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SAFETY IMPLICATIONS OF VARIOUS TRUCK CONFIGURATIONS

VOLUME III

SUMMARY REPORT

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16. Abstract

The purpose of this study is to examine changes to size and weight limits in order to determine their effects on the designs and configurations of heavy vehicles, the performance capabilities of the resulting vehicles, and the ensuing safety implications thereof.

The summary report provides results and findings from an analytical investigation of the influences of size and weight limits on trucks. In an analytical sense, pavement loading rules and bridge formulas are the inputs to the analyses and vehicle performances are the outputs.

Ultimately, the work shows the manner in which size and weight rules influence the safety-related performance of vehicles designed to increase productivity. By treating a number of projected size and weight scenarios, the study has developed a basis for generalizing to sets of principles that can be used in evaluating the possible safety consequences of changes in size and weight regulations.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
AREA				
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
AREA				
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectares (10 000 m²)	2.53	acres	ac
MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

These factors conform to the requirement of FHWA Order 5190.1A.

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EXECUTIVE SUMMARY

The purpose of this study was to examine changes to size and weight limits in order to determine their effects on the designs and configurations of heavy vehicles, the performance capabilities of the resulting vehicles, and the ensuing safety implications thereof.

The analyses performed in this study were directed towards **safety implications** and did not investigate the effects of trucks on pavement or bridge life. Rather, the study investigated the influences of size and weight limits on trucks. In an analytical sense, pavement loading rules and bridge formulas were the inputs to the analyses and vehicle performances were the outputs.

Ultimately, the work shows the manner in which size and weight rules influence the safety-related performances of vehicles designed to increase productivity. By treating a number of projected size and weight scenarios, the study has developed a basis for generalizing to sets of principles that can be used in evaluating the possible safety consequences of changes in size and weight regulations.

The first part of the study involved reviewing pertinent information on size and weight limits in meetings with experts from trucking organizations, vehicle manufacturers, and research personnel at the Federal Highway Administration (FHWA). Using the results from these meetings, researchers developed 18 scenarios corresponding to trucking environments based on 18 different sets of size and weight rules. The sets of size and weight rules were based on three types of bridge formulas (referred to as B, C, and TTI); three levels of pavement/axle loading constraints (including a set that corresponds to the "Turner" concept); the length provisions of the Surface Transportation Assistance Act (STAA) of 1982, or in its place an offtracking rule; and various gross weight caps including no direct limit on gross combination weight. Special scenarios were developed to address the transporting of ISO containers weighing 67,200 lb (30,240 kg) with a length of 40 ft (12 m). Also provisions allowing vehicles with twin steering front axles were considered. These 18 scenarios provided a representative sample of the types of size and weight constraints that might be considered in the future but they are not intended to exhaust the range of reasonable possibilities.

For each of the scenarios, vehicles have been designed with productivity in transporting payload as a goal. The designs range from those that amounted to "loading up" existing vehicles, to ones in which moderate changes in configuration and numbers of axles were employed, to examples of vehicles that attempted to carry as much load as the applicable rules will allow. Each of the example designs is the result of an iterative and creative activity. Given the differences in size and weight rules and the complicated natures of these rules, an all-purpose algorithm for generating designs is not to be expected. Nevertheless, a computer-aided procedure for checking designs made it possible to create the extraordinary number of vehicles examined in this study.

Once productive vehicles had been designed, existing computerized models were used to evaluate the intrinsic safety of these vehicles. This involves predicting vehicle performance in a set of safety-related maneuvers. The following maneuvering situations were examined:

- Low-speed offtracking.
- Friction demand in a tight turn.
- High-speed offtracking.
- Constant deceleration braking.
- Steady turn—rollover.
- Steady turn—handling.
- Obstacle evasion (rearward amplification).

The results from these analyses provide a basis for assessing vehicle performance with respect to the following practical goals:

- The rear end of the vehicle should follow the front end with adequate fidelity.
- The vehicle should safely attain a desirable level of deceleration during braking.
- The vehicle should remain upright (not roll over).
- The vehicle should be controllable and stable in following a desired path.

For each scenario this report presents graphs and tables comparing the performances of each projected vehicle in each safety-related maneuvering situation with respect to performance levels corresponding to those predicted for a typical five-axle tractor-semitrailer, and also with respect to a set of performance targets judged to be representative of the capabilities of practical designs using current technology.

The findings for each scenario are summarized in terms of the types of vehicles that would be most productive and the types of vehicles with either relatively good or poor levels of intrinsic safety qualities. All of this information is then examined from an overall perspective with regard to size and weight allowances. The following conclusions are the key generalizations derived from an examination of the results of this study:

- When going to more weight-productive size and weight rules, do not allow heavier loads on existing vehicles. If the loading of existing vehicles is taken care of properly, gross combination weights (GCW) limits might be eliminated or relaxed considerably.

- Axle load constraints should not be eliminated from size and weight rules. The ability to assess the performance of the highway system with respect to safety, productivity, and damage to the infrastructure depends upon the ability to monitor axle loads and the spreads between axles.

- In order to allow trucks to make maximum use of the space available on roads, an offtracking rule could be used as a length constraint. Under either the STAA rules or an offtracking rule, doubles would be more productive than tractor-semitrailers.

A shift to doubles might be anticipated from those operators desiring more cubic volume for their payload.

- As a first step in developing rules for more productive vehicles, constraints on the number of axles and axle spreads would prevent the possibility of promoting very long vehicles with excessive friction demands in tight turns. Constraining axle sets to having no more than three, or possibly four, axles in a set would alleviate this problem and ease the development of suitable designs.

- The five-axle tractor-semitrailer with tandem axle sets on both the rear of the tractor and the semitrailer is a well-optimized configuration for the current size and weight rules allowing 80,000-lb (36,287 kg) GCW's. This configuration would not benefit from an increase in the GCW limit alone.

- A six-axle tractor-semitrailer with a tridem-axle set on the semitrailer would allow more load up to GCW's of 86,000-88,000 (39,009 to 39,600 kg) while maintaining good intrinsic safety.

- In the case of doubles, there are both minimum and maximum wheelbases that bound the range of designs providing good performances. Twin 28-ft (8.4 m) cargo boxes are too short. Doubles with twin 35-ft (10.5 m) cargo boxes would be better.

- Innovative dollies with special hitching arrangements may be needed to control rearward amplification ("cracking-the-whip")—especially for triples and short doubles. (In these cases, design analyses and performance demonstrations might be required to build confidence in the new designs. There are analytical results and test data published elsewhere showing advantages of certain existing designs of innovative dollies.)

- The wheels-unlocked braking performance of empty trucks needs to be improved. This is true in all scenarios with the possible exception of the twin-steer vehicles in scenario 18. This general problem is a difficulty for most trucks with large differences between tare weights and GCW's. The countermeasures are changes in brake proportioning and the use of antilock braking systems.

- The rollover immunity of more productive heavy trucks would be maintained or improved if the tire stiffnesses per axle and the suspension roll stiffnesses per axle were maintained at the same levels of those properties as the levels pertaining to current tires and suspensions, even though the new heavier vehicles would have less load per axle than the loads per axle on current vehicles. (That is, the new, heavier vehicles would have more axles than current vehicles, but the load per axle would be less than that used on current vehicles. Nevertheless, the mechanical properties of tires and suspensions should be kept at their current levels.) The above specification on tires and suspensions would also aid in controlling rearward amplification ("cracking-the-whip") in multiarticulated vehicles.

In summary, the recommended elements of new sets of size and weight constraints are as follows:

- A pavement/axle loading rule that is directly related to pavement damage and to suspension, tire, and brake characteristics which pertain to the intrinsic safety of the vehicles allowed.

- A bridge formula that is directly related to the costs of providing structurally sound bridges.

- An offtracking rule that promotes efficient use of the space available on roadways.

- A statement of the intrinsic safety targets for the vehicles allowed to operate under these new rules.

- A statement of the types of previously used vehicles that are not to be allowed to operate in an overloaded state (that is, limits on existing types of vehicle designs that do not have provisions for carrying more load than that allowed previously).

- A statement of permit requirements, cost provisions, and safety factors for special types of heavy (possibly short) vehicles that are deemed important to the transportation of special items.

INTRODUCTION AND BACKGROUND

This is a summary report presenting the findings of a study that has investigated the influences of size and weight constraints upon the safety-related maneuvering performances of heavy trucks. This report differs from its technical counterpart primarily in that detailed technical results are not included here.[1] (This report is based upon the premise that the reader who is interested in technical details will read the technical report instead of this one.)

Objectives

The study is intended to aid the United States in addressing questions pertaining to the safety impacts of changes in size and weight regulations. The tasks of the research investigation have been structured to predict the effects that changes in size and weight restrictions would have on (1) the designs and configurations of heavy vehicles, (2) the resulting performance capabilities of the projected vehicles, and (3) the ensuing safety implications.

The study does **not** investigate the effects of trucks on pavement or bridge life. Those highway performance matters only enter the study indirectly insofar as certain size and weight scenarios acknowledge the desire to control the rate of wear of the highway system infrastructure . In an analytical sense, pavement loading rules and bridge formulas are the inputs to the analyses and vehicle performances are the outputs.

The ultimate goal of the work is to show the manner in which size and weight rules influence the safety-related performances of those vehicles that may be designed to increase

productivity. The findings of this study are intended to aid in the process of determining if safety-related constraints should be included in new sets of size and weight rules and, if so, in determining the nature of the constraints needed to enhance the likelihood of safe trucking. In summary, a purpose of this work is to illustrate how analyses of vehicle design and performance could be used in establishing future size and weight laws. By treating a number of projected size and weight scenarios, the study has developed a basis for generalizing to sets of principles that can be used in evaluating the possible safety consequences of changes in size and weight regulations.

History of Size and Weight Laws

The first size and weight restrictions in the United States were established in 1913 when Maine, Massachusetts, Washington, and Pennsylvania set weight limits. Pennsylvania also established a width limit in 1913. Since then, each State has developed its own set of size and weight laws. By 1929, a majority of States had restrictions on length, width, and height. By 1933, every State had enacted a weight limit. As combination vehicles became more common, separate weight and length requirements were specified for single-unit and combination trucks. Although specifications varied from State to State, the items typically covered by the early regulations are still considered in today's regulations. Currently, the following items are usually regulated:

- Weight on any single-axle or tandem-axle set (a pair of closely spaced axles).

- Gross weight of the total vehicle.

- Weight on each set of contiguous axles with a formula relating load carried by the set of axles to the spacing between the extreme axles of that set and the number of axles in the set. (This complicated statement is summarized by a formula or table, called a "bridge formula.")

- Length of single-unit trucks, combination trucks, and trailers.

- Number of trailers allowed.

- Width.

- Height.[2]

(See reference 2 for a detailed presentation of the history of size and weight laws in the United States. See reference 3 for a summary of the current State and Federal laws.)

The purposes of the limits on heavy trucks have been to control public costs associated with the highway system. The reasons for increasing the limits have to do with increasing the productivity of trucking. In order to preserve the highway infrastructure, State organizations have considered the influences of trucks on pavement damage, bridge fatigue, construction costs, congestion, and safety. They have also considered the economic well being of their citizens and the productivity of their industries. The overall trends developed by the process of protecting the infrastructure while increasing productivity show that the demand for productivity (as measured by the gross weight of vehicles and the lengths of trailers) has led to substantial increases in the sizes and weights

of trucks. For example, in 1950 the average gross weight of loaded combination trucks operating on main rural roads was reported to be approximately 40,000 lbs (18,133 kg), while in 1980 it was 58,000 lbs (26,308 kg); and the most common trailer length was 30 ft (9 m) in 1950 and 45 ft (13 m) in 1980.[2] Currently, the most common trailer length in production is 48 ft (15 m) and tractor-semitrailers (TST's) are often loaded to almost 80,000 lbs (36,287 kg).

As stated in Special Report 211 from the Transportation Research Board: "As the States have gradually liberalized size and weight limits, trucking has grown to become a primary component of the freight transportation system, the average size of trucks in use has increased, and U.S. roads have been greatly improved. These concurrent trends have influenced State decisions on size and weight limits and have themselves been accelerated by the evolution of State truck size regulations."[2]

State rules have been influenced by the policies recommended by the American Association of State Highway and Transportation Officials (AASHTO) in 1932,1946, 1964, 1974 and 1980. AASHTO has tried to promote uniform regulations to aid in standardizing highway design and to enhance safety and efficiency in highway transportation.[2] Nevertheless, size and weight rules vary significantly between States, with trends toward uniformity being promoted by Federal initiatives more than by other influences.

Federal regulation of truck size and weight limits began with the passage of the Federal-Aid Highway Act of 1956. This act, with revisions in 1975 and a subsequent act in 1976, restricted the width, axle loads, and gross weights of vehicles operating on the Interstate Highway System. Gross vehicle weights were increased from 73,280 lbs (33,239 kg) to 80,000 lbs (36,287 kg) in 1975. However, these initiatives allowed the States to apply preexisting State limits and to use lower limits than the Federal ones.

The Surface Transportation Assistance Act of 1982 (STAA '82) preempted State rules with regard to more restrictive prior limits. STAA '82 required the States to allow 48-ft (14.4 m) semitrailers and twin 28-ft (8.4 m) doubles to operate on interstate highways and a network of primary roads designated by the Secretary of Transportation. On these roads, the States could not restrict the overall length of tractor-semitrailers (TST's) or combinations with two trailers. The States could not set gross weight limits less than 80,000 lbs (36,287 kg). Vehicles could be up to 102 in (259 cm) in width. "The objectives of expanding federal control over size and weight were to remove barriers to efficient freight movement created by nonuniform State size and weight limits and to compensate truckers, through more liberal limits, for higher road-use taxes enacted at the same time."[2]

"Grandfather" clauses have allowed some States to have more liberal limits than those provided by Federal regulations. Regional permit systems for oversize trucks in New England and longer combination vehicles in a Western region of the U.S. have been established. Currently, the pressure to liberalize size and weight regulations continues in an environment of increasing concern with the influences of changes in truck designs and configurations on highway safety.

Size and Weight Constraints

Throughout the world, various countries have been considering changes in their sizes and dimensions restrictions.[4,5,6] Although the goals, such as greater productivity and protection of the highway infrastructure, are the same from country to country, the local approaches to highway and vehicle design are different enough that it is difficult to extrapolate from the vehicles employed in other countries to the vehicles that would be employed in U.S. trucking.

In tasks A and B of this study, two meetings were held in order to understand industry views on possible changes to current heavy vehicle size and weight limits and to project how truck designs might be influenced by these changes. At the first meeting, experts from trucking companies explained industry views. Primarily, they expressed opposition to arbitrary length and weight caps. They prefer an offtracking rule rather than specific length rules. They would like recognition of special-purpose vehicles and permits for auto transporters, construction vehicles, and other vehicles for specialized operations. They believe that the pressure for greater productivity is insatiable. In the short term, they look for changes that would allow an additional 2,000 lbs (907 kg); in the near future, they would like an allowance for ISO shipping containers and a 100,000-lb (45,360-kg) weight cap limit (which, although somewhat arbitrary, serves the purpose of accommodating ISO containers); and in the long run, they see demands for multiaxle, multiarticulated vehicles approaching GCW's of 150,000 lb (68,000 kg).

At the second meeting, engineers involved in the design and production of truck-tractors and trailers discussed the changes in vehicle components that might accompany changes in axle loads. In general, the manufacturers seemed to be prepared to respond immediately to requests for increases in axle loads. On the other hand, it was not clear how the industry might respond to requests for reductions in axle loads. Some of the possibilities mentioned included using single tires rather than duals and using smaller diameter tires to maximize cubic capacity for the payload. Lighter weight springs and brakes were a possibility.

Eventually, component mechanical properties might be scaled down in proportion to the reductions in the gross axle weight ratings. Tires and brakes would be the limiting factors. Brake packages might need space of at least 20 in (50.8 cm) in diameter. Also the lowest point on the vehicle would need to be at least 12 in (30.5 cm) from the ground. However, most of the manufacturers were wary of sudden changes in the designs of their products. They would prefer a smooth, gradual transition in the introduction of new hardware.

With regard to increased gross combination weight, the manufacturers believed that the power requirements could easily be met with existing engines. For example, a 300-hp (224-kw) engine is suitable for an 80,000-lb (36,287-kg) vehicle and a 367-hp (274-kw) engine would be satisfactory for a 112,000-lb (50,803 kg) vehicle.

Bridge formulas (B, C, and TTI)

Bridge formulas are difficult to describe in nontechnical terms because they are precise rules that are stated using tables or equations. They are used to convey constraints on the

allowable loading and placement of axles on vehicles. These rules are based on concerns for bridge life and the overstressing of bridges. In general these formulas require "spreading the load" over appropriate lengths (spans). The quantities e_{12}, e_{13}, etc. in figure 1 illustrate all of the axle placement and loading combinations that are examined when applying a bridge formula to a nine-axle double.

Given the nature of these rules, we have chosen to present them in mathematical and graphical form, even though this is a nontechnical report. The graphs and equations merely serve as concise descriptions of the constraints. (Please skip the formulas presented if mathematical notation in general is not meaningful to you.) The engineering technology underlying these rules is a separate subject not covered in the study. Figure 2 illustrates the provisions of the three types of formulas used as constraints on the distributions of axle loads. These formulas, which are listed below, have been used in the scenarios of this study in combination with various limits (including no explicit limit) on gross combination weight.

FORMULA B (This is the existing bridge formula.)

W = 500 (L N /(N - 1)) + 6000 N + 18,000

where   L is the length in feet between the extremes of any axle group

              N is the number of axles in that axle group

              W is the allowable gross weight in pounds carried on the axle group

FORMULA C (This is the same as formula B except for the constant term.)

W = 500 (L N /(N - 1)) + 6000 N + 20,000

FORMULA TTI (This formula was developed in a recently completed study.[7])

W = 1000 L + 34,000   for L less than 56 feet (W less than 90,000 pounds)

W = 500 L + 62,000   for L greater than 56 feet (W greater than 90,000 pounds)

(Note that the TTI formula does not depend upon the number of axles. Otherwise, it uses the same variables as the other formulas.)

Each of these formulas has a historical background. Formulas B and C were examined by the Highway Research Board in 1964. The adoption of formula B was recommended at that time.[7] Formula B was the choice used in the Federal weight law enacted in 1975. Formula B differs from formula C only in the constant term in the equations—with formula C allowing 2,000 lb (907 kg) more weight than from that allowed by formula B. Formula B or table B has formed the basis for weight regulations in most States.

It is understood that objections to using these formulas under certain conditions are strongly voiced by various organizations and knowledgeable persons. For example, formula B was not intended to allow short, heavy, many-axled vehicles to operate on H-15 bridges whose design is based on trucks weighing 30,000 lb (13,600 kg).[7] Also formula B was not to be applied to vehicles weighing more than 80,000 lbs (36,287 kg). On the other hand, various trucking organizations feel that the formula is overly restrictive.
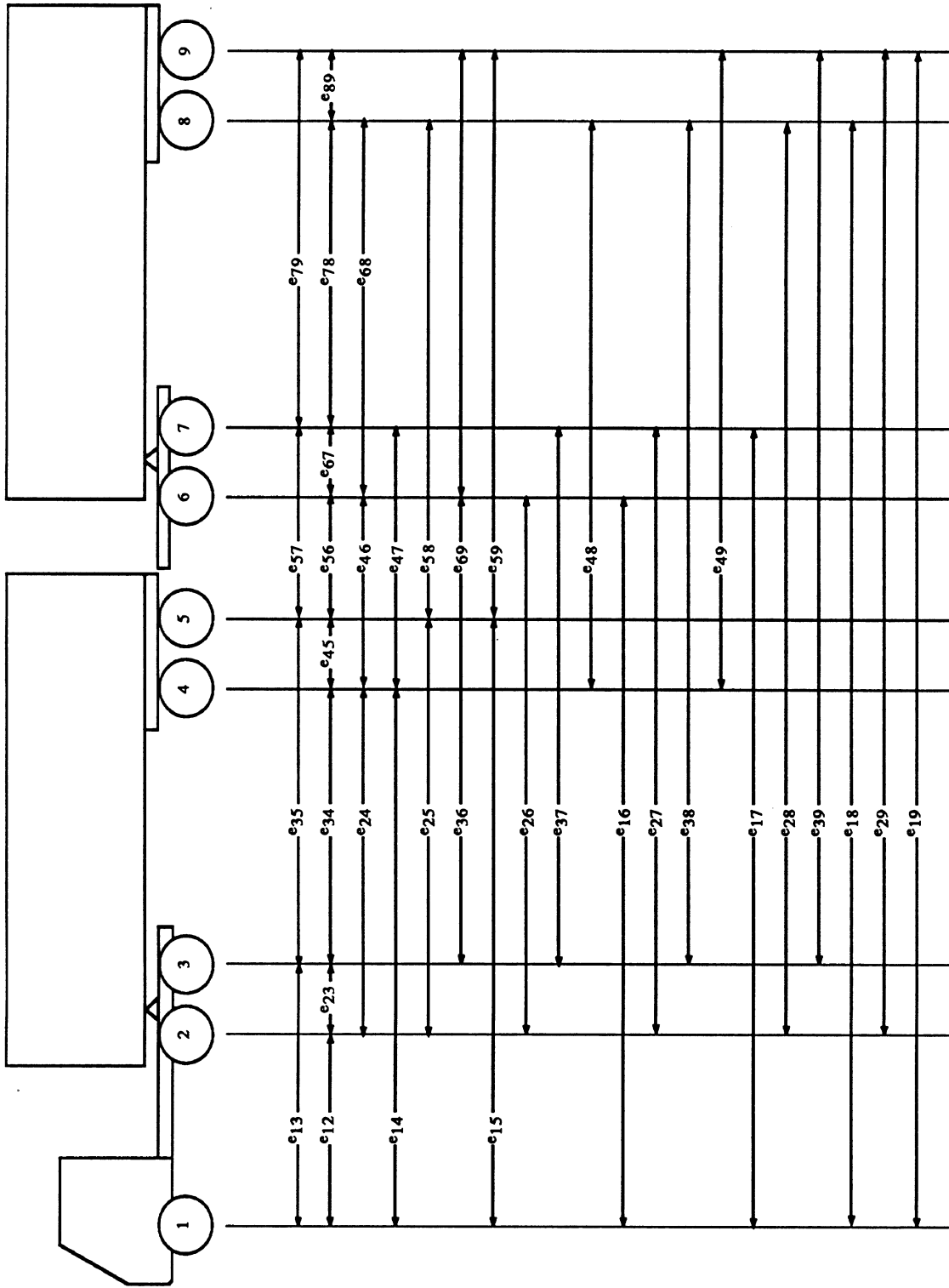
Figure 1. Bridge formula axle groups for a double.
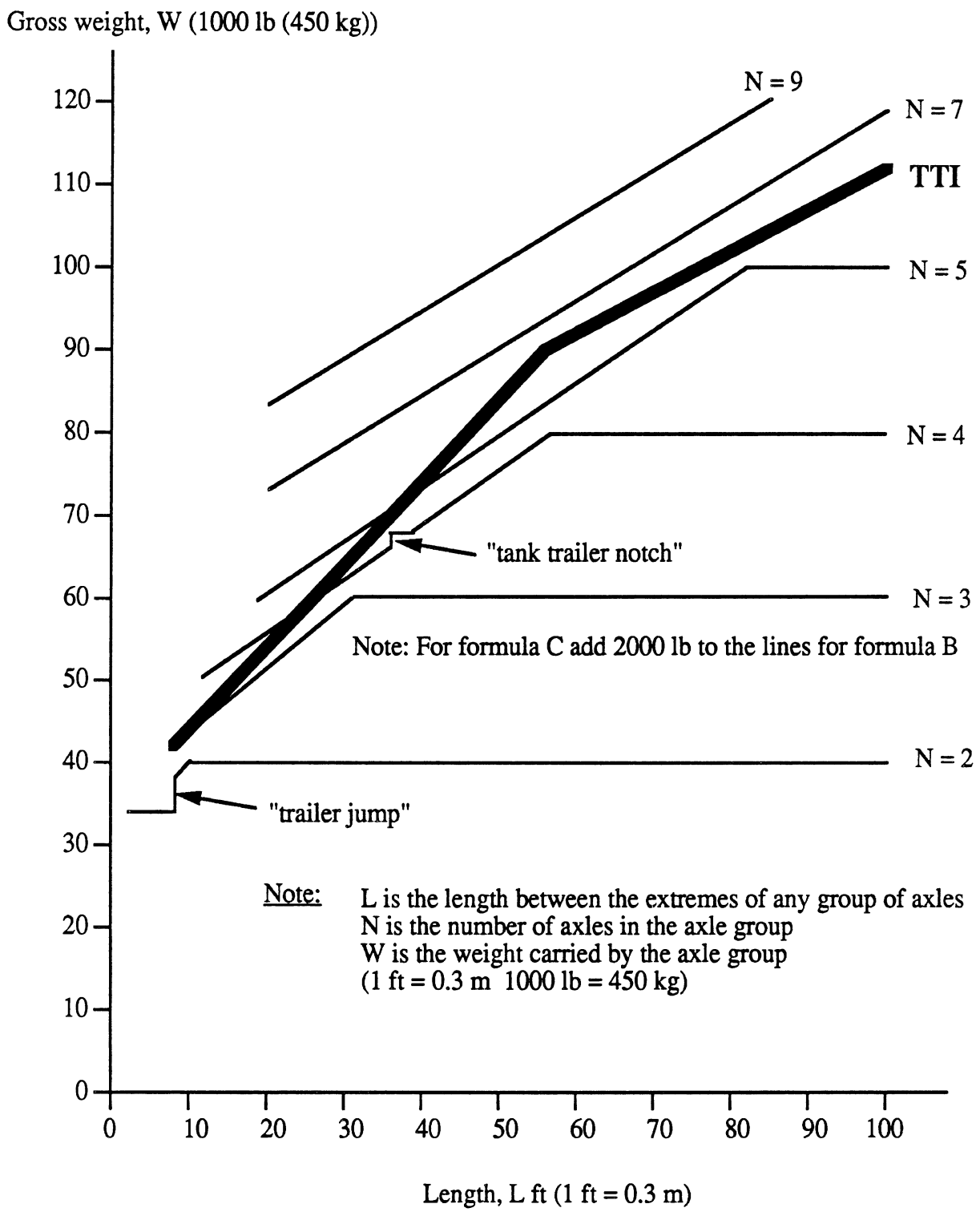
Figure 2. TTI formula superimposed on the current table B formula.

