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UMTRI-88-32

# SAFETY IMPLICATIONS OF VARIOUS TRUCK CONFIGURATIONS

VOLUME I

TECHNICAL REPORT

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December 1988

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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 technical 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.

This volume is the first in a series of three. The other two volumes are Volume II, Appendixes, FHWA Report No. FHWA-RD-89-019, and Volume III, Summary Report, FHWA-RD-89-085.


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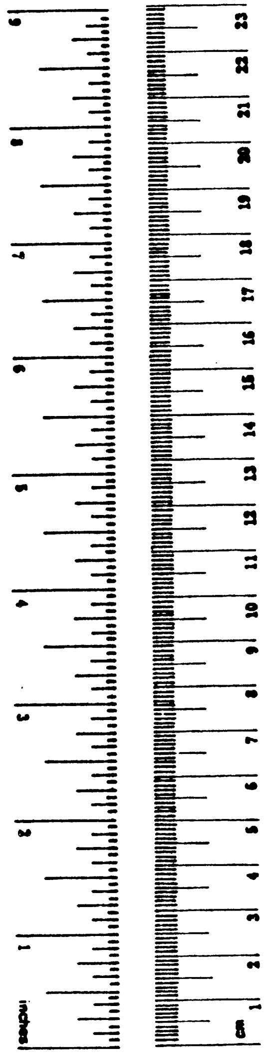
# METRIC (SI*) CONVERSION FACTORS

## 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 |

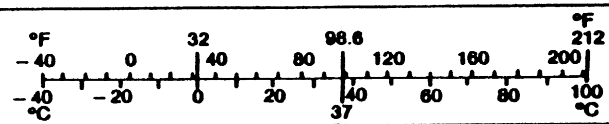
NOTE: Volumes greater than 1000 L shall be shown in m³.

| | | **TEMPERATURE (exact)** | | |
|---|---|---|---|---|
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |




## 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 | hectores (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.

* SI is the symbol for the International System of Measurements

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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.

# 1. INTRODUCTION

This study has investigated the influences of size and weight constraints upon the safety-related maneuvering performances of heavy trucks. A brief historical perspective on the regulation of vehicle dimensions, weights, and configurations is presented first to provide an understanding of the context in which this study was conceived. (A more complete presentation of the 75-year history of State and Federal regulation of motor vehicle size and weight in the United States is given in reference 1.)

## History of Size and Weight Laws

The United States Constitution gives each State the right to regulate transportation within that State. The Federal government has interceded when State actions have impeded interstate commerce. Under this arrangement, the various States have developed a wide range of size and weight allowances for heavy trucks. The current State limits are summarized each year in various publications. (See reference 2, for example.)

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:[1]

- 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.

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. [1] Currently, the most common trailer length 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." [1]

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. [1] Nevertheless, size and weight rules vary significantly between States, seemingly 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, revisions in 1975, and a subsequent act of 1976, restricted the width, axle loads, and gross vehicle 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 (15 m) semitrailers and twin 28-ft (8.5 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."[1]

"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.

## Objectives

The objectives of this study were developed by the Federal Highway Administration (FHWA) to aid the United States in addressing questions pertaining to the safety impacts of changes in size and weight regulations. The purpose of the research investigation is 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 thereof.

It should be emphasized that this study is directed towards **safety implications** and does not investigate other aspects of the effects of trucks on highway performance matters such as pavement or bridge life. Those highway performance matters only enter the study indirectly insofar as certain size and weight scenarios have been predicated by acknowledging the desire to control the rate of wear of the infrastructure of the highway system. 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.

## Brief Introduction to the Concept of a Size and Weight Scenario

The analyses of vehicle performance presented herein 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 the performance is assessed. (See figure 1.)

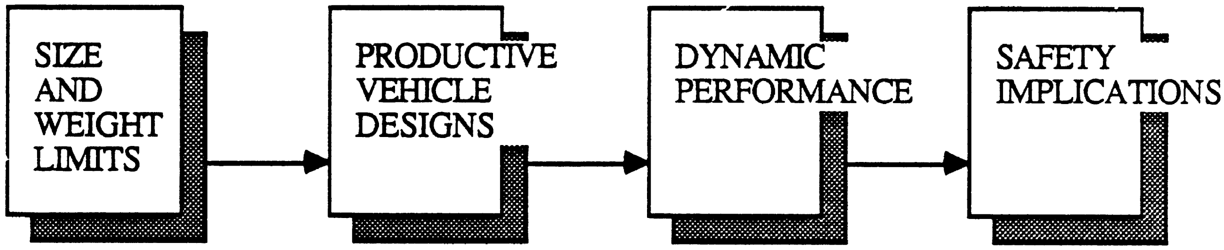



Figure 1. Safety implications of size and weight limits.

## Organization of the Report

The body of the report consists of (a) a background section defining and describing how the size and weight constraints, the vehicle designs, and the measures of intrinsic safety were chosen and developed, (b) a section discussing the implications of various size and weight constraints, (c) discussions of the size and weight scenarios associated with the sets of size and weight constraints given in table 1, (d) material on the influences of changes in tires, brakes, and suspensions, and also, the influences of loading variations, and (e) sections entitled "Conclusions From the Scenarios," "Overall Findings with respect to the Safety Implications of Size and Weight Issues," and "Recommendations."

The report has several appendixes covering items pertaining to (1) procedures for checking whether vehicle designs meet bridge formulas and other constraints, (2) results from checking the designs created in this study, and (3) listings of vehicle mechanical properties.

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 under FHWA support.
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.

# 2. BACKGROUND CONCERNING SIZE AND WEIGHT CONSTRAINTS, VEHICLE DESIGN CONSIDERATIONS, AND MEASURES OF INTRINSIC SAFETY

## Size and Weight Constraints

Throughout the world, various countries have been considering changes in their size and dimension restrictions for trucks. [3,4,5] 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 enough different 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 the U.S., for example, trucking organizations have succeeded in finding ways to legally permit the use of 53-ft (16 m) semitrailers and various types of longer combination vehicles—lengths and combinations that are generally not accepted outside of North America. In the U.S. there appears to be a process like osmosis by which permission to use larger vehicles spreads across the country from State to State. The U.S. appears to have a unique situation with regard to the development of size and weight regulations and productive vehicles.

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 in the rules and permits for auto transporters, construction vehicles, and other special-purpose 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) per axle group; in the near future, they would like an allowance for ISO shipping containers and a 100,000-lb (45,360-kg) weight cap (in this case the 100,000-lb (45,360-kg) limit, 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 (68,040 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) off of the ground.

Most 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. An example of the introduction of new hardware has to do with setback front axles on tractors. This hardware innovation allows tighter turning circles and higher front axle loads. However, these designs are likely to fail the bridge formula. Clearly, the people promoting setback front axles would prefer that front axles be removed from the bridge formula.

With regard to increased gross combination weight, the power requirements can 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-lbs (50,803 kg) vehicle.

*Bridge formulas (B, C, and TTI)*

Figure 2 illustrates the provisions of the three types of formulas used herein 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**

$W = 500\,(L\,N/(N-1)) + 6000\,N + 18{,}000$

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

(axle spacing is measured from the centerline of the axle)

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**

$W = 1000\,L + 34{,}000$ for $L \leq 56$ feet ($W \leq 90{,}000$ pounds)

$W = 500\,L + 62{,}000$ for $L \geq 56$ feet ($W \geq 90{,}000$ 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 an historical background. Formulas A, B, and C were examined by the Highway Research Board in 1964. The adoption of formula B was recommended at that time. [6] Formula B was the choice used in the Federal weight law enacted in 1975. Formula B differs from A and C only in the constant term in the

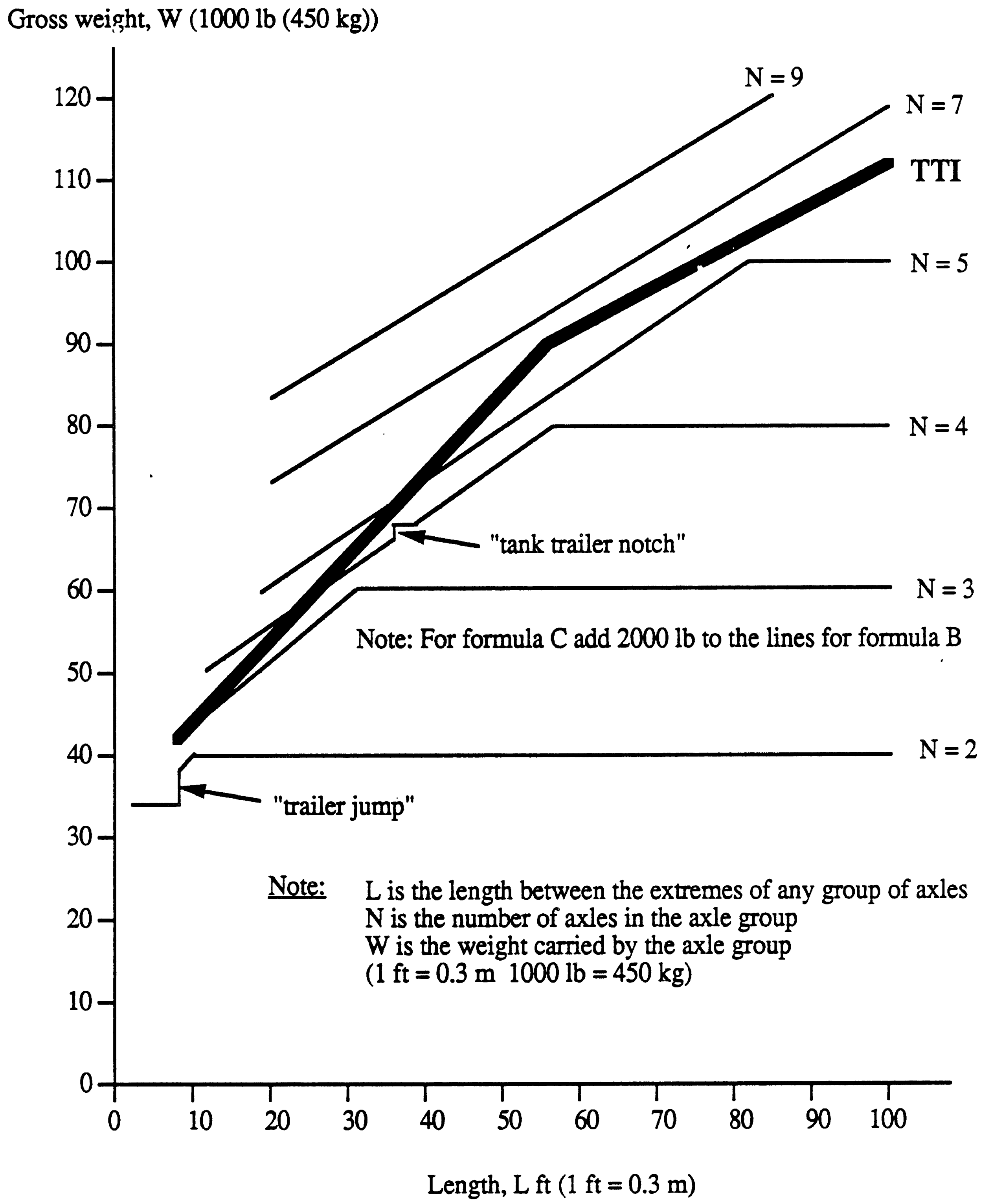



Figure 2. TTI formula superimposed on the current Table B formula.

equations—with each succeeding letter meaning 2,000 lb (907 kg) more weight. 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. 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 overrestrictive.

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). This shows up in the graph presented in figure 2 as a so-called "tank trailer notch" on the four-axle curve at a length of 36 ft (11 m). (In addition, there have been special provisions allowing short wheelbase vehicles with heavily loaded tank trailers, dump trailers, or ocean transport containers. These provisions have been extended until September 1, 1989 in the 1988 Department of Transportation Appropriation Act.)[7]

Also the two-axle curve in figure 2 shows a jump (labeled "trailer jump") at 8 ft (2.4 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 (2.4 m) are considered as a tandem pair and axles separated by more than 8 ft (2.4 m) are treated as single axles.

Recently, a new bridge formula was developed, prompted by concerns over the adequacy of formula B for treating vehicles weighing more than 80,000 lb (36,287 kg).[6] Above approximately 70,000 lb (31,752 kg), the TTI formula allows heavier five-axle vehicles than those allowed by formula B. (See figure 2.) The TTI formula 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. [8] 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 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 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. [9] It was chosen to respond to the truckers' desire 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.

## Vehicle Design Considerations

*Findings from tasks A and B*

The vehicle manufacturing experts had no difficulty with the idea of greater axle loads. They were prepared to increase axle load ratings. Brakes and tires would be the limiting factors. On the other hand, lighter axle loads would open numerous possibilities for changes. For example, dual tires might be replaced with singles or suspension stiffnesses might be reduced. It is clear that vehicle design has been highly dependent upon the constraints of 80,000 lb (36,287 kg) and formula B. The current demand for more cube has led truck users to consider small radius tires and trailers that are 14 ft (4.2 m) high. The information obtained from the trucking industry aided in defining the scenarios. However, it was the constraints provided by the scenarios that determined the layouts and axle loadings of the vehicles examined in this study.

*Reference to a procedure for checking vehicle designs with respect to size and weight constraints.*

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.

Using this process, three categories of example vehicles were designed—ones that had heavier loads than those currently carried on existing vehicle layouts, ones that had more axles than typically used now, and ones with multiple axles and articulation joints.

Appendix A (see volume 2) presents an automated procedure 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. Figures 3 and 4 indicate the various axle sets that need to be checked for compliance with any of the bridge formulas. The dimensions labeled $e_{ij}$ (where i indicates the front axle in an axle group and j indicates the rearmost axle in the axle group) illustrate the lengths of all of the axle groups to be considered in evaluating a vehicle.

*Concept of water level load*

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.)

