavement damage than is gross vehicle weight. Estimates are presented for the exponent in the exponential relationship posited between pavement damage and axle load (a relationship termed the "load equivalence law"). The estimates of this parameter were based on European road tests. From the tests on Italian flexible pavements, the study estimated exponents that varied between 1.58 and 2.95 depending on the type of axle, and that had a mean value of 2. From tests on French flexible pavements, the study obtained an exponent of 2 in the case of fatigue cracking of a bituminous course and 8 in the case of permanent deformation. For flexible pavements generally, an exponent of about 4, the same as in the AASHTO-based fourth-power law, was considered a reasonable value. For semi-rigid and rigid pavements, the study estimated an exponent of between 11 and 33.

On the basis of the various tests, the authors also found that:

- For a given load and type of axle, driving axles are more destructive than carrying axles.

- For flexible pavements, the clustering of axles on a vehicle is beneficial. 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 illustration, the OECD used load equivalence factors from the AASHTO design guide. For a flexible pavement with a PSI of 2.5 and an SN of 4.0, the load equivalence factor for a 36,000 lb tandem axle was 1.38; for the tridem axle, the load equivalence factor was 1.66.

- For rigid pavements, the evidence on the relationship between axle clustering and pavement damage is mixed. The AASHTO load equivalence factors indicated that bunching of axles into tandems or tridems exacerbates pavement damage, whereas the results of an Italian study indicated the opposite pattern. Damage to rigid pavements depends much more on load per axle component than on the extent to which axles are clustered.

- For a given load and number of components, a supersingle (wide-based tire) axle is more damaging than a twin-wheel axle.

A related focus of the OECD study was dynamic versus static loading. A previous study explained the distinction thus:

> A heavy truck travels along the highway, the axle loads applied to the pavement surface fluctuate above and below their average values. The

> degree of fluctuation depends on factors such as pavement roughness, speed, radial stiffness of the tires, mechanical properties of the suspension system, and overall configuration of the vehicle. (TRB 1990, p. 86)

The OECD found that dynamic loads will range from 90 percent to 110 percent of the static loads according to the conditions of the road.

Roberts F., Djakfar L. 2000, "Preliminary Assessment of the Cost of Pavement Damage Due to Heavier Loads on Louisiana Highways," 79th Annual Meeting of the Transportation Research Board, Washington, D.C.

Abstract from paper: "The current study makes a preliminary assessment of the impact of increasing the gross vehicle weight (GVW) from current legal limits to 100,000 lb (45,360 kg) on vehicles hauling sugarcane, rice, timber, and cotton. Sample sections of road in each area of the state where the commodities are hauled were identified, the amount of each commodity hauled on the road estimated, and the effect of increasing the GVW evaluated for each section of road using pavement design models. Design data were secured from the Louisiana Department of Transportation and Development computer database and project files to determine the pavement design parameters and traffic estimates for each road. The number of vehicles hauling the 1998 harvest payload was estimated, the projected increase in the production of each commodity was based on government statistics, and rehabilitations were designed using the 1986 AASHTO Design Guide for a 20 year analysis period. Net present worth (NPW) was calculated for each GVW scenario for each roadway. Comparisons of NPW between the weight scenarios showed that increases in GVW have more effect on Louisiana state and US highways than on interstate highways. Any elevation in GVW over current limits increases the cost of overlays and decreases the length of the time before an overlay is required. The cost increase due to raising the GVW is substantial. Fee structures need to be modified by the legislature to pay for these costs through the current registration and overweight-permit fee structure or some new tax such as a ton-mile tax."

Additional description: One of the authors of the study, Professor Freddy Roberts of Louisiana Tech University, provided the Center for Transportation Research with estimates of the cost in pavement consumption per ESAL-mile of travel, based on the study. The estimates were: 48.9 cents for state-numbered routes, 16.2 cents for U.S. highways, and 2.7 cents for Interstate highways. Professor Roberts is familiar with the road network in Texas and considers its FM roads to be structurally similar to the state-numbered routes in Louisiana. He also perceives substantial similarity between these states in the standards of their U.S. and Interstate highways. The estimates for each Louisiana road category are averages among sampled roadways—four state-numbered routes, four U.S. highways, and two Interstate highways. Within the state-numbered category, there was an outlier with an estimated cost per ESAL-mile of $1.55. The outlier, according to Professor Roberts, resembles roads in Texas that are load-zoned to 58,420 lb.

Transportation Research Board. 1990, *Truck Weight Limits: Issues and Options*, Special Report 225, TRB (National Research Council), Washington, D.C.

Like so many other studies, this study affirms that pavement damage from heavy vehicles depends mainly on axle weights. To compare the impacts of axles of different weight, it uses the concept of an equivalent single axle load (ESAL), which originated with AASHTO. The benchmark in this concept is an 18,000 lb single axle: for example, an axle with 3 ESALs can be expected to cause the same pavement damage as three passes of the benchmark axle. The AASHTO tables of ESALs were based on road tests conducted in the 1950s; they indicate that ESALs increase in roughly exponential fashion with axle weight, with the exponent having a value of about 4. This is the so-called fourth-power rule (an approximation, really).

The total pavement impact for a given vehicle can thus be measured by the ESALs summed across all axles. Using the AASHTO tables, the TRB calculated for illustration the numbers of ESALs on typical vehicles. The results, shown in the following table, illustrate that heavier trucks can be pavement-friendlier than some lighter trucks with fewer axles. This pattern emerges from comparison of the two tractor-semitrailers: at 88,000 lb and six axles, the pavement damage is less than at 80,000 lb and five axles. The possibility of configuring trucks to carry heavier loads and at the same time cause less pavement damage inspired the proposal for "Turner trucks" in a companion TRB study.

Table 1: Relative Pavement Impacts of Different Trucks as Measured by Number of Equivalent Single Axle Loads

Truck Type	GVW (lb)	ESALs for Flexible Pavements	ESALs for Rigid Pavements
3-Axle Single-Unit Truck	48,000	1.48	2.10
4-Axle Single-Unit Truck	56,000	1.11	1.78
5-Axle Tractor-Semitrailer	80,000	2.37	4.07
5-Axle Double	80,000	4.05	4.09
6-Axle Tractor-Semitrailer	88,000	1.88	3.57
7-Axle Double	101,000	2.57	3.56
8-Axle B-Train Double	122,000	2.97	5.52
9-Axle Double	129,000	2.66	4.43

Source: Transportation Research Board (1990), Figure 4-3

Another important observation in the TRB's study is that there are strong economies of scale in designing new pavements for higher traffic loadings. "For example, a 10 percent increase in ESALs can be accommodated by a 1.5 percent increase in pavement thickness." The construction cost per ESAL thus tends to be much lower for a high-volume highway.

The TRB modeled several scenarios for reforms to TS&W limits (see the discussion in the bridge section of this annotated bibliography). The results from the scenario for the Uncapped Bridge Formula B (with the 80,000 lb limit on gross vehicle weight removed) indicate that this reform would have a negligible effect on pavement costs. As the study explains, such reform would induce a shift toward freight from the 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, consistent with the fourth-power rule. This explains the prediction of essentially no change in pavement damage cost, even though the reform is also predicted to increase the total road freight tonnage (owing to substitution of freight from rail to truck).

The following findings from the TRB study are also germane:

- A 10 percent increase in the number of ESALs on the nation's highways would increase pavement-related costs to highway agencies by about $375 million per year. This is the extra amount of spending required to maintain pavements in the same condition as without the increase in ESALS. Of this amount, $350 million (93.3 percent) would be for existing pavement and $25 million (6.7 percent) would be new and reconstructed pavements.

- At the national level, if all pavements in poor condition (PSI of 2.0 or less) were upgraded to good condition (PSI of 3.0 or more), highway users would save about $1 billion per year through reductions in fuel, repair, and other vehicle operating costs.

- Current tire pressures are much higher than those in the 1950s. These high tire pressures increase the rate of both rutting and cracking in flexible pavements. The effect is more significant for thinner pavement surface.