Formula B has been modified to allow two tandem-axle sets separated by 36 ft (11 m) to carry 68,000 lbs (30,845 kg).[7] This shows up in the graph presented in figure 2 as a so-called "tank-trailer notch" on the 4-axle curve at a length of 36 ft (11 m). (In addition, there have been special provisions allowing short tank-trailers with heavy loads. These provisions will expire on September 1989 if they are not extended again.)[8]

The two-axle curve in figure 2 also shows a jump (labeled "trailer jump") at 8 ft (2 m). This is where tandem loading rules switch to the bridge formula B and, in the case of two axles, the curve levels off at a single axle limit of 20,000 lb (9,072 kg) per axle—again an axle loading rule. This means that two axles closer than 8 ft (2 m) are considered as a tandem pair, and axles separated by more than 8 ft (2 m) are treated as single axles.

The development of formula TTI was prompted by concerns over the adequacy of formula B for treating vehicles weighing more than 80,000 lb (36,287 kg).[7] Above approximately 70,000 lb (31,752 kg), formula TTI allows heavier 5-axle vehicles than those allowed by formula B. (See figure 2.) Formula TTI has been criticized because it does not address pavement damage and, if used alone, it might increase pavement damage if heavy five-axle vehicles were the major cause of pavement damage. On the other hand, formula TTI protects bridges as it was intended to do. For example, the large gross combination weights allowed for nine-axle vehicles by formula B are not allowed by formula TTI. It appears that the inclusion of the number of axles in formula B represents a concession to pavement loading and allows bending moments on bridges that exceed the maximums tolerated for vehicles with fewer axles. This study examines the vehicle design and safety implications of bridge formulas, regardless of considerations concerning pavement damage and bridge fatigue.

Axle/Pavement loads (36/22, 34/20, 28/16)

In this study, maximum single- and tandem-axle loads represent pavement protection goals. The case with 36,000-lb (16,330 kg) tandems and 22,000-lb (9,979 kg) singles (symbolized by "36/22") corresponds to the provisions of bridge formula C. The current restriction of 34/20 is applied along with bridge formula B, and the 28/16 rule might be an axle load restriction corresponding to a variant of the Turner concept, which is a new idea recently proposed as a way to preserve pavements while increasing productivity.[9] To make distinctions between bridge formula and axle-loading constraints, a specification of 8 ft (2.4 m) is used as the axle spread separating tandem-axle pairs from sets of two single axles. As already noted in figure 2, spreading a pair of axles by just over 8 ft (2.4 m)) can produce a sizeable increase in the allowable load on those two axles. Although it may not be obvious, the number of axles on a vehicle may be determined as much by bridge formula considerations as by the single-axle limit given in the pavement loading rules. The reasons for this have to do with the prevailing length constraints.

Length or offtracking (STAA, 12/40)

The reasons for length constraints do not appear to be well documented in available literature and their justifications are not generally known. Of the two length constraints studied here, the designation "STAA" means the allowances of the Surface Transportation

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Assistance Act of 1982; that is, 28-ft (8.5 m) cargo boxes for doubles and 48-ft (15 m) cargo boxes for semitrailers. Historically, tractor lengths were purposely not specified to provide the opportunity for more room for the driver. Also dolly lengths were not limited.

The other length restraint is an offtracking requirement where the "12/40" designation means that the vehicle's offtracking should be no larger than that of a tractor with a 12-ft (3.6 m) wheelbase pulling a semitrailer with a dimension of 40 ft (12 m) from the kingpin to the center of the rear suspension. This constraint corresponds to the space available at many present-day intersections.[10] It was chosen to respond to the truckers' desires for an offtracking rule rather than an arbitrary length limit. The idea is to allow trucks to be designed to use the space available on the roadway.

Measures of Intrinsic Safety

Safety-related goals

The results of this study and previous studies show that performance in safety-related maneuvering situations depends significantly upon the axle loads and geometric layouts of the vehicles involved. Hence, size and weight constraints may have important implications with respect to the intrinsic safety of heavy trucks and truck combinations. This subsection gives background material pertaining to an approach for evaluating the inherent or intrinsic safety of heavy trucks.

The following practical goals have been used to develop analytical procedures for evaluating vehicle performance in safety-related maneuvers:[11]

- The rear end of the vehicle should follow the front end with adequate fidelity.

- The vehicle should safely attain a desirable level of deceleration during braking.

- The vehicle should remain upright (not roll over).

- The vehicle should be controllable and stable in following a desired path.

The following maneuvering situations have been used for assessing vehicle performance relative to the practical goals listed above:
- Low-speed offtracking
- Friction demand in a tight turn
- High-speed offtracking
- Constant deceleration braking
- Steady turn—rollover
- Steady turn—handling
- Obstacle evasion (rearward amplification)

Specialized models, based on these maneuvering situations, provide a fundamental understanding of the vehicle's performance relative to (a) mechanical properties of critical components such as suspensions, tires, and brakes, and (b) dimensions of the vehicle's

configuration.[11,12,13] A performance rating or "measure" can be evaluated for the vehicle in each of the maneuvers analyzed. For instance, in a steady-turning maneuver, the roll angles of the vehicle's units increase as the severity of the turn increases. At the limit of performance, one of the vehicle's units rolls over at a level of lateral acceleration called the "rollover threshold." For heavily loaded trucks, rollover thresholds range from approximately 0.25 g to 0.45 g. In this case the rollover threshold is the safety-relevant performance measure.

In order to judge vehicle performance, it is useful to arrive at performance targets representing desired levels of performance. Ideally, one might wish that these performance targets could be based on analyses of the accident record. Unfortunately, information on the performance qualities of trucks is not usually available in data on accidents or exposure to risk. (However, rollover is an exception which has received attention.[14])

Another approach is to use the performance of a baseline or reference vehicle to establish a reference set of performance targets. In this study, the performance of an approximately 80,000 lbs (36,287 kg) 3-S2 tractor-semitrailer has been used as a baseline for comparing vehicles.

Furthermore, reference performance targets, based on a judgmental assessment of the capabilities of current technology, have been used to provide another basis for evaluating the safety-related attributes of the projected vehicle designs. This approach has similarities to the presentation in the Canadian report on "Recommended Regulatory Principles for Interprovincial Heavy Vehicle Weights and Dimensions."[15] Even so, the authors of this report, while appreciative of the desire for specified performance targets, do not mean to imply that the performance targets used in this study have undergone sufficient testing, evaluation, and scrutiny to be viewed as established specifications for vehicle design. (See references 11 and 16 for discussions of a vehicle synthesis procedure involving the establishment of performance targets.)

The evaluation procedures for the size and weight scenarios which appear in the following sections have been selected in consideration of predicted performance in several maneuvers. Vehicles that exhibit performances that meet or exceed the reference levels for the following maneuvers have higher levels of intrinsic safety than many vehicles in current service.

Developers of future size and weight regulations may want to consider the appropriateness of establishing performance levels for the purposes of promoting truck safety. Currently, there are no "fully justified" levels of performance in the sense that benefits/costs are completely understood and connections with the accident record are irrefutable. However, examinations of the accident record may provide useful perspectives as to the relative importance of the various maneuvering situations. It is not reasonable to assume that these maneuvering situations are all equally important. In particular, based on the accident record, rollover and braking have been considered to be more important than the other safety items. Nevertheless, we have made judgments regarding poor performance as indicated in the following "target performance levels." If one accepts these judgments and, also, recognizes that these analyses represent the performance of idealized vehicles that do not suffer from practical problems that occur in the trucking environment, then the

relative differences in performance can be used in guiding changes that are expected to represent directions for improving both productivity and safety.

Low-speed offtracking:

Low-speed offtracking is of concern at intersections. The rear of long vehicles may track several feet to the inside of the path of the front of the vehicle. Vehicle configurations with long units may be incompatible with the roadway system and may endanger roadside appurtenances, pedestrians, and parked or stopped vehicles.

The evaluation procedure is based upon a quasi-static analysis of a vehicle turning a tight corner at low speed. The first unit, the towing unit, is assumed to be steered such that the front axle follows a preselected path, typically a 90-degree segment of a circular arc with tangent sections preceding and following the curve. Given wheelbases and hitch locations, a computerized algorithm then calculates the offtracking of the various units of the vehicle. The maximum offtracking of the rear axle of the last unit is used to quantify the low-speed offtracking performance of the vehicle.

Target performance level:

For a 90-degree turn with a radius of 41 ft (12.5 m) to the center of the front axle, the desired limit for the path of the center of the rear axle is set at no more than 17 ft (5.2 m) inside of the path of the front axle. This compares with a calculated value of 17.34 ft (5.3 m) for the baseline 3-S2.

Friction demand in a tight turn:

The tire/road friction needed to negotiate a tight turn such as an intersection can be a problem for vehicles with widely spaced axles.[13] On slippery surfaces, the friction level demanded of the tractor's rear axles may exceed the available friction if the semitrailer has a widely spread axle set. This has been known to lead to tractor jackknifing and the potential for low-speed collisions with other vehicles. Concerns with this problem, as well as with excessive tire wear on high friction surfaces, has caused truck operators to employ one or more liftable axles in suspension sets with five or more axles.

The previous model of tight turning represents multiple-axle sets by a single, centrally located axle. This is a reasonably good approximation for conventional vehicles, but it is inadequate for vehicle units with many and/or widely spread axles. The "friction demand" computation considers the scrubbing of tires during a tight turn and includes the influences of low-friction surfaces. It uses tire lateral force characteristics to predict the turning ability of multiaxle vehicles on a variety of low- and high-friction surfaces. Performance in this maneuvering situation is degraded by the use of many and/or wide spread axles in a suspension group on a vehicle unit. (The calculation is based on the results obtained in reference 13.) The level of road friction required by the vehicle is the performance measure for this maneuver. Smaller values for this measure imply a better maneuvering ability during a tight turn.

Target performance level:

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The maximum level of friction demand used for a baseline has been set at 0.2. This choice is fairly arbitrary because the current understanding of this phenomenon is not complete and, in addition, the choice depends upon the level of highway slipperiness that is deemed acceptable. Friction levels given in the AASHTO green book are 0.17 and above for the friction factor for tight, low-speed turns. Even though this application may be taking the AASHTO numbers out of context, the AASHTO friction levels give an idea of the characteristics of a poor road.

High-speed offtracking

At highway speeds, the driver's unit (the tractor or truck) is steered to follow a desired path. The trailing units are expected to follow the path of the lead unit.

At low speeds, the units of a combination vehicle will track towards the inside of the curve. As the speed increases, however, the offtracking begins to diminish and actually becomes zero at some speed. At speeds above that point, the trailing unit or units may track to the outside of the path of the lead unit; trailer tires may strike a curb (thereby precipitating a rollover on a ramp, for example), or the trailer may hit an adjacent vehicle or obstacle.

The analysis applies to the operation of vehicles on highway curves at highway speeds. These calculations determine the offtracking of each unit as a function of speed and turn radius. The outboard offtracking attained by the rear axle of the last trailer is then used as the performance measure for the maneuver.

Target performance level:

The vehicle is envisioned to be in a steady turning situation on a radius of 1,200 flt (366 m) and traveling at 55 mi/h (88 km/h). The selected target is for the center of the vehicle's last axle to track not more than 1 ft (0.3 m) outside of the path of the center of the front axle. The value of this measure for the baseline 3-S2 is 0.24 ft (.072 m). This level is based on ideas generated in Sweden where an 0.5 m offtracking limit was proposed. Generally, drivers do not come as close as 1 ft (0.3 m) to curbs and other obstacles. Hence, this is probably the least critical of the intrinsic safety measures with vehicles like the baseline tractor-semitrailer being able to easily meet this goal.

Constant deceleration braking:

The quality of the overall braking system as an accident-avoidance mechanism depends upon the ability to stop quickly in a stable and controllable manner. Truck stability and control during braking depend upon avoiding wheel locking. If the front wheels lock, the vehicle will not be responsive to steering. If the tractor rear wheels lock, a tractor-semitrailer may jackknife. If trailer wheels lock, a trailer swing may ensue. All of these conditions are undesirable and each of them could lead to an accident. Each of them represents a situation in which the braking force demand at some axle set exceeds the amount of force capability available from the load on the axle set and the prevailing friction level of the tire/road interface.

The analysis procedure examines the proportioning of the braking system by calculating the friction level required at each axle to prevent its wheels from locking up. The ratio of deceleration to the highest friction level required at any axle is the braking efficiency of the vehicle at that deceleration level. This simplified representation of the braking process is useful for illustrating braking arrangements and situations that will lead to poor deceleration performance. The braking efficiency of the vehicle at various levels of deceleration (for example, 0.2 g and 0.4 g) provide the performance measures during braking.

Target performance level:

Braking efficiency is the fraction of the available tire/road friction that can be used in an emergency stop without locking any wheels. Braking efficiency varies with loading conditions and the levels of deceleration involved. A target of at least 0.7 has been selected. For the baseline 3-S2 with a full load, the braking efficiencies are 0.887 and 0.843 at 0.2 and 0.4 g, respectively. These excellent levels are attained because the braking systems on heavy trucks in the U.S. are proportioned in accordance with the gross axle weight ratings. When the 3-S2 is empty, the braking efficiencies are 0.672 and 0.645 at 0.2 and 0.4 g, respectively. These lower levels of efficiency are probably the cause of empty vehicles being overly involved in accidents in which the vehicle folds up ("jackknifes").

Steady turn—rollover

Heavy trucks with high centers of gravity are prone to rolling over in turning maneuvers. Examinations of the accident record have shown that the static roll stability of trucks correlates well with rollover experience. [14,17,18] The results of these examinations indicate that the rollover of heavy tractor-semitrailers is very sensitive to their intrinsic rollover thresholds, especially where the rollover thresholds are less than 0.4 g.

The calculations used model the rolling performance of a vehicle during steady-turning maneuvers. The calculation procedures represent analytical equivalents of tilt-table experiments. The model includes the primary factors influencing roll, namely, c.g. heights, axle track widths, spring and tire rates, spring spreads, roll center heights, and axle loads. The computations predict the level of lateral acceleration at which rollover will occur.

Target performance level:

The level of lateral acceleration which can be achieved without rolling over in a steady turn is selected to be 0.38 g for fully laden vehicles with the center of gravity of the payload at the center of the cargo container. This level is believed to be achievable with current hardware, especially if free plays in the springs and fifth wheel are kept to a minimum. The comparable performance level predicted for the baseline tractor-semitrailer is 0.375 g. (Some current vehicles with soft springs, 96-in (2.4 m) track widths, high payloads, and considerable suspension lash may have rollover thresholds as low as 0.25 g.)

Steady turn—handling

The ease of directional control depends upon handling properties. Vehicles that are directionally unstable, or nearly so, require constant attention to the desired path and continual steering corrections to maintain that path.

"Handling" calculations are concerned with the steering angles required for a given type of steady turn. These calculations indicate the possibility for the vehicle to become directionally unstable.

For straight and articulated heavy trucks, the handling calculations are complex. The vehicle's response to steering may be linear only up to 0.15 g of lateral acceleration. Due to nonlinearities in tire cornering stiffnesses and the distribution of roll stiffnesses at the various suspensions, some vehicles may become directionally unstable at lateral acceleration levels below their rollover thresholds. The steering sensitivity, that is, the rate of change of steering angle with respect to lateral acceleration, indicates the margin of stability and is evaluated at 55 mi/h (88.5 km/h) and 0.3 g of lateral acceleration to define the performance measure for the vehicle. If the vehicle can become directionally unstable at 0.3 g of lateral acceleration, the lowest speed at which this instability occurs is calculated. (This is called the critical speed.)

Target performance level:

A steering sensitivity of 0.1 rad per g of lateral acceleration has been selected as a basis for comparing the directional control and stability of heavy trucks. This may be conservative in that the baseline 3-S2 has a steering sensitivity of 0.065 rad per g at 0.3 g of lateral acceleration. Nevertheless, the selected value is believed to be a reasonable value given the mechanical properties of current tires and suspensions. The appropriate level is hard to assess even though it applies to a basic situation like directional stability during turning.

Obstacle evasion (rearward amplification):

This is a phenomenon that pertains primarily to vehicles with more than one articulation point, for example, truck-full trailers and doubles and triples combinations. It occurs during obstacle-avoidance maneuvering in which the driver has to react quickly—situations such as when a car pulls out or stops quickly in front of a truck and the truck driver attempts to drive around the obstruction, proceeding at highway speed in the original direction of travel. (In general, rearward amplification is small and of no concern in those more normal situations in which the driver has time to plan ahead.) The phenomenon is believed to be the cause of a number of rollovers of double-bottom tankers in Michigan and it has been demonstrated in proving grounds tests and in driver training films.

The model offers a first look at the response of a combination vehicle to rapid changes in steering. In obstacle-avoidance maneuvers, multitrailer vehicles experience a "cracking-the-whip" phenomenon where the lateral accelerations of rear trailers are amplified considerably. In this context, the lateral acceleration of the first unit may be viewed as the independent input variable employed in evaluating the extent to which the motion of the last unit exceeds that of the first unit. Frequency domain calculations are used to study

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rearward amplification, which is technically defined as the ratio of the lateral acceleration of the last unit to the lateral acceleration of the first unit of the vehicle. The maximum amount of amplification is then used as the performance measure for this maneuver.

Target performance level.

A value of 1.4 has been chosen as the target level of rearward amplification. This level can be reached by doubles combinations with stiff tires, relatively long trailers, and favorable hitch locations. Innovative dollies with special hitching arrangements and the use of semitrailer-semitrailer doubles (B-trains) are measures that can be used to control rearward amplification. For tractor-semitrailers rearward amplification is approximately 1.0. Hence, the baseline tractor-semitrailer does not encounter the same concerns with amplification-induced rollover or transient high-speed offtracking as vehicles with multiple articulation points. Nevertheless, a value greater than 1.0 has been chosen to represent a possible bound for vehicles with more than one articulation joint.

If this performance level cannot be met through the use of stiff tires, long trailers, and favorable hitch locations, controlled-steering dollies can be used to greatly reduce rearward amplification. For example, controlled-steering B-dollies have been used to reduce rearward amplification from 2.3 for particularly poor examples of Western doubles to 1.5.[19]

METHODOLOGY

The Concept of a Size and Weight Scenario

The analyses of vehicle performance presented in the technical report are centered around various size and weight scenarios in which each scenario consists of the following parts: (1) a set of rules governing the sizes and weights of heavy trucks; (2) a set of vehicle designs representing the types of vehicles that would be productive under the given set of size and weight rules; (3) an analysis of the performance of the projected vehicles in safety-related maneuvers; and (4) an evaluation of the intrinsic safety of the vehicles evolving under the given set of size and weight constraints.