*Number of articulations, 5 basic types of vehicles*

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 vehicles of these types are illustrated in figure 5. Codes such as 3-S2, 2-S1-2, etc., are used as a shorthand means for designating vehicle configurations (see figure 5). 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 5, 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.

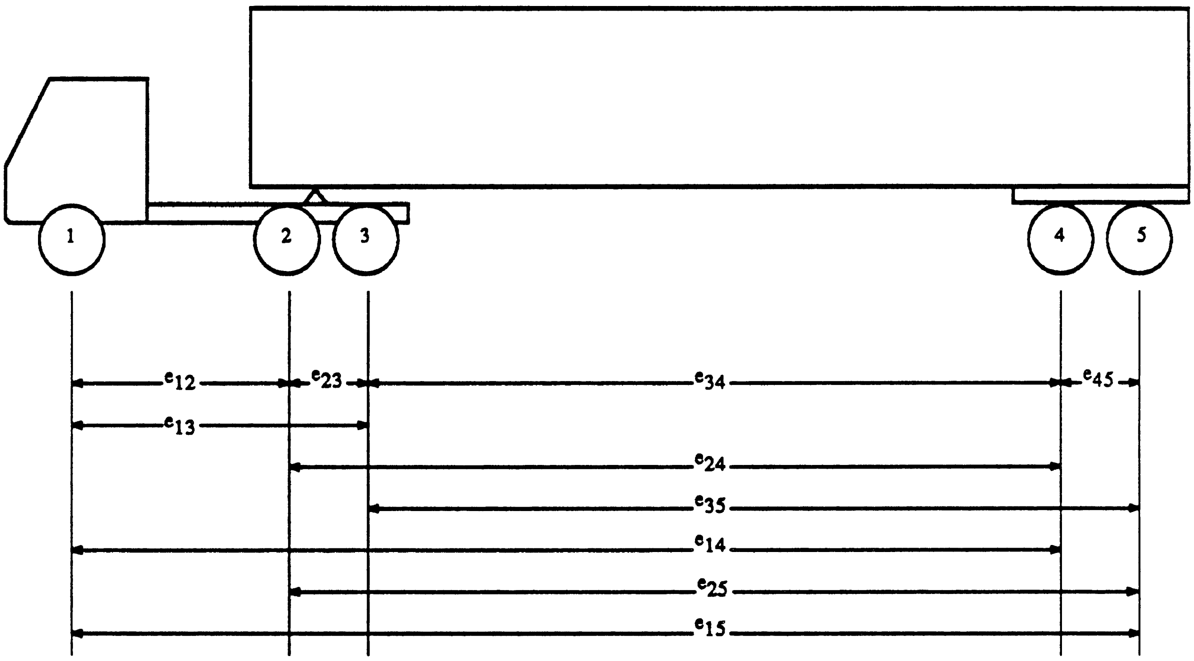



Figure 3. Bridge formula axle groups for a tractor semitrailer.

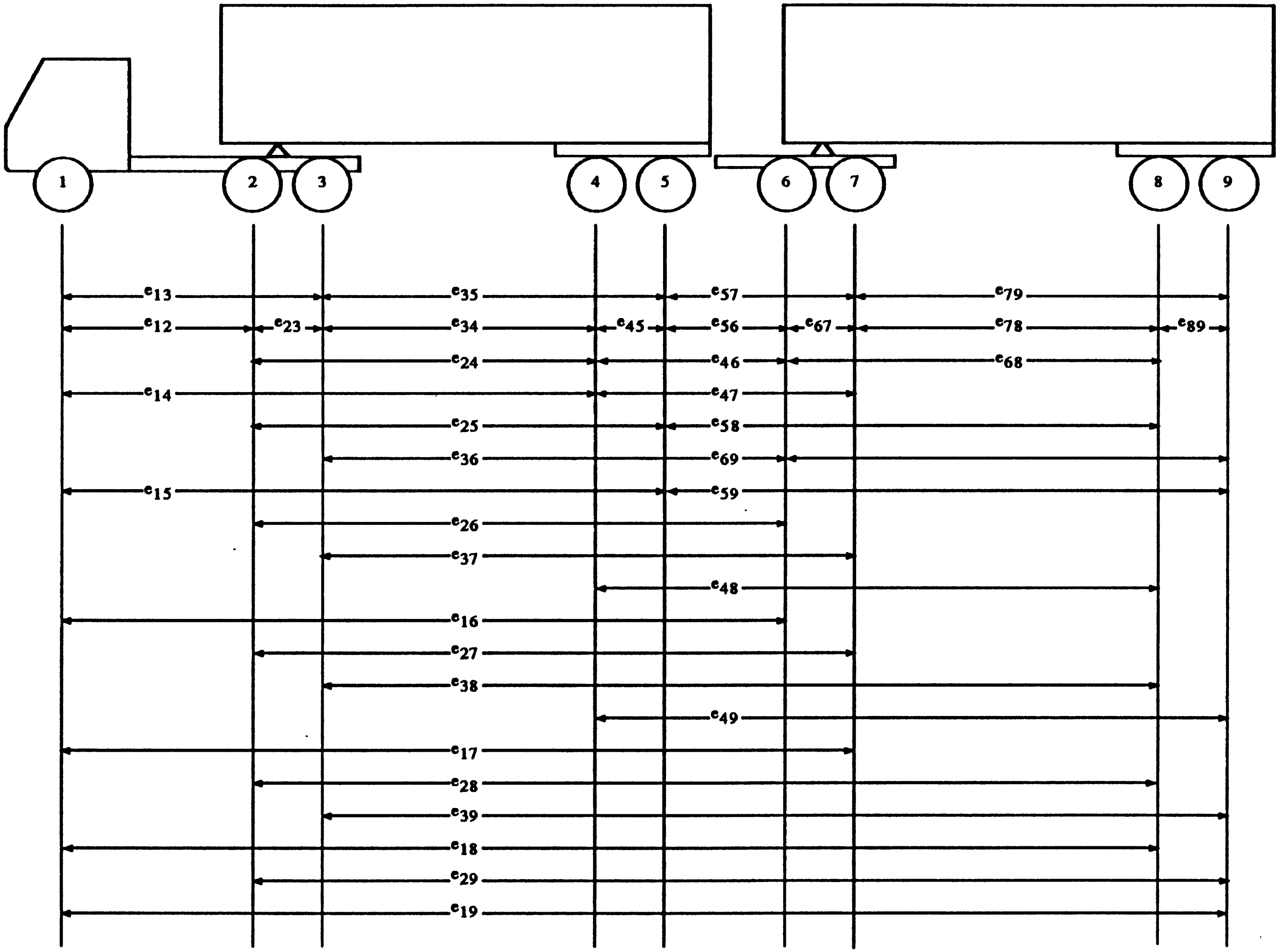



Figure 4. Bridge formula axle groups for a double.

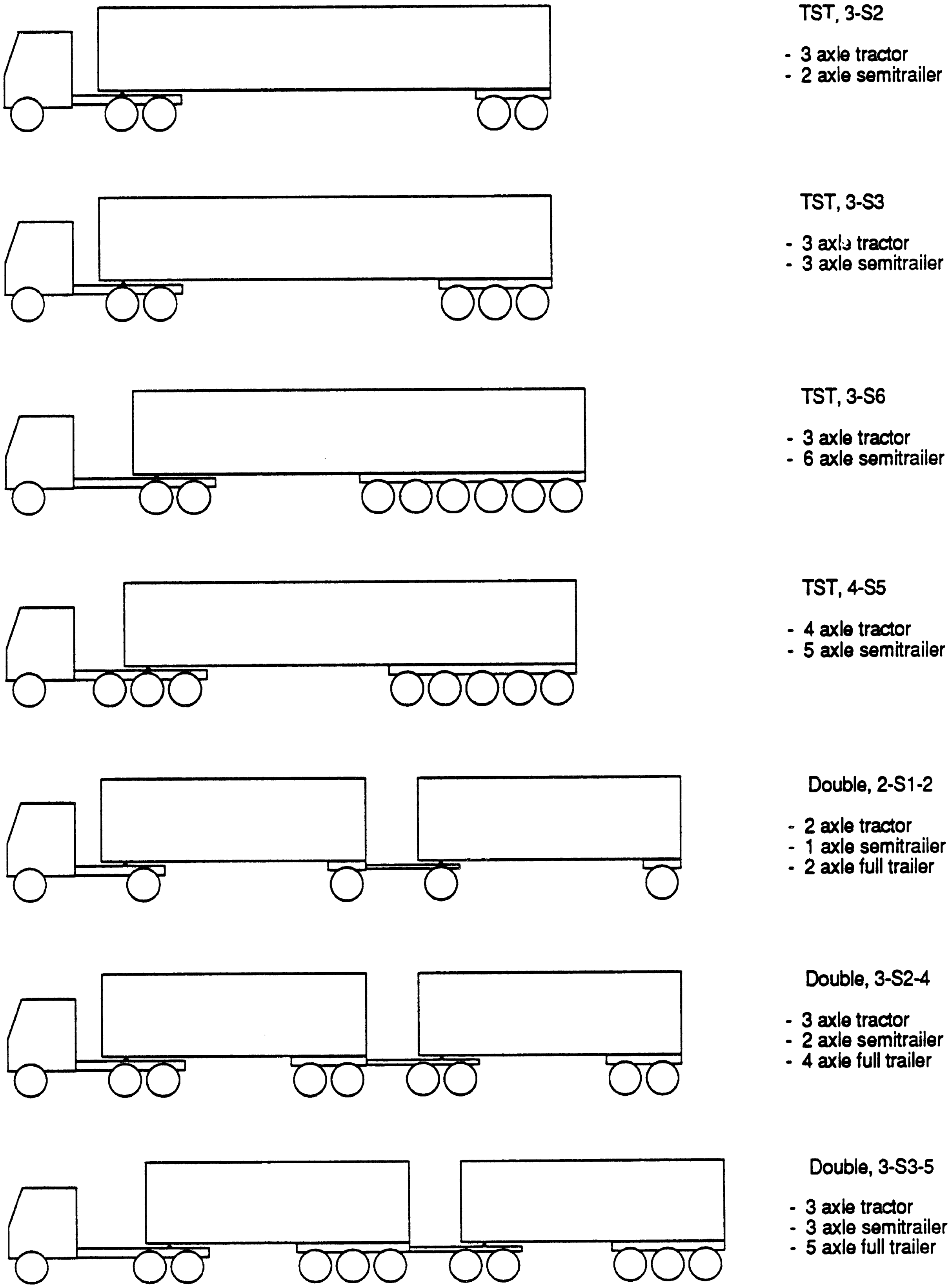



Figure 5. Example vehicle configurations and codes.

*Dimensions for geometric layout*

The following dimensions (see figure 6) are used to describe a vehicle's size and weight characteristics:

Wheelbase (WB): In the case of trucks and tractors, the wheelbase is measured between the front axle and the center of the rear suspension. The wheelbase of a full trailer is measured between the center of the dolly's suspension and the center of the trailer's suspension. Due to the absence of a front suspension, the wheelbase of a semitrailer is measured between the kingpin and the center of the rear suspension.

Fifth wheel offset (OS): The fifth wheel offset on tractors and dollies is the distance that the fifth wheel is *forward* of the center of the rear suspension. In the case of dollies, a negligible offset implies that the fifth wheel is directly above the center of the suspension.

Pintle hitch location (OS): The variable name OS is used interchangeably between fifth wheel and pintle hitch locations. In the case of trucks and trailers, OS is used to locate the pintle hitch with respect to the *last* axle on the particular unit.

Rear suspension information (NR & SR): All the example vehicles are assumed to have load-equalizing suspensions. In other words, if the rear suspension of a semitrailer carried a total suspension load of FR, then individual axle loads would be given by (FR/NR), where NR is the number of axles on the rear suspension. The variable name SR is used to define the distance, or "spread," between consecutive axles on the rear suspension.

Front suspension information (NF & SF): Similarly, NF and SF are used to define the number and the corresponding spread between the axles on a front suspension. In the case of full trailers, NF and SF correspond to the dolly's suspension. For trucks and tractors, however, the two variables are trivial until double-steering axles are treated in scenario 18.

Length of the box (LB): From a vehicle dynamics standpoint, different loading arrangements result in unique vehicle performance characteristics. The longitudinal and vertical locations of the center of gravity (c.g.) of the payload are important in determining the vehicle's performance in braking, roll, and handling. The payloads in this analysis are assumed to be uniformly distributed, thus, locating the longitudinal position of the c.g. at the midpoint of the container. The length of the container, LB, is therefore useful to determine the vehicle's axle loads.

Kingpin offset (KOF): The kingpin offset on semitrailers is defined as the distance between the front of the container and the kingpin. In addition to influencing the kingpin load, the kingpin offset is used to determine the clearance between consecutive units in a vehicle combination. In this analysis, the kingpin offset is allowed to vary between 2.5 ft (.7 m) and 3 ft (.9 m).