- The substitution of single tires for dual tires also increases pavement wear. The differential wear effect of single tires diminishes with increases in pavement stiffness, the width of the single tire, and the tire load.

- Whereas researchers generally agree that an increase in tire pressure and the use of single tires on trucks have adverse effects on pavements, there is no agreement on the size of the these effects. Regulation of tire pressure and the use of single tires could be warranted if more pessimistic analysis proved to be correct. Ongoing and future studies of these effects should be monitored carefully to determine whether regulation is needed.

USDOT 2000, *Comprehensive Truck Size and Weight Study: Volume II, Issues and Background*, Publication FHWA-PL-00-029 (Volume II), USDOT.

USDOT 2000, *Comprehensive Truck Size and Weight Study*, *Vol. III*: *Scenario Analysis*, Publication FHWA-PL-00-029 (Volume II), USDOT.

This study includes a background discussion of the effects of vehicles on pavements. The following observations in the study have particular relevance to the analysis of truck size and weight (TS&W) policies:

- Although the fourth-power "law" has been the rule of thumb since the AASHTO tests of the 1950s, more recent evidence indicates that the relationship between axle load and pavement deterioration generally may have a power closer to 3 than to 4.

- Increasing the spread of axles within an axle group reduces damage to rigid pavements, but increases fatigue damage to flexible pavements.

- On the Interstate highway system, half of the mileage has rigid or semi-rigid pavements. Among all hard-surface highways in the U.S., however, flexible pavements predominate: only 11 percent of highways have rigid or semi-rigid pavements.

- A vehicle's impact on a pavement depends partly on pavement characteristics and weather conditions. It also depends on the characteristics of the vehicle, especially the number of axle loadings, axle weight, and the spacing within axle groups. Of secondary importance are the type of suspension system on the vehicle, tire pressure, and tire type.

For each reform scenario, and for the scenario of no change in TS&W policies, the study estimated the costs required for pavement rehabilitation over 20 years (from 2000). Costs were measured at 1994 prices and discounted to a year 2000 present value. The analysis omitted the influence on pavement deterioration of differences among vehicles in suspension system, tire pressure, and tire type. In addition to considering these characteristics to be of secondary importance, the study saw "no reason to suppose" that they generally differ among the alternative truck configurations in the scenarios modeled.

As was mentioned above (see entry for USDOT 2000 under **BRIDGES**), the analysis indicated that one of the modeled liberalizations—the establishment of a national network for triples—would have virtually no effect on pavement costs.

The other liberalizations that were modeled would, according to the study's estimates, reduce pavement costs. The simulation of allowing 51,000 lb tridem axles (in the North American Trade scenario) produced the largest estimated reduction, about $3.1 billion. By increasing the average payload per truck, this reform would reduce the total miles that trucks must travel to carry a given volume of freight. This is one reason why the simulation indicated savings in pavement costs. The other reason is that the reform would cause the mix of heavy trucks to shift toward vehicles with more axles. The reform would favor, for example, tractor-semitrailer combinations with six axles (steering, tandem, and tridem) rather than five axles (steering plus two tandems). Spreading the weight of a vehicle over a larger number of axles does much to reduce pavement damage. Indeed, the study's illustrative calculations indicate that a six-axle tractor-semitrailer combination that weighs 90,000 lb causes less pavement damage per vehicle mile than does a 5-axle tractor-semitrailer combination that weighs 80,000 lb.

Zhang, Z., Kawa, I., and Hudson, R. 2000, "Impact of Trunnion Trucks on the Performance of Highway Infrastructure," Report to the Texas Department of Transportation, Center for Transportation Research, The University of Texas at Austin.

This study evaluates the impacts of trunnion trucks on pavements and bridges and compares them to the impacts of tridem axles. Performance-based fatigue models are introduced for flexible pavements with an asphaltic concrete (AC) surface and for rigid pavements with a Portland cement concrete (PCC) surface.

For flexible pavements, the study finds that tridem axles are more damaging than trunnion axles, with the percent difference being greater for thinner pavements. At the bottom of a 3-inch AC surface layer, a tridem axle imposes a peak strain that is 9.67 percent greater than that imposed by a trunnion axle under the same axle load condition. Increasing the surface layer to 6 inches reduces the maximum values of peak strains of both axle types and also reduces the percent differential between them: the tridem axle now imposes only about 3 percent more strain than does the trunnion axle. In terms of damage to an AC pavement surface, the estimated differences between axle types are more striking: compared to a trunnion axle of the same weight (60 kips), a tridem axle causes more than three times as much damage.

In contrast, for rigid pavements, the study finds that tridem axles are less damaging than trunnion axles, and that the percentage difference is not sensitive to pavement thickness. On PCC pavement slabs of either 8 inches or 12 inches, the tridem axle imposes a maximum stress that is about one-third less than that imposed by a trunnion axle. Translated to pavement damage, the trunnion axles are about 1.28 times worse than the tridem axles, when the axle loads are both 60 kips.

GEOMETRIC DESIGN

Beckham 1994, S. 1994, *Regional Trucking Issues: Truck-Routing Alternatives, Geometric Considerations for Large Trucks, and Regulation of Texas Trucking*, prepared for North Central Texas Council of Governments, Arlington. Available on the Web (www.bts.gov/smart/cat/TEX.html).

This report examines some issues pertaining to trucking in Texas: intrastate regulation, geometric design for large trucks, and routing restrictions on municipal roads. A framework for evaluating truck routing alternatives (including the no-restriction alternative) is presented for use by municipalities. The framework incorporates such factors as the impacts on roads, traffic conditions, safety, and the environment. The history of truck size and weight (TS&W) standards in Texas is discussed along with the then-current standards. The section on geometric design summarizes some design considerations necessary for large trucks and contains some general guidelines. Briefly discussed are the effects of intrastate trucking regulation— of control of entry into the industry and of freight rates.

Blue, D., and B. Kulakowski. 1991, "Effects of Horizontal—Curve Transition Design on Truck Roll Stability," *Journal of Transportation Engineering* vol. 117 no. 1: pp. 91–102.

This article describes a study on the effects of horizontal-curve transition design on truck roll stability. The study was done on twelve different curves using three types of transition geometry for each. One of the transition types considered was a spiral curve; another was a curve with all of the superelevation developed on the tangent. The other transition type was a combination: The entire curve has a constant radius, with two-thirds of the maximum superelevation developed on the tangent and one-third developed at the beginning of the curve. The study entailed computer simulation using a modified version of the program PHASE-4, as applied to a three-axle tractor with a 48 foot two-axle semitrailer. The assumed gross weight of this combination was 80,000 lb, and a center of gravity location was 90 inches. For all cases studied, the obtained critical speeds exceeded the AASHTO design speeds. The spiral curve was found to provide the best transition, followed by the two-thirds – one-third transition curve.

Batelle Team. 1995, "Roadway Geometry and Truck Size and Weight Regulations," working paper 5 for Comprehensive Truck Size and Weight Study Phase 1 Synthesis, prepared for FHWA (U.S. Department of Transportation). Available on the Web (www.fhwa.dot.gov/reports/tswstudy/TSWwp5.pdf).

USDOT 2000, *Comprehensive Truck Size and Weight Study: Volume II, Issues and Background*, Publication FHWA-PL-00-029 (volume II), USDOT. (The publication is also available on the Web: http://www.fhwa.dot.gov/reports/tswstudy.)

The working paper draws on many studies to examine the roadway-geometry-related effects of changes in truck size and weight (TS&W) regulations. Performance characteristics of large trucks that are covered include traction, low- and high-speed offtracking, and changes in, or maintenance of, speed. The paper considers the interaction between these characteristics and specific roadway geometric features, including interchange ramps, intersections, alignment, and cross sections. Also discussed are the implications of possible changes to regulations of vehicle or trailer lengths, distance from the kingpin to rear axle, rollover threshold, and length for double combinations. The paper concludes with a summary of knowledge gaps and research needs.