In the context of this study, the concept of a size and weight scenario springs from the idea of viewing size and weight regulations as guides to vehicle design which have been postulated as reasonable approaches for enhancing trucking while maintaining the integrity of the highway transportation system. Given a set of size and weight guidelines, one can develop a scenario in which productive vehicle designs are created, the performances of these vehicles are predicted, and the safety implications of their performances are assessed. (See figure 3.)
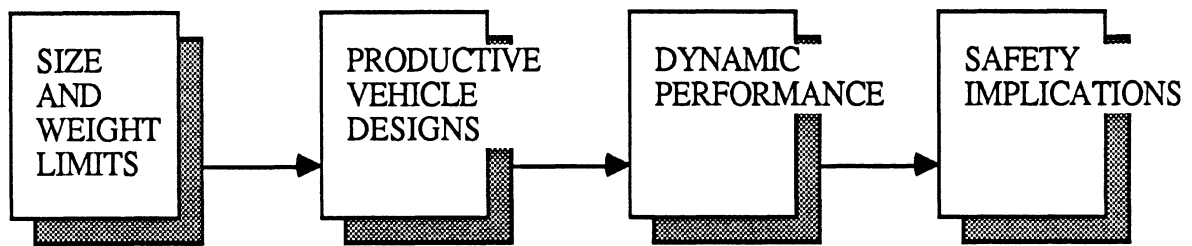
Figure 3. Safety implications of size and weight limits.

Selection of Specific Sets of Size and Weight Limits

Specific sets of size and weight limits (see table 1) were chosen as the starting points for the 18 scenarios considered in this study.

This set of scenarios was not meant to represent a list of all of the reasonable possibilities for future regulations. Given that size and weight laws are the results of political processes, they represent judgements based on many aspects of the influences of truck transportation on society. Clearly, future proposals for size and weight regulations could well lead to scenarios that have not been addressed in this study. Rather than being aimed at saying that one of the chosen scenarios is better than another, the intention of this study is to employ the 18 scenarios as examples to be used in developing a general understanding of the influences of size and weight rules on vehicle design and performance.

Nevertheless, the size and weight limits examined here are intended to represent rationalized, interesting possibilities. They have been based on discussions with persons from trucking companies, vehicle manufacturing firms, and the FHWA. The chosen set of 18 size and weight constraints reflects truckers' concerns with arbitrary weight and length caps and their desires for more productivity. In addition, the list of size and weight scenarios given in table 1 incorporates scenarios based upon new types of bridge formulas and new limits on axle loads (pavement loading) for various vehicle configurations. In one manner or another, many of the latest ideas with respect to changing size and weight rules are represented in table 1.

Conceptually, scenario 1 illustrates a very direct notion for increasing productivity—simply drop the 80,000 lb (36,000 kg) cap. This idea is carried over into scenarios 2 and 3 but with additional changes in the bridge formulas. Scenarios 4 and 5 are based on new bridge formulas alone. Scenarios 6 and 7 encompass many types of vehicle configurations and an offtracking rule is used to constrain lengths for these configurations. Scenarios 8 through 12 represent situations in which pavement loading would be reduced below current limits. Scenario 13 was meant to allow more load on tractor-semitrailers exclusively. (It turns out that this cannot be done without relaxing some of the other constraints for the 3-S2.) Scenarios 14 through 16 address the transportation of the largest and heaviest shipping containers. Scenario 17 contains a higher but arbitrarily chosen gross combination weight limit. And, finally, scenario 18 involves a design innovation (twin

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Table 1. Size and weight scenarios.

Scenario Number	Maximum[1] Weight	Bridge[2] Formula	Pavement[3] Loading	Length[4] Factors	Vehicle[5] Configurations
1	None	B	34/20 K	STAA	STAA
2	None	C	36/22 K	STAA	STAA
3	None	TTI	34/20 K	STAA	STAA
4	80 K	C	36/22 K	STAA	STAA
5	80 K	TTI	34/20 K	STAA	STAA
6	None	B	34/20 K	12/40	Basic 5
7	None	TTI	34/20 K	12/40	Basic 5
8	None	B	28/16 K	STAA	STAA
9	None	B	28/16 K	12/40	Basic 5
10	None	TTI	28/16 K	STAA	STAA
11	None	TTI	28/16 K	12/40	Basic 5
12	None	C	36/22 K	12/40	Basic 5
13	88 K	B	34/20 K	STAA	3-S2
14	ISO (90 K)	B	34/20 K	12/40	TST/ISO
15	ISO (90 K)	C	36/22 K	12/40	TST/ISO
16	ISO (90 K)	TTI	34/20 K	12/40	TST/ISO
17	100 K	B	34/20 K	12/40	Basic 5
18	None	B	34/20 K	12/40	2 Front

Note: (2.2 lb = 1 kg and 1 ft = 0.3 m)

1. Maximum weight limits are in 1000's of lb, e.g., 80 K = 80,000 lb.

2. Three bridge formulas are considered. Formula B is the current rule. Formula C increases the load on any group of axles by 2,000 lb over that allowed by formula B. The TTI formula has recently been developed.

3. "Pavement loading" refers to the loads allowed on single- and tandem-axle sets. For example, the "28/16 K" designation means 28,000 lb on tandem axles and 16,000 lb are allowed on single axles. (These pavement loadings represent an example derived from the "Turner Concept.") The pavement loading requirements apply whenever they are more stringent than the bridge formula requirements.

4. Two types of length constraints are listed. The notation "STAA" refers to the lengths specified for TST's (tractor-semitrailers) and doubles in the Surface Transportation Assistance Act of 1982. The notation "12/40" corresponds to offtracking equivalent to that of a tractor with a 12 ft wheelbase pulling a semitrailer with 40 ft from the kingpin to the center of the rear suspension.

5. The numbers of articulation points and axles are indicated by the entries in this column. "STAA" means TST's and doubles. "Basic 5" means the set of vehicles consisting of single unit trucks, truck-full trailers, TST's, doubles, and triples. "3-S2" refers to a tandem axle tractor pulling a tandem-axle semitrailer. "TST/ISO" refers to a tractor-semitrailer designed to transport ISO containers. Finally, "2 Front" refers to trucks and TST's with two steering axles at the front of these vehicles.

steering front axles) that has not been employed to any extent in the U.S.A. All of these different situations form bases for creating designs for productive vehicles.

Creation of Productive Vehicle Designs

The design of vehicles currently in service has been highly dependent upon the length constraints of STAA of 1982, the 80,000 lb (36,287 kg) weight cap, and the provisions of bridge formula B. However, the new constraints provided by the scenarios have determined the layouts and axle loadings of the vehicles examined in this study.

The vehicle designs developed in the size and weight scenarios are tailored to the constraints involved. This is done by postulating a productive design and checking to see if the layout of the proposed vehicle satisfies the given constraints. If not, the design is modified and rechecked until the constraints are satisfied.

An automated procedure was developed for checking whether vehicle designs will pass various sets of size and weight constraints. It would have been very difficult and time consuming to perform the task of developing vehicle designs without automating the checking procedure. (For example, figure 1 indicated the various axle sets that need to be checked for compliance with any of the bridge formulas.)

The distribution of payload has clear implications with respect to the distribution of axle loads. Experts from trucking firms believe that vehicle designs should be based on water level loads (that is, uniform loading of the trailers). Other special loading arrangements to optimize payload are not realistic. The example vehicles pursued here are based on uniform loading. (However, the influences of nonuniform loading arrangements are considered.)

The five basic types of vehicles studied are single-unit trucks, tractor-semitrailers (TST's), truck-full trailers, doubles, and triples. Examples of the layouts of TST's and doubles are illustrated in figure 4. Codes such as 3-S2, 2-S1-2, etc., are used as a shorthand means for designating vehicle configurations (see figure 4). Note that designs are required for each of these configurations if these configurations are allowed in the scenario to be examined. In the codes, an "S" stands for a semitrailer and the numbers designate the number of axles on each unit. Hyphens separate the units in the combination. For example, although not shown in figure 4, a currently typical triple would be designated as a 2-S1-2-2, meaning that the vehicle has a two-axle tractor towing a single-axle semitrailer followed by two full trailers with two axles each. This vehicle would look like the 2-S1-2 double except that it would have another full trailer attached to the double's full trailer.

In addition to the numbers of axles, the fundamental differences among the types of vehicles are the numbers of articulation points (points where angular rotations take place in the horizontal plane). Each semitrailer requires an articulation point and each full trailer has two articulation points. Each full trailer is made up of a short semitrailer called a "dolly" plus another semitrailer that contains the load. Hence, a TST has one articulation point, a truck-full trailer has two articulation points, a double has three articulation points, and a triple has five articulation points.

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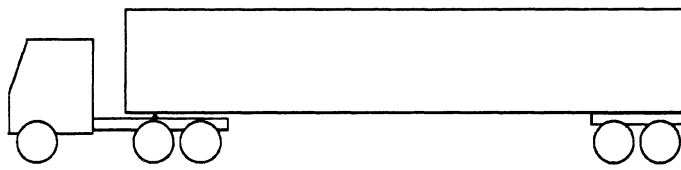
TST, 3-S2

- 3 axle tractor
- 2 axle semitrailer
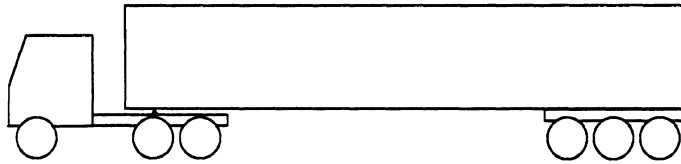
TST, 3-S3

- 3 axle tractor
- 3 axle semitrailer
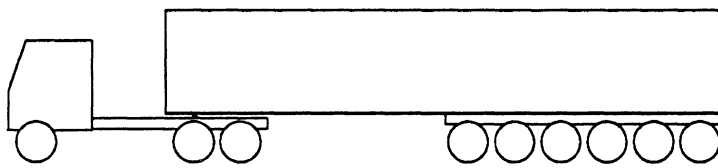
TST, 3-S6

- 3 axle tractor
- 6 axle semitrailer
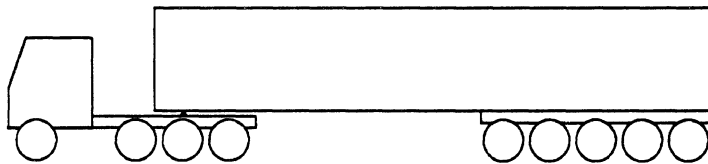
TST, 4-S5

- 4 axle tractor
- 5 axle semitrailer
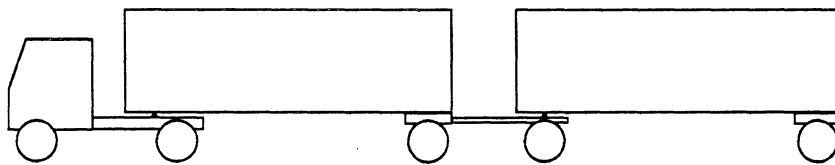
Double, 2-S1-2

- 2 axle tractor
- 1 axle semitrailer
- 2 axle full trailer
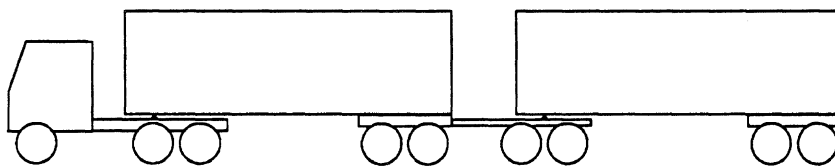
Double, 3-S2-4

- 3 axle tractor
- 2 axle semitrailer
- 4 axle full trailer
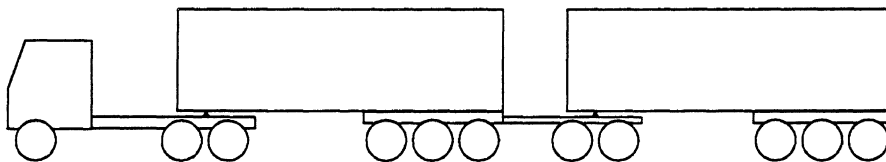
Double, 3-S3-5

- 3 axle tractor
- 3 axle semitrailer
- 5 axle full trailer

Figure 4. Example vehicle configurations and codes.

The dimensions that were used in laying out vehicles are illustrated in figure 5. The most important dimensions in analyzing a vehicle design are the distances between suspension centers and hitch locations. These dimensions are determined by selecting cargo box lengths, the axle spreads, and numbers of axles on semitrailers. For the tractor, the wheelbase and the fifth wheel offset are assumed to be adjustable. The weight of the payload is varied in creating a vehicle design. The dolly tongue lengths must be specified for full trailers.

In this study, front axle loads are determined by the tare weights of the tractors and the loading at the fifth wheel, that is, by current vehicle design practices. The allowable loads on nonfront axles are determined in accordance with the constraints involved in each scenario. For empty vehicles, the tare weights of various vehicle units and axles are set in accordance with presently typical vehicle properties.

Increased productivity can mean one of two things, depending upon the density of the cargo to be carried. Light cargo densities imply the need for more space; heavy cargo densities imply the need for more weight. The bridge formulas have the feature that as units get longer they are allowed to carry more load. Hence, the objective of greater load-carrying capacity tends to satisfy the desire for more cargo space. On the other hand, a gross weight cap may be a severe limitation on the transport of heavy commodities, although it may have little influence on the transport of light goods. In general, we have created vehicles that are examples that represent (a) heavier loading of existing vehicles, (b) first-order increases in load-carrying capacity, or (c) large increases in load-carrying capacity.

All of the vehicle design considerations discussed in this section have been employed in the context of creating designs that would be more productive than current trucks. These new designs are intended to represent vehicles that might be used by trucking companies (with a few exceptions illustrating unusual circumstances created by particular combinations of size and weight rules). A hierarchy of examples has been constructed to try to anticipate changes ranging from (a) increases in productivity that could be achieved almost immediately with little change in design; (b) intermediate designs requiring modest revisions in vehicle layout; to (c) designs that attempt to reach the maximum load-carrying capacity that might be achieved using substantial changes in design. The design process has been a creative one in that no universal algorithm for producing optimum designs has been found. In general, no claim is made that any of the designs created herein are to be taken as the most productive ones that could be created. They are, however, intended to be examples of very productive designs.

Prediction of Vehicle Performance

Once vehicle designs exist, the mechanical properties of these vehicles are known. Given the mechanical properties of a vehicle and its components, computerized vehicle dynamics analyses can be used to predict vehicle performances in the safety-related maneuvering situations described previously in the section entitled "Measures of Intrinsic Safety." In this study the results from such analyses have been compared with target performance goals to assess the safety implications of the vehicles developed for each
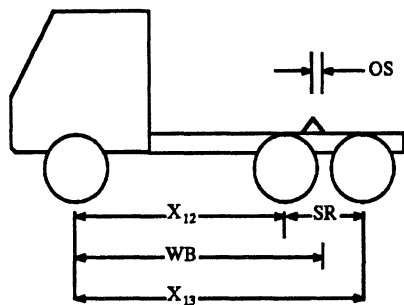
(a) Tractor
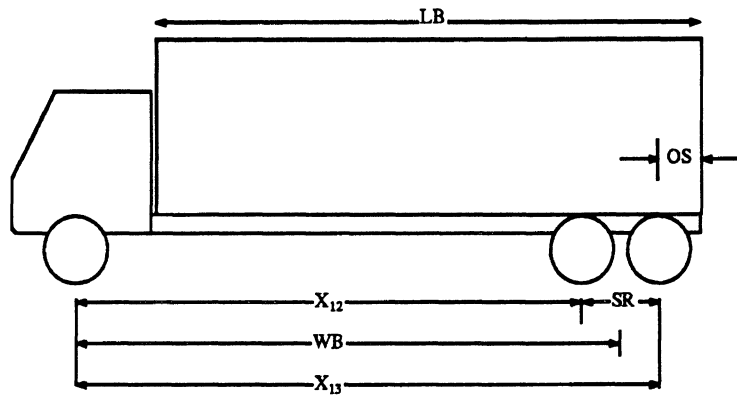
(b) Truck
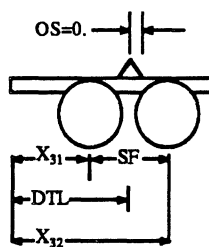
(c) Dolly
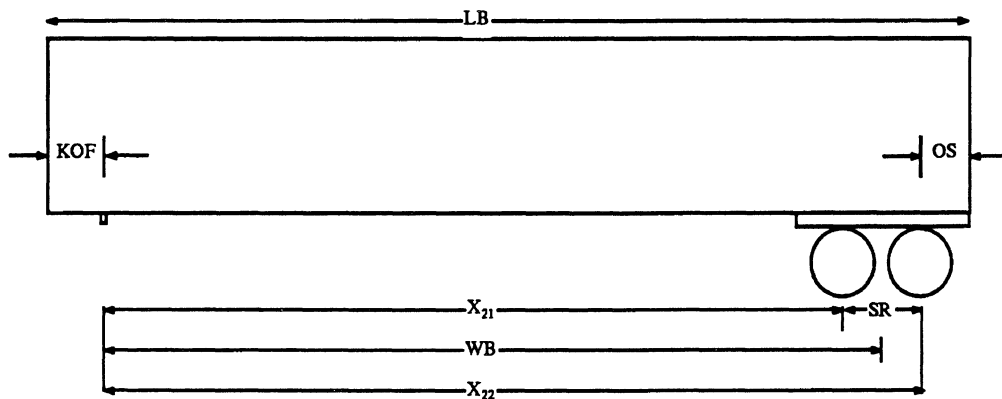
(d) Semitrailer

Figure 5. Layout information for various vehicle units.

scenario. In this manner we can predict the consequences of new vehicle designs that would be encouraged by changes in size and weight rules.

Vehicle performance is highly dependent upon the mechanical properties of the tires, brakes, and suspensions employed on the vehicle. These components are designed to withstand the stresses and strains encountered in service. Hence, these components are usually specified in terms of the gross axle weight ratings of the axles they are installed on. Recently, mechanical properties such as tire cornering stiffnesses, suspension roll stiffnesses, and brake gains have been obtained by measurements of the respective components.[12] These types of properties,which are the pertinent mechanical properties with respect to braking and steering performances, have been used in this study for the purposes of specifying component characteristics. The idea is that we want to do more than assuring that the vehicle does not fall apart (which is obviously important)—we want to understand its turning and braking performances.

The mechanical properties of the components used in the new designs examined in this study are based on measured properties of typical (existing) tires, suspensions, and brakes. This methodology (strategy) has two important features. First, we know that non-exotic components can be built with these properties (because current components have these properties). Second, we know that this will lead to higher levels of tire cornering stiffnesses, suspension and roll stiffnesses, and brake gains per pound of load carried on lightly loaded axles. (As will be discussed later, the vehicle performance results will show that this is an appropriate choice for tires and suspensions but it would be a poor choice for brakes.)

SPECIFIC FINDINGS

Design Implications of Individual Size and Weight Constraints

Generalized understandings of the roles of various size and weight constraints have been ascertained through the process of designing vehicles and predicting their performance. The implications of individual size and weight rules with respect to vehicle layout are summarized here as an introduction to the scenarios that follow later.

Bridge Formula Constraints

<u>FORMULA B</u>

        • Formula B promotes the use of extra axles to gain weight allowances with or without increasing length. It allows approximately 6,000 lb (2,722 kg) of extra vehicle weight for an additional axle in a given axle set.

        • Due to the size of the fixed allowance for additional axles, the pavement load on each axle of a set of equally loaded axles decreases with every axle added to a suspension. Consequently, this bridge

formula contains a pavement loading restriction. (It might be said that formula B has a version of the Turner concept built into it.[9])

FORMULA C

- Other than an additional 2,000 lb (907 kg) weight allowance on an axle set, formulas B and C are identical. Vehicles developed under formula C would be similar to vehicles developed under formula B except that they would be 2,000 lb (907 kg) heavier.

FORMULA TTI

- Unlike formulas B and C, the TTI bridge formula is a "length-to-weight" rule that does not provide any weight allowances for additional axles. Consequently, the TTI formula encourages widely spaced axles with no benefits for extra axles.
- The TTI bridge formula allows more liberal loading on axle spreads that are less than 56 ft (16.8 m) than it does on spreads that are greater than 56 ft (16.8 m).

Pavement Loading Constraints

"36/22 RULE"

- Since the pavement loading constraint only applies to single and tandem axles, the loads on multiaxle (more than two axles) groups is governed by a bridge formula constraint.
- The 36/22 rule is used in conjunction with formula C and limits tandem axles to 36,000 lb (16,329 kg) and single axles to 22,000 lb (9,979 kg).
- In certain situations the ability to carry higher loads (2,000 lb (907 kg) more than the prevailing "34/20 rule") on a limiting axle group improves the overall weight carrying capacity of the vehicle. (This turns out to be useful for obtaining slight increases in payload when water level loading is used in the design process.)

"34/20 RULE"

- The 34/20 rule is the currently prevailing pavement constraint and limits tandem axles to 34,000 lb (15,422 kg) and single axles to 20,000 lb (9,071 kg).
- Multiaxle (more than two axles) suspensions or wide-spread single axles can be used to circumvent the restriction of the pavement loading constraint.
- The layout of the baseline 3-S2 is an example of a vehicle in which the 34/20 rule and bridge formula B provide a limit layout at a GCW of 80,000 lb (36,287 kg).

<u>"28/16 RULE"</u>

- The 28/16 rule is based on the Turner Concept and limits tandem axles to 28,000 lb (12,701 kg) and single axles to 16,000 lb (7,257 kg). (This is just one possibility for implementing a Turner concept.)
- Multiaxle (more than two axles) suspensions or wide-spread single axles are likely to be used to meet the more restrictive pavement loading constraint.

Length Constraints

<u>STAA VEHICLES:</u>

- The notation "STAA" refers to the lengths specified for tractor-semitrailers (TST's) and doubles in the Surface Transportation Assistance Act of 1982. The STAA limits TST semitrailer lengths to 48 ft (15 m) and double trailer lengths to 28 ft (8.5 m). There is no explicit constraint on the lengths of tractors and dollies.
- If bridge formula rules are used in conjunction with the length constraint, long tractors and dollies could be used to increase the overall length, thereby increasing the vehicle's weight-carrying capacity.

<u>"12'/40' OFFTRACKING RULE":</u>

- Under this constraint, vehicles must have low-speed offtracking characteristics equivalent to that of a tractor with a 12-ft (3.7 m) wheelbase pulling a semitrailer with 40 ft (12.2 m) from the kingpin to the center of the rear suspension.
- The offtracking rule promotes more articulation joints and shorter effective wheelbases in the vehicle layout.
- Depending upon the bridge formula in effect, multiaxle suspensions or wide-spread axles could be used to shorten effective wheelbases. With no explicit constraint on the lengths of units, long vehicles with small amounts of offtracking can be developed, but they might require high levels of friction in tight turns. To counter the friction demands, liftable axles might be promoted.

Maximum Weight Constraints

<u>80 K, 100 K, NONE:</u>

- The maximum weight cap is used with a bridge formula rule to determine vehicle layouts.
- Under the TTI formula, the weight cap establishes a minimum vehicle length for vehicles that are at the weight cap. Under formula B, the number of axles is also required to set the minimum length.
- If the weight cap is raised, vehicles may need to get longer to obtain the higher weight. Presuming that axles are added in sufficient (but

not excessive) quantity, the number of axles will be influenced by the weight cap and the pavement loading rule.