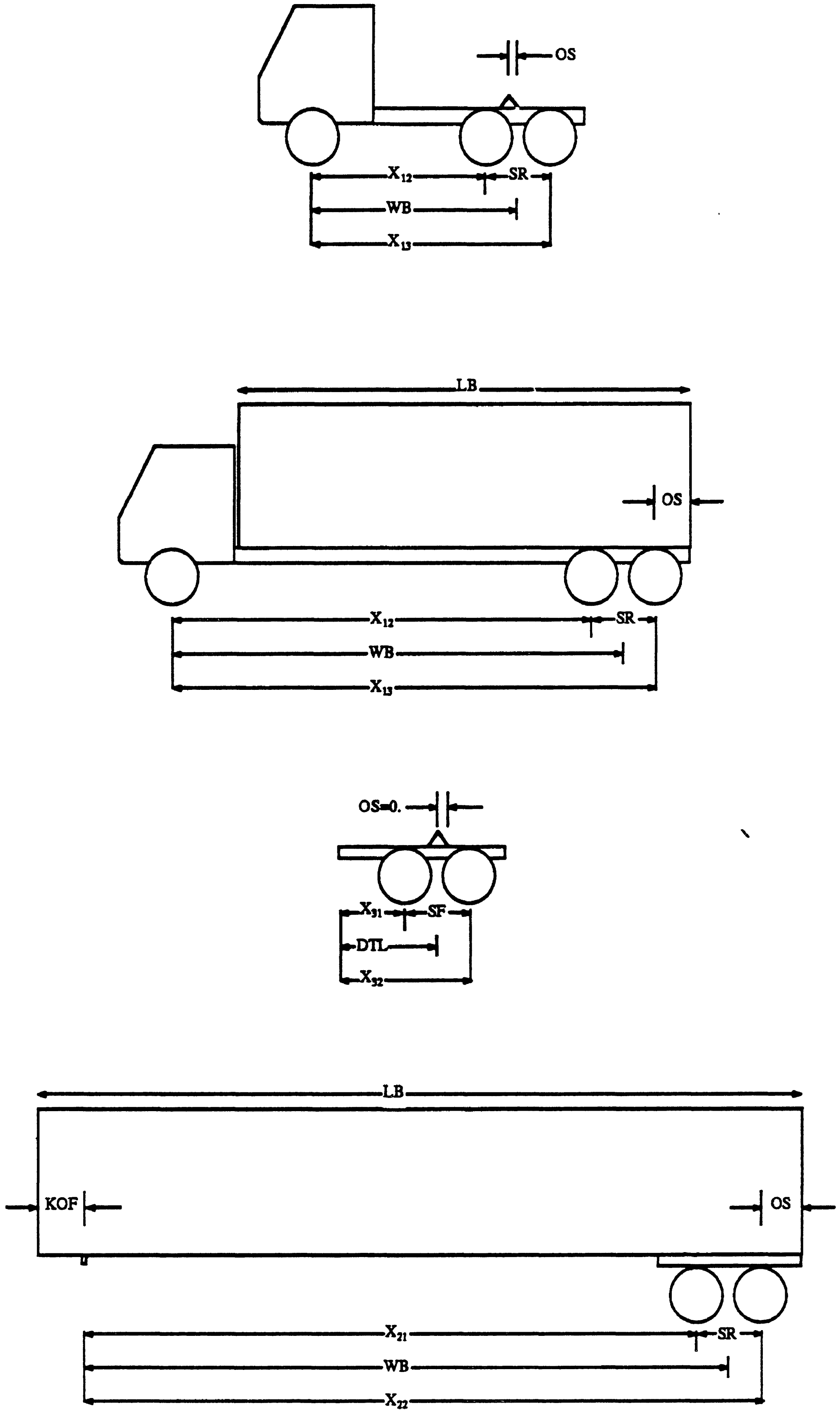



Figure 6. Layout information for various vehicle units.

Trailer load (PL): The bridge formula and pavement loading rules determine the trailer load, PL, that vehicle units can carry. In order to specify axle loads, standard tare weights are used for the vehicle units. The two-axle tractor has tare loads of 8,500 lb (3,855 kg) and 5,500 lb (2,495 kg) on its front and rear axles. The three-axle tractor is assumed to have the same front axle load, but carries a tare weight of 8,000 lb (3,629 kg) on its rear tandem axles. The tare weights of trailers depend upon whether they are vans, tanks, flatbeds, or incorporate some other type of load supporting structure. To eliminate the variability due to trailer design, the sprung weight of a trailer (that is, the tare weight less the weight of the axles and associated mounting hardware) is included in its trailer load, PL. The sprung weight of dollies, however, is assumed to be 1,000 lb (454 kg). With regard to axle weights, front axles weigh 1,200 lb (544 kg), drive axles 2,500 lb (1,134 kg), and trailer/dolly axles 1,500 lb (680 kg) plus an additional weight of 500 lb (227 kg) for mounting hardware for trailer axles. (The trailer load differs from the payload by the weight of the box or other container, the mounting hardware for trailer axles, and the trailer frame.)

Dolly tongue length (DTL): The tongue length of a dolly is defined as the distance between the pintle hook and the center of the dolly's suspension.

*Adjustable dimensions*

The adjustable dimensions are those that were varied in laying out vehicles meeting the size and weight constraints on design. 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. The adjustable dimensions and their symbols are illustrated in figure 6.

*Fixed dimensions*

Certain dimensions are held fixed because they are often close to the same size used in various vehicles today. For reasonable ranges of the values of these dimensions, their influences on vehicle performance are usually small. Examples of the variables held fixed are the distance from the kingpin to the front of a semitrailer and the distance from the last axle to the rear of a semitrailer.

The fixed dimensions could have a large influence on performance; however, the aim of greater load-carrying capacity tends to restrict the ranges of values for these dimensions. Experience has shown that putting the last axle close to the rear of a semitrailer is usually the appropriate location for maximizing the efficiency of handling water level loads; 2 ft (.6 m) has been used here. The distance from the kingpin to the front of a semitrailer is approximately 2.5 to 3 feet (.7 m to .9 m) in many current layouts of combination vehicles. This has proven to be a good location for uniform loading and it does not pose clearance problems between semitrailers and tractors or between semitrailers given reasonable dolly lengths.

*Axle loads*

Axle loads for single and tandem axles are currently based on the provisions of formula B. Front axle loads are specified by many States, also drivers are known to be concerned with high front axle loads. Tractor manufacturers, wanting to use setback front axles, wish to increase front axle loads. Some truck users feel that the ability to build better quality pavements is increasing. As a result, they feel that higher axle loads should be allowed. It seems that trucking companies see higher axle loads as a desirable goal.

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. (See appendix A for numerical values of tare weights.)

*Increases in productivity*

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, but it may have little influence on the transport of light goods. In general, the payloads have been selected in order to create vehicles examples that represent heavier loading of existing vehicles, first-order increases in load carrying capacity, or large increases in load-carrying capacity.

*General rules followed in designing trucks*

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 to (b) intermediate designs requiring modest revisions in vehicle layout and finally 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.

## 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 safety-related objectives have been used to develop analytical procedures for evaluating vehicle performance: [10]

- *Tracking fidelity.*
- *Directional control and stability during rapid braking.*
- *Rollover immunity.*
- *Steering controllability.*

These objectives correspond 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.

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).*

* *Transient turning (response time).*

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. [10, 11, 12] 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 lateral acceleration 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. [13])

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 a 3-S2 tractor-semitrailer weighing approximately 80,000-lb (36,287 kg) has been used as a baseline for comparing vehicles.

Furthermore, target performance levels, 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". [14] Even so, the authors of this report, while appreciative of the desire for specified performance targets, do not mean to imply that the target performance levels used in this study have undergone sufficient testing, evaluation, and scrutiny to be viewed as established specifications for vehicle design. (See references 10 and 15 for discussions of a vehicle synthesis procedure involving the establishment of performance targets.)

Figure 7 illustrates how the reference performance targets have been used in displaying performance results. Arrows are employed to indicate the direction of performance that is worse than the reference levels for the maneuvering situation involved. For example,

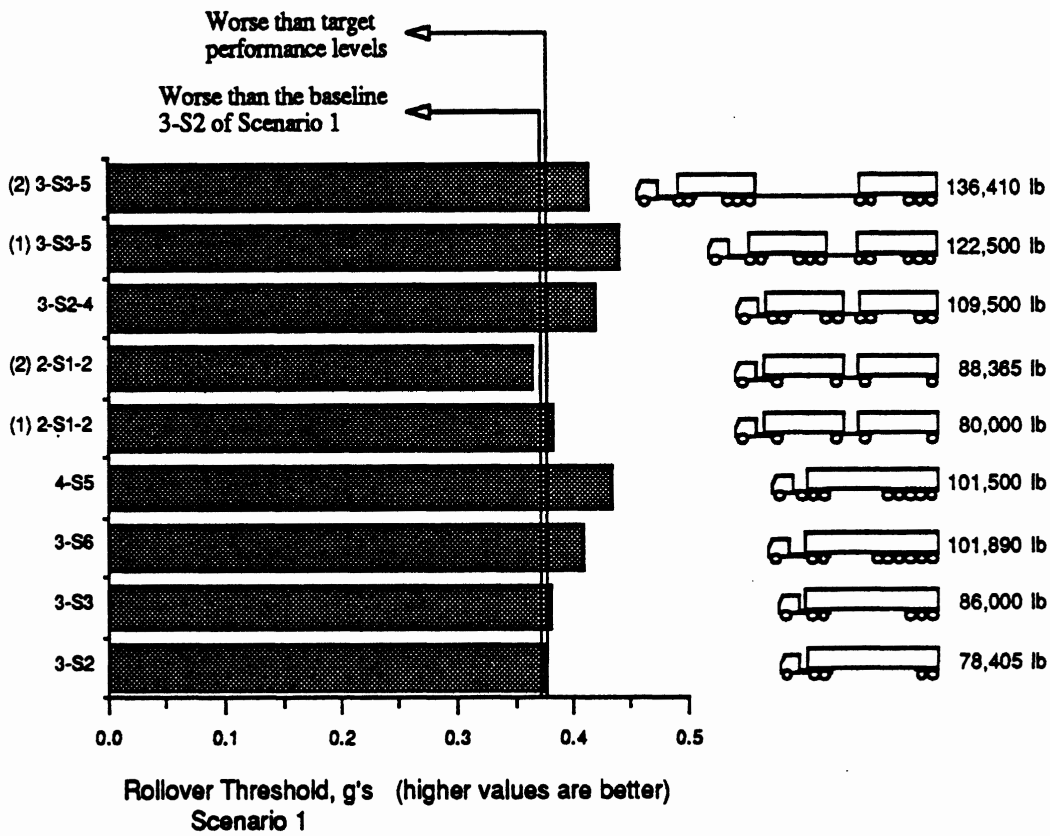



Figure 7. Example of the use of performance targets.

lower rollover thresholds are worse in the sense that vehicles with lower rollover thresholds are expected to be more likely to roll over than vehicles with higher rollover thresholds (see figure 7).

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 performance levels for the following maneuvers have higher levels of intrinsic safety than many vehicles in current service.

In some cases, the target performance levels are close to the performance characteristics of the baseline 3-S2 (for example, see figure 7). In other cases, the performance achievable with a 3-S2 tractor-semitrailer with closely spaced tandem axles far exceeds that needed for reasonable performance in particular maneuvering situations. Specifically, the target performance levels for friction demand in a tight turn, high-speed offtracking, and obstacle evasion (rearward amplification) do not require performance better than that of the baseline 3-S2. On the other hand, in one case pertaining to braking efficiency, the performance of the baseline 3-S2 is not judged to be acceptable and the target performance level is set appreciably higher than that predicted for the baseline 3-S2. Also in handling as evaluated by the sensitivity of the steering during an 0.3 g turn, the performance level of the baseline 3-S2 is poorer than that of the target performance level.

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 cost/benefits 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 judgements regarding poor performance as indicated in the following "target performance levels." If one accepts these judgements 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 ( as illustrated in figure 7, for example) 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 tracking 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 negotiation a tight turn such as an intersection can be a problem for vehicles with widely spaced axles. [12] 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 12.) 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:

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 steers his unit (the tractor or truck) to follow a desired path. The trailing units are expected to follow the path of the lead unit. In high-speed turning, 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.

This analysis applies to the operation of vehicles on highway curves at highway speeds. 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 beyond that point, the trailing units begin to track towards the outside of the turn. This calculation determines 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 1200 ft (366 m) and traveling at 55 mi/h (88 km/h). The selected target is for the center of 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 a 0.5 m offtracking limit was proposed. Generally, drivers do not come as close as one foot (0.3 m) to curbs and other obstacles. Hence, this is probably the least critical of the intrinsic safety measures with vehicles like the 3-S2 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 TST 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 is a simplified representation of the braking process that 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. On the other hand, the empty combination has efficiencies of 0.672 and 0.645 at 0.2 and 0.4 g. These lower levels of efficiency are probably the reason why empty vehicles tend to be overly involved in accidents in which the vehicle folds up ("jackknifes"). (The graphical comparisons presented in this study are for the empty condition.)

*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. [12,16,17] The results of these examinations indicate that the rollover of heavy TST's 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 3-S2 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 radians 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 radians 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 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 TST's rearward amplification is approximately 1.0. Hence the baseline 3-S2 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 can not 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.[18]

# 3. SUMMARY OF THE 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 and vehicle performance are summarized here as an introduction to the scenarios that follow later.

## Bridge Formula Constraints

### *FORMULA B*

*Vehicle Layout:*

- Allows approximately 500 lb (227 kg) of vehicle weight for an additional foot of distance in a given axle set.
- Allows 6,000 lb (2,722 kg) of vehicle weight for an additional axle in a given axle set.
- Formula B, therefore, promotes the use of extra axles to gain weight allowances with or without increasing length.
- Due to the amount of the allowance for additional axles, the pavement load on each axle decreases with every axle added to a suspension. Consequently, this Bridge Formula contains a pavement loading restriction. (It might be said that formula has a version of the Turner concept built into it. [8] )

*Vehicle Performance:*

- Extra axles within fixed lengths reduce the effective wheelbases of the various units, thereby, reducing the amount of low-speed offtracking of the vehicle.
- The use of extra axles, however, increases the friction requirements during tight turning.
- The additional braking effort of the extra axles tends to make the vehicle "over-braked", especially on the lightly loaded axles.
- Due to the added roll stiffnesses of the extra axles, the vehicle's roll stability improves.

- The shorter effective wheelbases of the various units tend to increase the amount of rearward amplification, thereby, degrading the vehicle's evasive maneuvering performance.

*FORMULA C*

*Vehicle Layout:*

- Other than an additional 2,000-lb (907 kg) allowance on an axle set, formulas B and C are identical.
- The vehicle layout guidelines of formula B, therefore, apply to formula C. In other words, 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.