The same issues are covered in the final report. Of particular interest, the report finds that many intersections on the existing highway and street network are inadequately designed for offtracking by combination vehicles. The most common combination vehicle — the 5-axle tractor-semitrailer — will have to encroach on other lanes when turning at these intersections, or otherwise strike the curb, curbside objects, or other vehicles. A relatively long wheelbase exacerbates low-speed offtracking, which poses a problem for the expanded use of some types of longer combination vehicles.

Ervin, M., Barnes, M., MacAdam, C., and Scott, R. 1985, *Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges*, prepared for the FHWA (U.S. Department of Transportation), Report FHWA/RD-86/057, National Technical Information Service, Springfield, VA.

The study entailed a collection of accident data from several state agencies and isolating the truck accidents caused by geometric design attributes. The computer simulation model, PHASE-4, was run for six cases with varying speeds and frictional conditions. The cases investigated were situations of excessive levels of side friction demand, awkward compound curves, a short deceleration lane leading to a tight-radius curve, a curb placed along the outside of the curve, a downgrade leading to a tight curve, and poor pavement friction-level on a high-speed curve. The simulations indicated that:

- Loss-of-control accidents for trucks on interchange ramps were usually rollover and jackknife events.
- Jackknife accidents were most common at sites with high-friction demand.
- For certain trucks, the AASHTO policy for geometric design provides virtually no margin of safety against rollover.
- The AASHTO policy does not provide long enough deceleration lanes for truck combinations.
- The length of acceleration lanes provided frequently does not meet the needs of truck accelerating characteristics.

- The AASHTO policy of accepting ramp downgrades as high as 8 percent may need to be reconsidered when there is a sharp curve to be negotiated at the end.

- In some cases, curve warning signs were improperly placed (i.e., not in accordance with the Manual of Uniform Traffic Control Devices).

Finally, some recommendations are given.

Fambro, D., Mason, J., and Cline, N. 1988, "Intersection Channelization Guidelines for Longer and Wider trucks," ***Transportation Research Record*****, no. 1195, pp. 48–63.**

This paper summarizes a study that simulated vehicle offtracking using a computer model, the Truck Offtracking Model. The simulations tracked the traveled paths with different turning radii at several angles of turn for five large-truck combinations. The truck combinations used were the WB-50, WB-55, WB-70, WB-105, and WB-100. The WB-105 was found to be the most critical vehicle tested because it has the worst turning characteristics.

Glauz, W., and Harwood, D. 1991, "Superelevation and Body Roll Effects on Offtracking of Large Trucks," ***Transportation Research Record*****, no. 1303, pp. 1–10.**

This study investigated whether superelevation of a curve and body-roll effects influence offtracking of large trucks. It found that independent of vehicle speed, superelevation increases low-speed, but reduces-high speed, offtracking. This means that offtracking to the inside of the curve increases. The effect of superelevation depends upon the truck weight, the tire-cornering coefficient, and the roll-steer coefficient. The effect increases with truck weight and the roll-steer coefficient, but is weaker for trucks with worn tires.

Harkey, D., Council, F., and Zegeer, C. 1996, "Operational Characteristics of Longer Combination Vehicles and Related Geometric Design Issues," ***Transportation Research Record*****, no. 1523, pp. 22–28.**

In assessing the operational characteristics of longer combination vehicles that relate to geometric design issues, this paper focuses on Rocky Mountain doubles, turnpike doubles, and triples. Differences in low and high-speed offtracking for the longer combination vehicles (LCVs) are reported, along with the design implications for lane width and turning radius. The stability of LCVs in terms of checking rollover, trailer sway, and rearward amplification are compared to that of conventional tractor semitrailers. LCVs were found to be comparatively unstable, a problem that increases when shorter trailers are used and when the number of articulation points increases. Studies on braking and stopping distance are discussed, along with field observations of LCVs. Evidence on whether LCVs have worse than average braking characteristics was determined to be inconclusive. Finally, some accident studies that would add to our knowledge of LCVs are recommended.

Harwood, D., Glauz, W.D., Elefteriadou, L., Torbic, D.J., and McFadden, J. 1999, "Distribution of Roadway Geometric Design Features Critical to Accommodation of Large Trucks," *Transportation Research Record*, no. 1658, pp. 77–88.

This study evaluated the geometric design of the current roadway system for its ability to accommodate large trucks. The 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. Data on geometrics of interchange ramps and at-grade intersections were collected from California and from two states in each of the four regions into which the rest of the U.S. was divided (west, midwest, northeast, and southeast). The data revealed 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 12 m (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.

Harwood, D., and Mason, J. 1994, "Horizontal Curve Design for Passenger Cars and Trucks," *Transportation Research Record*, no. 1445, pp. 22–33.

This paper evaluates the 1990 AASHTO geometric design policy for vehicle safety on horizontal curves. Low-speed curves were considered along with high-speed or open-highway curves. A sensitivity analysis was conducted for passenger cars and trucks traveling at the design speed on minimum-radius curves conforming to AASHTO policy. The results indicated that the existing design policy for high-speed curves provided adequate margins of safety against skidding and rollover. For low-speed curve design, however, it was recommended that the design criteria be revised.

Harwood, D., W. Glauz, and L. Elefteriadou. 1999, "Roadway Widening Costs for Geometric Design Improvements to Accommodate Potential Larger Trucks," *Transportation Research Record*, no. 1658, pp. 89–97.

This paper presents a study of the costs of widening existing roads that would be required to accommodate larger trucks. Low-speed offtracking was the criterion for judging where widening would be needed. Among the twelve truck types considered, the amount of offtracking (as measured by the swept-path width) was least for the benchmark truck, a tractor pulling a single 48 ft semitrailer.

Institute of Transportation Engineers (ITE) 1992, "A Summary of an ITE Informational Report: Geometric Design and Operational Considerations for Trucks," *ITE Journal* vol. 62 no. 8, pp. 12–15.

Institute of Transportation Engineers (ITE) 1992, *Geometric Design and Operational Considerations for Trucks*, Pub. no. IR-062, ITE, Washington, D.C.

Abstract of the report: "The information in this report has been obtained from experiences of transportation engineering professionals and research. The purpose was to

assemble in one document current information on large trucks that will be useful to highway and traffic engineers in adequately accommodating trucks on roadways. The report contains information on truck dimensions and performance characteristics. It also provides details for use in the design of roadway elements, such as intersections and horizontal and vertical geometry. Other areas covered include the impact of trucks on highway capacity and methods for handling trucks in work zones."

Additional description: Among the truck performance characteristics considered are rollover stability, stopping sight distance, turning radii and offtracking, and acceleration characteristics. For rearward amplification, the report found that triples create the most amplification, followed by the shorter doubles; the longer doubles are more stable comparatively. The geometric design issues covered include sign placement.

Keller, J. 1993 "Interchange Ramp Geometrics — Alignment and Superelevation Design," *Transportation Research Record*, no. 1385, pp. 148–154.

This paper considered several aspects of interchange ramp design that pertain to alignment and superelevation. Trucks were not the main focus but situations in which special considerations are necessary for trucks were discussed. Sight distance and superelevation were the two main components related to trucks that were addressed. The paper reported that the growth in large truck-trailer combinations was eroding safety margins because these vehicles have superelevation and stopping distance requirements that exceed those of automobiles. It also concluded that "spiral curves provide the most appropriate means to effect superelevation and be certain that the roadway and motorist interact in the manner expected."

Mason, J., Fitzpatrick, K., Harwood, D.W., and True, J. 1993, "Intersection Design Considerations to Accommodate Large Trucks," *Transportation Research Record*, no. 1385, pp. 32-40.

In this paper, the authors review evidence from studies related to geometric and operational considerations for large trucks and offer some recommendations. Topics considered include truck physical characteristics, offtracking, intersection sight distance, channelization, and traffic engineering elements. The paper notes that where the curb radius is large enough to accommodate trucks without encroachment, the paved area of an intersection may become so substantial that drivers may not know where to position their vehicles. In these situations, intersection channelization becomes a necessity for controlling and directing traffic movements.

Miaou, S., and Lum, H. 1993, "Statistical Evaluation of the Effects of Highway Geometric Design of Truck Accident Involvements," *Transportation Research Record*, no. 1407, pp. 11–23.