• The 80 K weight cap, 34/20 rule, and formula B tend to make the five-axle tractor-semitrailer (TST) a productive vehicle for carrying 80,000 lb (36,287 kg). Higher weight caps tend to make other vehicle layouts more productive than the five-axle TST's.

Highlights and Consequences of the 18 Scenarios

This section contains conclusions as to which types of trucks would be encouraged, the safety implications of these trucks, and what types of constraints might be considered for individual scenarios or groups of scenarios. It is to be emphasized that this study is not intended to arrive at conclusions such as scenario 16 is better than scenario 2. The 18 scenarios considered in this study do not exhaust the list of reasonable possibilities. The following conclusions are intended to provide information that will allow interested persons to reach general conclusions as to (a) how size and weight constraints could influence the designs of trucks in service, and (b) the safety implications associated with vehicles resulting from various size and weight constraints.

Scenario 1 — no weight cap, formula B, STAA lengths

This scenario is key to the discussions that follow. It is a straightforward extension of the current rules to allow heavier, more productive vehicles.

The length provisions of STAA of 1982 limits fleet operators to using a single 48-ft (14.6 m) trailer or two 28-ft (8.5 m) trailers in their TST's and doubles configurations. There is no explicit constraint on the lengths of tractors and dollies.

"Less-than-truck-load" (LTL) operators, whose vehicles are more often "cubed-out" (filled up) prior to approaching the gross weight limit, would not benefit greatly from a removal of the weight cap in this scenario where the lengths of the cargo boxes are fixed. Nevertheless, if LTL carriers have not already changed from tractor-semitrailers (TST's) to doubles to increase their cargo volume, the change in the weight rule might encourage them to modify their fleets from TST's to doubles to provide flexibility for carrying more weight. On the other hand, carriers of dense cargo might use long tractors and dollies to increase their allowable payload weight through increasing the overall lengths of their vehicles.

In addition to allowing higher weights over longer lengths, formula B provides a weight allowance for the use of additional axles in an axle set. In general, from the standpoint of vehicle performance, extra axles within a fixed length reduce the effective wheelbases of the various units. Short wheelbases on units have a tendency to increase the amount of rearward amplification, thereby degrading the maneuvering performance of multiarticulated vehicles. The use of extra axles in a suspension group also increases the amount of tire/road friction required during tight turning maneuvers. The braking performance of the empty vehicle is a general problem, that is, it does not result from the constraints of this or any other set of weight rules. In the loaded state, the braking effort of

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the additional axles tends to make the vehicles slightly "overbraked," especially on the lightly loaded axles. From the roll stability viewpoint, the added roll stiffnesses of the extra axles helps to improve the vehicle's resistance to rolling over.

More specifically, for the TST's to have GCW's greater than 80,000 lb (36,287 kg), and still satisfy the loading and axle separation requirements of bridge formula B, additional axles would have to be added. Results from trial designs indicate that GCW's could increase by approximately 6,000 lb (2727 kg) for each axle over five axles (80,000 lb (36,287 kg) can now be carried on the five-axle TST shown in figure 6). With respect to maneuverability and mobility, the main drawback resulting from additional axles concerns the ability to turn tight corners when the road surface is slippery. Calculated results show that semitrailers with five or six closely-spaced rear axles would have problems turning corners when the road is slippery. Semitrailers with closely spaced tridems are not predicted to have these troubles, and long semitrailers with four closely-spaced axles might be considered acceptable.

If the 80,000-lb limit were removed for the doubles allowed under STAA of 1982, the situation would be more complex than that applying to TST's. The double would also be more productive than TST's for those persons wishing to carry dense cargo. These findings are based on an examination of the loading and axle separation requirements of formula B.

The double has 56 ft (16.88 m) of cargo length (two 28-ft (8.4 m) "boxes" on the semitrailers) while the TST has 48 ft of cargo length. Since formula B allows more weight by "spreading the load" over more length, the double would have the potential for carrying significantly more load than that carried by the TST. To maximize productivity for carrying dense products like liquids and bulk commodities, vehicle owners and operators would choose doubles over TST's, given the constraints of scenario 1. That is, under scenario 1 companies carrying dense cargos would switch from tractor-semitrailer trucks to twin-trailer trucks in order to increase productivity.

If the gross weight cap were removed, bridge formula B would allow current "Western" doubles to go immediately from 80,000-lb (36,000 kg) to approximately 88,000-lb (36,000 kg) (see figures 7 and 8). This additional weight would make these vehicles more susceptible to rolling over, that is, the rollover threshold would occur at a less severe level of turn. Also, the handling control of these heavier 2-S1-2 doubles would be more difficult. These analytical results indicate that the safety-related performance of the current design of the Western double would be decreased if the 80,000-lb (36,000 kg) cap were removed.

In order to carry greater payloads additional axles could be added to the double. For example, if single axles on the 2-S1-2 were to be replaced with tandem-axle sets to make the 3-S2-4 double (figure 9), formula B would allow the 3-S2-4 vehicle to have a GCW equal to approximately 109,000 lbs (49,000 kg). Furthermore, the use of tridems on the double's semitrailers could lead to a practical vehicle (the 3-S3-5 shown in figure 10) that would be legally allowed to have a GCW of 122,500 lb (56,000 kg). These vehicles (the 3-S2-4 and the 3-S3-5) would be very attractive to the trucking industry because of their

Figure 6. Tractor-semitrailer (3-S2; GCW=78,405 lb; payload=48,105 lb).

Figure 7. Double (2-S1-2; GCW=80,000 lb; payload=49,500 lb).
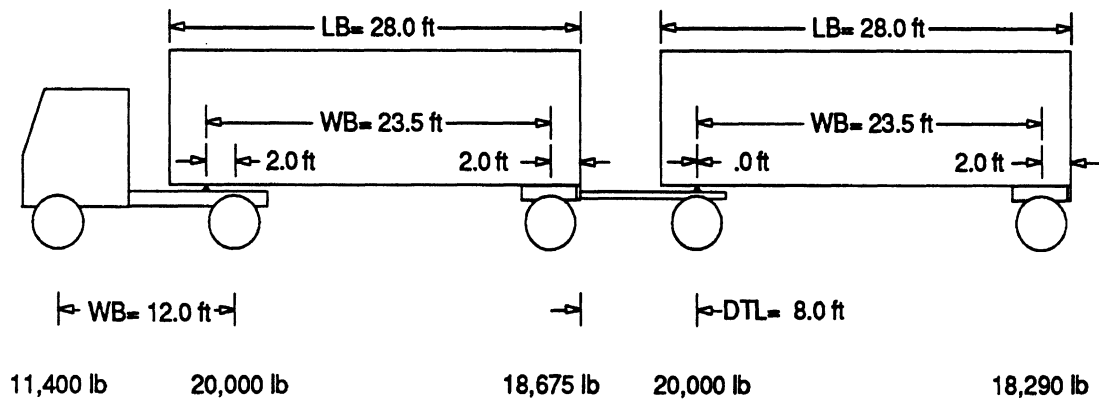
Figure 8. Double (2-S1-2; GCW=88,365 lb; payload=57,865 lb).
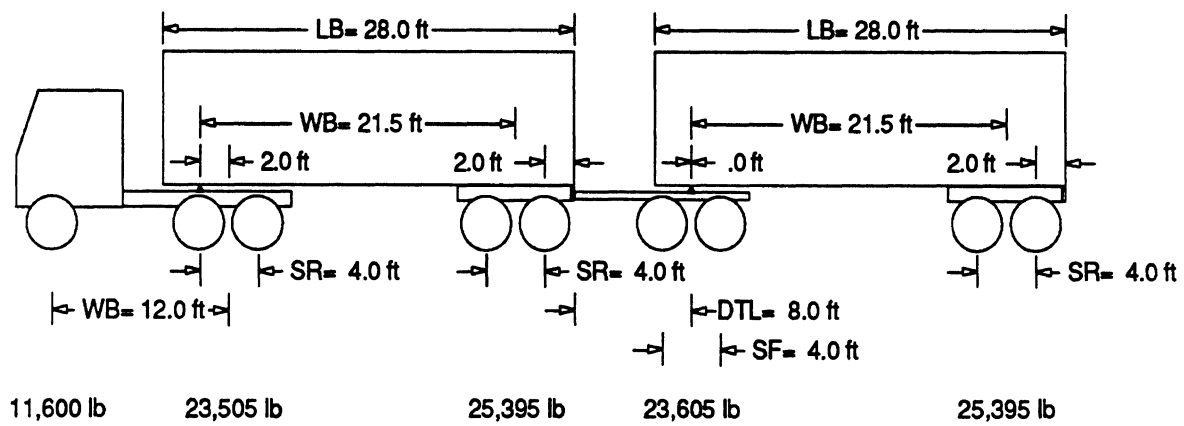
Figure 9. Double (3-S2-4; GCW=109,500 lb; payload=70,500 lb).

Figure 10. Double (3-S3-5; GCW=122,500 lb; payload=79,500 lb).

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productivity in carrying heavy payloads and their mobility in negotiating corners in an urban environment.

Calculations indicate that the heavier doubles with additional axles would have more of a tendency to amplify the motion of the last trailer in an obstacle-avoidance maneuver. This rearward amplification can cause exaggerated motion of the last trailer, and could cause a rollover of the last trailer if the last trailer has a high center of gravity. Since the heavier double could carry 1.6 times more payload than the current 80,000-lb (36,000 kg) double, the accident rate per pound of load delivered might be less for the heavier vehicle. Nevertheless, the driver would be at greater risk because of the elevated level of rearward amplification.

In general, calculations show that the addition of axles to either the TST's or doubles could cause changes in braking efficiency and a small improvement in rollover immunity. These changes are based on using brakes and suspensions equivalent to those used in current vehicles. If suspensions with less roll stiffness than current suspensions were to be used in future heavier vehicles, rollover immunity might be degraded. On the other hand, less effective brakes on some axles could improve the proportioning and braking efficiency of new designs

The low level of braking efficiency for empty vehicles is the result of the current practise of proportioning braking effort based on a fully laden vehicle. This problem can be corrected by proportioning the level of braking at each axle. In general, this means decreasing the braking effort on rear axles of the "new" vehicles. This could be accomplished by selecting braking hardware tailored to the vehicle or by using automatic systems such as load sensing proportioning or antilock braking systems. Although antilock braking systems are costly, they represent an available system for avoiding the safety consequences resulting from locking wheels.

In order to increase the safety-related performances of new designs, decision makers could consider hardware and design improvements such as advanced braking systems, special design specifications for suspension roll stiffnesses, and innovative dollies for reducing rearward amplification.

A variety of safety consequences have been discussed in this section. These discussions have been based on the results of design analyses pertaining to safety-related maneuvering situations. The purposes of these paragraphs are to summarize the results and to suggest types of constraints that might be included in scenario 1 to ensure that unsafe vehicles are not built and operated on the highway network.

Examination of the results for scenario 1 indicates that the braking performances of empty trucks are a general problem. If the 3-S2 TST, shown in figure 6, is used as a reference for making relative judgements, some of the vehicles projected under scenario 1 have poorer performance than the reference vehicle. These findings suggest that decision makers consider requiring antilock braking systems for vehicles allowed under scenario 1. The decision to require antilock systems might be partially justified on the grounds that the additional productivity would easily pay for the additional costs.

(In general, the projected vehicles are based on increased productivity. And hence there is an implicit belief that it is reasonable to use some of the benefits of increased productivity in ways that attempt to ensure safety. This assumption aids in satisfying some of the concerns with regard to needs for benefit/cost evaluations related to safety improvements.)

If an antilock constraint is deemed to be too controversial, then something else should be done to improve braking performance. One might consider setting performance levels for braking. However, this is not easily done without making difficult decisions as to how much improvement in safety is justified and how to determine reasonable performance levels for real vehicles. The results given by the analyses performed in this study are likely to be very optimistic compared to what is currently achieved in practice. One way to attack these major difficulties is to go to a type approval approach in which vehicles allowed under scenario 1 are individually evaluated and approved.

If the braking problems are resolved, examination of the results indicates that the 3-S3 TST appears to be a relatively trouble-free vehicle. A possible approach to the introduction of Scenario 1 would be to allow the development of 3-S3's (see figure 11) as an initial step in expanding the types of vehicles allowed under scenario 1.

Further examination of the results for the other TST's indicates that the friction demand is predicted to be large when the semitrailers are equipped with five and six axles. This subject needs to be investigated further before these vehicles are allowed. At present the number of axles on a semitrailer might be restricted to 3, or 4 at most.

Now consider the doubles. The results for rearward amplification illustrate a problem with obstacle avoidance maneuvers. Solutions to this problem involve requiring tires with high side-force capabilities, long-wheelbase trailers, special means for locating hitch points, and special hitching arrangements. All of these solutions are difficult to specify and changes in hitching could require major changes in vehicle configurations as compared to those that are currently used in the U.S. Before the 3-S2-4 or the 3-S3-5 would be allowed, one might consider some process in which prototype vehicles are developed and evaluated. Given evidence that these vehicles are expected to be both productive and safe enough, these vehicles could be introduced into service on a permit basis.

The results indicate that the 2-S1-2 weighing approximately 88,000 lb (39,600) should be specifically disallowed unless the rollover threshold of this vehicle is increased. A way to do this would be to restrict the allowable c.g. height of the loaded semitrailers, however this would be difficult to enforce. Possibly, some sort of restrictions on roof or tank heights could be worked out if the demand for this type of vehicle merited it.

Since these doubles have a rearward amplification problem, none of them should be allowed to carry hazardous materials without furnishing evidence that their propensity to roll over or swing out into other lanes has been cured. Innovative hitching arrangements in the dollies are a means for improving performance.

Finally, one might want to set limits on dolly lengths and set an offtracking limit such as 17 feet in the maneuver considered here.
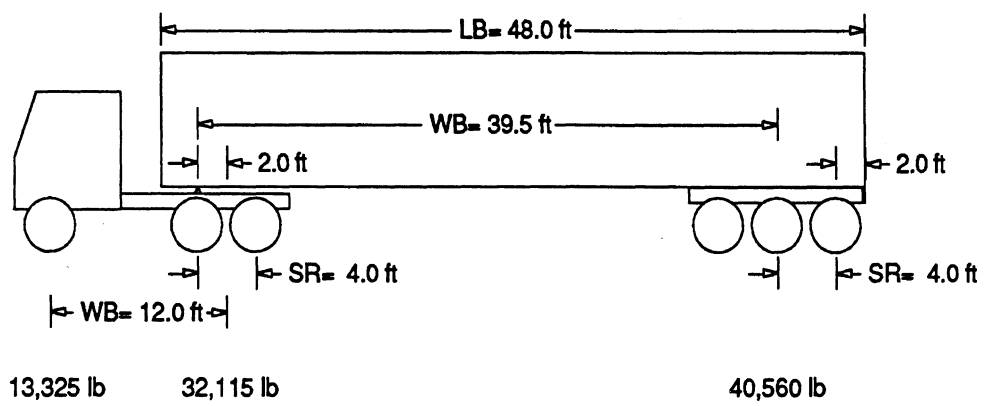
Figure 11. Tractor-semitrailer (3-S3; GCW=86,000 lb; payload=53,700 lb).

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Scenario 2 — no weight cap, formula C, STAA lengths

The constraints in this scenario are very similar to those discussed for scenario 1. In addition to the length restriction of the STAA, the projected vehicles in this situation are constrained by formula C and the associated "36/22" pavement rule. The vehicles are also allowed to operate without the restriction of a gross weight cap.

Formulas B and C are very similar in their definition. They are both "length-to-axle-weight" rules that provide allowances for additional axles and permit higher weights over longer lengths. The only difference between the two rules is that formula C allows an additional 2,000 lb (907 kg) on any given axle set.

The "36/22" pavement rule is used in conjunction with formula C and addresses the 2,000-lb (907-kg) allowance of the bridge formula. This pavement rule allows 22,000 lb (9,979 kg) on single axles and 36,000 lb (16,329 kg) on tandem-axle sets. The more lenient pavement rule often helps vehicles with biased load distributions reach higher gross combination weights without exceeding axle load limits. For example, in this scenario, the TST in figure 6 would be allowed to weigh 82,270 lb (37,317 kg) (see figure 12).

With the primary difference between scenarios 1 and 2 being the 2,000-lb (907 kg) allowance in the bridge formula and pavement rule, the projected vehicles in this scenario would be similar to those developed in the previous chapter. In other words, removal of the weight cap and a restriction on trailer lengths (STAA), could result in longer dollies and more axles on both TST's and doubles.

Since the projected vehicles are similar in the two scenarios, their performance characteristics are predictably very similar. Short wheelbases, caused by multiaxle suspensions, increase the amount of rearward amplification in multiarticulated vehicles. Also, extra axles degrade vehicle performance in tight-turning and constant-deceleration maneuvers. From the roll stability viewpoint, heavier loads on existing axle layouts from scenario 1 result in lower rollover thresholds and higher levels of yaw instability. This is explained by the higher proportion of payload (allowed by formula C) associated with the same roll-resisting capabilities of the vehicle. The additional constraints that might be considered for this scenario are the same as those suggested for scenario 1.

Scenario 3 — no weight cap, formula TTI, STAA lengths

Unlike the bridge formulas discussed previously, formula TTI is strictly a "length-to-weight" formulation. Since the number of axles is not considered in the bridge formula, there are no weight allowances for additional axles. Consequently, in the absence of a gross weight cap, proposed vehicles under formula TTI would have fewer axles than those developed under formulas B and C.

The weight allowance provided by formula TTI depends on the length of the axle set under consideration. Comparing the weight allowances provided for additional length, the TTI bridge formula is more liberal than formula B for distances less than 56 ft (17 m). At lengths greater than 56 ft (17 m), however, formula TTI becomes more restrictive than formula B. In comparing the two bridge formulas, formula TTI is more lenient for shorter vehicles, such as straight trucks and TST's, but its effects are more severe on the longer
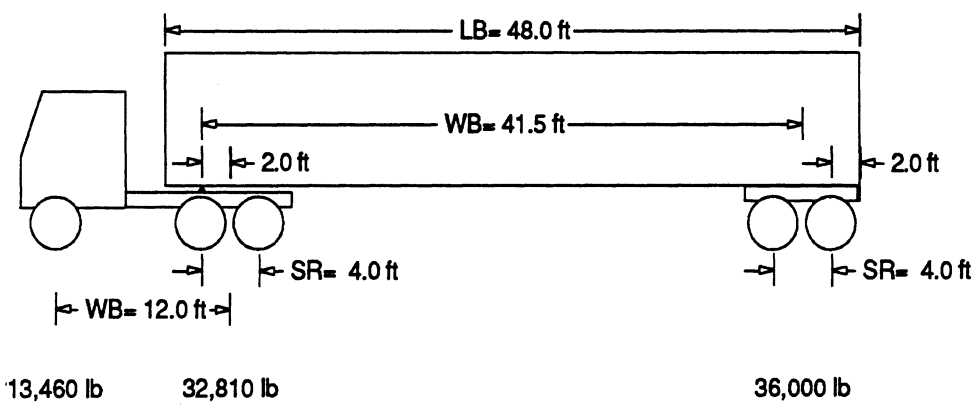
Figure 12. Tractor-semitrailer (3-S2; GCW=82,270 lb; payload=51,970 lb).

truck-full trailers, doubles, and triples. A simplification of this tendency would indicate that long vehicles would have to get lighter, and heavy vehicles would have to get longer.

With trailer lengths constrained by the STAA and no allowance for additional axles, gross combination weights can be kept under control by the bridge formula. In the case of doubles, however, long tractors and dollies could be used to increase the overall vehicle length resulting in higher weight limits. Unlike the proposed vehicles in scenarios 1 and 2, the vehicles developed in this scenario would have fewer axles.

Fewer axles on the vehicles result in better proportioning of the braking effort, thereby improving the braking efficiency. Heavier axle loads, resulting from fewer axles on the vehicle, could result in lower levels of roll and yaw stability. Longer wheelbases on the doubles (resulting from fewer axles) improve their evasive maneuvering capabilities. Conversely, the long wheelbases would lower the vehicles' low-speed offtracking performance.

More specifically, the introduction of the TTI formula would mean that multiaxle, short, heavy vehicles would not be permitted. For example current designs of multiaxle cement mixers and other construction vehicles would need to be redesigned.

The TTI formula was developed to protect bridges and it turned out to be more restrictive than formula B for heavy vehicles with multiple axles. In general this means that very heavy vehicles (in that sense, very productive vehicles) would be longer under the TTI formula than they would be under formula B—or, for a given length the vehicles developed under scenario 3 would be less productive than those developed under scenario 1. The trend towards vehicles with fewer axles and less GCW would mean that doubles would be attractive for increases in payload volume but that doubles would not be as attractive, compared to TST's, for increases in payload weight as the doubles were in scenario 1.

The safety-related results obtained for scenario 3 are remarkably similar to those for scenario 1. Accordingly, the safety-related countermeasures for this scenario are nearly the same as those for scenario 1. Braking of the empty vehicles could be improved by better proportioning of braking effort. In this scenario, with no weight allowance for additional axles, the analyses did not consider combinations with more than 3 axles (tridems) in an axle set. The use of no more than tridems is a conservative bound for controlling friction demand in a tight turn. Although the rearward amplifications for doubles combinations were less than those in scenario 1, they were predicted to be high enough to be of concern. These constraints lead to vehicles with longer wheelbases and less weight than the comparable vehicles considered in scenario 1. Although these differences contribute to lower rearward amplification in general, the absolute values of these reductions are not large enough in this case to obviate the need for the countermeasures specified for scenario 1. Since this scenario would allow as much or more weight for the Western double as that allowed in scenario 1, the heavily loaded Western double would be as susceptible to rollover as it was in the first scenario. In summary, although rolling and rearward amplification performances of the heaviest vehicles pertaining to this scenario may be somewhat better than those of the heaviest vehicles designed under scenario 1, they are not enough better to accept the vehicles without considering countermeasures.

Scenarios 4&5 — using formulas C and TTI instead of formula B

Scenarios 4 and 5 represent considerations of the prospect of changing bridge formulas to C and TTI for the STAA vehicles with an 80,000 lb (36,000 kg) cap. The main effect of using formula C is that it would make it easier to reach the 80,000 (36,000 kg) cap with a water level load. Since the TTI formula is less restrictive on length than formula B for five-axle vehicles weighing less than 80,000 lb (36,000 kg), it would allow slightly shorter two-axle semitrailers to be used in TST's carrying 80,000 lb (36,000 kg). As determined by examining vehicles developed in the other scenarios, the most important influence of a slight load increase is a small degradation in rollover threshold and the most important influences of slight reductions in semitrailer wheelbases are improved offtracking and slight reductions in handling performance and high-speed maneuvering. These deficiencies are believed to be relatively minor in general, but even slight changes in bridge formula or pavement loading could produce unfavorable changes in the performances of conceivable trucks. For example, one could postulate a double that is as short as permitted for carrying 80,000 lb (36,000 kg). Based on either formula C or the TTI formula, such a vehicle would have higher rearward amplification than the current Western double.