*Vehicle Performance:*

- Since the vehicle layouts under formulas B and C are almost identical, their performance characteristics are similar.

*FORMULA TTI*

*Vehicle Layout:*

- Unlike formulas B and C, the TTI bridge formula is a "length-to-weight" rule which ignores the number of axles in an axle set. Consequently, it does not provide any weight allowances for additional axles.
- For lengths under 56 ft (17 m), the TTI bridge formula provides 1,000 lb (454 kg) for an additional foot of distance in an axle set. However, for lengths over 56 ft (17 m), the bridge formula becomes more restrictive and provides only 500 lb (227 kg) for an additional foot of distance. Consequently, the TTI formula encourages widely spaced axles with no benefits for extra axles.

*Vehicle Performance:*

- Due to longer vehicle lengths (as needed to gain weight allowances), the low-speed offtracking performance of the vehicle might suffer. Spreading axles in a suspension by placing or moving leading axles forward, however, tends to reduce the effective wheelbase of a unit and helps reduce the amount of offtracking.
- Fewer axles reduce the amount of friction required during a low-speed turn. Large axle spreads in a suspension, however, increase the amount of friction needed. Increasing the spread between axles has a powerful influence on increasing the friction demand in a tight turn.
- With fewer axles, the ratio of total weight to total roll stiffness decreases, thereby, degrading the vehicle's roll stability.
- Longer wheelbases on the various units improve the vehicle's evasive maneuvering performance.

## Pavement Loading Constraints

*"36/22 RULE"*

*Vehicle Layout:*

- 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.)

*Vehicle Performance:*

- The pavement loading constraint only becomes a significant factor in determining a vehicle's performance if it becomes more restrictive on axle loads than the bridge formula. (Usually this does not happen, and the bridge formula prevails.) From the standpoint of maneuvering capability, axle loading and tire and brake properties need to be considered together. In general, truck tires and brakes have been developed so that their mechanical properties are compatible with the 36/22 or 34/20 rules.

*"34/20 RULE"*

*Vehicle Layout:*

- 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 (9,071kg).
- Multiaxle (more than two axles) suspensions or wide-spread single axles are used to circumvent the more restrictive 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).

*Vehicle Performance:*

- The pavement loading constraint only becomes a significant factor in determining a vehicle's performance if it becomes more restrictive on axle loads than the bridge formula. (Usually this does not happen, and the bridge formula prevails.) From the standpoint of maneuvering capability, axle loading and tire and brake properties need to be considered together. In general, truck tires and brakes have been developed so that their mechanical properties are compatible with the 36/22 or 34/20 rules.

*"28/16 RULE"*

*Vehicle Layout:*

- 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.

*Vehicle Performance:*

- In this case, vehicles might employ tires and brakes that are different from those currently employed. These changes could either improve or degrade performance.

## Length Constraints

*STAA VEHICLES:*

*Vehicle Layout:*

- 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 are no explicit constraints 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.

*Vehicle Performance:*

- With no constraint on overall length, long tractors and dollies would increase the low-speed offtracking of the vehicle.
- Long wheelbases improve the handling characteristics of tractors.
- With limits on trailer lengths, short effective wheelbases (resulting from extra axles) would degrade the evasive maneuvering characteristics of the vehicle.

*"12'/40' OFFTRACKING RULE":*

*Vehicle Layout:*

- 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.

*Vehicle Performance:*

- Since the vehicles are governed by an offtracking rule their low-speed offtracking performance is predictable.
- Multiaxle suspensions and wide spread axles increase the friction requirements during tight turning maneuvers.
- Short effective wheelbases and more articulation joints increase the amount of rearward amplification.

## Maximum Weight Constraints

*80 K, 100 K, NONE:*

*Vehicle Layout:*

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

*Vehicle Performance:*

- The influences of maximum weight constraints depend heavily upon the "length-to-weight" relationship of the prevailing bridge formula.
- Nevertheless, higher maximum weight constraints tend to promote longer vehicles regardless of the bridge formula involved. The advantages and disadvantages of longer vehicle lengths come into play. For example, longer wheelbases promote maneuvering stability but they degrade offtracking. Additional articulation joints

might be added to reduce lowspeed offtracking of long vehicles, however this would increase rearward amplification and high-speed offtracking.

# 4. SCENARIO 1 — NO WEIGHT CAP, FORMULA B, STAA LENGTHS

## Vehicle Design

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | B |
| Length constraints: | STAA vehicles |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

Formula B provides weight allowances for longer lengths and additional axles. The bridge formula allows approximately 500 lb (226.8 kg) for an additional foot (0.3 m) of distance in a given axle set. In the case of additional axles, however, it provides nearly 6,000 lb (2,722 kg) for every axle added to a given length. Formula B, therefore, promotes the use of additional axles to gain weight allowances with or without increasing length.

Since the bridge formula permits only 6,000 lb (2,722 kg) for every additional axle, it forces a smaller pavement load with the addition of each axle. For example, four axles with 4-ft (1.2 m) spreads between them are allowed only 12,500 lb (5,670 kg) per axle. Though four axles could be considered as a pair of tandems with an allowable 34,000 lb (15,422 kg) per tandem set, the bridge formula allows only 25,000 lb (11,340 kg) on each set. The bridge formula, therefore, has a decreasing weight return for additional axles and tends to be more restrictive than the pavement loading rule in limiting axle loads.

Vehicle configurations in this scenario are limited to tractor-semitrailers and doubles (STAA vehicles). From the point of view of length, trailer dimensions are restricted by the STAA. In the case of TST's, with the trailer length limited to 48 ft (14.6 m), the only means of reaching a higher GCW is by adding axles to the existing hardware. In spite of formula B allowing only 6,000 lb (2,722 kg) for each additional axle (with the tare weight of the axle accounting for 2,000 lb (907 kg)), the extra 4,000 lb (1,814 kg) of payload results in higher levels of productivity for the vehicle. In the case of doubles, additional axles and longer vehicles could be used to maximize gross vehicle weight. As mentioned earlier, the STAA does not restrict the lengths of dollies. Also, the bridge formula (being a "length-to-weight" rule) allows higher loads across longer distances. Consequently, operators could use longer dollies to increase the overall lengths of their doubles, thereby increasing their GCW's. As in the case of the TST, doubles could also use additional axles on their trailers to increase their payload weight.

In summary, the two driving forces in this scenario are the bridge formula and the length restriction of the STAA. With the lengths of trailers restricted, there is a limit to the number of axles that can be added to the trailer. This, in effect, is an indirect cap on the amount of payload that the vehicles can carry. The combined effects of these two constraints, therefore, could result in longer dollies on doubles and more axles on both TST's and doubles.

*Example vehicles*

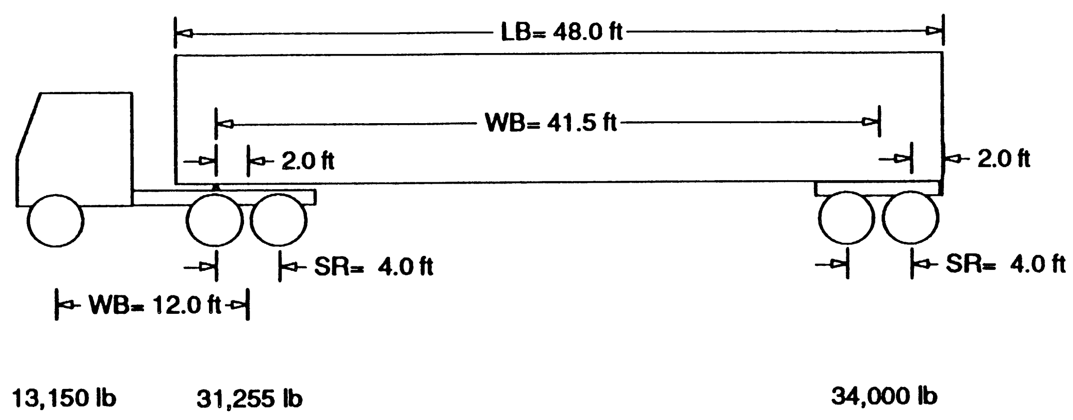
As in all the other scenarios, the dimensions and axle weights for the example vehicles were checked for compliance with the pertinent size and weight constraints using the procedures described on page 14 and presented in appendix A of volume 2. The axle weights were chosen to make the vehicles very productive without violating any of the size and weight allowances for a water level load.

Tractor-Semitrailers: Applying the constraints of this scenario to the current three-axle tractor and tandem-axle semitrailer (figure 8), we find that removing the gross weight cap is of no consequence in this vehicle and axle layout. A "water-level" loading of the semitrailer results in a 34,000-lb (15,422 kg) suspension load on the rear of the semitrailer which limits the vehicle's total weight to 78,405 lb (35,564 kg). A forward-biased loading of the semitrailer would allow the vehicle to reach 80,000 lb (36,287 kg), with 34,000 lb (15,422 kg) on the tandem axles and 12,000 lb (5,443 kg) on the front axle.

Using additional axles to obtain the weight advantage provided by the bridge formula, a three-axle tractor and a tridem-axle semitrailer (figure 9) is found to be extremely productive when compared with the five-axle TST. The additional axle, which increases the vehicle's GCW by nearly 7,600 lb (3,447 kg), improves the load distribution and increases the allowable payload weight by approximately 5,600 lb (2,540 kg).

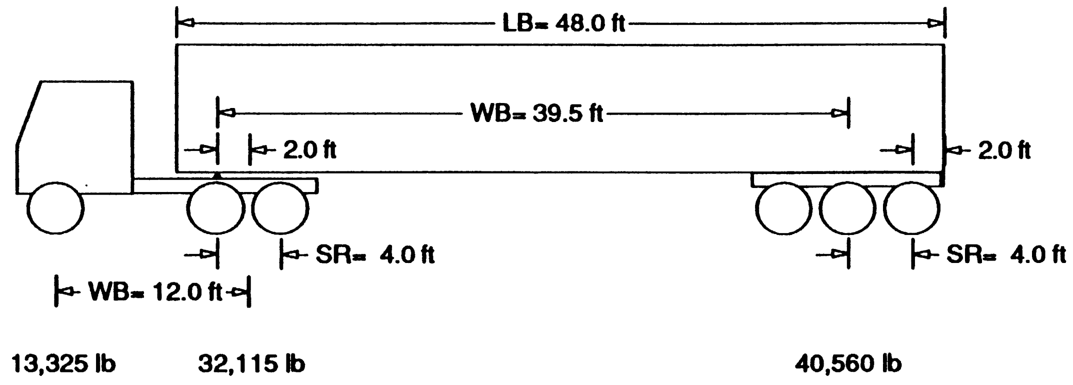
Using the "axle-effect" of formula B to maximize GCW, another TST with a total of nine axles is allowed to weigh approximately 102,000 lb (46,266 kg). The three-axle tractor and six-axle semitrailer (figure 10) has a tare weight of 38,300 lb (17,373 kg) and carries a payload of 63,590 lb (28,844 kg). A fourth TST, also with a total of nine axles, uses a four-axle tractor and a five-axle semitrailer (figure 11). Though the GCW of this vehicle is 500 lb (227 kg) less than the TST in figure 10, it uses a tridem set on the rear of the tractor so that all nine axles carry approximately the same amount of load. Though the last two TST examples (figures 10 and 11) might appear to be extreme, they are included to provide an insight into the variety of vehicles possible under the given set of constraints.

Doubles: Using the same vehicle development scheme for doubles, the constraints of this scenario are applied to the "Western Double." The "Western Double" is made up of a two-axle tractor, a single-axle semitrailer, and a two-axle full trailer. The vehicle layout and load distribution for such a vehicle operating under a 80,000-lb (36,287-kg) gross



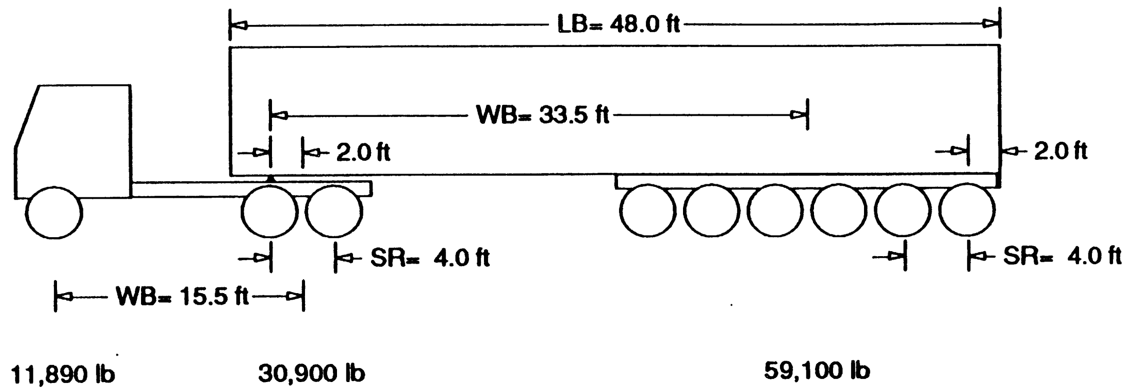

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 41.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 57907. lb | 48.0 ft | .0 ft |

Figure 8. Tractor-semitrailer (3-S2; GCW=78,405 lb; payload=48,105 lb).