The effects of highway geometric design on truck accident involvement rates were modeled using Poisson regression for this study. Also considered were expected reductions in accidents from improvements in various highway geometric design features. The study focused on Utah data from the Highway Safety Information System.

Miaou, S. 1994, "The Relationship Between Truck Accidents and Geometric Design of Road Sections: Poisson Versus Negative Binomial Regressions," ***Accident Analysis and Prevention*** **vol. 26 no. 4, pp. 471–482.**

Article abstract: "This paper evaluates the performance of Poisson and negative binomial (NB) regression models in establishing the relationship between truck accidents and geometric design of road sections. Three types of models are considered: Poisson regression, zero-inflated Poisson (ZIP) regression, and NB regression. Maximum likelihood (ML) method is used to estimate the unknown parameters of these models. Two other feasible estimators for estimating the dispersion parameter in the NB regression model are also examined: a moment estimator and a regression-based estimator. These models and estimators are evaluated based on their (1) estimated regression parameters, (2) overall goodness-of-fit, (3) estimated relative frequency of truck accident involvements across road sections, (4) sensitivity to the inclusion of short road sections, and (5) estimated total number of truck accident involvements. Data from the Highway Safety Information System are employed to examine the performance of these models in developing such relationships."

Additional description: Using the ML estimation, the author found that estimated regression parameters are similar for all three models, with no relative difference in estimated truck accident involvements across road sections. For developing a relationship in an initial model, the use of Poisson regression model is suggested. Caution is advised in using the NB regression model, estimated using either the moment or regression-based method.

Perera, H., Ross, H., and Humes, G. 1990, "Methodology for Estimating Safe Operating Speeds for Heavy Trucks and Combination Vehicles on Interchange Ramps," ***Transportation Research Record*****, no. 1280, pp. 208–215.**

Presented in this paper is a methodology for estimating safe operating speeds for heavy trucks and combination vehicles on interchange ramps. The methodology entails a modified version of the computerized model PHASE-4; the input information includes specifications of the ramp geometry and the design vehicle. The critical speed is the threshold beyond which the vehicle rolls over or runs off the ramp. A safe operating speed is calculated by dividing critical speed by a factor of safety. An example is given in which the safe operating speeds are less than those given in the AASHTO Green Book. This suggests that the Green Book designs for ramps may provide large trucks with an inadequate margin of safety against rolling over or running off of the ramps.

SAFETY

USDOT 2000, *Comprehensive Truck Size and Weight Study: Volume II, Issues and Background*, Publication FHWA-PL-00-029 (Volume II), USDOT. (The publication is also available on the Web: http://www.fhwa.dot.gov/reports/tswstudy)

USDOT 2000, *Comprehensive Truck Size and Weight Study*, *Vol. III*: *Scenario Analysis*, Publication FHWA-PL-00-029 (Volume II), USDOT. (The publication is also available on the Web: http://www.fhwa.dot.gov/reports/tswstudy)

This study cites several initiatives that have contributed to the marked decline in commercial truck accident rates from 1985 through 1995:

- Introduction of nationally uniform licensing of truck drivers and tracking of drivers' traffic violations and accident experiences
- Increased safety technology in truck designs, such as improved seat belt designs and antilock braking systems
- Audits and inspections performed under the Motor Carrier Safety Assistance Program
- Industry-sponsored initiatives such as upgraded driver training

The accident risk associated with different types of heavy trucks is discussed extensively. The study was skeptical about the ability of analyses of crash records to yield a clear picture. It noted, for one thing, that analyses of this type have produced disparate findings:

> Many past studies have attempted to estimate the singular effect on crash propensity of size and weight differences among various truck configurations, with particular focus on double-trailer combinations, or more specifically longer combination vehicles (LCVs). Their conclusions vary from slightly positive to slightly negative, to no difference. This disparate in findings is explained, in large part, by the different methodologies and data sets used to conduct the various studies. (vol. III, p. VIII-2)

Also noted was that few of these past studies had statistical controls for vehicle operating environment and other confounding influences on crash rates. Without such controls, the results can be deceptive: for example, a truck with poor safety characteristics could have a relatively low crash rate if it happens to travel more than other vehicles on relatively safe roadways. Another problem identified was the scarcity of crash data in which LCVs are distinguished from other double combinations.

In light of these problems with crash data, the study relied instead on the evidence from tests of vehicle and driver performance.

One source of evidence was a study sponsored by the FHWA Office of Motor Carriers to investigate whether drivers experience more stress or fatigue when driving longer combination vehicles (LCVs). The investigation entailed a test in which twenty-four experienced LCV drivers operated under representative daytime schedules on limited access highways. The findings suggested that the most significant contributions to driver fatigue were individual driver characteristics, the number of hours worked since the last rest period, and the number of consecutive days of work. The type of vehicle played a "marginal" role. Drivers appeared to perform somewhat better in tests involving a single-trailer (48 foot trailer) combination than in the tests with triple combinations. The measures of performance were based on lane tracking, fatigue/physiological recovery, and subjective workload.

Other evidence came from investigations of particular aspects of vehicle performance. In brief, the study's discussion ran as follows:

Low-speed offtracking causes the rear of a vehicle to track inward of the swept path of the vehicle's front. Although longer wheelbases on trailers generally worsen offtracking, this does not mean that offtracking increases with overall vehicle length. In fact, the standard STAA double and triple combinations (with 28 foot trailers) offtrack less than a standard tractor and 53-foot semitrailer combination. This is partly because the individual trailers in these multi-trailer combinations have relatively short wheelbases. The other reason is that additional points of articulation on a combination reduce the extent of offtracking. Low-speed offtracking is not a serious safety problem; it has minimal effect on the likelihood of serious crashes (fatal or injury-producing). More significant consequences are traffic disruption and damage to infrastructure (such as curbs).

High-speed offtracking has the opposite effect of low-speed offtracking, causing the rear of a vehicle to track outward of the swept path of a vehicle's front. Conceivably, a combination truck that high-speed offtracks on a curve could hit the curb and then roll over. However, high-speed offtracking has not been linked to any appreciable number of truck crashes.

Vehicle acceleration and speed maintenance are especially important for preventing accidents on grades and at non-signalized intersections. The use of higher horsepower engines and suitable powertrains can enable large and heavy trucks to perform adequately in these respects. On steep grades, special truck climbing lanes can be provided to prevent traffic conflicts between slow-moving trucks and other, faster-moving vehicles.

Braking performance "is a general concern that applies to all trucks and is not particularly influenced by changes in TS&Ws, if the requisite number of axles and brakes are added as the vehicle's weight increases and all the vehicle's brakes are well-maintained." (vol. III, p. V-20)

Sight distance requirements increase with vehicle length. The additional lengths of LCVs increase the accident risk for vehicles attempting to pass them. To offset this added risk, cars passing LCVs on two-lane roads need as much as 8 percent more sight distance. Additional truck length also increases the sight distance that trucks need to safely traverse non-signalized intersections. Equipping longer vehicles with powertrains that ensure adequate acceleration can, however, minimize the need for additional sight distance.

The summary of the evidence on safety and truck performance states:

> Multi-trailer combinations without compensating design features have inferior performance capabilities compared to single-trailer combinations and these differences, especially if frequently challenged in traffic conflict situations, result in incrementally higher crash likelihoods. (vol. II, p. V-23)

DATABASES

Insurance Institute for Highway Safety and Highway Loss Data Institute, *Large Trucks*, available on the Web (http://www.iihs.org/safety_facts/qanda/trucks.htm).

This web site presents facts and figures on large-truck safety, though often without full references to sources. To the question, Are multiple-trailer trucks more likely to crash than single-trailer trucks?, the site provides this answer:

> Multiple-trailer trucks have more handling problems than single-trailer trucks. In general, the additional connection points contribute to greater instability, which can lead to jackknifing, overturning, and lane encroachments. But the relationship between multiple-trailer trucks and crash risk isn't firmly established. A study in Washington State found doubles (tractors pulling two trailers) were two to three times as likely as other rigs to be in crashes, but a study in Indiana found doubles didn't show increased crash risk except on roads with snow, ice, or slush. Doubles often are operated by drivers with good safety records working for large companies with active safety programs.