Scenario 6 — no weight cap, formula B, and an offtracking limit

Vehicle lengths in the first five scenarios were constrained by the STAA of 1982. Though trailer lengths were fixed, operators were free to lengthen their tractors and dollies so as to meet bridge formula requirements. Consequently, vehicles with extremely long tractors and dollies produced large amounts of low-speed offtracking. In this scenario, instead of the STAA, an offtracking limit is used to augment the set of constraints. The removal of the STAA restriction on trailer lengths is also accompanied by an elimination of the constraint on vehicle configurations. In addition to TST's and doubles, other vehicle configurations (such as straight trucks, truck-full trailers, and triples) would be governed under the set of constraints for scenario 6.

Under the "offtracking rule," the low-speed offtracking of a proposed vehicle should be equivalent to the offtracking of a 12-ft (3.7 m) tractor pulling a semitrailer with a 40-ft (12 m) wheelbase. The wheelbase of a unit is given by the distance between the front articulation joint and the suspension center. Short distances, obtained by having more articulation joints and shorter wheelbases, help reduce the amount of offtracking. Moving the center of the suspension towards the front articulation joint reduces the wheelbase of a unit. Adding a leading axle to a unit's suspension produces the same effect; that is, it moves the center of the suspension closer to the front of the unit, thereby reducing its wheelbase. In fact, each additional axle reduces the unit's wheelbase by a distance equal to half of the spread between consecutive axles. Consequently, extra axles could help improve the low-speed offtracking of long vehicles.

Formula B is the other important constraint in this scenario. As discussed in the first scenario, formula B encourages the use of extra axles to gain weight allowances. The bridge formula and the length constraint, therefore, reinforce each other in encouraging the use of more and more axles. With no formal constraint on "bumper-to-bumper" lengths of

tractors, trailers, and dollies, the two constraints could produce long vehicles with numerous axles.

Since the proposed vehicles in this scenario are constrained by the "offtracking rule," their low-speed offtracking performance would be considered acceptable. The longer triples, however, could pose a problem at highway speeds. Though extra axles improve low-speed offtracking, they increase the vehicles' friction requirements during tight turns. The increased amount of roll stiffness, resulting from the extra axles, helps the vehicles remain more stable in roll. With shorter wheelbases and heavier payloads, the multi-articulated vehicles could experience increasing amounts of rearward amplification.

The set of constraints for this scenario open up the possibilities for vehicle designs covering a wide range of layouts. In order to eliminate the possibility for very long vehicles with many axles, suspension sets on any unit could be restricted to tridems, or at most to axle sets with four or fewer axles. Even so the friction demands of the vehicles with multiple axles could exceed 0.1, the limit chosen in Canada where roads are often icy in bad winter weather.

Limits on the lengths of units could be used to try to improve dynamic performance. However there are tradeoffs between short and long units. Short wheelbases are good for low-speed mobility in tight corners, but these short wheelbases can contribute to problems concerning friction demand, rearward amplification of multiarticulated vehicles, handling qualities of towing units, and even rollover if short length means stacking the load higher. Possibly a reasonable countermeasure is to look for ranges of wheelbases that are neither too short nor too long. For example, the nine-axle double, shown in figure 13, has 27.5 ft (8.4 m) wheelbases with cargo box lengths of 35 ft (10.7 m). The wheelbases of this vehicle are short enough to meet the offtracking requirements, while being long enough to keep rearward amplification within the 1.4 limit set for these calculations. This vehicle is predicted to have better dynamic performance than the Western double with 28 ft (8.5 m) cargo box lengths.

Other steps which might be considered are to develop a load to length relationship such that short trailers are allowed if their load is restricted to keep rearward amplification small.

One final countermeasure to ensure satisfactory dynamic performance would be to restrict the speed of vehicles based on their performance capabilities. Dynamic performance measures such as rearward amplification, critical speed, high-speed offtracking, and rollover threshold pertain to or are highly dependent upon forward speed. In one way or another vehicle performance degrades in the related maneuvering situations when speed is increased. A possible approach would be to demonstrate with prototype vehicles the speeds at which they could achieve adequate levels of intrinsic safety. (This approach implies the possibility for different speeds for different vehicles — a possibility that has been opposed by highway and traffic engineers in this country but one that has been practiced in other countries and has been adopted here with regard to the 65 mi/h (104 km/h) speed limit in some jurisdictions.)
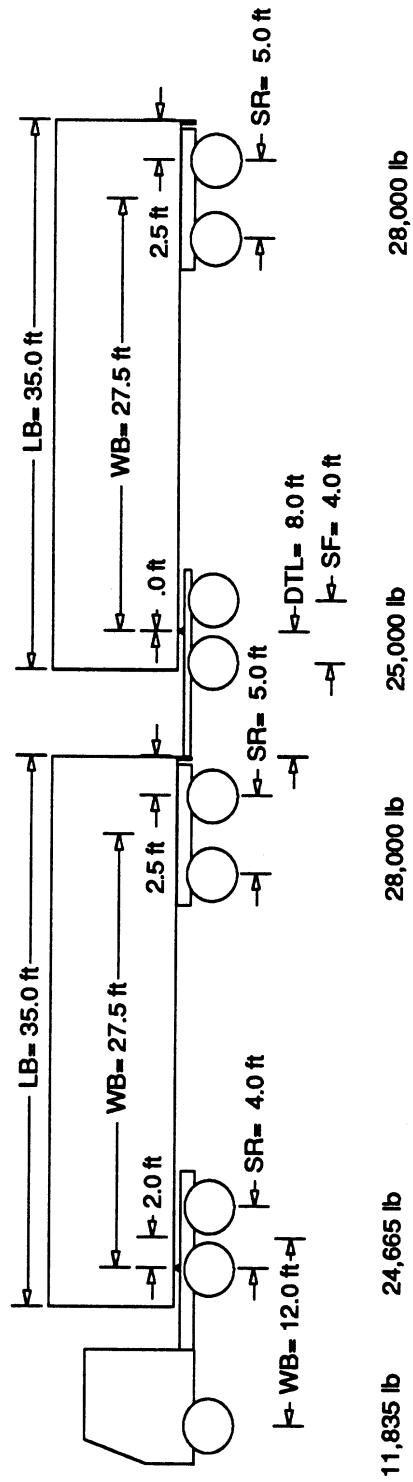
Figure 13. Double (3-S2-4; GCW=117,500 lb; payload=74,960 lb).

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Scenario 7 — no weight cap, formula TTI, and an offtracking limit

In order to satisfy the "offtracking rule" in scenario 6, vehicles used additional axles to shorten the wheelbases on the independent units. In the process, the vehicles gained substantial weight allowances from formula B. Though the constraints in this scenario are similar to those in scenario 6, the vehicles are governed by formula TTI which does not provide weight allowances for extra axles. Instead, it encourages fewer axles with longer distances between them. The "offtracking rule" limits wheelbases and it would seem that the two constraints, that is, the bridge formula and the length restriction, would effectively constrain the design of the proposed vehicles. Under the offtracking assumptions, however, spreading the axles by moving the leading axles forward in a suspension has the same effect as adding axles to a suspension, that is, it tends to reduce the effective wheelbase by moving the center of the suspension closer to the front of the unit. Specifically, spreading the axles reduces the unit's wheelbase by a distance equal to half of the spread between consecutive axles. Consequently, to satisfy the "offtracking rule," wide spreads can be used between axles to shorten the wheelbases of long units. In fact, this scenario is similar to scenario 6 where the bridge formula and the "offtracking rule" reinforce each other to produce extremely long vehicles.

From the viewpoint of vehicle performance, high-speed offtracking could pose a problem, especially for the longer doubles and triples. Wide-spread axles, encouraged by the "offtracking rule" and formula TTI, increase the friction required during tight turns. As in scenario 3, fewer axles and a better proportioning of the braking effort leads to improved braking efficiencies. Fewer axles in the vehicle layout also reduce the total amount of roll stiffness, thereby lowering the levels of roll stability. In contrast with the vehicles in scenario 6, lighter payloads in this scenario help control the amount of rearward amplification in multiarticulated vehicles.

As in scenario 6, there is a range of semitrailer lengths that appears to be suitable for optimizing the performance of doubles in safety-related maneuvers. Another nine-axle double with cargo box lengths of 35 ft (10.7 m) is shown in figure 14. The dimensions of this vehicle are very much like those of the comparable nine-axle double that performed well in scenario 6.

The results for the triples examined in this and other scenarios indicate very high levels of rearward amplification. These levels are high because rearward amplification increases in a multiplicative manner as units are added to a vehicle. (That is, each full trailer contributes another factor to the product representing the total amplification to the rear unit.) Furthermore, in order to meet the offtracking requirements, the trailers in the triple need to have wheelbases of approximately 20 to 22 ft (6.6 m). These wheelbases are too short to produce low levels of rearward amplification. Without some sort of innovative hitching arrangement there does not appear to be any way to control the rearward amplification of the triple. One might consider testing triples with innovative hitches to demonstrate suitable performance.
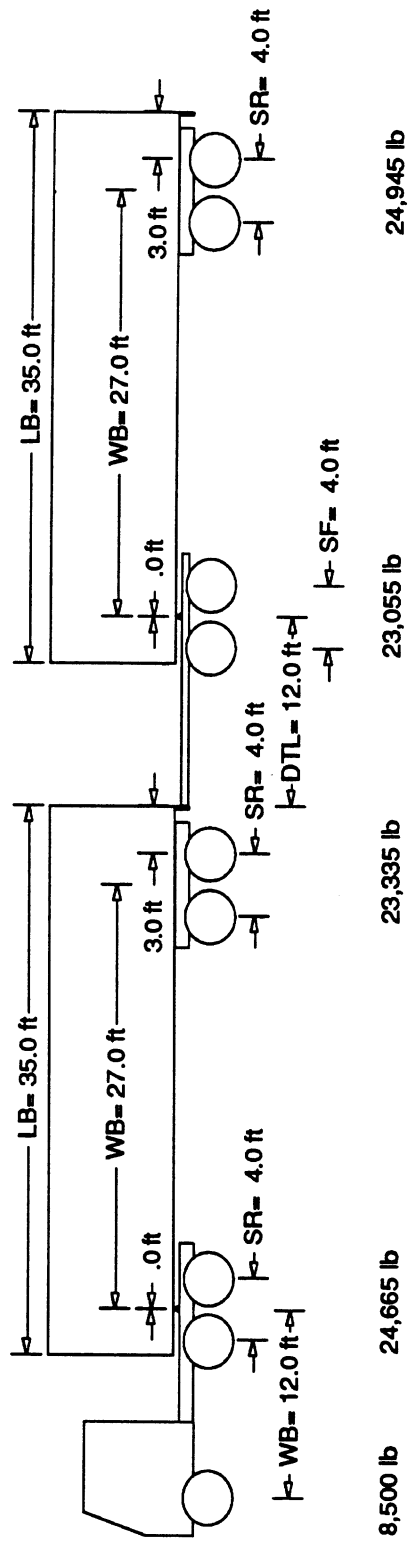
Figure 14. Double (3-S2-4; GCW=104,500 lb; payload=61,962 lb).

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Pavement loading constraints corresponding to the Turner concept (Scenarios 8 to 11)

These scenarios are examples of situations in which single-axle loads are limited to 16,000 lb (7,200 kg) and tandem-axle loads are limited to 28,000 lb (12,600 kg). One might think that these are rather stringent requirements compared to the current allowances of 20,000 lb (9,000 kg) and 34,000 lb (16,300 kg) for singles and tandems. However, for very productive heavy vehicles with uniform loading conditions, bridge formulas B or TTI tend to limit axle loads to less than the 28/16 rule. (One might say that pavement considerations have been hiding behind bridge considerations all along, so to speak.)

Seven of the vehicles designed under scenario 6 turn out to satisfy the 28/16 rule because once the single-axle limit is exceeded, tandems are required; but the tandem cannot carry more than that allowed by the bridge formula. This same process applies to going from tandems to tridems and so forth. This appears to work well for developing doubles with tandem-axle suspensions throughout.

A net result of these observations is that the double which was distinguished for its favorable safety qualities in scenario 6 is also a type of Turner double that might be given attention as a possible design for a more productive heavy truck with a potentially suitable level of inherent safety. (On top of that it would have the pavement preservation properties motivating the Turner concept.)

When considering the TTI formula, the results for scenario 7 can be used in the same way as those for scenario 6 were just used. Analogously, the double discussed in scenario 7 is a type of Turner double with a potentially suitable level of intrinsic safety.

It should be emphasized that these conclusions pertaining to Turner doubles are based upon predictions assuming suspension and tire properties that are comparable to those currently employed on new STAA vehicles. The needs for adequate roll stiffnesses, enough cornering stiffness per unit load on the tires, and proper distributions of these properties are still critical to good performance in safety-related maneuvers. Clearly the intrinsic safety of all trucks depends upon maintaining mechanical properties at their design levels.

Discussions of vehicles for hauling ISO containers (Scenarios 14 — 16)

In the previous scenarios, the aim was to maximize the vehicle's payload capacity under the given set of constraints. In these scenarios, however, the payload is an ISO container weighing 67,200 lb (30,481 kg), and the objective is to develop a vehicle that satisfies the pavement loading, the offtracking, and the bridge formula constraints. Nevertheless, the same techniques for optimizing the active constraints are used in the design of the proposed vehicles. For example, under formulas B and C, additional axles can be used to gain weight allowances. Under formula TTI, longer lengths and wide-spread axles can be used to optimize the vehicle's design. An example vehicle has been developed for each of the three bridge formulas (see figures 15, 16, and 17).

In all three cases, tight turning in dock areas could pose a maneuverability problem. The additional axles, under formulas B and C, and the wide-spreads axles, under formula TTI, increase the amount of tire/road friction needed for making tight turns to levels that are
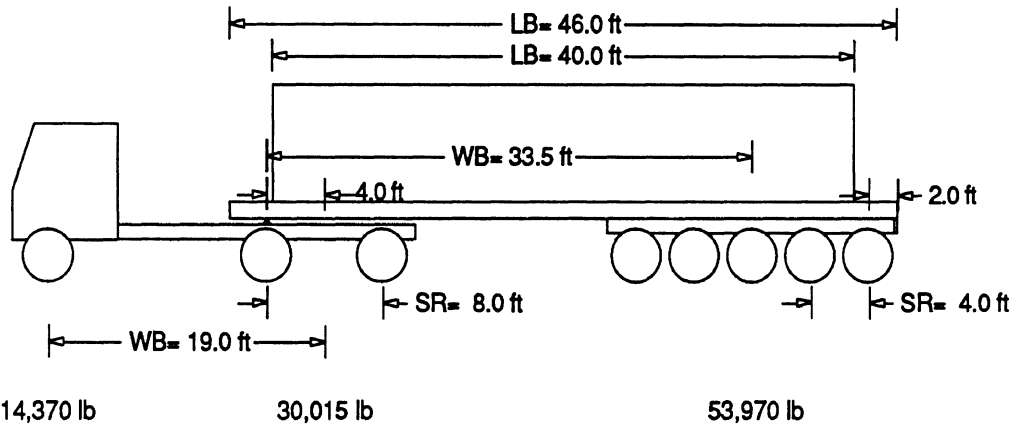
Figure 15. Tractor-semitrailer (3-S5; GCW=98,355 lb; payload=67,200 lb).
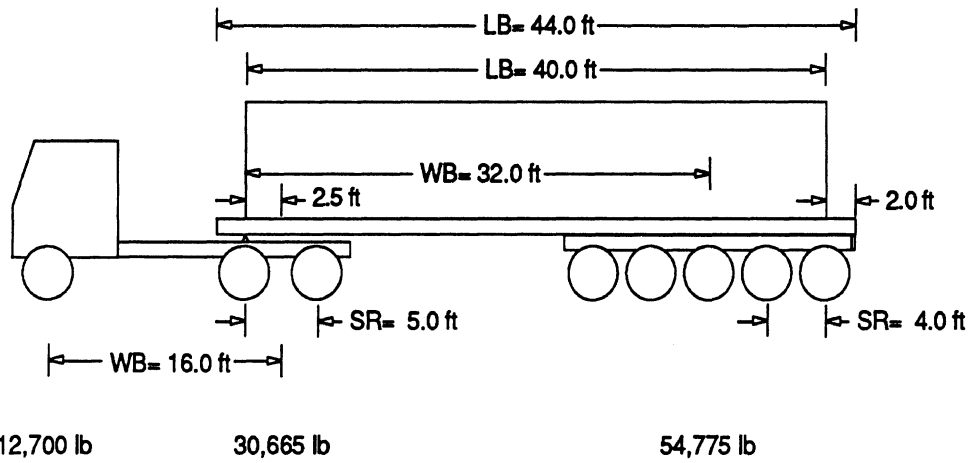
Figure 16. Tractor-semitrailer (3-S5; GCW=98,140 lb; payload=67,200 lb).
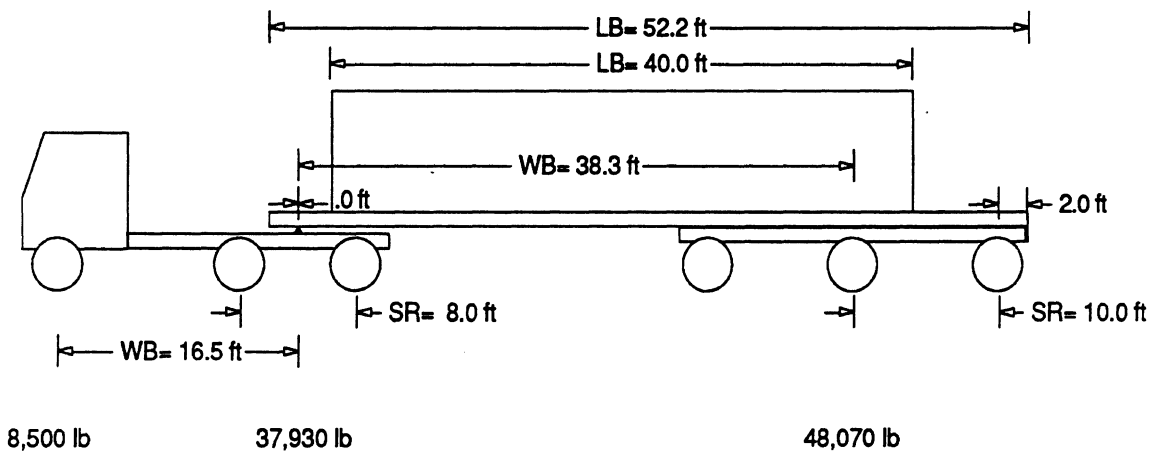
Figure 17. Tractor-semitrailer (3-S3; GCW=94,500 lb; payload=67,200 lb).

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nearly unacceptable. With the exception of a possible yaw instability in the case of the TTI design, the performance characteristics for the three vehicles would be considered acceptable. The braking performances of the empty vehicles, however, continue to be problems.

The ISO container is 40 ft (12 m) long. The vehicles for carrying ISO containers are longer than the container because the bridge formulas require it. This is the situation faced by all carriers of heavy goods or items. The rear wheels on semitrailers for carrying dense commodities such as grains, powdered substances, and liquids often are located after the cargo container because the bridge formula requires it for the amount of load that is economical to carry.

Possibly, we have not found a suitable design for this vehicle. The axles on the semitrailer are either too numerous (five axles) or, in the case of the TTI formula, a wide-spread tridem. Only in the case of formula C were we able to use a tractor without an exceptionally long spread for the rear tandem. Other arrangements with more axles on the tractor and fewer axles on the semitrailer might be preferable to the trucking industry. Even so, there does not seem to be a "nice" vehicle for carrying the 67,200-lb (30,481), 40-ft (12 m) ISO container.

The constraints that have been considered here are not compatible with this type of load. The pavement constraints and bridge formulas force the use of many axles and the spreading of axles. If the economic demands for carrying ISO containers merit it, the U.S. should consider building higher quality roads and bridges, or giving vehicles carrying ISO containers special allowances which might be paid for by higher road use taxes. Given suitable allowances, it seems practical to develop a 3-S3 without spread axles that would be a good vehicle for transporting this type of container.

If the three proposed designs are to be used, operators of these vehicles may need to employ liftable axles for use in loading and unloading areas. They could greatly reduce the friction demand, for example, by lifting the two rear axles on the five-axle semitrailers or the third axle on the tridem semitrailer. This would also improve their low-speed offtracking. As long as these vehicles with lifted axles or reduced loads on their axles are operated at low speeds in restricted areas they should be acceptable. Possibly, brake proportioning could be adjusted so that good performance is achieved when axles are lifted.

To achieve satisfactory performances at highway speeds, careful attention needs to be applied to obtaining suitable levels of roll stiffness (particularly for the tridem suspension on the semitrailer under the TTI formula) and to brake proportioning for the 5-axle semitrailer suspensions. Also, the handling qualities of the vehicle developed under the TTI formula are less than what they might be. Improvements could be considered such as those deriving from steering system modifications, adjustments in tire properties, or suspension roll-steer characteristics.

Scenario 17 — 100k cap, bridge formula B, and an offtracking limit

The constraints in this scenario are very similar to those discussed in scenario 6. As mentioned earlier, the situation in scenario 6 is not effectively constrained and the size and

weight rules allow a wide variety of vehicle and axle layouts. As a possible solution, a maximum weight cap could be used to supplement the set of constraints.

In this scenario, a maximum weight cap of 100,000 lb (45,359 kg) is used to augment the size and weight rules of scenario 6. The weight cap would be a limiting constraint and would be an upper bound on length and the total number of axles. Unless payload volume is a motivating factor, the upper bound on weight capacity eliminates the need to add axles and/or increase vehicle lengths. Consequently, vehicles would have fewer axles and shorter overall lengths.

Since the proposed vehicles in this scenario would be similar to those developed in scenario 6, their performance characteristics would be equivalent. For example, vehicles with multiaxle suspensions would require high levels of tire/road friction during in-town cornering. Also, vehicles with multiaxle suspensions would have higher levels of roll stability. Since the vehicles are constrained by the "offtracking rule," their low-speed offtracking would be acceptable. However, longer vehicles, such as the triples, could pose an offtracking problem at highway speeds.

More specifically, this scenario might promote truck-full trailer combinations but weight productive versions of these vehicles may have unacceptable levels of rollover thresholds and rearward amplification plus poor handling qualities. Also the triples would have high-speed offtracking and rearward amplification problems.