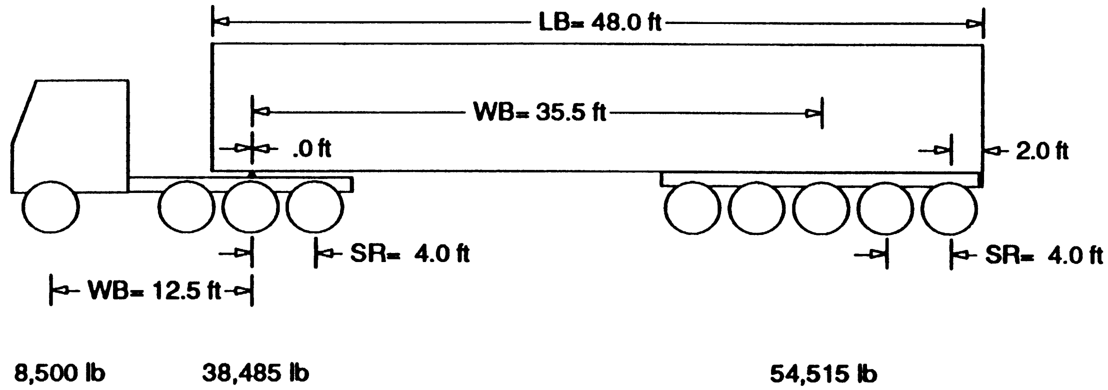

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 63495. lb | 48.0 ft | .0 ft |

Figure 9. Tractor-semitrailer (3-S3; GCW=86,000 lb; payload=53,700 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 15.5 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 33.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 6. | 73390. lb | 48.0 ft | .0 ft |

Figure 10. Tractor-semitrailer (3-S6; GCW=101,890 lb; payload=63,590 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.5 ft | .0 ft | .0 ft | 1. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 35.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 5. | 73500. lb | 48.0 ft | .0 ft |

Figure 11. Tractor-semitrailer (4-S5; GCW=101,500 lb; payload=63,700 lb).

weight cap is shown in figure 12. The load distribution for the same vehicle, but without the restriction of the weight cap, is shown in figure 13. By the removal of the weight cap, the "Western Double" is allowed to carry an additional 8,365 lb (3,794 kg) without any modification to its axle layout. In the case of the TST, however, it was necessary to increase the number of axles to increase the vehicle's GCW.

Tandems instead of single axles help boost the GCW of a double with 28-ft (8.5 m) trailers from 88,500 lb (40,143 kg) to 109,500 lb (49,668 kg). This provides a major increase in payload capability without going to three or more axles in a suspension set. The nine-axle vehicle with its load distribution is shown in figure 14.

Again, exploring the possibilities of extreme designs, the trailer tandems are replaced with tridem-axle sets. Also, the dolly's wheelbase is increased from 8 ft (2.4 m) to 13.5 ft (4.1 m). The resulting eleven-axle vehicle has a gross combination weight of 122,500 lb (55,565 kg) and is displayed in figure 15. A fifth double-trailer design, with an even longer dolly (a 40-ft (12.2 m) dolly shown in figure 16) reaches a GCW of 136,410 lb (61,874 kg). Although a double with a 40-ft (12.2 m) dolly would probably not be built, it illustrates what could happen if size and weight regulations are not thoroughly analyzed.

The vehicle and axle layouts for the nine vehicles developed in this scenario are summarized in table 2. The columns containing payload weight and volume are useful in determining relative productivity levels for the vehicles.

### *What kind of vehicles would be promoted*

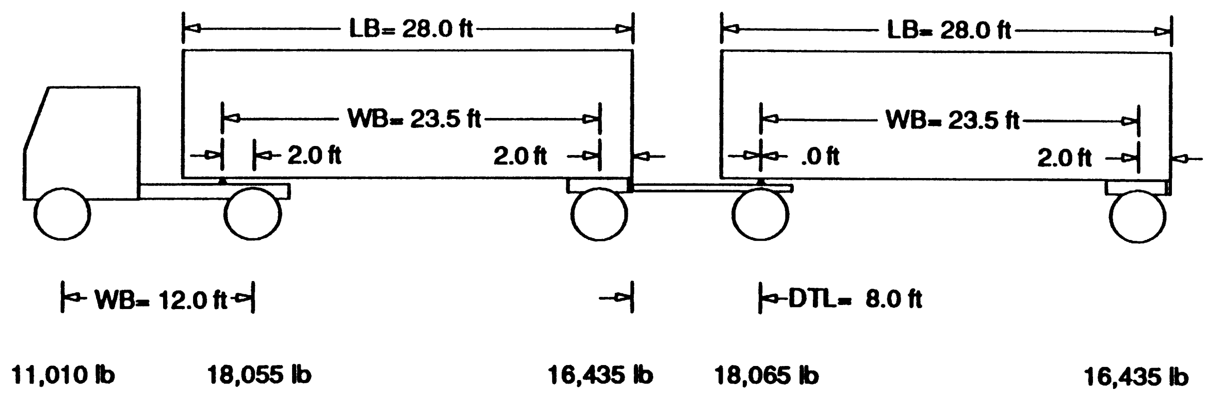
With the STAA in effect restricting the volume available for carrying payload, LTL fleets using TST's would not benefit substantially from removal of the gross weight cap. From the standpoint of productivity (increased volume and, if needed, increased payload weight), LTL fleets would find doubles to be more attractive than TST's.

For liquid- and dry-bulk haulers and operators hauling dense cargo, TST's would still be a viable alternative. The vehicles would have to be modified to have more axles to take advantage of the higher allowable GCW's. In the case of doubles, longer dollies and tandem-axle sets could be used to achieve vehicles with GCW's over 110,000 lb (49,895 kg). In general, doubles would have productivity advantages over TST's.

## Vehicle Performance

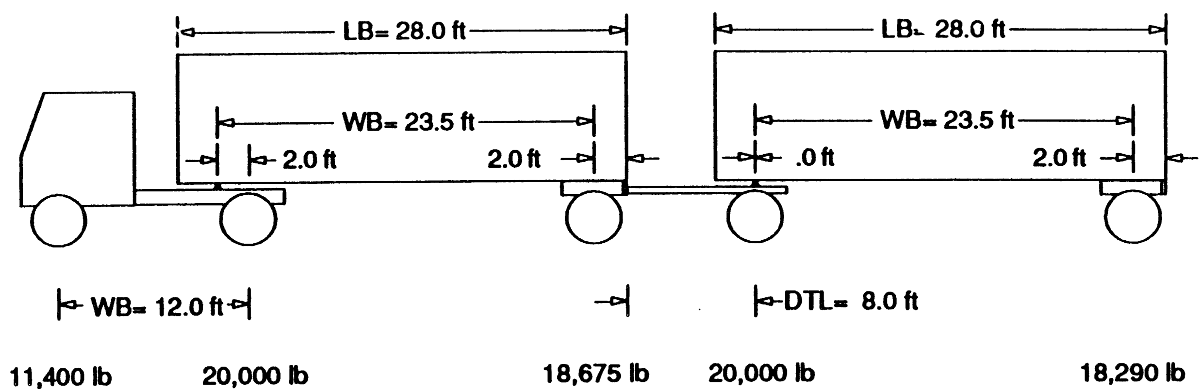
### *Performance summary*

Using the safety related goals and the maneuvering situations discussed in section 2, the performance measures of the nine vehicles developed in this scenario are shown in table 3. Vehicle codes and GCW's are used to differentiate between the various vehicles and axle layouts. In the case of similar vehicle codes, such as the last two double-trailer layouts, the GCW is used to identify the respective designs.



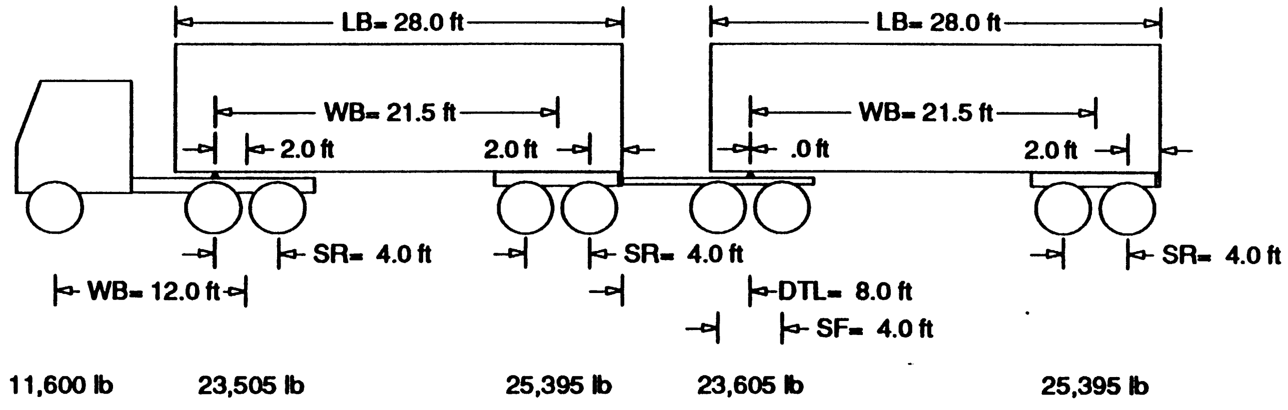

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 29500. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 29500. lb | 28.0 ft | 8.0 ft |

Figure 12. Double (2-S1-2; GCW=80,000 lb; payload=49,500 lb).



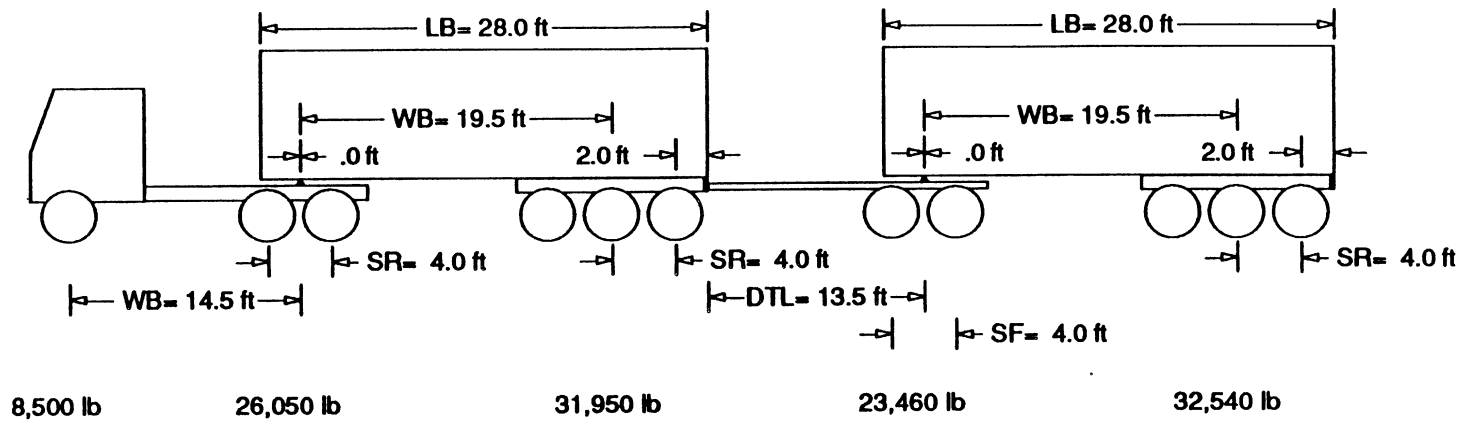

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 34075. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 33290. lb | 28.0 ft | 8.0 ft |

Figure 13. Double (2-S1-2; GCW=88,365 lb; payload=57,865 lb).



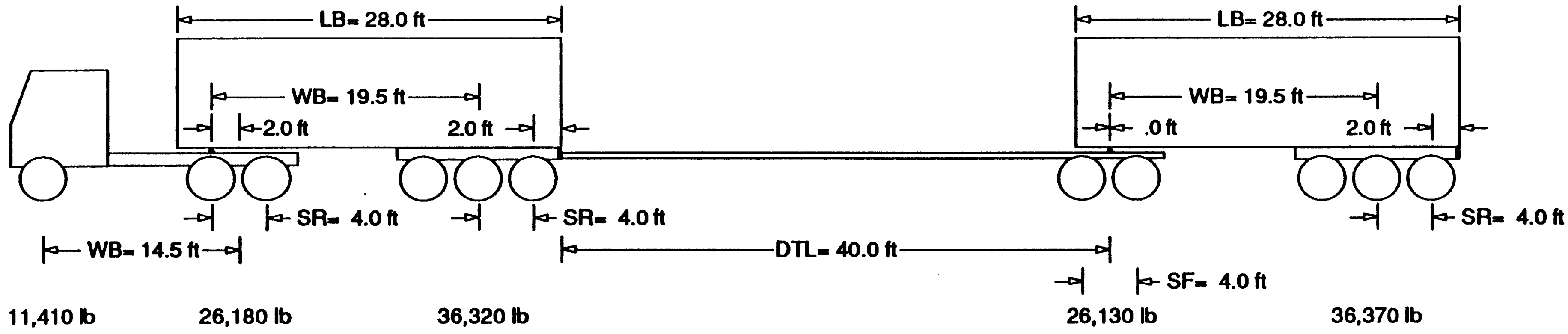

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 40000. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 40000. lb | 28.0 ft | 8.0 ft |

Figure 14. Double (3-S2-4; GCW=109,500 lb; payload=70,500 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 14.5 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 19.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 44000. lb | 28.0 ft | .0 ft |
| full trailer | 19.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 3. | 45000. lb | 28.0 ft | 13.5 ft |

Figure 15. Double (3-S3-5; GCW=122,500 lb; payload=79,500 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 14.5 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 19.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 51410. lb | 28.0 ft | .0 ft |
| full trailer | 19.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 3. | 51500. lb | 28.0 ft | 40.0 ft |

Figure 16. Double (3-S3-5; GCW=136,410 lb; payload=93,410 lb).