The site also contains links to the Institute's publications.

"Traffic Safety Facts 1998: Large Trucks," USDOT and National Highway Transportation Safety Administration, DOT HS 808 952, available on the Web (http://www.nhtsa.dot.gov/people/ncsa/factsheet.html).

This factsheet contains many of the same statistics as does the USDOT's Truck Crashes, except that its data are more current. The data show that large trucks (over 10,000 lb GVW) were involved in 475,000 traffic crashes in 1999. These crashes caused 5,362 fatalities and another 142,000 injuries; fatalities per fatal crash were 1.095.

Large trucks have a relatively high rate of fatal accidents per mile traveled. They accounted for 7.4 percent of vehicle miles traveled in 1998, the most recent year for which the factsheet gives a VMT breakdown. In comparison, in 1999, large trucks accounted for 8.6 percent of vehicles involved in fatal crashes. Yet in the same year, they accounted for only 4.4 percent of vehicles involved in nonfatal crashes. These numbers show, as one would expect, that large truck involvement increases the severity of traffic accidents. Indeed, in 1999, one out of eight traffic fatalities resulted from a crash involving a large truck.

Of the fatalities resulting from crashes involving large trucks, 78 percent were occupants of the other vehicle, 8 percent were non-occupants, and 14 percent were occupants of a large truck. Of the nonfatal injuries resulting from large truck crashes, 74 percent were occupants of another vehicle, 3 percent were non-occupants, and 23 percent were occupants of a large truck.

The factsheet also reveals a continuing decline in the rate of accidents involving large trucks per mile they travel. For fatal accidents, the annual rate per 100 million large truck miles declined from 3.5 to 2.5 between 1989 and 1999.

The factsheet also contains data on points of impact for two-vehicle fatal crashes involving large trucks. The four situations that claim the most lives are truck front/car front (29 percent of crashes), truck front/car left side (17 percent), truck rear/car front (15 percent), and truck front/car right side (14 percent).

Center for National Truck Statistics n.d., "1996 Trucks Involved in Fatal Accidents," available on the Web (http://www.umtri.umich.edu/cnts/release.htm).

The statistics contained in this report are based on investigation of over 3,200 fatal accidents involving trucks. Light trucks, such as pickups, were evidently excluded from this sample, which was drawn from the Fatal Accident Reporting System file. For each sampled accident, the Center for National Truck Statistics contacts a knowledgeable person, usually the driver, owner, or safety director, for a complete physical description of the truck at the time of the accident. Tractor-semitrailer combinations accounted for 60 percent of the cases; about 28 percent were straight trucks without trailers.

STATISTICS AND DATA ANALYSIS

Chira-Chavala, T. 1991, "Data from TRB-Proposed National Monitoring System and Procedures for Analysis of Truck Accident Rates," ***Transportation Research Record*****, no. 1322, p 44.**

Abstract from article: "To follow trends of truck accident involvement rates requires reliable information on truck accidents and travel. Procedures for estimating truck accident involvement rates and their confidence limits on the basis of variabilities inherent in the sample design of the TRB-proposed National Monitoring System (NMS) are presented. Formulas for computing confidence limits of national and state truck accident involvement rates per mile of travel are given for any level of disaggregation. The quality of truck accident and travel data that may be expected from implementing the NMS, together with consistent estimation of confidence limits of accident involvement rates, would represent significant improvement over truck safety statistics available from existing data programs."

Additional description: This article notes significant discrepancies between databases in the numbers of truck accidents by region and period. In the TRB-proposed monitoring system, police officers would be required to provide very detailed information about accidents involving trucks, including: vehicle type, carrier, driver information, accident description, type of roadway, environment at time of accident (i.e., weather, light condition). A pilot test of this system was conducted in several Midwest states and none reported any major problems. The estimates based on the TRB-proposed system would nevertheless be subject to random errors. The author's proposed procedure for deriving confidence limits would provide an indication of the likelihood of errors of given magnitudes.

Lyles, R. W., Campbell, K. L., Blower, D. F., and Stamatiadis, P. 1991, "Differential Truck Accident Rates for Michigan," *Transportation Research Record*, no. 1322, pp. 62–69.

Abstract from article: "Major changes in the trucking industry have resulted from federal legislation that relaxed the regulation of trucks in interstate commerce, allowed the use of double-trailer combinations nationwide on Interstate highways, and required states to regulate trailer length instead of overall length. Because Michigan has long had extremely liberal truck size and weight regulations, its experience with truck safety is of significant interest. A project by the University of Michigan and Michigan State University was undertaken to develop statistical information on accidents, travel, and the risk of accident involvement for Michigan-registered trucks in Michigan. The study objective was to calculate disaggregate truck accident 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. Major findings included the following: bobtails consistently have the highest accident rates; all-accident and casualty rates for single and double configurations are similar to one another; the most significant and consistent factor associated with truck accident rates was the roadway class (highest rates on the "local" road system, lowest on limited-access highways); urban accident rates were lower than rural rates; night rates were higher than day rates for casualty accidents but lower for all accidents; and tractor drivers aged 19-20 have an accident rate five times the average. The findings indicate that differences in truck safety by roadway class are more important than those between singles and doubles. Discussion and recommendations concerning improvements in truck accident and exposure data as well as further work on the relationship between truck accidents and geometry are included."

Additional description: The accident data came from the state police accident reports for the period May 1987 through April 1988. Drivers over the age of 60 were found to have accident rates 1.5 times the average. Urban accident rates for doubles varied according to time of day (20 per million vehicle miles during the day versus 35 per million vehicle miles during the night).

Mingo, R. D., Esterlitz, J. R., and Mingo, B. L. 1991, "Accident Rates of Multiunit Combination Vehicles Derived from Large-Scale Data Bases," *Transportation Research Record*, no. 1322, p. 50-61.

Abstract from article: "The operating characteristics of multitrailer vehicles could be expected to make them more dangerous than other vehicles, but previous accident involvement studies have produced mixed results, with no consistently strong indications of greater hazard. A review of these studies, however, indicates sufficiently severe limitations in their sample sizes and data reliability to readily explain the great degree of scatter in their findings. The size and reliability issues of previous studies are overcome by using large national data sources to calculate overall involvement rates of various vehicle configurations. No suitable sources of nonfatal accidents or disaggregate travel information were located. Use of national data rather than state and highway-type-specific data obscures the safety effects of differences in vehicle operations but at least allows an overall comparison of fatal accident involvement rates. Because current multitrailers are concentrated more than single trailers on the safest highways, rural Interstates, multitrailers appear in this study to be safer than they would if differences in operations were considered. The most reliable sources of fatal accident and travel data indicate that multitrailers, single trailers, and single-unit trucks have fatal accident involvement rates of 9.96, 6.01, and 3.00 per 100 million miles traveled, respectively. The ratio of fatal accident involvement rates for multitrailers to single trailers is 1.66. The multitrailer to single-unit truck ratio is 3.32. Most previous studies have indicated doubles or multitrailer fatal accident rates to be higher than singles, but with less difference. The higher ratios here can be attributed in part to larger and more reliable data sources than have been used in the past."

Additional description: The data for 1988 are discussed with comparisons to earlier years. Data on fatal accidents were obtained from the Fatal Accident Reporting System and the database used for the publication, "Trucks Involved in Fatal Accidents" (see above entry, under Center for National Truck Statistics). Estimates of vehicle miles of travel by state and vehicle type were derived from the Highway Performance Monitoring System and from the Truck Inventory and Use Survey. Fatality involvement rates per 100 million vehicle miles are presented by state and vehicle type. For Texas, the rates are similar to the national figures when it comes to passenger cars and single-trailer combinations. But for single-unit trucks and for double-trailer combinations, the rates are substantially lower for Texas than for the rest of the nation. As the authors caution, the variation between states partly reflect random variations. (Fatal accidents are rare events relative to miles traveled, so one could expect a fair amount of year-to-year variation for some of the smaller vehicle classes in smaller states.) One must also bear in mind the problems with the data on vehicle miles traveled. As the authors note, the Highway Performance Monitoring System relies on traffic counting and classification procedures that tend to overstate combination truck travel, especially that of double-trailer combinations.