As in other scenarios, there is a double that appears to have somewhat optimized performance qualities for the given set of constraints. This vehicle is much like those distinguished in the conclusions for scenarios 6 and 7 (only in this case, the GCW is limited to 100k obviously). This vehicle can also be viewed as a Turner double with tandem suspension loads less than 23,000 lb (10,400 kg). Given this low level of tandem load, the trucking industry would consider single rather than dual tires on the tandem axle suspensions. However, if the tires have adequate lateral force capability, the vehicle could have satisfactory performance.

The main safety-related drawback of this type of double and those discussed in scenarios 6 and 7 is the rearward amplification associated with doubles in general. The distinguishing features of these doubles over the current Western double are the longer wheelbases and the tandem axles. The tandem axles provide greater weight carrying capacity and enough additional roll stiffness to more than compensate for the additional weight. The longer wheelbases are the key to obtaining lower rearward amplification. Longer wheelbases, although they could provide further reductions in rearward amplification, would result in too much low-speed offtracking. To obtain less rearward amplification, one might consider comparable vehicles that have either fewer articulation joints—i.e., tractor-semitrailer-semitrailer vehicles (B-trains)—or innovative dollies with special hitches and controlled steering of dolly wheels.[19]

Scenario 18 — twin steering axles

From the standpoint of improved safety, especially after front tire blowouts, twin-steer vehicles are generating public interest. Besides the unique twin-steer design, the vehicles

are governed by the same set of constraints as in scenario 6, that is, the "offtracking rule," formula B, and the "34/20" pavement rule.

From the standpoint of productivity, twin-steer front axles could have productivity advantages due to the additional weight capacity of the front axles. The increase in productivity, however, depends upon the vehicle layout and the load distribution.

With two front axles, the braking efficiencies of the vehicles are improved significantly. In addition to improving the braking performance, the extra front axle tends to improve the vehicle's yaw stability.

The main safety disadvantage of the straight (single-unit) trucks designed for this scenario is their relatively poor rollover immunity. These trucks do not have enough roll stiffness for the load that they are carrying.

On the other hand, the TST with nine-axles (see figure 18) has enough roll stiffness to have a relatively high level of predicted rollover immunity. In hindsight, a vehicle of this type with greater spreads between trailer axles, a more forward fifth-wheel location, and a trailer with a light tare weight might be a good candidate for hauling large ISO containers or other dense loads or heavy nondivisible items.

OVERALL FINDINGS WITH RESPECT TO THE SAFETY IMPLICATIONS OF SIZE AND WEIGHT ISSUES

What Are the Fundamental Findings of This Study?

There is more to this study than a number of different scenarios with isolated instances in which safety is a concern. The conclusions from the example scenarios may be sufficient to cause decision makers to realize that their choices of size and weight rules will have serious safety implications in particular situations. As important as that realization may be, it needs to be supplemented with knowledge and guidance that can be used in addressing size and weight issues in general. With respect to safety implications of size and weight issues, this section provides two sets of findings based on generalizations of the results of this study. The first set of findings pertains to relationships between pertinent vehicle design variables and measures of intrinsic safety for heavy trucks. The second set of findings relates to an overall perspective derived from the approach to vehicle design and analysis used in this study. The purpose of this second set of findings is to provide an understanding of how size and weight constraints influence the intrinsic safety of the heavy trucks that may be selected to deliver goods and equipment.

Relationships between Design Variables and Intrinsic Safety

The findings from the studies of size and weight scenarios indicate that sets of size and weight constraints generally allow some truck configurations to be more productive than other types of truck designs. This means that the predicted safety implications of a
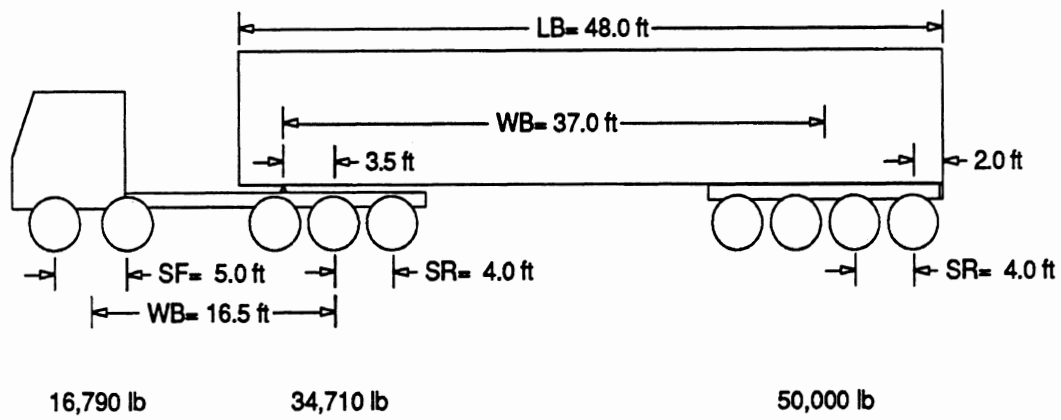
Figure 18. Tractor-semitrailer (5-S4; GCW=101,500 lb, payload=64,200 lb).

specified set of size and weight constraints will depend to a large extent upon the intrinsic safety of the vehicles that would be very productive and hence favored under the given allowances or constraints on maximum weight, length factors, bridge fatigue, and pavement distress. The design features that would be adjusted to promote productivity include (a) the basic configuration which means the number of hitches (articulation joints or pivot points) determining whether the vehicle is a single-unit truck, tractor-semitrailer, truck-full trailer, double, or triple, (b) the distances between the hitches and the axle groups which means the wheelbases and the overhangs of the units comprising the vehicle, (c) the number of axles in a suspension, (d) the spreads between axles, and (e) the weight carried by the axles in a suspension.

In order to furnish a knowledge base to use in anticipating safety consequences that might be associated with changes in size and weight allowances, relationships between design features of trucks and measures of intrinsic safety are reviewed here. These relationships represent generalizations of the findings presented in the previous section. The material in the previous section was tailored to the implications of specific size and weight allowances. Table 2, which follows, presents a summary of generalized qualitative relationships between measures of intrinsic safety and design features of various truck configurations without specific references to particular size and weight allowances.

(The perspectives given in the next subsection entitled **"A Truck Design Approach to Size and Weight Rules"** will complete the picture in the sense that those perspectives will provide a logical framework for understanding how size and weight constraints determine the design features of trucks and therefore intrinsic safety.)

The items listed in the left-hand column of table 2 represent design features that are controlled to a large degree by size and weight allowances. If size and weight allowances were to be liberalized, designers and specifiers of heavy vehicles would consider changing these features of their vehicles in order to be more productive. To a certain extent, more than one of these items might be changed in determining a vehicle design. Nevertheless, the entries in the table reflect an attempt to characterize the individual influences of each design feature, assuming that the others are not changed.

The entries in the table indicate possible advantages and disadvantages of changes in the design features listed in table 2. **It is believed that the safety payoff for extraordinarily good performance is not large but that the consequences of small degradations in poor performance can be crucial. The trick is to try to avoid very poor performance in any category of intrinsic safety. Given this point of view, the most important entries in the table are those entered as "SD," standing for significant degradation.**

Discussions of the measures of intrinsic safety

The measures of intrinsic safety listed across the top of the table might be given different weights, depending upon their importance to accident involvements. For most of the measures of intrinsic safety, the work needed to quantify relationships to accidents has not been done. The needed information is very difficult to obtain without detailed studies of the characteristics of the vehicles and the circumstances associated with accidents. In

Table 2. General relationships between measures of intrinsic safety and truck configurations.

CHANGE IN DESIGN FEATURES	MEASURES OF INTRINSIC SAFETY						
	Low-Speed Offtracking	Friction Demand in a Tight Turn	High-Speed Offtracking	Constant Deceleration Braking *braking efficiency*	Steady Turn Rollover *rollover threshold*	Steady Turn Handling *steering sensitivity*	Obstacle Evasion *rearward amplification*
Increasing the number of articulation points	S I	M D	M D	?	N A	N A	S D
Longer wheelbase	S D	M I	M I	M I	N A	M I	S I
Longer overhangs to rear hitches	M I	N A	M D	N A	N A	M I	S D
Increasing the number of axles	M I	S D	M D	S D	S I	?	S D
Increasing axle spreads	M I	S D	M D	N A	N A	?	S D
Increasing axle loads	N A	M D	M D	?	S D	?	S D

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Key
S D  :  Significantly degrades level of intrinsic safety
M D  :  Moderately degrades level of intrinsic safety
N A  :  Not applicable / small effect
M I  :  Moderately improves level of intrinsic safety
S I  :  Significantly improves level of intrinsic safety
?    :  May be important and might improve or degrade
        safety depending upon other factors
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general, the needed information has not been directly available for accidents involving heavy trucks.

However, rollover accidents have been studied with some success. Evidence based on the accident record can be used to show a very strong dependence of the likelihood of rollover to the level of the rollover threshold.[17] Furthermore, rollover accidents are a major source of truck driver fatalities. Clearly rollover problems would be ranked as one of the most important concerns with truck safety.

Probably because accidents involving jackknifing or trailer swinging can be identified almost as well as rollovers, there is some pertinent information on these types of accidents. The accident data show an over involvement of unladen vehicles in accidents classified as jackknifing. This tendency towards the involvement of unladen vehicles is believed to be a result of poor braking efficiency which contributes to directional instabilities. This is a problem that could be addressed within size and weight rules, even though it is not unique to size and weight issues. As indicated in the table, it could be exacerbated by adding axles, if the braking effort at these axles were not proportioned appropriately. The countermeasures that are available involve proportioning of the braking torque at the various axles so that the wheels on one axle will not lock up prematurely before the wheels on other axles lockup. Good reliable antilock braking systems would reduce the incidence of jackknifing and trailer swinging types of directional instabilities during braking, possibly to rates that are equal to or better than the jackknifing accident rates attributable to fully laden vehicles.

Accident problems with double tankers led to the identification of problems with rearward amplification in obstacle-avoidance maneuvers. Subsequent analyses and vehicle experiments have shown that rearward amplification can be an important problem for heavy vehicles with more than one articulation pivot (that means truck-full trailers, doubles, and triples). As indicated in the table, increasing numbers of articulation joints can make this problem worse. Hence, for vehicles with multiple articulation points, attention to controlling rearward amplification is an important goal.

Although braking and steering (handling) are the most fundamental of safety-related vehicle operations, quantified relationships between measures of performance in these areas and accidents are not generally available. It seems that braking performance is accepted as a safety matter even though it is difficult to pin down relationships between braking performance and relevant types of accidents other than jackknifing or trailer swinging. These situations, in which articulated vehicles fold up, represent poor directional performances that can be brought about by poor braking efficiency, but they are not examples in which direct measures of stopping decelerations are related to accident involvements. With regard to steering, it seems that steering is somewhat ignored as a safety issue, possibly because vehicles are easily steered to follow a chosen path. The relationships between accidents and steering performance might be very important, but demonstrating it might be nearly impossible because of interactions with other factors such as driver skill and judgement. Nevertheless, braking and steering performances are so fundamental to the safe operation of vehicles that they are included in the measures of intrinsic safety employed here.

Handling performance is largely dependent upon the mechanical properties of the tractor as loaded at its fifth wheel. Semitrailers can have some influence on handling and the possibility of directional instability if they have multiple axles and widely spread axles. The distribution of roll stiffnesses from suspension to suspension can have an important influence on truck handling especially in severe turning situations. Handling is, to an important extent, the balance between the forces generated by front and rear tires. If the front tire forces dominate, the vehicle may be directionally unstable. If the rear tire forces dominate, the vehicle may be stable but tend to overshoot in reaching a steady-turning situation. The determination of improvement or degradation is not readily ascertained for the conditions covered by the table because those conditions are not detailed enough to allow entries other than question marks. In summary, we are trying to say that handling is important and, although handling is difficult to work with, we have set desirable levels of intrinsic safety based on practical stability margins.

The first two columns of entries in the table apply to low-speed offtracking and friction demand in a tight turn. These are both low-speed maneuvering situations. The other measures of intrinsic safety pertain to situations in which velocity is a key factor. To the extent that velocity is seen as a primary element of severe accidents, low-speed offtracking and friction demand in a tight turn may be questioned as to whether they are primarily mobility issues rather than safety concerns. Clearly, pedestrians are killed by trucks and slowly moving trucks are formidable obstacles. However, if a vehicle does not have mobility, it is useless. But also, if a vehicle becomes immobilized, it is a traffic hazard. Possibly a reasonable position is to view low-speed offtracking and friction demand as both mobility and safety issues. The mobility aspects are extremely important to the transportation mission and they are readily observable and easily demonstrated. Low-speed offtracking has been a primary factor in the design of both vehicles and highways without considering safety implications. Friction demand, as manifested in tire scrubbing and possibly pavement damage, is a major reason for not using multiple-axle suspensions and wide spread axle sets. Nevertheless, these low-speed measures are also part of the intrinsic safety picture.

A vehicle's intrinsic safety becomes interactive with the driver's judgement and willingness to take risks when velocity is involved in the maneuvering situation. Velocity is something the driver chooses. It is not an inherent or intrinsic property of the vehicle. Yet the severity of the safety-related maneuver is highly dependent upon the velocity at which the maneuver is performed. Consequently, the study of accidents to determine vehicle properties that contribute to accidents can be clouded by driver influences. Even so, an appropriate goal is to provide the driver with a vehicle that performs well in accident-avoidance maneuvers.

Even though some of the measures of intrinsic safety may have more direct connections to the accident record than the connections of others, the total set of measures represents a balanced set of goals with regard to the safety-related maneuvers that vehicles need to be able to perform well in service. If one were to drop any of these measures, some fundamental aspect of safety-related performance would be omitted.

Conflicts between measures of intrinsic safety

Inspection of the entries in table 2 shows that design features that may improve performance with respect to one measure of intrinsic safety may degrade performance with respect to another measure of intrinsic safety. There are conflicts between low-speed offtracking and friction demand, high-speed offtracking, and rearward amplification, for example. These conflicts indicate the need for compromises in designing vehicles to meet opposing demands. In order to achieve acceptable performances in all categories of intrinsic safety, it is necessary to change more than the various design features given in the table. As indicated earlier in this section, brakes need to be proportioned in accordance with the loads their axles are carrying to aid in preventing premature wheel lock. In addition, suspension roll stiffnesses should be high enough to raise rollover thresholds to acceptable levels. The cornering stiffnesses of tires should be adequate to provide the lateral forces per pound of load carried needed for acceptable performance in high-speed offtracking, handling, and, in the case of multiarticulated vehicles, obstacle-avoidance maneuvers. Furthermore, if the selection of tire, brake, and suspension properties will not do the job, there are special countermeasures such as antilock braking systems or innovative hitching arrangements in dollies that can aid in solving vehicle dynamics problems. Again, the basic idea is to avoid poor performance in any area of intrinsic safety.

A Truck Design Approach to Size and Weight Rules

The relationships between size and weight rules and their safety implications can be more easily understood if they are approached from the point of view of a person whose goal is to specify a truck that will be productive in transporting goods. The purpose of this direction of approach is not to attempt to make everyone into a truck designer. Rather, the array of size and weight rules are diverse and complex enough that it is easy to lose sight of the overall situation without a structure to use as a guide. The work performed in this study indicates that a sequence of fairly simple vehicle selection considerations can be used to reveal how size and weight regulations interact with the intrinsic safety of heavy trucks.

Consider figure 19 which is a conceptual diagram showing constraints on the characteristics of vehicles allowed for trucking. The range of "ALLOWABLE VEHICLES" is bounded by length constraints at the top of the diagram, weight constraints (GCW or axle load limits) on the right side, and a bridge protection limit running diagonally to the upper right. As illustrated in the diagram, the length limit does not depend upon weight directly, so it is represented as a horizontal line. Similarly, the GCW limit does not depend upon length, so it is represented as a vertical line. Since the bridge formula is a length-to-weight relationship, it depends upon both length and weight in this conceptual representation of the overall situation.

An axle load limit is also shown as a vertical line because the loads on single axles and closely spaced tandem and tridem axle sets are set by pavement protection considerations which are independent of the length of the vehicle. The weight limit determined by the sum of the axle loads depends upon the number of axles on the vehicle and the sizes of the
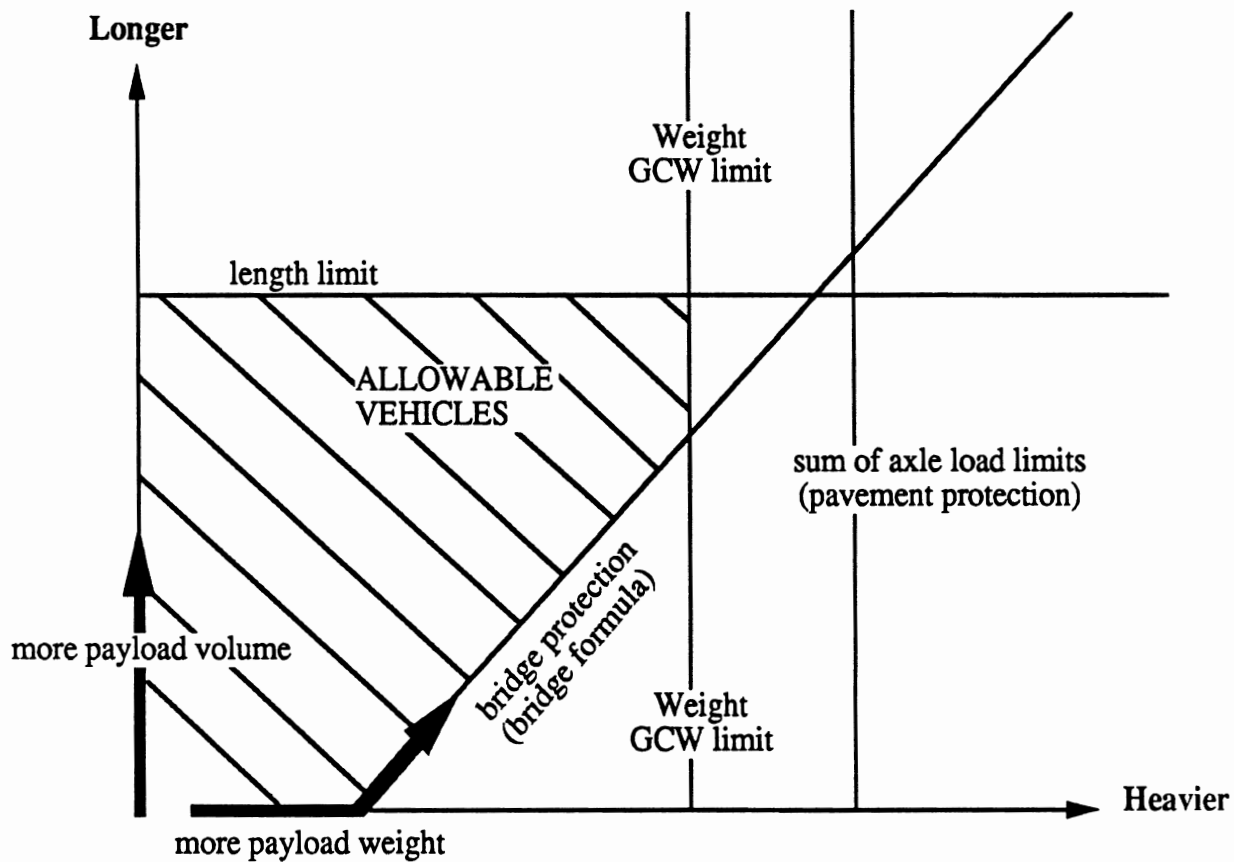
Figure 19. The range of allowable vehicles as constrained by size and weight rules.

allowable individual axle loads. If the GCW limit were to be eliminated, the sum of the allowable axle loads would act as a weight limit.

Figure 19 is intended to represent the perspective on size and weight rules seen by persons who are trying to specify vehicles that will be as productive as allowed by those rules.

Designs based on increasing truck volume carrying capacity

Now consider a situation where the trucker has a light cargo to carry and knows that weight constraints are not likely to be a concern. In this situation, the trucker seeks more payload volume by proceeding up the vertical axis labeled "**Longer**" in the conceptual diagram. The trucker's progress towards greater productivity is ended when a length limit is reached.

The reason for dealing with length matters first is not that they are more (or less) important than weight matters—rather, that they are easier to explain. Experience has shown that it is easy to get lost in the intricacies of size and weight rules and that understanding needs to be established before importance can be meaningfully addressed.

Upon reaching a length limit, the competent truck specifier examines the length rule to see if the rule favors one type of vehicle design. For example, in the STAA of 1982 tractor-semitrailers are allowed cargo box lengths of 48 ft (14.4 m) and doubles are allowed two boxes that are each 28 ft (8.4 m). Hence, the rule favors double trailers over single trailers by a margin of 56 to 48 (16 percent) with regard to productivity related to payload volume.

What are the safety implications of the productivity advantages of doubles over singles? Let "length limit 1" in figure 20 represent the bound on tractor-semitrailers and "length limit 2" represent the bound on doubles. The vehicles represented by the region between length limits 1 and 2 would all be doubles and they would be the more productive vehicles. In this case there could be safety concerns regarding doubles that do not apply to tractor-semitrailers. Also, there could be problems pertaining to long tractor-semitrailers, but not to doubles. In fact, both types of problems exist. Specifically, twin 28-ft (8.4 m) doubles exhibit large amounts of rearward amplification (cracking-the-whip) in emergency obstacle-avoidance maneuvers at highway speeds. However, as long as the doubles remain very lightly loaded, rearward amplification may be small, but if the vehicle is used to carry heavy loads on backhauls or in other situations, rearward amplification could be a safety concern On the other hand, 48-ft (14.4 m) semitrailers have much larger amounts of low-speed offtracking than twin 28-ft (8.4 m) doubles. The long tractor-semitrailer would be more prone to causing damage at intersection turns than doubles would be. In this case, a safety concern is that the STAA length provisions are favorable to the double and consequently create a situation in which high-speed accidents may become more prevalent on roads where traffic conflicts occur.