Table 2. Summary of example vehicles for scenario 1.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Tractor-semitrailer | 3-S2 | 30,300 lb | 78,405 lb | 48,105 lb | 3,672 | 53.5 ft | 5 |
| Tractor-semitrailer | 3-S3 | 32,300 lb | 86,000 lb | 53,700 lb | 3,672 | 53.5 ft | 6 |
| Tractor-semitrailer | 3-S6 | 38,300 lb | 101,890 lb | 63,590 lb | 3,672 | 57.0 ft | 9 |
| Tractor-semitrailer | 4-S5 | 37,800 lb | 101,500 lb | 63,700 lb | 3,672 | 56.0 ft | 9 |
| Double | 2-S1-2 | 30,500 lb | 80,000 lb | 49,500 lb | 4,284 | 67.0 ft | 5 |
| Double | 2-S1-2 | 30,500 lb | 88,365 lb | 57,865 lb | 4,284 | 67.0 ft | 5 |
| Double | 3-S2-4 | 39,000 lb | 109,500 lb | 70,500 lb | 4,284 | 67.0 ft | 9 |
| Double | 3-S3-5 | 43,000 lb | 122,500 lb | 79,500 lb | 4,284 | 77.0 ft | 11 |
| Double | 3-S3-5 | 43,000 lb | 136,410 lb | 93,410 lb | 4,284 | 101.5 ft | 11 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

Table 3. Summary of performance measures for example vehicles (scenario 1).

| | Tractor-semitrailer | | | | Double | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vehicle Code | 3-S2 | 3-S3 | 3-S6 | 4-S5 | 2-S1-2 | 2-S1-2 | 3-S2-4 | 3-S3-5 | 3-S3-5 |
| Gross Combination Weight (GCW) | 78,405 lb | 86,000 lb | 101,890 lb | 101,500 lb | 80,000 lb | 88,365 lb | 109,500 lb | 122,500 lb | 136,410 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | **17.34** | 16.23 | 13.90 | 14.23 | 14.05 | 14.05 | 12.47 | 12.69 | **22.75*** |
| 2. Friction demand in a tight turn | 0.01 | 0.03* | **0.23*** | 0.12* | 0.00 | 0.00 | 0.02* | 0.06* | 0.07* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.242 | 0.277* | 0.518* | 0.447* | 0.718* | 0.718* | 0.732* | 0.906* | 0.745* |
| 4. Braking efficiency (Loaded) - 0.2 g's | 0.887 | 0.826* | 0.742* | 0.850* | 0.882* | 0.888 | 0.905 | 0.836* | 0.841* |
| - 0.4 g's | 0.843 | 0.784* | **0.699*** | 0.804* | 0.805* | 0.810* | 0.847 | 0.755* | 0.759* |
| 5. Braking efficiency (Empty) - 0.2 g's | **0.672** | **0.638*** | **0.666*** | 0.707 | **0.615*** | **0.615*** | **0.684** | **0.687** | **0.687** |
| - 0.4 g's | **0.645** | **0.613*** | **0.641*** | **0.682** | **0.568*** | **0.568*** | **0.642*** | **0.645** | **0.645** |
| 6. Rollover threshold (g's) | **0.375** | 0.380 | 0.409 | 0.433 | 0.382 | **0.365*** | 0.419 | 0.440 | 0.414 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | None | None | **54.34*** | **31.18*** | None | None | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | **0.065** | 0.119 | 0.147 | 0.107 | **< 0** | **< 0** | 0.118 | 0.105 | **0.047*** |
| 8. Maximum rearward amplification | - | - | - | - | **1.445*** | **1.484*** | **1.601*** | **1.851*** | **1.858*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2. The 3-S2 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 and poor.

The performance of the "baseline" three-axle tractor and tandem-axle semitrailer (3-S2), shown in figure 8, is used as the basis for comparing the vehicles developed in this and other scenarios. Entries with asterisks indicate performance measures that are worse than the 3-S2. A bold face type is used to identify performance characteristics that are judged to be poor relative to current technology. The performance of the 3-S2 and acceptable levels of safety (relative to current technology) are used as references for comparing the different vehicle designs.

Graphical representations of table 3 are displayed in figures 17 through 24. Each figure illustrates a particular row of table 3 and shows the performance of the various vehicles in a specific maneuver. The figures are useful in comparing the vehicles' performances relative to the two reference levels of performance.

### *Safety and operational concerns*

Low-Speed Offtracking: At low speed the rear end of the vehicle offtracks well towards the inside of the turn. Shorter distances, by having more articulation joints and shorter wheelbases, help reduce the amount of offtracking. Figure 17 displays the measure of the vehicle's offtracking ability, or the distance (in feet) by which the last axle of the vehicle is offset from the front axle in a 90-deg intersection turn. Clearly, doubles (except the vehicle with the 40-ft (12.2 m) dolly) are better than TST's with respect to maneuverability around tight corners. The results in figure 17 also illustrate the improvement in offtracking by the addition of axles to suspension sets. In this scenario, though the semitrailers in the TST configurations are of similar length, the six-axle semitrailer (figure 10) offtracks by an amount 4 ft (1.2 m) less than that of the tandem-axle semitrailer (figure 8). This is because the addition of an axle reduces the effective wheelbase (measured between the articulation joint and the suspension center) of the unit, thereby, reducing the amount of offtracking.

Friction Demand: The information in the second row of table 3 and in figure 18 shows the disadvantages of multiple-axle arrangements. The tires on units with multiaxle suspensions produce a turn-resisting moment when the vehicle attempts to make a tight in-town turn. In order to "scrub" these tires around the corner, there must be enough tire/road friction for the tractor's drive wheels to generate the necessary force to overcome the turn-resisting moment. The friction demand increases as (i) the spread and number of axles increases, (ii) the wheelbase of the semitrailer decreases, and (iii) the vertical load on the drive axles decreases. As indicated in figure 18, none of the doubles require high levels of friction during tight-turning maneuvers. This is because they have no more than three axles on any of their semitrailers. In the case of the TST with five axles on its semitrailer (figure 11), the tractor's tridem suspension helps generate the necessary lateral and longitudinal forces to overcome the turn-resisting moment of the five-axle suspension. However, the TST, with six axles on its semitrailer (figure 10), would have trouble negotiating corners on icy and snow-covered surfaces.

High-Speed Offtracking: The results in figure 19 pertain to the offtracking towards the outside of a 1,200-ft (365.8-m) turn traversed at 55 mi/h (89 km/h). The results for all these vehicles indicate that the rear ends of these vehicles will not be more than 1 ft

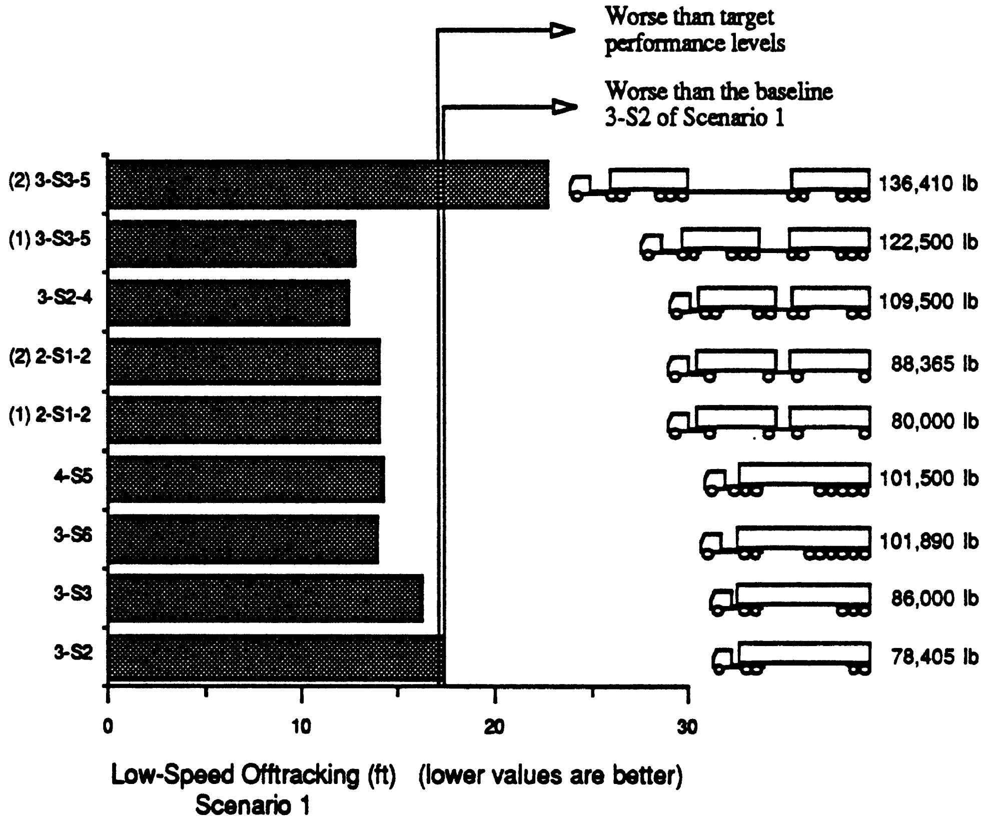



Figure 17. Low-speed offtracking, scenario 1.

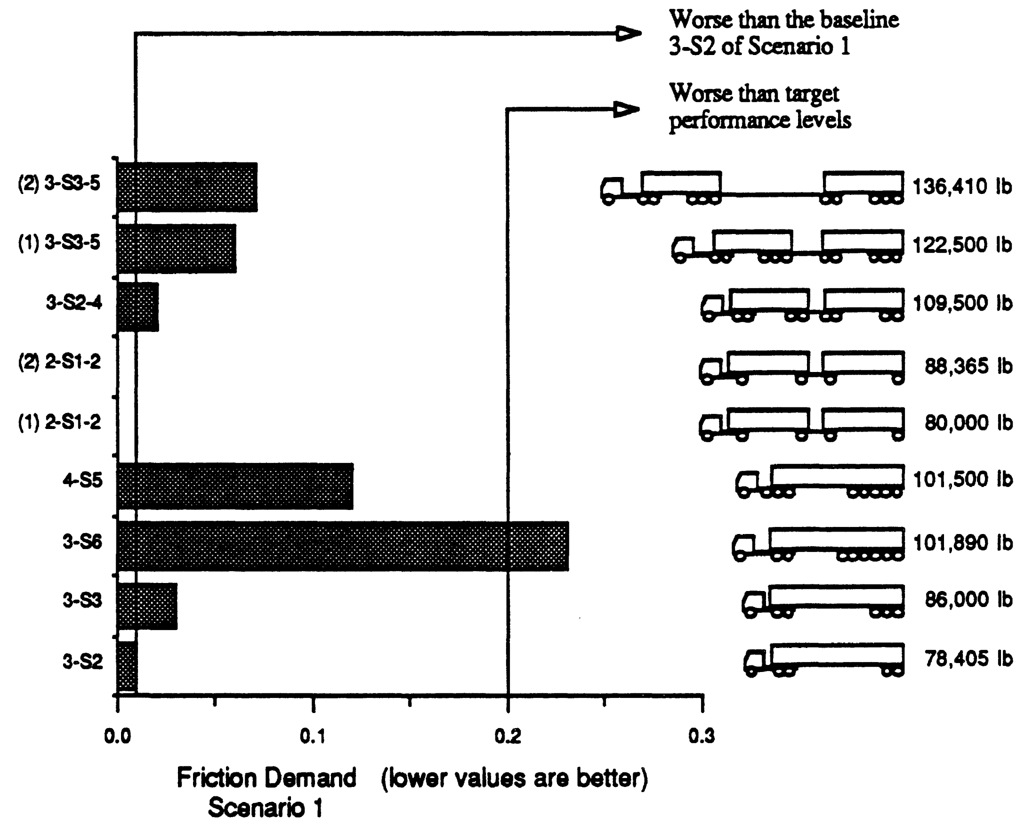



Figure 18. Friction demand, scenario 1.

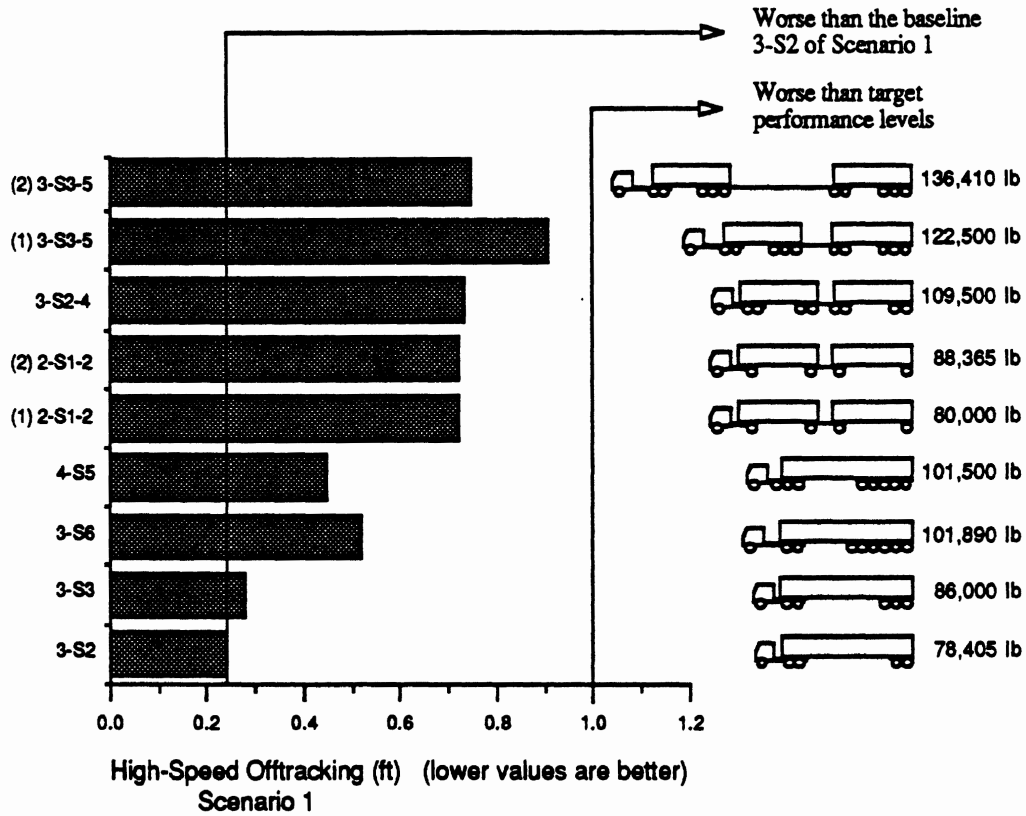



Figure 19. High-speed offtracking, scenario 1.