Cerelli, E.C. 1998, *Trends in Large Truck Crashes*, NHTSA Technical Report HS-808 690, National Technical Information Service, Springfield, VA. (An abbreviated version is available on the Web (http://www.nhtsa.dot.gov/people/ncsa/LargeTruck.html).

Abstract from report: "Large trucks account for about 3.5 percent of all vehicles and for approximately 7 percent of all motor vehicle travel, while accounting for about 12 percent of all traffic fatalities. However, large truck travel has more than doubled during the 1975-1995 time period, while the number of all large truck-related fatalities has not changed appreciably. When occupant fatalities in crashes between large trucks and other vehicles are examined, another pattern appears to emerge, i.e., large-truck occupant fatalities have declined during the 1975-1995 period, while fatalities of occupants of the other vehicle have remained at the 3,000-4,000 per year level. This study examines data on driver licenses, vehicle registrations, vehicle miles traveled, all crashes, fatal crashes and fatalities involving large trucks and other vehicles for the period 1975-1995. The involvement of various driver age groups in large truck crashes is examined more closely for the last three years, i.e., 1993-1995. Younger drivers appear to be under-represented in large truck crashes. The risk of fatality to passenger vehicle drivers involved in large truck crashes was found to be greater for younger drivers than for older drivers."

Additional description: According to this report, the number of vehicle miles of travel by large trucks increased 113 percent between 1975 and 1995. As a percentage of all traffic fatalities, large truck accidents have consistently accounted for 12 percent over this period. Thus, for other vehicle classes, the picture is broadly similar to that for large trucks: the number of the fatal accident involvements has changed little, at the same time that vehicle-miles traveled have grown.

Levy, D.T., and Miller, T. 2000, "Review: Risk Compensation Literature – The Theory and Evidence," *Crash Prevention and Injury Control*, vol. 2, no.1, pp. 75–86.

Abstract from article: "Risk compensation denotes offsetting behavioral responses to safety improvements. Theoretical arguments suggest that, when drivers are required to drive safer cars or drive in a safer manner, they will tend to increase their driving speed or drive in some other risky manner. The purpose of this paper is to review critically the theory and evidence on risk compensation. The general conclusion is that the application of risk compensation theory, especially to some types of regulations, is questionable, and the empirical support for significant offsetting behavior is weak. Specifically, 1) the role of limitations in processing information is not appreciated, especially regarding risk perceptions and the learning component associated with new regulations; 2) the types of regulations and types of driving behavior are not adequately distinguished; and 3) the empirical studies have mixed results and are subject to important limitations."

Scopatz, R.A. 2001, "Crashes Involving Long Combination Vehicles (LCVs): Data Quality Problems and Recommendations for Improvement," paper presented to the 80th Annual Meeting of the Transportation Research Board, January 7–11, 2001. Washington, D.C. (available on the pre-print CD-ROM distributed by the Transportation Research Board, Washington, D.C.).

Abstract from paper: "In 1999–2000, the AAA Foundation for Traffic Safety conducted a research program to identify the barriers to analysis of large truck safety experience in the US. Their primary focus was on so-called longer combination vehicles (LCVs) — the "doubles" and "triples" running on major highways throughout the country. Five states (Florida, Idaho, Nevada, Oregon, and Utah) participated in a review and evaluation of their data collection and analysis practices. Two of the states (Oregon and Utah) also participated in an audit of completed crash reports for crashes involving large trucks and specifically doubles and triples. The results show that none of the five states has a crash reporting system that adequately supports the 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. Without good data on configuration and good measures of exposure, the main question about LCV safety (i.e., are they more or less safe than other large commercial motor vehicles?) cannot be answered empirically. The report concludes with a series of recommendations for improving the quality of data for crashes involving large trucks and for improving the states' ability to analyze LCV crashes specifically."

Additional description: The study defined an LCV as "any combination vehicle with two or more cargo spaces, in which one of the spaces is longer than 28 feet, and which is operating at greater than 80,000 pounds Gross Vehicle Weight Rating." The study found that only Utah among the surveyed states uses crash report forms with sufficient detail to identify LCVs. Florida, for example, codes double combinations without distinguishing between Turnpike Doubles—the only LCV allowed in the state—and STAA doubles (not an LCV). Other findings included these:

- Each of the surveyed states collects supplementary information on crashes involving commercial motor vehicles. In the three states that collect this information on a form separate from the primary crash report, non-completion of the supplementary form occurs often enough to be a concern. The states that integrate the primary and commercial motor vehicle crash reports into a single form—Idaho and Utah—have better chances of receiving the CMV-related information.

- An important problem is that persons completing the crash report forms are inadequately trained for this task. 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.

PERFORMANCE MEASURES OF LARGER COMBINATION VEHICLES

Fancher, P.S., Campbell, K. L. 1995, "Vehicle Characteristics Affecting Safety," *Truck Size and Weight Study, Phase I: Working Papers 1 and 2 combined.* 6 February, available on the Web (http://www.fhwa.dot.gov/reports/tswstudy/).

Abstract from paper: "This paper addresses the relationship of truck size and weight (TS&W) policy, vehicle handling and stability, and safety. Handling and stability are the primary mechanisms relating vehicle characteristics and safety. Vehicle characteristics may also affect safety by mechanisms other than handling and stability. For example, vehicle length may affect safety through interactions with other vehicles, such as passing maneuvers and in clearing intersections, in addition to its influence on vehicle handling and safety. However, the safety effect of vehicle length due to its influence on handling and stability is within the scope of this paper, while safety effects arising through mechanisms other than handling and stability, such as passing and intersection clearance, are not."

Additional description: The vehicle performance measures discussed in this paper are roll threshold, rearward amplification, braking, and offtracking. The authors conclude that liberalization of TS&W policy does not necessarily compromise safety. Liberalization could even occur along with an increase in safety under certain conditions. For this to happen, vehicles would need to be redesigned to maintain stability with the new dimensions. Also necessary would be more powerful engines (for ease of acceleration), better brakes (for safer stopping), and changes to highway geometric design (to decrease problems of sway and off-tracking).

Another theme of the paper is that performance standards may deal with concerns about truck safety somewhat better than regulations of vehicle dimensions. Such standards would require that performance measures—the rollover threshold or degree of offtracking, for example—stay within acceptable bounds. The paper also reviews the Turner Truck Study, which proposed higher gross combination weights for vehicles with axle loads below the current limits.

Harkey, D. L., Council, F. M., and Zegeer, C. V. 1995, "Operational Characteristics of Longer Combination Vehicles and Related Geometric Design Issues," *Transportation Research Record*, no. 1523, pp. 22-28.

Abstract from article: "As the size and configuration of trucks operating on public highways continues to change, how these vehicles operate needs to be better understood to accommodate them through better geometric designs or regulate them through more stringent laws and better enforcement. Longer-combination vehicles (LCVs), a group that includes Rocky Mountain doubles, turnpike doubles, and triples, fall into this category.

LCVs handle and perform differently from tractor semitrailers or twin trailers because of their increased lengths and weights. These differences in handling and performance may jeopardize the safety of the LCV as well as other vehicles on the roadway. Several of the LCV's operational characteristics are believed to have an impact on transportation safety and the relationship of these characteristics to geometric design. There is a clear need to conduct additional research to further evaluate LCV operations. Several such research efforts are recommended."