Now return to the truck specifier who might wish to see if there are more liberal length limits. For example, approximately 66 percent or more of the States allow 53-ft (15.9 m) semitrailers (sometimes through recently developed permit systems). To prevent very poor

Longer

length limit 2 (doubles)

DOUBLES WITH
MORE CUBE

length limit 1 (TST's)

sum of axle load limits
(pavement protection)

bridge protection
(bridge formula)

GCW
limit

Heavier
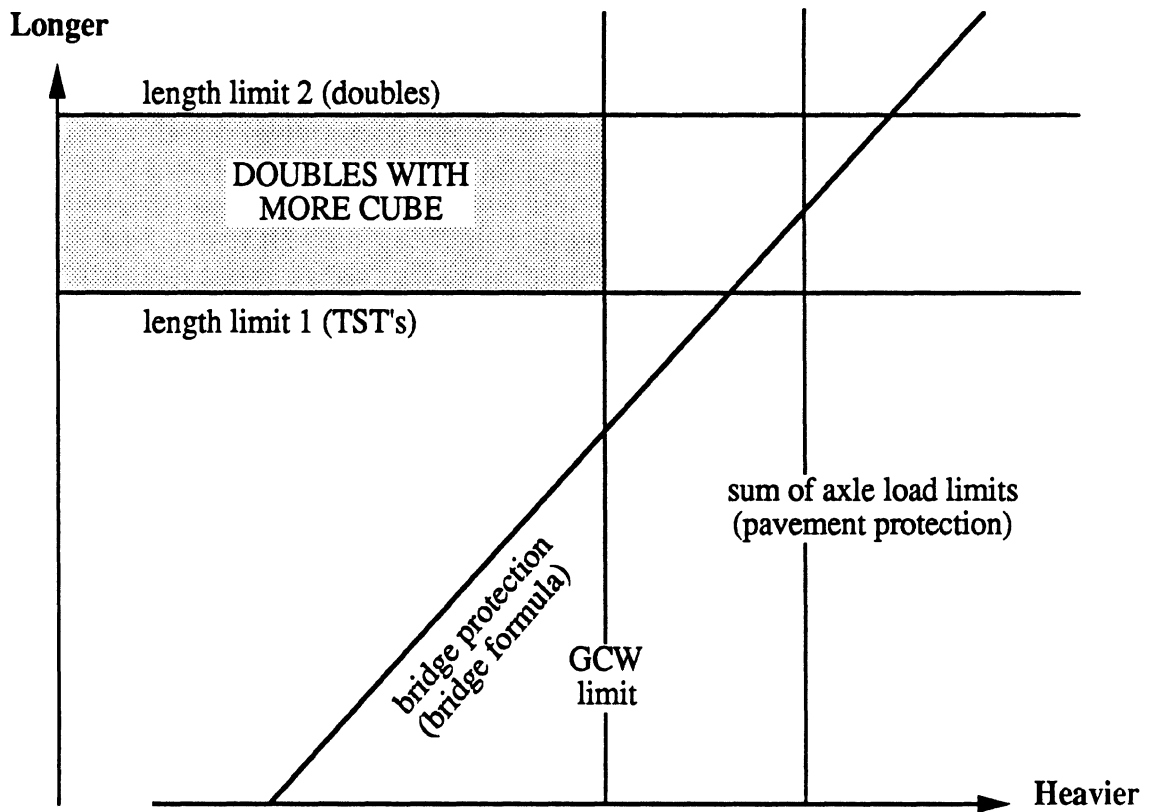
Figure 20. Different length constraints for doubles and tractor-semitrailers (TST).

offtracking from long trailers, some jurisdictions have established limits on the distance between the kingpin and the last axle on a semitrailer.

Since offtracking is a measure of the amount of roadway needed for vehicles to make tight turns, vehicle experts, both in and outside of the trucking industry, have asked whether an offtracking constraint might not be the proper way to control length. As long as the vehicle does not need more space (roadway width) than that available, it should be allowed (everything else being satisfactory). In this study, an offtracking constraint was used in several size and weight scenarios because offtracking is a key issue with respect to the geometric layout of existing intersections.

The findings presented here indicate that a double with twin cargo boxes of approximately 35 ft (10.5 m) would require no more space at intersections than a tractor-semitrailer with a 48-ft (14.4 m) cargo box. The offtracking constraint that allows a 48-ft (14.4 m) semitrailer would allow 70 ft (21 m) of cargo length for doubles—a productivity advantage of 70 to 48, or approximately 44 percent (STAA of 1982 allowed a 16 percent productivity advantage to the doubles configurations). The additional articulation points of the double allow it to bend in the middle, so to speak, and consequently a double is much better at turning tight corners than a vehicle with a single long trailer with tires at the rear end. One might say that the double's productivity advantage is justified because it is a more efficient design for using the space available on roadways.

With regard to safety implications, the longer double corresponding to the 35-ft (10.5 m) box lengths is significantly better than the twin 28-ft (8.4-m) double in emergency obstacle-avoidance maneuvers. This is because longer wheelbases reduce the amount of rearward amplification of the motions of doubles (cracking-the-whip) in sudden steering maneuvers. By allowing an increase in offtracking up to that of a typical tractor-semitrailer, one obtains a safer double in obstacle-avoidance maneuvers at highway speeds, as well as a substantial increase in that aspect of productivity related to cargo volume.

If not satisfied with doubles, the specifier may consider triples to increase productivity. These types of longer combination vehicles are allowed in some western States and they consist of triple 28-ft (8.4 m) cargo boxes. These vehicles have low-speed offtracking approximately equal to that of the five-axle tractor-semitrailer with a 48-ft (14.4 m) cargo box. Hence, they would satisfy an offtracking rule that allowed the STAA tractor-semitrailer. These vehicles would be expected to have very poor performance in situations with numerous traffic conflicts that require obstacle-avoidance maneuvers for satisfactory resolution. With standard pintle hitches (even ones with very little free play), the rearward amplification would be expected to be on the order of 1.5 times that of the double created by dropping the third trailer from the triple. For this type of vehicle to have good intrinsic safety, innovative dollies and special hitching arrangements are needed.

Clearly, the length provisions of size and weight rules will have direct implications with regard to the types of vehicles that will increase trucking productivity. Equally obviously, but by no means as easily understood, length allowances will influence the intrinsic safety of the productive vehicles. As illustrated by the examples discussed here, seemingly subtle differences in size and weight rules (such as going from the STAA provisions to the offtracking provisions) can have a favorable effect on both productivity and intrinsic safety.

Designs based on increasing truck weight carrying capacity

Now consider a situation in which there are trucking demands to carry dense cargos (such as metals, liquids, gravel, grains, fruits and vegetables, logs, etc.). In concept, vehicle specifiers would start out along the horizontal axis labeled **"Heavier"** in figure 19. The first constraint encountered in the diagram is called "bridge protection" and it represents a bridge formula.

(There are important differences in the fundamental natures of the bridge formulas currently being considered in the U.S. The currently applicable formula B is a relationship between vehicle weight and length plus allowances for more weight if more axles are used. On the other hand, the recently developed TTI formula for protecting bridges from overstresses is strictly a weight-to-length relationship. It can be argued that the TTI formula corresponds directly to the idea of bridge protection and that formula B contains provisions that allow more bridge stress if pavement damage is reduced. Nevertheless, the weight-to-length provisions of the formulas cause the vehicle designer to recognize that heavier vehicles are expected to be longer than lighter vehicles—the idea is to spread the load over a greater length.)

Again, vehicle designers or specifiers might look for relaxation of the bridge formula either in general or in special cases, but whatever the formula, the vehicle specifier seeking maximum productivity for the vehicle proceeds up the bridge protection line, noting that more load can be carried as long as the vehicle gets longer.

Truckers intending to haul very dense commodities will observe that the bridge formula requires a vehicle that is much longer than the cargo length required to contain the payload. For example, rolls of steel and bulk commodities are carried in trailers that are much longer than the load. Under formula B, the designer has the option of adding axles to the design in order to carry more payload weight. Short vehicles have advantages over long vehicles when maneuvering at low speed in loading and unloading areas. (The offtracking of short vehicles is less than that of comparable configurations of long vehicles.) Hence, the designer might choose a length that was appropriate for delivering the product and then add axles until a reasonable load would be allowed. For example, current designs of concrete mixers and also semitrailers for hauling construction equipment and materials often have many axles.

With regard to nondivisible heavy loads, an ISO shipping container, that is 40 ft (12 m) long weighing 67,200 lb (30,500 kg), has been used in this study as an example of an object whose transportation is expected to be very important in the future. Under existing U.S. size and weight rules and under hypothesized future possibilities for size and weight rules, the ISO container is awkward to deal with because it is long, and yet, it is too heavy for its length to be compatible with bridge formulas. The truck has to be longer than the cargo. (It is like vehicles for hauling liquid tanks or bulk hoppers which are shorter than the axle spacings required by bridge formulas.) The examples given in the body of this report show semitrailers with five axles or a wide-spread tridem. None of these designs appear to be acceptable. Possibly the rules need to be changed some to accommodate this and other similar trucking demands, even if the shippers have to pay something towards the distress and fatigue damage of the highway system.

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Given that the tare weight of the tractor and semitrailer used for hauling ISO containers might be roughly 30,000 lb (13,600 kg) , the GCW would be about 97,000 lb (44,000 kg). If 13,000 lb (5,900 kg) were carried on the front axle of the tractor, the tractor's rear axles and the semitrailer's axles would be carrying approximately 42,000 lb (19,000 kg) each. The pavement protection advocates might be satisfied by tridem axle sets. The bridge people might be hard pressed to accept 84,000 lb (38,000 kg) in a spread of 40 ft (12 m), because 50 ft (15 m) is required to satisfy formula B. Nevertheless, this is what might make a reasonable truck from the specifier's point of view. Assuming the bridge contingent were satisfied, the truck specifier might try to see if the pavement people would allow a 42,000-lb (19,000 kg) tandem under these circumstances. If so, the trucker could end up with a vehicle somewhat like those used in some parts of Europe.

If the trucker were to pay something to obtain a permit for this vehicle, it might be clearer to keep pavement and bridge costs separate. If so, bridge formulas and pavement protection rules that do not infringe on each other's bailiwick would make it a lot easier to understand the implications of various types of vehicle designs. In this study, the fact that formula B treated the number of axles and the TTI formula did not has been confusing and has made comparisons difficult.

When addressing weight-related aspects of productivity and safety, many factors come into play and the situation can become jumbled in a mass of details concerning vehicle design. In the general context of this discussion, vehicle design includes the number of trailers, the number of axles, tare weights of units, lengths of units, locations and types of hitches, locations of axles, mechanical properties of components (tires, brakes, suspensions), axle loads, heights of centers of gravity, and payload properties (size, weight, location). All of these factors are important with respect to the safety qualities of vehicles. The main body of the report and the appendixes treat all of these factors in detail. In this discussion, it is presumed that those responsible for decisions on size and weight allowances will recognize that design details can be worked out once the influences of the size and weight constraints on productivity and safety are understood.

Consequences of changing weight regulations

Returning to figure 19, assume the specifier proceeds up the bridge protection line until the gross combination weight (GCW) limit is reached. If the designer does not want to add axles or the bridge formula involved does not allow more weight for more axles, the point at the intersection of the GCW limit and the bridge protection line corresponds to the shortest length that can be used to carry the maximum load. In order to carry more load, the designer may suggest that the GCW limit be relaxed.

Furthermore, designers and specifiers might wonder if the GCW limit is not arbitrary. By inspecting figure 19, it seems that the gross weight limit could be eliminated altogether without hurting anything. That is, there is a length limit that aids in ensuring that the vehicle does not occupy any more than the available space on the roadway; also, there is a bridge protection limit, and there is a pavement protection limit. What else is there to protect? As far as can be seen, the GCW limit serves no purpose. In fact, it eliminates a set of vehicles illustrated conceptually by the region below the length limit to the right of the

GCW limit and above the bridge protection limit. These are very productive vehicles with respect to carrying heavy loads. (By adding axles, the pavement protection boundary can be made to lie to the right of the intersection of the bridge protection line and the length limit.) Given enough axles, vehicle specifiers might ask, "why not specify an offtracking rule and a bridge formula and be done with it?"

The problem with this reasoning is that there are very serious safety consequences that could result if the gross weight cap (GCW limit) were to be suddenly removed without prohibiting existing vehicles from carrying heavier loads. The consequences of granting more load are fundamentally different from those obtained by granting more length. When length is changed the vehicle is usually changed, but when the load limit is increased the vehicle need not change at all—after the increase, the trucker may be free to add more payload without changing anything else.

Under current rules, the five-axle tractor-semitrailer with a 48-ft (14.4 m) semitrailer has been pretty well optimized in the sense that the length, GCW, pavement, and bridge constraints all intersect at 80,000 lb (36,300 kg). In other words, raising the gross weight cap will not change the productivity of this vehicle if all the other constraints still apply. On the other hand the Western (twin 28-ft (8.4 m)) double could go immediately to 88,000 lb (40,000 kg) by adding 8,000 lb (3,600 kg) of payload.

The safety implications for the Western double are as follows:

- Rollover immunity would be reduced. Rollover accidents would be more likely.

- Rearward amplification of tractor motions would be increased. Obstacle-avoidance maneuvers would be more likely to result in accidents because the rear trailer rolled over or struck something by swinging laterally.

A currently popular concern with changes in size and weight restrictions is that the changes will result in reduced safety or create vehicles that are less safe. The simple process of allowing more load on a vehicle without compensating for the increased load results in vehicles that are less safe than they used to be. The needed compensation could result from the addition of more axles or changes in suspension roll stiffnesses roughly in proportion to the increases in load. For example, a six-axle tractor-semitrailer with a tridem axle on the semitrailer could be a vehicle with reasonable levels of intrinsic safety with a GCW of 86,000 lbs (39,000 kg).

These concerns with "overloading" existing vehicles are very important with respect to transporting hazardous materials. If the gross weight cap were to be removed, double tankers might be built by putting tanks on Western doubles because these vehicles would be productive for carrying liquids such as gasoline. The GCW of these vehicles would be 88,000 lb (40,000 kg) and their rollover potential would be a grave concern since rollover is a major cause of spills of hazardous commodities.

Now say that the problem of allowing existing vehicles to be overloaded is resolved through appropriate legislation, and that gross combination weight limits are increased substantially or eliminated altogether. How can productivity be increased? Designers and specifiers of trucks will observe that they can increase productivity by adding axles. Figure 19 is not complicated enough to illustrate all of the ways in which productivity can be

increased by adding axles, but this conceptual diagram can be used in discussing axle load limits.

If the number of axles on a vehicle were specified and there is an axle load limit, these two items, in effect, set a limit on the gross combination weight. As mentioned earlier, the designer might choose to add axles so that the axle load limit is not more restrictive than the other size and weight constraints. (The "pavement protection" line would be moved far enough to the right that it would be to the right of the intersection of the length limit and the bridge protection boundary, as shown in figure 19.)

The specifier of trucks may be hesitant to add axles because for each axle there is another set of tires, brakes, and suspensions to maintain. There is a continuing cost associated with the addition of axles. The specifier needs to determine whether the improved productivity is worth the associated cost. Since the demand for productivity is believed to be insatiable, there should be applications where even small improvements in productivity are either more profitable or more competitive.

In practice, the designer finds that as weight increases, bridge formulas usually restrict axle loads to be less than the axle load limits. This means that some axles cannot be loaded to their individual limits (or tandem limits) in most heavy vehicles. (Special provisions have been added to formula B so that the tandem suspensions on five-axle tractor-semitrailers can carry 34,000 lb (15,400 kg). Formula B has a small "notch" that allows 68,000 lb (31,000 kg) on a set of four axles whose extremes are at least 36 ft (10.8 m) apart. This provides some relief (at the expense of a small amount of bridge stress) for carrying cargos such as liquids without requiring a semitrailer wheelbase which seems unreasonably longer than that needed for containing the load.)

The designer might ask, "Why is an axle load limit needed if the bridge formula controls axle loads?" The answer is that axle load limits protect pavements and tend to promote uniform loading of all axles (with the exception of steering axles). Without an axle load limit, vehicles could be loaded nonuniformly such that some axles carried loads that were very damaging to pavements. With regard to safety, vehicles can be made to have poor handling, rolling, and braking qualities by loading some axles much more than other axles. Although axle load limits do not completely solve all vehicle dynamics problems, they limit the severities of the control and stability difficulties brought about by nonuniform loading.

In fact, axle loads are so important to pavement damage, bridge fatigue, and vehicle performance in safety-related maneuvers that monitoring of axle loads and axle separations appears to be a key requirement for assessing the safety and damage-related performance of the truck transportation system.

Productivity, along with axle load limits, tends to promote uniform loading of all axles. The general idea here is that if some axle is not carrying all it is allowed, then the designer will look for some way to put more payload on the lightly loaded axles. The vehicle "designs" developed in this study have nearly uniform axle loads (to the extent that we were clever enough to achieve them in a realistic manner). This means that these designs do not have safety problems that can be introduced (in almost any heavy truck) by poor loading practices. Furthermore, these vehicles are protective of pavements in that their

ratios of payload weight to equivalent axle loads (ESAL's) are relatively large. (See appendix C in volume 2.)

Given that, in one way or another, any vehicle has a maximum gross combination weight, axle load limits restrict the amount of load that the vehicle is allowed to carry when it is loaded nonuniformly. Hence, the axle load limits provide a built-in mechanism for compensating for some of the safety problems caused by nonuniform loading (that is because the gross combination weight has to be less than it would have been if the axles were loaded uniformly). In this study, the example calculations performed for nonuniformly loaded heavy vehicles illustrate that safety qualities tend to be preserved when axles are not allowed to be overloaded—that is, when the differences between lightly loaded and heavily loaded axles are no more than that achievable under the axle load limit.

Consequences of using more than five or six axles

Once designers and specifiers decide to use multiple axles, the questions are, "How many?" and "Where are they located?" In Michigan, vehicles are allowed up to 11 axles with loads on all but the steering axle restricted to no more than 13,000 lb (5,900 kg). These vehicles are highly productive with respect to weight in that they can have GCW's approaching 148,000 lb (67,000 kg). (Of course, they have a high tare weight given all of those axles so that the ratio of payload weight to GCW is less than those of vehicles with fewer axles.) An 11-axle limit means that a 3-axle tractor could be pulling an 8-axle semitrailer. (Such vehicles exist in Michigan.) A major concern with these vehicles is the scrubbing of tires when turning a corner. Not only can this scrubbing action wear tires rapidly and deform the surface of flexible pavements, but it can also lead to friction demands that are greater than those available when the road is slippery. This results in a phenomenon called "power jackknifing" that happens when the drive wheels of the tractor can no longer produce enough side force to turn the trailer.

The analyses in this study indicate that semitrailers with three closely spaced axles will not challenge the friction available for turning corners on very slippery roads. Even sets of four closely spaced axles appear to be satisfactory for the vehicles examined here. The qualifier "closely spaced" is important because the amount of tire scrubbing is greatly increased as the distance between axles is increased. For example, the amount of tire scrubbing would be roughly equivalent for a tridem-axle set and a two-axle set made by removing the center axle from the tridem. (Liftable axles or load-reducible axles are installed at the ends of groups of axles in order to reduce turn-resisting moments.)

If designers and specifiers are considering doubles, three axles on the semitrailers are probably more than enough. A nine-axle double could consist of a three-axle tractor, a tandem-axle semitrailer, and a four-axle full trailer consisting of a two-axle dolly and a two-axle semitrailer. An 11-axle combination could consist of a 3-axle tractor, a 3-axle semitrailer, and a 5-axle full trailer employing a tridem semitrailer. Even in Michigan where bridge design has taken these types of vehicles into account, 11 axles provide enough load-carrying capacity to fully utilize the capabilities of the highway system. (Currently, there are those who contend that formula B was not intended to be applied to vehicles weighing more than 80,000 lb (36,000 kg). The TTI formula was developed to

protect bridges of current design if they were to be used by vehicles weighing more than 80,000 lb (36,000 kg). The TTI formula allows much less GCW than that allowed by formula B when formula B is applied to a nine-axle vehicle. Furthermore, bridge formulas have not been developed for U.S. bridges for vehicles weighing over 150,000 lb (68,000 kg).)

In this study, vehicle designs were created for nine-axle doubles in several of the scenarios with differing bridge formulas. There turned out to be nine-axle doubles that did fairly well in the assessment of intrinsic safety. Under bridge formula B, the GCW for a very productive vehicle was found to be 117,500 lb (53,000 kg). The cargo boxes were 35 ft (10.5 m) long. Under the TTI formula, the cargo boxes would be the same length, but the GCW was 104,500 lb (47,400 kg). Due to its lower weight, the nine-axle double designed under the TTI formula had a substantially higher rollover threshold (that is, it had substantially more rollover immunity) than the comparable nine-axle double designed under formula B. Nevertheless, both designs had good rollover immunity in comparison to target performance levels based on current technology, because they had roll stiffnesses per axle that were as large as those associated with current axles and they had less load per axle than that present on fully laden current vehicles.

In the current five-axle tractor-semitrailer and five-axle Western double, axles (other than the steering axle) are loaded to approximately 17,000 lb (7,650 kg). Due to the nature of bridge protection constraints, these axles would be carrying much less load in many-axled vehicles such as the nine-axle double. Analyses have been made to examine the influences of reductions in suspension, tire, and brake properties that are proportional to the reductions in the loads that these components would carry in new vehicle designs. The following conclusions are supported by the results:

- Rollover immunity would be degraded. Reductions in the vertical stiffnesses of the tires and the roll stiffnesses of the suspensions would lower rollover thresholds to levels of turning that are significantly less than those obtainable using current tire and suspension stiffnesses.

- The level of tire lateral force capability would be degraded to the extent that high-speed offtracking and rearward amplification would be considerably worse. Performance in obstacle-avoidance maneuvers would be poor compared to what it could be if tire properties were maintained at their current levels.

- Brake proportioning would be improved. Braking efficiency would be higher. The braking performance of some of the new vehicles would be better than the poor level of performance exhibited by many current vehicles when they are operated in the unladen condition.

In summary, brakes should be proportioned to obtain better braking performance, but intrinsic safety can be maintained or improved if tire and suspension stiffness are maintained at their current levels even though these components may be carrying less load. (Smaller and lighter components are important to increasing productivity and this not to say that they should not be used—rather, that to maintain intrinsic safety, new versions of these components should have the same mechanical properties as they used to have with regard to tire stiffnesses and suspension roll stiffnesses.)

The "Turner" concept is an idea in which axle loads are purposely reduced to obtain less pavement damage, but truckers that do this would be allowed to carry more than 80,000 lb (36,000 kg), thereby increasing their productivity. As observed in this study, the nine-axle doubles, which had fairly good intrinsic safety under formula B or TTI, are in fact vehicles that satisfy the intention of the Turner concept. For example, the 104,500-lb (47,000 kg) nine-axle double designed under the TTI formula would have tandem-axle loads that are less than 25,000 lb (11,300 kg). Clearly, the conclusions above apply to the tires, brakes, and suspensions installed on these lightly loaded axles.

Although it was not an explicit goal of the Turner concept, the idea of requiring a change in vehicle design to achieve greater productivity is a means for avoiding the problem of allowing truckers to overload existing vehicles. That is, decision makers may want to consider policies of a form saying that greater productivity is allowed if specific requirements are satisfied. Some of these requirements could be based on intrinsic safety as well as protection of the highway infrastructure. The set diagrams presented in figure 21 are intended to illustrate the conceptual difference between (a) simply removing or increasing the gross weight cap (model A), and (b) saying that vehicles are allowed to operate with GCW's greater than 80,000 lb (36,000 kg) if they meet specified requirements (model B). In the case of model B, the size and weight specifications would attempt to allow vehicles with acceptable levels of intrinsic safety and avoid vehicles with poor levels of intrinsic safety.