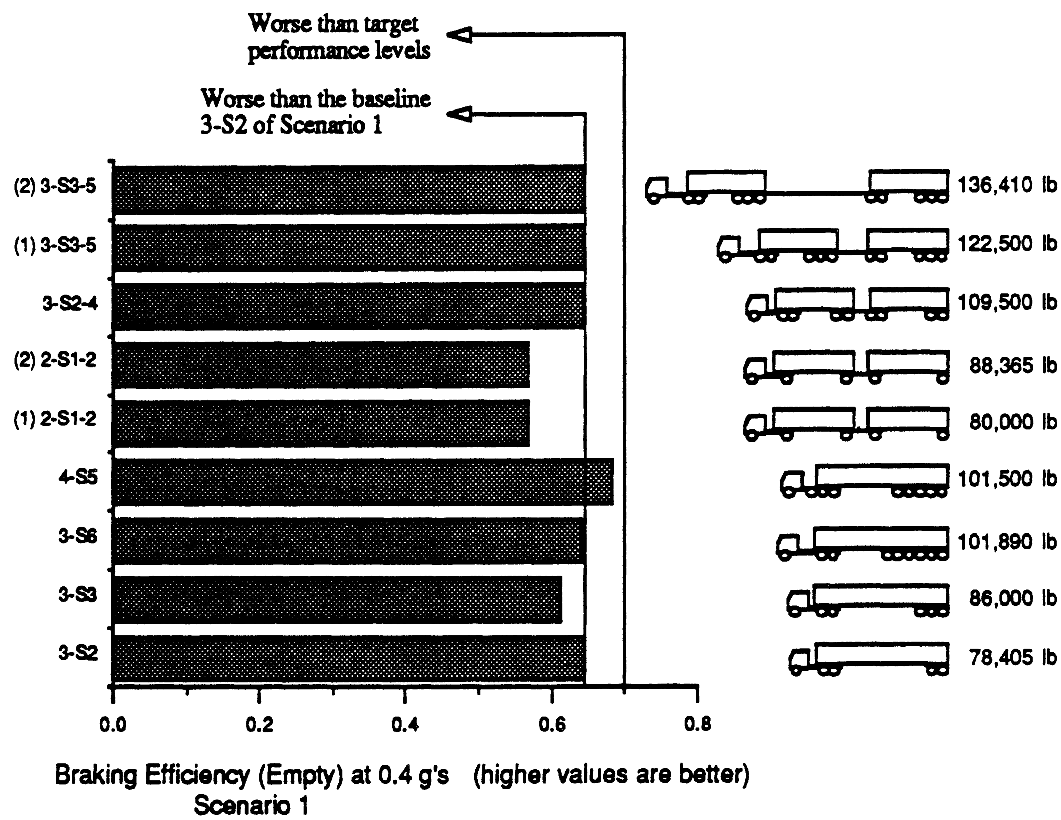



Figure 20. Braking efficiency, scenario 1.

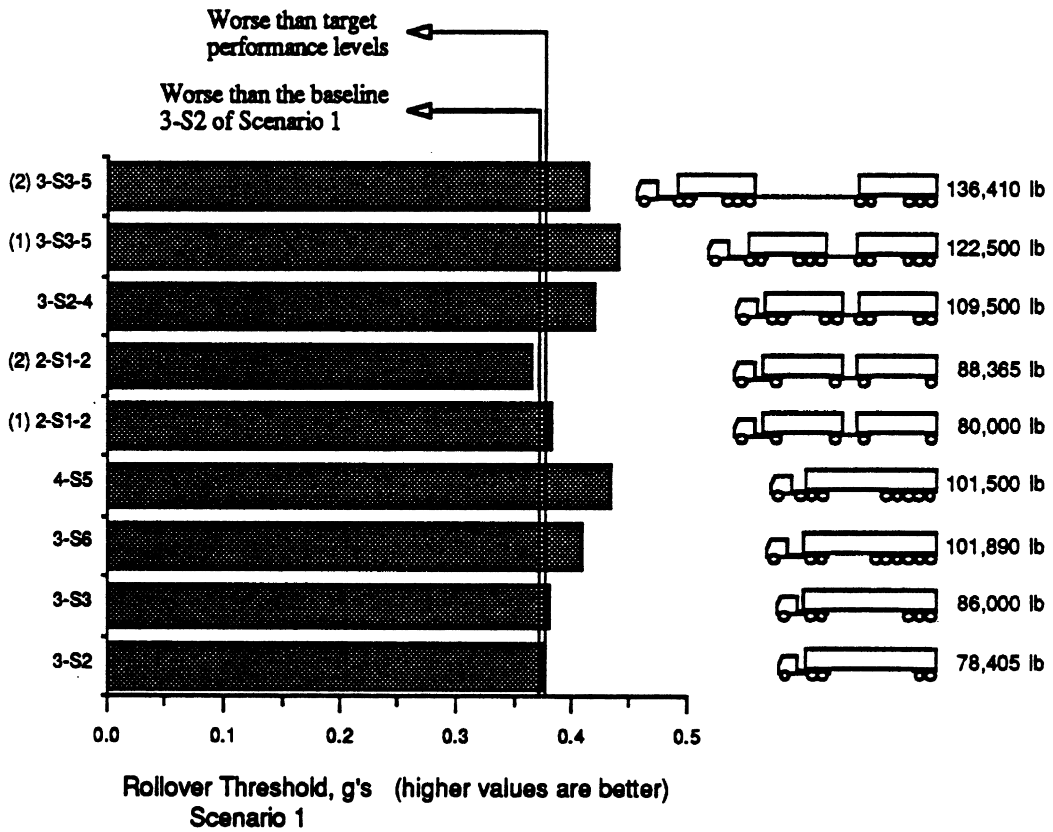



Figure 21. Rollover threshold, scenario 1.

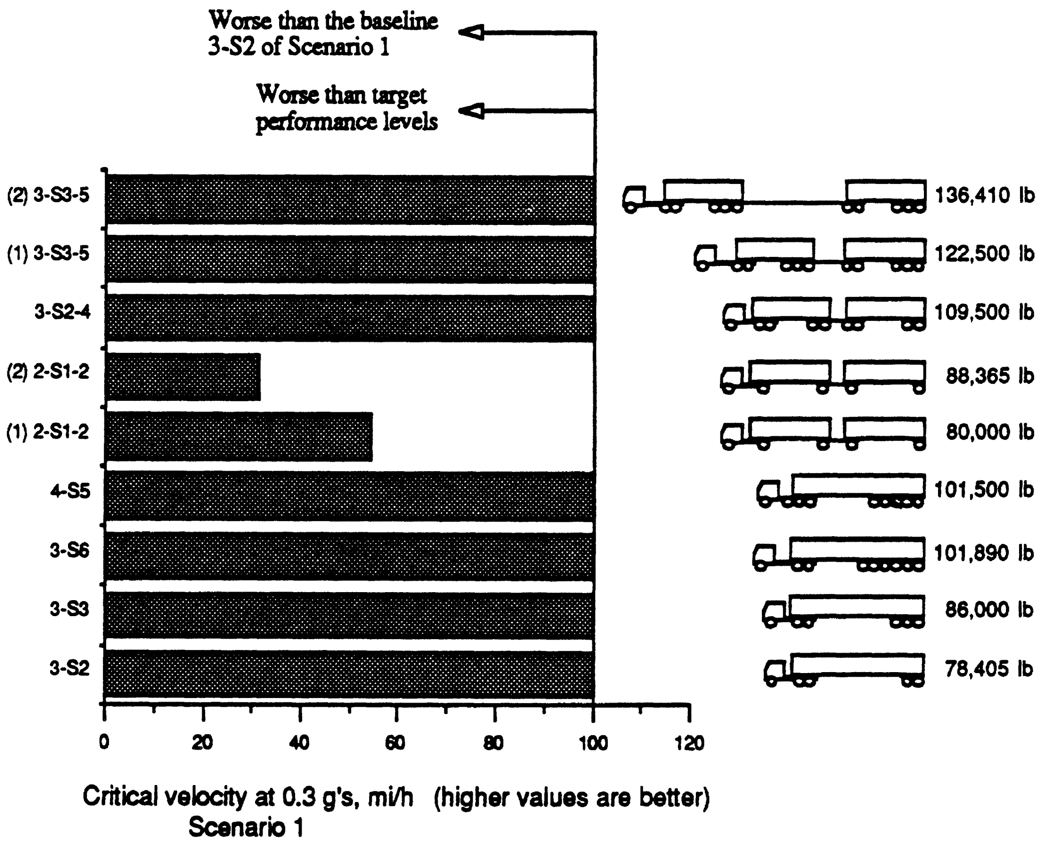



Figure 22. Critical velocity, scenario 1.

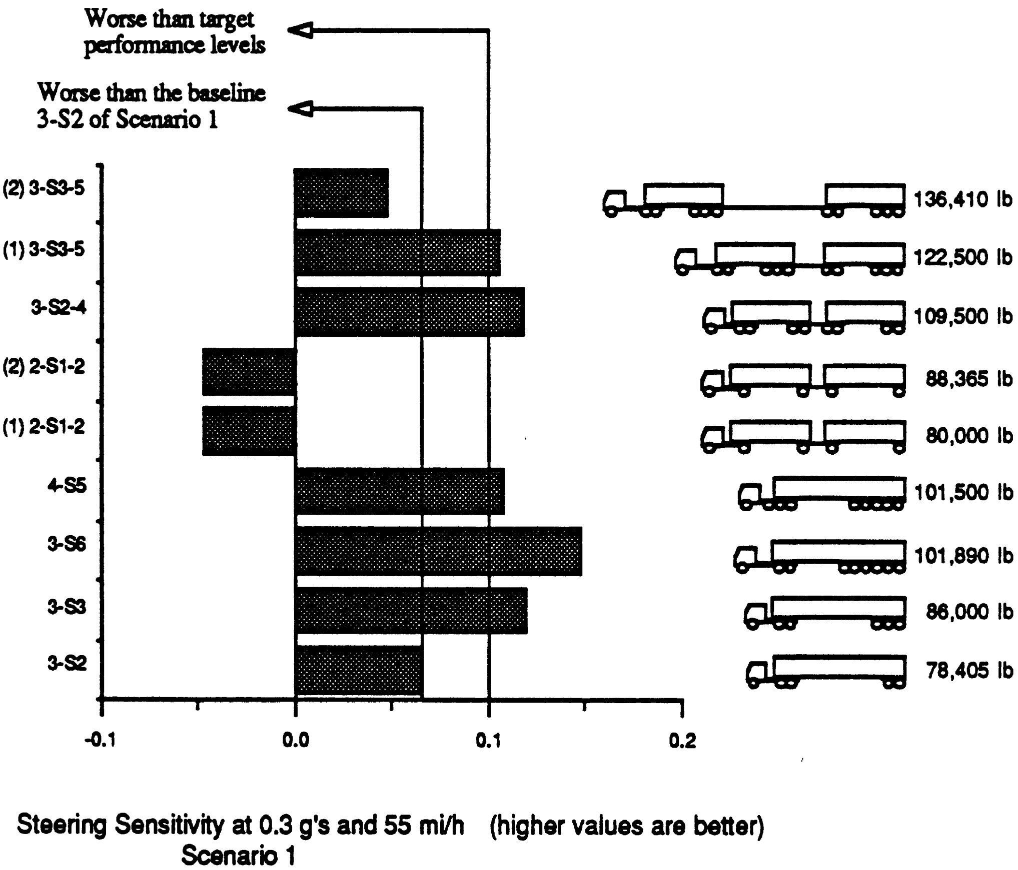



Figure 23. Steering sensitivity, scenario 1.

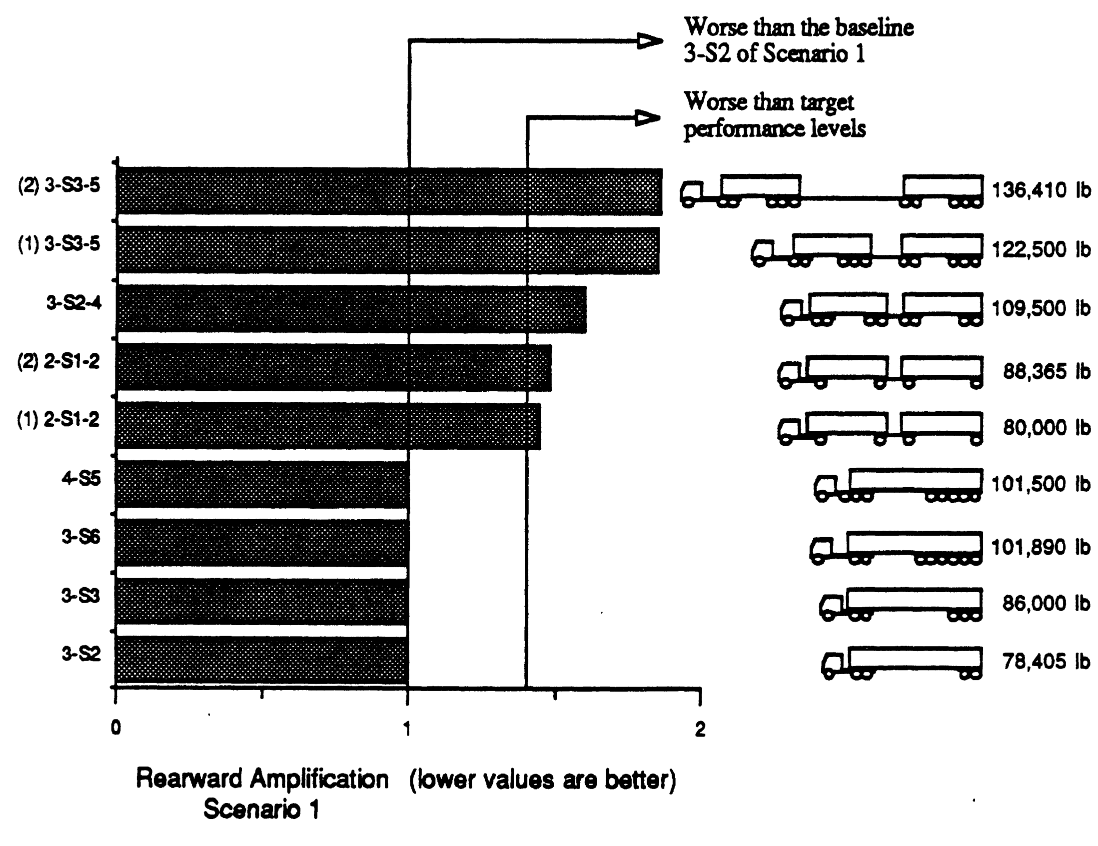



Figure 24. Rearward amplification, scenario 1.