Additional description: In looking at LCVs and sway, this article reports that triple trailers have been shown to sway up to 1 foot—encroaching into adjacent lanes. The influence of "in-lane" trailer sway on passing and or queuing vehicles is identified as still requiring testing. The larger number of brakes on LCVs is identified as a safety concern in light of evidence that brake maintenance is often neglected. The evidence cited comes from a survey conducted in Maryland and California, which found that approximately one-fourth of trucks checked had 40 percent of their brakes out of adjustment. The article also examines the safety issues pertaining to rearward amplification, stopping distance, acceleration and speed differentials. The importance of speed differentials emerges clearly from these estimates: When a truck travels 10mi/hr less than the prevailing speed, its likelihood of being in an accident increases by 3.7, a difference of 20 mi/hr increases the likelihood of an accident by a factor of 15.5. After the examination of various performance characteristics, it is still undetermined whether LCVs are less stable than other trucks.

DRIVER SAFETY AND RIGHTS

"Application of the Fourth Amendment to the Inspection of Commercial Motor Vehicles and Drivers," ***National Cooperative Highway Research Program, Legal Research Digest*****, March 2000, no. 43.**

This report reviews legal issues surrounding the search and seizure of commercial vehicles and their drivers. This has relevance to the enforcement of potential regulatory arrangements for truck size and weight. For example, some people might see a fourth amendment violation in the use of Global Position Systems to monitor and collect data on truck travel (routes, mileage, etc.). This article indicates how tricky it can be to collect accurate data and assure the safety of the driver and others while allowing truckers their fourth amendment rights.

Bogren, S. 1989, "CDLs: A Move Toward Safety," ***Community Transportation Reporter*****, December, pp. 8–9.**

This article provides a brief review of what the Commercial Motor Vehicles Safety Act of 1986 mandated. It focuses mostly on the Act's implementation, particularly regarding the commercial drivers' license requirements. The article brings to light that many truckers lack the reading and writing skills necessary to pass the license tests, despite having clean driving records.

Jovanis, P. P., Kaneko, T., and Lin, T-D. 1991, "Exploratory Analysis of Motor Carrier Accident Risk and Daily Driving Patterns," *Transportation Research Record*, no. 1322, pp. 34–43.

Abstract from article: "Driving at different times of day within one day and over several days is associated with different levels of accident risk. Analyses of accident and nonaccident data from a less-than-truckload carrier representing six months of operation in 1984 are used to explore changes in daily and multiday accident risk. Cluster analysis is used to extract a distinct pattern of driving over a seven-day period from a sample of 1,066 drivers (including those with accidents and nonaccidents on the eighth day). The analyses yielded clear interpretable driving patterns that could be associated with levels of relative accident risk. Higher risk was generally, but not exclusively, associated with extensive driving in the two to three days before the day of interest. The two patterns with the highest risk of an accident were those that contained heavy driving during the preceding three days and consisted of driving from 3:00 p.m. to 3:00 a.m. (Pattern 1) and from 10:00 p.m. to 10:00 a.m. (Pattern 8). The lowest risk was associated with driving from 8:00 p.m. to 6:00 a.m. but with limited driving on the preceding three days. Given the virtually limitless possible combinations of driving schedules, it is encouraging that interpretable distinct multiday patterns could be extracted from a data base of more than 1,000 observations. Within each pattern, drivers experienced similar duty hours: cumulative driving during the seven days ranged from 47 to 49 hr. Continuous driving (between mandatory eight-hr off-duty periods) ranged from 7.8 to 8.4 hr. Individual drivers also experienced a cycle of on-duty and off-duty time that ranged from 22.3 to 23 hr, closer to the 24-hr period that is desirable from the perspective of human performance theories. The findings suggest that it is possible to identify and extract patterns of multiday driving and that these patterns are associated with different levels of accident risk. Additional empirical tests and the development of refined accident risk models are suggested for future research."

Additional description: The article reports that the most accident-prone drivers are those who consistently drive 12 hour stints that overlap with the times of a natural diurnal drop in arousal (4 a.m. to 6 a.m.).

NARROW ROADS AND SAFETY

Zegeer, C. V., Hummer, J., and Hanscom, F. 1990, "Operational Effects of Larger Trucks on Rural Roadways," *Transportation Research Record,* no. 1281, p. 28–39.

Abstract from article: "Ability of various truck configurations to negotiate rural roads with restrictive geometry was examined in addition to effects of such trucks on traffic operations and safety. Truck sizes included truck-tractor semitrailers with trailer lengths of 40, 45, and 48 ft (i.e., semi-40, semi-45, and semi-48) and twin-trailer combinations with 28-ft trailers (i.e., twins or double 28). Test sites consisted of approximately 60 mi of rural, two-lane roads in New Jersey and California with a variety of lane widths, shoulder widths, and horizontal and vertical alignment. Field testing involved following control trucks of each truck type along the selected routes. Photographic and radar equipment were used in a 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 semi-48 and twins 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 twins and longer tractor semitrailers."

Additional description: The authors examined the reactions of other drivers to wide trucks (102 inches) of varying lengths on narrow roadways. They found that drivers recognized "double trailers as a formidable vehicle" and would move away from the centerline. Drivers did not generally take this precaution, however, with the equally dangerous 53-foot single-trailer combinations. The authors make a good case for requiring better markings (i.e., more lights) on heavier and larger trucks, as well as for restricting these vehicles to wide, well-maintained roads (i.e., the National Network).

GENERAL REFERENCES

Hanscom, F. R. 1990, "Operational Effectiveness of Truck Lane Restrictions," *Transportation Research Record*, no. 1281, pp. 119–126.

Abstract from article: "The operational effectiveness of restricting trucks from designated lanes on multilane roadways is addressed. Three locations with no truck restrictions were treated with signing restricting trucks to certain lanes. The applied field study was of a before-and-after design (with matched control sites). Truck lane restrictions were implemented at two three-lane sites and one two-lane location. Favorable truck compliance effects were evident at all three locations. Before-and-after comparisons indicated significant truck lane use shifts; however, violation rates were higher (i.e., 10.2%) at the two-lane site in comparison with the three-lane sites (i.e., 0.9% and 5.7%). Higher violation rates at the two-lane site resulted from increased truck densities caused by restricting trucks to a single lane. An emphasis was placed on determining traffic flow effects to nontrucks in the traffic stream. Beneficial effects on three-lane roadways were realized in terms of reduced congestion and fewer trucks impeding vehicles (at both sites) and shorter following queue lengths (at one site). This finding supports the conclusion that traffic congestion at three-lane sites was reduced as the result of the restriction. An adverse effect, observed at the two-lane restriction, was reduced speeds of impeded vehicles following trucks. However, a slight benefit was found in that fewer trucks impeded following vehicles. All-vehicle speed comparisons were examined to determine whether increased differential speeds were likely to occur between the restricted and adjacent lanes. No speed changes were observed to indicate an adverse effect of the truck lane restriction."

Additional description: The study sites were in the U.S. Midwest. The author noted the need to examine the impact on pavement conditions and cost of highway repairs before implementing lane restrictions.

Hewitt, J., Stephens, J. , Smith, K., and Menuez, N. 1999, "Infrastructure and Economic Impacts of Changes in Truck Weight Regulations in Minnesota," ***Transportation Research Record*****, no. 1653, pp. 42-51.**

Abstract from paper: "The overall impacts of changes in truck weight limits on the economy in Montana were determined. Four scenarios were considered with different maximum allowable gross vehicle weights (GVWs). Three scenarios, with maximum GVWs of 36,300 kg (80,000 lb), 39,300 kg (88,000 lb), and 47,900 kg (105,500 lb), represented reductions in GVWs. The fourth scenario represented an increase in allowable GVW to 58,100 kg (128,000 lb). Predictions were made of the vehicle fleets under each scenario and of the changes in demands and performance of the highway infrastructure. 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 36,300 kg (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."

Additional description: The article describes truck weight limits in Montana that are identical to the federal limits, except that the 80,000 lb cap on gross vehicle weight (GVW) is absent. "Maximum GVWs are determined by the Federal Bridge Formula." Trucks that operate under these rules include combinations that weigh 114,000 lb with seven axles, 118,000 lb with eight axles, and 123,000 lb with nine axles.

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. The increase reflects the predicted effect of such a restriction on the composition of the truck fleet. Vehicles with lower GVWs and fewer axles would replace the vehicles that now operate over 80,000 lb. The lower GVWs would increase the number of trips required to perform the same freight tasks, which, combined with the reduction in the number of axles, would increase pavement damage.