The items listed in the "Key" of figure 21 represent subsets of vehicles with poor levels of intrinsic safety. Ideally, as illustrated figuratively in model B of figure 21, the set of proposed allowable vehicles would avoid designs with poor braking efficiencies, poor rollover thresholds, and poor directional responses, for example. In order to avoid designs with poor levels of intrinsic safety, the definition of the set of allowable, more productive vehicles could include specific requirements directed towards braking, roll, and steering performance.

The truck specifier would have to use new types of vehicles to be productive, and hence competitive. Specifiers could consider adding axles to existing vehicles if their goal was to carry more payload weight. (With respect to more volume, their options are pretty well limited to buying longer trailers.) Under the conclusions given here for lightly loaded axles, adding axles would not necessarily degrade safety if the added axles had tire and suspension properties equivalent to those achievable with current technology. The goals would be to have these added axles do their share of the work and also for the components on all axles to provide current levels of stiffness per pound of load. (This might also be the occasion to upgrade the brake system through reproportioning and/or installing antilock systems.) To control friction demands associated with tire scrubbing, additional axles could be kept close to existing axles. If axles are added in front of existing axles on semitrailers, the effective wheelbase would be shortened and rearward amplification would increase for doubles. However, the additional tire stiffness would partially (but not completely) compensate for the shorter effective wheelbase. In the case of twin 28-ft (8.4 m) doubles, the use of innovative dollies and/or special hitching arrangements might be required for achieving safety in obstacle-avoidance maneuvers when extra axles have been added to the vehicle to allow greater payload weight.

Model A
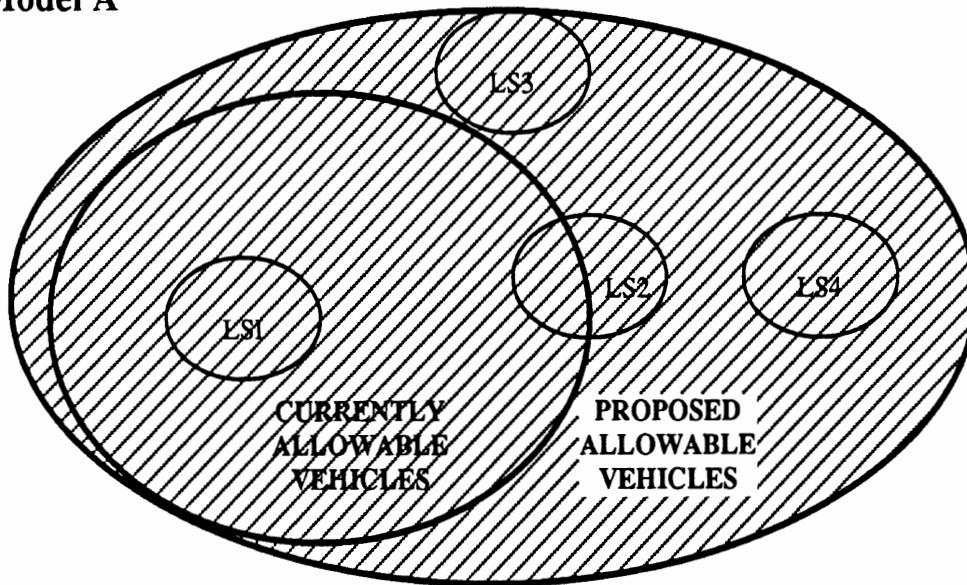
Model B
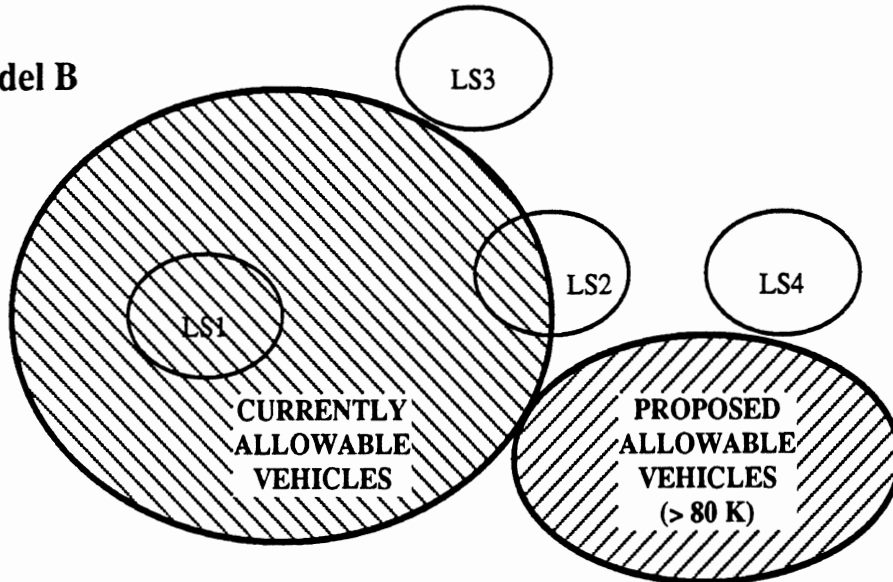
Key
  LS1 — existing designs with poor performance
  LS2 — designs with poor braking efficiency
  LS3 — designs with poor rollover thresholds
  LS4 — designs with poor directional responses

Figure 21.   Set diagrams illustrating conceptual relationships between allowed vehicles and intrinsic safety.

If the number of axles is not limited, there is a technical difficulty with using an offtracking rule. Technically, the overall length of vehicles could get to be very long because the effective wheelbase of a semitrailer is approximately from somewhere near the center of the axles to the kingpin at the front of a semitrailer; that is, low-speed offtracking will not increase when the length of the semitrailer increases. By adding axles so that the effective wheelbases are kept fixed but the extreme axles are further apart, the load could be increased as much as the bridge formula and axle loading rules would allow, which is very much under current rules. (Although this type of design might not be likely to occur in practice, the report contains examples illustrating this situation.) This anomaly is avoided if the maximum number of axles is prescribed, and its influence is reduced if axle sets are closely spaced with no more than four axles in a set on a semitrailer unit.

The final design feature covered in the study was twin-steering front axles. The specifier of trucks might be interested in this innovation from both productivity and safety aspects. The consequences of a front tire blowout might be greatly reduced if the design were such that the vehicle was easy to handle with a tire blown out. In addition, the predicted performance results indicate that more load could be carried on the front of the vehicle in designs with relatively good intrinsic safety.

Summary

The following generalizations summarize points made in this section:

- When going to more weight-productive size and weight rules, do not allow higher loads on existing vehicles. If this problem is taken care of properly, GCW limits might be eliminated or relaxed considerably.

- Axle load constraints should not be eliminated from size and weight rules. The ability to assess the performance of the highway system with respect to safety, productivity, and damage to the infrastructure depends upon the ability to monitor axle loads and the spreads between axles.

- In order to allow trucks to make maximum use of the space available on roads, an offtracking rule could be used as a length constraint. Under either the STAA rules or an offtracking rule, doubles would be more productive than tractor-semitrailers. A shift to doubles might be anticipated from those operators desiring more cubic volume for their payload.

- As a first step in developing rules for more productive vehicles, constraints on the number of axles and axle spreads would prevent the possibility of promoting very long vehicles with excessive friction demands in tight turns. Constraining axle sets to having no more than three, or possibly four, axles in a set would alleviate this problem and ease the development of suitable designs.

- The five-axle tractor-semitrailer with tandem axle sets on both the rear of the tractor and the semitrailer is a well-optimized configuration for the current size and weight rules allowing 80,000 lb (36,000 kg) GCW's. This configuration would not benefit from an increase in the GCW limit alone.

- A six-axle tractor-semitrailer with a tridem-axle set on the semitrailer would allow more load up to GCW's of 86,000 to 88,000 lb (39,000 to 40,000 kg) while maintaining good intrinsic safety.

- For doubles, there are both minimum and maximum wheelbases that bound the range of designs providing good performances. Twin 28-ft (8.4 m) cargo boxes are too short in the sense that the wheelbases of their trailers would not be long enough to obtain good performance in obstacle-avoidance maneuvers. Doubles with twin 35-ft (10.5 m) cargo boxes would be considerably better.

- Innovative dollies with special hitching arrangements may be needed to control rearward amplification (cracking-the-whip)—especially for triples and short doubles. (In these cases, design analyses and performance demonstrations might be required to build confidence in the new designs. There are analytical results and test data showing the advantages of certain existing designs of innovative dollies.)

- The wheels-unlocked braking performance of empty trucks needs to be improved. This is true in all scenarios with the possible exception of the twin-steer vehicles in scenario 18. This general problem is a difficulty for most trucks with large differences between tare weights and GCW's. The countermeasures are changes in brake proportioning and the use of antilock braking systems.

- The rollover immunity of more productive heavy trucks would be maintained or improved if the tire stiffnesses per axle and the suspension roll stiffnesses per axle are maintained at the same levels of those properties as the levels pertaining to current tires and suspensions, even though the new heavier vehicles would have less load per axle than the loads per axle on current vehicles. (The new, heavier vehicles would have more axles than current vehicles, but the load per axle would be less than that used on current vehicles. Nevertheless, the mechanical properties of tires and suspensions should be kept at their current levels.) The above specification on tires and suspensions would also aid in controlling rearward amplification (cracking-the-whip) in multiarticulated vehicles.

RECOMMENDATIONS

The fundamental conclusions derived from this study have just been presented in the previous section. The following recommendations provide a basis for action steps supported by those conclusions.

1. What are the Elements of a Set of Size and Weight Constraints that will Provide both Increased Safety and Increased Productivity

In order to allow maximum productivity, size and weight constraints should not be arbitrary or more restrictive than they need to be to provide protection for the infrastructure. Axle load limits are needed for protecting pavements. These pavement constraints should

also specify loading allowances and dimensions for sets of closely spaced axles . A length-to-weight relationship is needed to protect bridges. An offtracking limit is needed to prevent long vehicles from requiring more turning space than the roadway system can adequately provide. Constraints on the total number of axles allowed on one vehicle and the number of axles allowed in a closely spaced set of axles on a vehicle unit should be included in the axle loading, bridge protection, and offtracking constraints. Beyond the three basic types of constraints (pavement and bridge protection plus offtracking), decision makers should be very hesitant to add rules for protecting the roadway without evidence of the type and amount of damage attributable to the size or weight property that is a candidate for restriction.

Changes in gross weight limits (either directly or indirectly through combinations of new length and weight allowances) should have a rational basis in terms of the types of increases in productivity that these changes are attempting to promote. If so, changes in gross weight caps might be used in conjunction with the process of liberalizing size and weight rules. Arbitrary increases in gross weight should not be allowed because they would allow the overloading of existing vehicles and thereby promote a decrease in the intrinsic safety of the vehicles in the truck fleet.

Changes in size and weight constraints that allow increases in gross weight should be accompanied with provisions to ensure that active (intrinsic) safety is not degraded. These safety provisions should be developed in light of the performance and component recommendations presented later in this section.

In summary, the recommended elements of new sets of size and weight constraints include:

- A pavement/axle loading rule that is directly related to pavement damage, and suspension, tire, and brake characteristics pertaining to the intrinsic safety of the vehicle.

    (Specific recommendations concerning the mechanical properties of tires, suspensions, and brakes are given in part 3 of this section on recommendations. Those recommendations pertain directly to situations in which axle loads are reduced to reduce pavement distress.)

- A bridge formula that is directly related to the costs of providing structurally sound bridges.

    (Although bridge stresses were not studied herein, the need for separating bridge and pavement cost factors was observed in connection with developing size and weight rules that both protect the highway infrastructure and allow advances in the productivity of trucking. A coherent set of size and weight rules is seen as being very helpful to the process of developing reasonable guidelines concerning the safety of new, more productive trucks.)

- An offtracking rule that promotes efficient use of the space available on roadways.

    (An example of the type of offtracking requirement recommended appears after the first bullet in part 2 of these recommendations.)

- A statement of the intrinsic safety targets for the vehicles allowed to operate under these new rules.

(A list of intrinsic safety targets is presented in the next part (part 2) of these recommendations.)

- A statement of the types of previously used vehicles that are not to be allowed to operate in an overloaded state (that is, limits on existing types of vehicle designs that do not have provisions for carrying more load than that allowed previously).

(Specific concerns with overloading of Western doubles were presented in the previous section .)

- A statement of permit requirements, cost provisions, and safety factors for special types of heavy (possibly short) vehicles that are deemed important to the transportation of special items.

(Size and weight rules may tend to require awkward vehicles for use in transporting heavy objects and loads such as shipping containers. The purpose of this recommendation is to provide a mechanism for alleviating these types of difficulties.)

2. How Should Safety Implications be Evaluated

Measures of intrinsic safety should be used to evaluate the safety implications of proposed truck designs.

Intrinsic safety pertains to those inherent properties of a vehicle that determine the performance capabilities of the vehicle in safety-related maneuvers. The current state of development of this approach to crash avoidance is based on straightforward "axioms" such as the vehicle should have an acceptable level of immunity to rollover, or the back end of a long vehicle should follow the path of the front end with adequate fidelity. In addition, the vehicle should be readily steered to follow a desired path and should be capable of stopping rapidly without directional control difficulties. This approach to assessing safety-related performance provides a means for understanding how the properties of heavy trucks as determined by their size and weight allowances can contribute to accidents.

At this time the accident record does not contain the type of information needed to predict the performance of new types of vehicles. A basic difficulty with the information in the accident record is that trucks are often poorly described from a vehicle dynamics standpoint (for example, axle loads and axle separations are not ascertained and saved in either accident data or data describing the exposure of trucks to the risk of an accident). Even if the accident record were more complete, it would seem to pertain primarily to previous vehicles—not to current vehicles and certainly not to future vehicles. However, the accident record could pertain to future vehicles if vehicles in the record (both accidents and exposure) were described in terms of their levels of intrinsic safety. In other words, measures of intrinsic safety bridge the gap between the past and the future. If we were to make vehicles longer or heavier in a manner that did not change their levels of intrinsic safety, then (presuming that we had identified the important aspects of intrinsic safety) we

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would not expect the accident record to be influenced noticeably. On the other hand, if some aspect of intrinsic safety were to be degraded in new vehicles, we would expect those new vehicles to be overinvolved in certain types of accidents. For example, if rollover or jackknifing immunity were to be degraded, we would expect to see more rollovers and jackknifes in comparable service uses (exposure). In summary, it is recommended that more work be done in which the accident record is approached from the point of view of intrinsic safety.

The current accident record has been used to study the influence of rollover threshold on rollover accidents and it is clear that current tractor-semitrailer trucks when fully laden have low rollover thresholds and that these vehicles are overinvolved in rollover accidents. Even so, the evaluation of new vehicles requires that levels of intrinsic safety be determined so that acceptable new vehicles can be separated from unacceptable ones. The consequences of setting levels of intrinsic safety are unknown with respect to the levels needed to maintain or improve the overall accident record or the costs associated with achieving prescribed levels. Accordingly, the performance targets used in this study are recommended as starting points for iterative processes in which new vehicle designs are modified and performance targets are adjusted to achieve practical designs with known levels of intrinsic safety. Decision makers (vehicle designers, truck specifiers, rule makers, or whoever they may be) should give critical attention to the advantages and disadvantages of the following performance goals and their suitability for use in evaluating vehicle designs:

- Offtracking of no more than 17 ft (5.1 m) in a 90 degree turn with a radius of 41 ft (12.3 m) to the center of the front axle.

- Friction demand of no more than 0.2 in a tight turn.

- High-speed offtracking of no more than 1.0 ft (0.3 m) in a turn with 1200 ft (366 m) radius while traveling at 55 mi/h (88 km/h).

- Braking efficiencies of greater than 0.7 (particularly in the unladen condition of the vehicle without compromising the efficiency attainable in the fully laden condition.)

- Rollover threshold of greater than 0.38 g of lateral acceleration in a steady turn.

- Steering sensitivity of greater than 0.1 radians per g at 55 mi/h (88 km/h) at 0.3 g of lateral acceleration.

- Rearward amplification of less than 1.4 between the first unit and the last unit of a multiarticulated vehicle in an obstacle-avoidance maneuver while traveling at 55 mi/h (88 km/h).

3. What Properties of Tires, Suspensions, and Brakes are Needed to Ensure Good Performance in Safety-Related Maneuvers

Since the vehicles that are likely to evolve from liberalizing size and weight constraints will probably have more axles but less load per axle, it is important to specify mechanical

properties of vehicle components that are appropriate for providing good performance in safety-related maneuvers.

Certain mechanical properties of tires and suspensions should not be scaled down in proportion to the load carried on an axle when more productive designs employ less load per axle.

In order to ensure good performance in high-speed turning maneuvers and with respect to rollover immunity, the lateral and vertical characteristics (vertical stiffnesses and cornering stiffnesses) of the tires used on new designs of heavy trucks should be at least as stiff as those available in the radial tires currently employed on heavy trucks. (This is not to say that they have to be radial tires—rather that they achieve these levels of stiffness.) Even if the load per axle is decreased, tire lateral force capabilities per axle should not be allowed to be less than those of current axles employing radial tires.

With regard to suspension properties, roll stiffness levels corresponding to those of current leaf-spring suspensions are recommended even though a new vehicle design may result in less load on the axles associated with that suspension. (This not to say that leaf springs have to be employed or that the vertical stiffness has to be comparable to that of leaf springs—rather, that suspension roll stiffnesses are to be equal to current levels.)

Smaller and lighter suspensions and tires can have important benefits to productivity. The intentions of these recommendations are not to eliminate new designs of these components. However, the recommendations indicate that currently available components would be suitable for the new, more productive vehicles; and that, if new types of tires and suspensions are to be developed for axles with loads that are less than current axle loads, the mechanical properties of the new versions of tires and suspensions should have levels of tire stiffnesses and suspension roll stiffnesses that are equivalent to the levels of these properties currently achieved on single axles allowed to carry 20,000 lb (9,000 kg) and on tandem axles allowed to carry 34,000 lb (15,300 kg).

The situation with brakes is different from that pertaining to tires and suspensions. Ideally, braking at each axle should be proportioned in accordance with the load on that axle at each instant in time. That is, brake gains at each axle should be proportional to the load carried on each axle. Hence, brakes with gains selected for higher axle loads will degrade vehicle performance if they are used on axles with less load. Brake proportioning should reflect the load to be carried by the axle.

However, brakes proportioned in accordance with the maximum load allowed on an axle will have very poor performance when the truck is unladen. Better proportioning of braking effort when the vehicle is unladen is needed for heavy trucks in general. Poor proportioning is liable to lead to wheel lockup and associated problems with directional control and stability. In this regard, antilock braking systems should be considered if directional control and stability are to be maintained during rapid stops on slippery surfaces and in emergency stops.

In summary the basic recommendations with respect to tires, suspensions, and brakes are as follows:

- The lateral and vertical characteristics (vertical stiffnesses and cornering stiffnesses) of tires used on new designs of heavy trucks should be at least as stiff as those available in the radial tires currently employed on heavy trucks.

- Roll stiffness levels corresponding to those of current leaf-spring suspensions are recommended even though new vehicle design may result in less load on the axles associated with that suspension.

- Braking at each axle should be proportioned in accordance with the load on that axle at each instant in time.

4. How Can the Findings of This Study be Used to Enhance the Efficiency, Safety, and Acceptability of Truck Transportation on the Nation's Highways

The findings of this study are intended for use in developing new size and weight rules that will allow more productive vehicles to be used in truck transportation. To aid in ensuring that new vehicles developed under new size and weight rules will have adequate performance in safety-related maneuvers, the study has produced findings delineating mechanical properties of vehicle components and levels of vehicle performance measures that will contribute to achieving (or surpassing) current levels of intrinsic (active) safety. The first recommendation, presented in this section, outlines the elements of sets of size and weight rules that are intended to simultaneously promote productivity, preserve the highway infrastructure, and maintain safety on a per truck basis. The next two recommendations have summarized safety factors pertaining to vehicle performance and vehicle components. Given the prior recommendations, the basic thrust of this final recommendation is to apply the other recommendations in allowing acceptable increases in vehicle sizes and weights.

The underlying notion here is that changes in size and weight rules can be justified for acceptance if they enhance the efficiency of the delivery of goods in a manner that will contribute to maintaining trends towards improved highway safety, relieving traffic congestion, and controlling the costs of highway maintenance.

The approach to vehicle design used here is directed towards producing vehicles that will be efficient in the delivery of goods. The resulting designs are aimed at increasing payload volume and/or payload weight. The efficiencies of these designs can be assessed through measures such as the ratio of payload weight to gross combination weight, or the ratio of cargo volume to overall length or gross combination weight. Other measures of trucking efficiency might employ the amount of payload per axle or per articulation joint. Nevertheless, the more productive vehicles "designed" in this study could serve as starting points for practical and pragmatic experts to use in optimizing the efficiencies of new vehicle designs for trucking applications.

Efficient designs tend to have pertinent by-products such as the possibilities of using fewer vehicles to deliver the same amount of goods and having fewer vehicles exposed to the risk of accidents. Given that the demand for truck transportation is likely to increase, the same idea can be stated in terms of the amounts of product delivered; efficient designs

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in terms of payload weight and volume will contribute to controlling the amount of congestion and the number of accidents occurring per the amount of goods delivered.

The basic nature of the safety qualities of the designs produced here have undergone analyses that serve as a first-order screening of their performances in safety-related maneuvers. Hence, the findings from each scenario provide a basis for understanding the safety implications of various types of designs. The results can be examined to select types of designs that are expected to have good safety qualities with respect to current trucks. Again, the designs presented in this study could be used as starting points for experts from the trucking industry to use in developing vehicles with good safety qualities.

The scope of the applications of trucking is so large that this study serves as a set of examples of what can be done to maintain the safety of productive vehicles. The study by no means claims to have exhausted the possibilities for safe, efficient designs. Nevertheless, it has produced designs that have been scrutinized in a manner that represents an effort to consider safety implications in assessing the acceptability of productive vehicles that may result from changes in size and weight allowances. It is recommended that these or improved methods for evaluating intrinsic safety be applied when considering future changes in size and weight regulations. Although there could well be many other types of vehicles that exhibit currently acceptable levels of intrinsic safety, this study has produced preliminary designs that are recommended as starting points to be used in developing the following types of vehicles:

- Six-axle tractor-semitrailer with a tridem axle set on a 48-ft (14.4 m) semitrailer.

- Nine-axle double with 35-ft (10.5 m) cargo boxes.

The above list is short because productive designs tend to be very specific to the size and weight constraints defining the types of vehicles allowed. For general guidance in developing acceptable size and weight rules, it is recommended that decision makers pay particular attention to the generalizations presented at the end of the overall conclusions presented in the previous section.

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