In the study's liberalization scenario, relaxation of the bridge formula makes possible an increase in GVW up to the new limit of 123,000 lb. The estimated impacts on infrastructure costs are marginal increases for both pavements and bridges. The estimate for bridges is only about 25 percent larger than that for pavements, but neither estimate includes the cost of disruption to traffic during repair or replacement of infrastructure.

The estimates of infrastructure impacts have the further limitation of not reflecting induced changes in the volume of freight moved by truck. The study identifies two ways in which the modeled changes to GVW limits could affect the volume of truck freight moved on Montana highways. One way is to cause diversion of freight between truck and other modes; however, based on discussions with truckers and evidence from TRB studies, the authors assess this effect as negligible.

The other way is for the modeled changes in weight limits to affect the total demand for freight services (all modes) that involve movements within Montana. This demand for freight services depends on activity levels throughout in Montana industries. From its statewide economic modeling, the study concludes that while the simulated changes in weight limits would affect the Montana economy, these effects would “not be so dramatic as to immediately affect the [total] demand for transportation services.”

The statewide economic modeling in the study was based on the REMI (Regional Economic Modeling System, Inc.) model, which can be customized to any region of the United States. The study notes that changes in trucking productivity, such as would result in changes to vehicle weight limits, cannot input directly into the REMI model; they can only be represented as a change in overall productivity. For this reason, the modeling does not capture the possibilities for substitution between trucking and other inputs to an industry’s production.

GLOSSARY

Equivalent single-axle load (ESAL). A single-axle load of a specified weight, conventionally 18,000 lb, serves as the benchmark for the ESAL measure of pavement damage. A traffic stream that generates, say, 200,000 ESALs has the same pavement impact as 200,000 passes of the benchmark axle.

High-speed offtracking. “High-speed offtracking … results from the tendency of the rear of the truck to move outward due to the lateral acceleration of the vehicle as it follows a curve at higher speeds. As the speed of the truck increases from very slow, offtracking to the inside of the curve [low-speed offtracking] decreases until, at some particular speed, the rear trailer axles follow exactly the tractor steering axle trailers. At still higher speeds, the rear trailer axles will track outside the track of the tractor steering axle [high-speed offtracking]” (USDOT 2000). See figure 3**.**

Jackknife. “Vehicle controllability during braking is related to the lockup of the wheels on one or more of the axle sets. When lockup occurs on the wheels of the tractor’s rear axle or on the wheels of a dolly’s axle, the tractor or dolly is unstable in yaw; the ensuing rapid rotational motion is commonly termed jackknifing” (TRB, *Twin Trailer Trucks*, Special Research Report 211, TRB, National Research Council, Washington, D.C., 1986, p. 276).

Load equivalence factor (LEF). An LEF measures the extent to which pavement damage increases with axle weight. Conventionally, the benchmark axle is an 18,000 lb single axle. If a 20,000 lb axle has an LEF of 1.5 that means, under this convention, that each pass of such an axle causes 50 percent more damage than one pass of an 18,000 lb axle.

Longer combination vehicle (LCV). The Intermodal Surface Transportation Efficiency Act of 1991 defined an LCV as "any combination of a truck tractor and 2 or more trailers or semitrailers which operates on the Interstate System at a gross vehicle weight greater than 80,000 pounds" (http://iti.acns.nwu.edu/clear/infr/gopher90.txt). The Comprehensive Truck Size and Weight study (USDOT 2000) adhered to this definition, as have many other discussions of TS&W issues. Some discussions, however, have added to this definition a length criterion for the cargo-carrying units. Scopatz (2001) added the criterion that one or more of the cargo-carrying units be longer than 28 feet. This excludes from the definition of an LCV the STAA double combinations as well as most triples.

Low-speed offtracking. "When a combination vehicle makes a low-speed turn—for example a 90-degree turn at an intersection—the wheels of the rearmost trailer axle follow a path several feet inside the path of the tractor steering axle. This is called low-speed offtracking" (USDOT 2000). See Figure 2.

Present Serviceability Index. A measure of pavement condition that is based on road user perceptions of ride quality. Although it includes terms for cracking and rutting, the value of the index depends mainly on surface roughness.

Rocky Mountain Double. A combination of a truck-tractor, a front trailer between 40 feet and 48 feet long, and a shorter 20-foot to 28-foot rear trailer.

Structural number (SN). A measure of pavement strength that is a weighted sum of the thickness of each pavement layer. The weight for a layer depends on the material that the layer contains (see OECD, *Pavement Management Systems*, OECD, Paris, 1987, p. 52).

STAA double. A combination of a truck tractor and two 28-foot trailers. The Surface Transportation Assistance Act of 1982 (STAA) authorizes the use of these vehicles on a National Network. "Today, with over 200,000 miles of roadway, the NN [National Network] includes virtually all Interstate Highways (44,000 miles) as well as other highways" (USDOT 2000, vol. III, p. II-6).

Turnpike Double. A combination of a truck-tractor and two trailers of equal length, typically 48 feet or 53 feet.

Figure 2: Low-Speed Offtracking

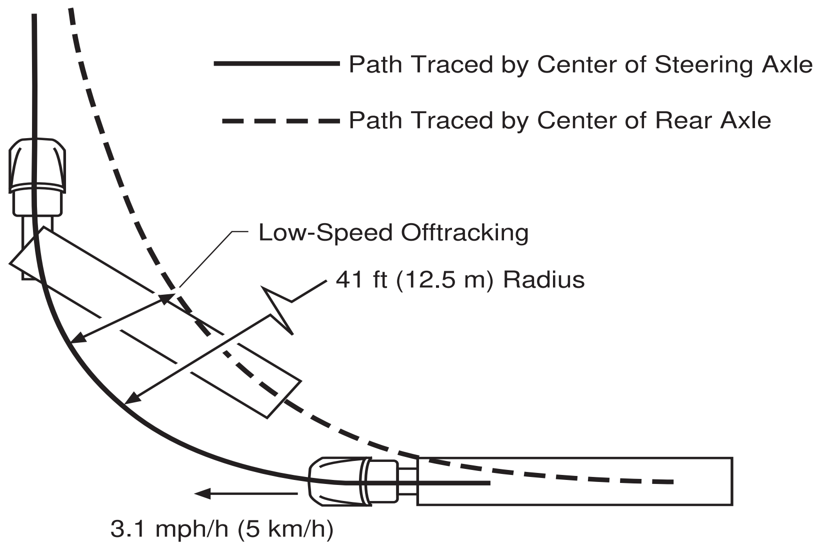
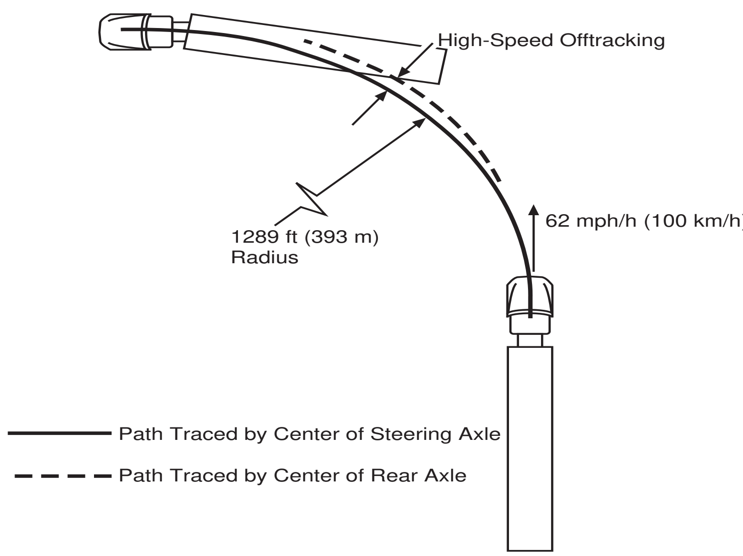


Figure 3: High-Speed Offtracking



Sources: USDOT (2000), Volume III, p. VII-2.