(0.3 m) outside of the path of the front axle. The offtracking results for all nine vehicles are considered acceptable relative to current technology.

Constant Deceleration Braking: The braking efficiency of a vehicle is the ratio of its deceleration to the level of the tire/road friction required to prevent wheel lockup. Braking results for the nine vehicles are presented in the fourth and fifth items of table 3. In contrast to the situation when the vehicle is loaded, the braking efficiencies of all nine vehicles are quite low when they are empty. This problem is largely due to the fact that brakes on heavy vehicles in the U.S. are proportioned to be efficient when the vehicles are fully loaded. Since the empty vehicles perform so poorly in this maneuver, especially at 0.4 g's, figure 20 contains the braking efficiencies for the nine vehicles in such a situation. The tridem-axle semitrailer (figure 9) and the "Western Doubles" (figures 12 and 13) have braking efficiencies that are both poor and less than that of the "baseline" TST (table 3). In the case of the "Western Double," short wheelbases increase the amount of "rear-to-front" load transfer, thereby, lightening the trailers' axles. Moreover, the single-axle suspensions do not generate a large enough share of the total braking force before the wheels on the trailer axles begin to lock-up. The combined effects of these two events degrade the vehicle's braking efficiency. In the case of the tridem semitrailer, the brakes on the three-axle suspension generate too much braking force on the lightly loaded end of the semitrailer. This results in the trailer's rear axles locking-up before the vehicle has achieved a sufficient level of deceleration. The loaded 3-S6 has a similar problem — the extra axles on the semitrailer tend to make the vehicle slightly "overbraked" in this maneuver. In other words, the brakes are too effective compared to the light loads carried on those axles. Anti-lock braking systems or load-proportioning mechanisms could alleviate some of the problems of "overbraked" axles. Unlike the other vehicles with multiaxle suspensions, the braking efficiency of the empty 4-S5 (figure 11) is slightly better than that of the "baseline" TST. In this case, the tractor's rear tridem suspension generates much of the braking force on heavily loaded axles (due to the forward-pitching motion of the trailer) to maintain a relatively high level of efficiency.

Steady Turn—Rollover: The rollover thresholds for the nine vehicles are given in the sixth item of table 3 and are shown in figure 21. As indicated in the previous discussion on braking, extra axles tend to lower the braking performance of projected vehicles. In the rollover situation, however, extra axles result in vehicles with rollover thresholds better than those of current designs. This is due to the higher ratio of total roll stiffness to total weight. For example, the "Western Double" with the GCW of 88,365 lb (40,082 kg) is the only vehicle in this scenario that has a rollover threshold lower than that of the "baseline" TST. The vehicle was designed without the restriction of the weight cap and carries an additional 8,365 lb (3,794 kg) on its axles. The lower roll stiffness per pound of axle load results in a lower rollover threshold for the vehicle. Other mechanical properties that influence the rollover threshold of the vehicle are the c.g. height of the payload and the track width of the axles. Though these variables were fixed in these analyses, their effects should be considered at the design stage to improve the rollover immunity of projected vehicles.

Steady Turn—Handling: Two measures of vehicle handling are presented in the seventh item of table 3. The critical speed (table 3, 7.a. and figure 22) is the velocity at which an instability would occur, given that the lateral acceleration of the steady turn is 0.3 g's. The steering sensitivity (table 3, 7.b. and figure 23) provides a stability margin for the vehicle where negative values represent the range of unstable operation. Both "Western Double" configurations have critical velocities that are well within the current operating conditions. While the current 2-S1-2 is unstable at speeds over 54 mi/h (87 km/h), the more heavily loaded vehicle is unstable above 31 mi/h (50 km/h). Since both vehicles would be unstable at 55 mi/h (89 km/h), their steering sensitivities are negative. Otherwise, the remaining vehicles are fairly well behaved.

Obstacle Evasion: The last safety-related maneuver involves a rapid steering reversal. In this maneuver, the rear trailer of a double experiences a more severe lateral motion than that of the tractor. The ratio of the lateral acceleration of the last trailer to that of the tractor is referred to as the "rearward amplification" for the vehicle. The results of such a maneuver are presented in the eighth item of table 3. The results in figure 24 show that the amount of amplification increases as the vehicles get heavier. This is due to two effects — short wheelbases on trailers and a higher ratio of payload to the number of tires cause greater amounts of rearward amplification. In the case of the two 3-S3-5 configurations, heavy loads and shorter wheelbases on the trailers cause noticeably more amplification than the lighter 2-S1-2 configurations. In this situation, advanced countermeasures, such as, innovative hitching mechanisms, can be applied to improve the evasive maneuvering capabilities of projected vehicles.

# 5. SCENARIO 2 — NO WEIGHT CAP, FORMULA C, STAA LENGTHS

## Vehicle Design

*Definition of the constraints on vehicle design*

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | C |
| Length constraints: | STAA vehicles |
| Pavement loading restrictions: | 36,000 lb (16,329 kg) for tandems;<br>22,000 lb (9,979 kg) for singles. |

*Implications with respect to vehicle design*

Due to their similarities, the influence on vehicle design by formula C is very similar to the effects of formula B. As mentioned earlier, the main difference between the two bridge formulas is that formula C allows an additional 2,000 lb (907 kg) on any given axle set. In most vehicle configurations, the most limiting axle set is the overall axle group. That is, an application of the bridge formula on the overall axle set, determined by the first axle on the tractor and the rearmost axle on the vehicle, frequently decides the total allowable weight of the vehicle. Consequently, vehicles operating under formula C would be 2,000 lb (907 kg) heavier than the same vehicle under formula B.

Analogous to formula B, there is still the tendency under formula C to add axles to gain weight allowances with or without increasing length. Though the "36/22" pavement rule is a more lenient restriction (compared with the "34/20" restriction), the vehicle's axle loads are also governed by formula C which, like formula B, has a decreasing weight return for additional axles. With respect to pavement loads, formula C is more restrictive than the associated "36/22" loading rule. In the case of vehicles with biased load distributions, however, the pavement rule helps gain weight allowances by allowing single- and tandem-axle sets to carry slightly heavier loads. For example, the "baseline" tractor-semitrailer in scenario 1 (figure 8), was limited to 78,405 lb (35,564 kg) by the 34,000-lb (15,422-kg) suspension load on its semitrailer. Also, the single axles of the "Western Double" in figure 13 were limited to 20,000 lb (9,072 kg) by the "34/20" pavement rule. Though both vehicles were allowed higher GCW's under the bridge formula, the "34/20" pavement rule was more restrictive and the vehicles were forced to carry lighter payloads. Under the "36/20" rule, the same vehicles would be allowed to carry 36,000 lb (16,329 kg) and 22,000 lb (9,979 kg) on tandems and single axles, respectively. This would help the vehicle meet the weight limit set by the bridge formula. Consequently, with less of a constraint on axle loads, vehicles with biased load distributions could be <u>more</u> than 2,000 lb (907 kg) heavier than the same vehicles under formula B and the "34/20" rule.

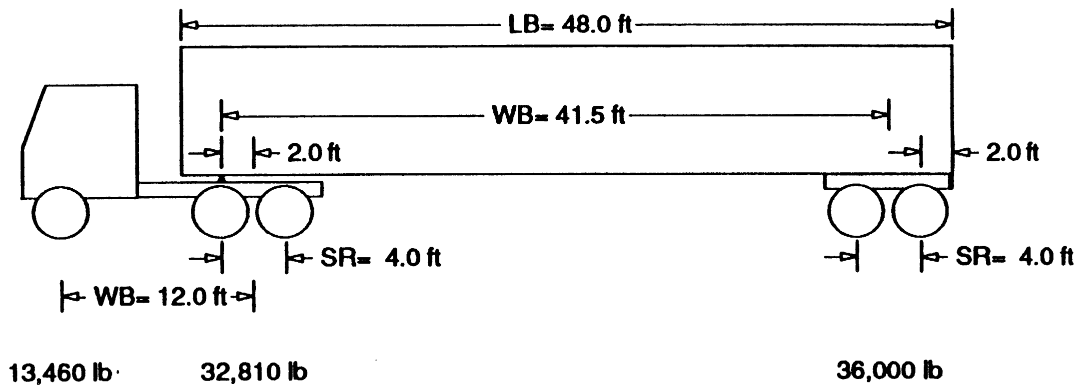
The remaining constraints, that is, the length and weight constraints, in this scenario are identical to those discussed in the previous chapter. Vehicle configurations are limited to TST's and doubles, and trailer dimensions are restricted by the STAA. Also, the vehicles are allowed to operate without a predefined restriction on their gross combination weights. With the bridge formula and the length restriction being the dominant forces in this scenario, the combined effects of the four constraints lead to longer dollies on doubles and more axles on both TST's and doubles.

*Example vehicles*

<u>Tractor-Semitrailers:</u> Since the vehicles in scenario 1 would be similar to those in this scenario, they are used as initial choices in the development process. As mentioned earlier, the three-axle tractor and tandem-axle semitrailer in figure 8 would be much more productive under formula C and the "36/22" pavement rule. The load distribution for this vehicle under the new set of constraints is shown in figure 25. The less restrictive pavement rule helps the vehicle gain an additional 3,865 lb (1,753 kg) of allowable weight. Though the bridge formula allows a GCW higher than 82,270 lb (37,317 kg) attained by the vehicle, the pavement rule remains a dominant constraint. A forward-biased loading of the semitrailer would assist in meeting the pavement constraint.

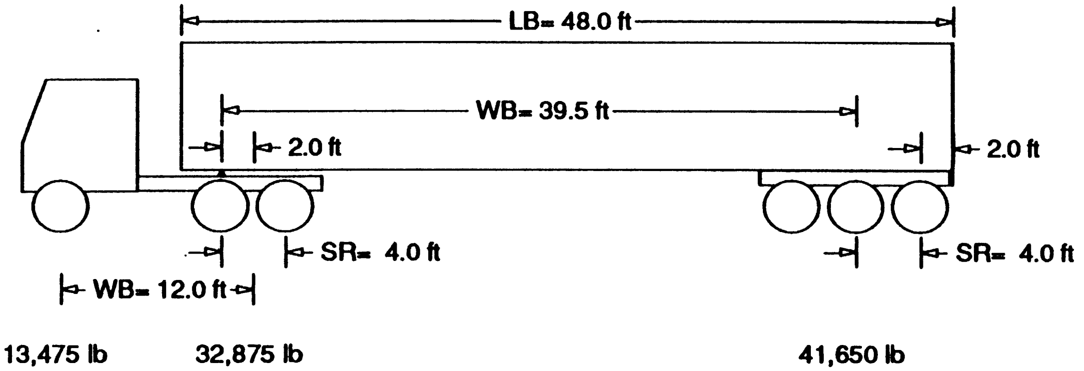
Since the bridge formula is the more dominant constraint (instead of the pavement rule) in the case of the three-axle tractor and tridem-axle semitrailer (figure 9), the vehicle is only 2,000 lb (907 kg) heavier in this scenario. The axle layout and load distribution for the vehicle is shown in figure 26. Similarly, the remaining TST's developed in scenario 1 (figures 10 and 11) would be 2,000 lb (907 kg) heavier under this set of constraints.

<u>Doubles:</u> The "Western Double" of figure 13 is another situation where the advantages of the "36/22" rule are apparent. The "Western Double" (figure 27) in this scenario is



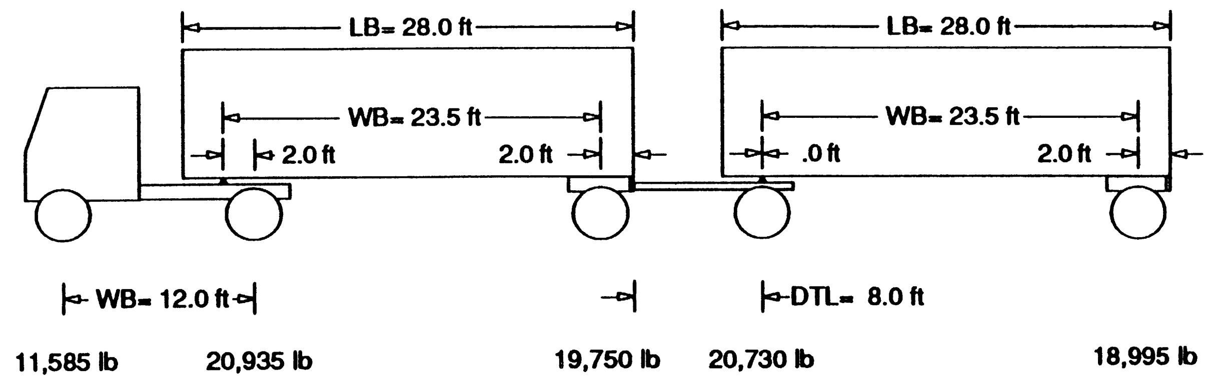

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 41.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 61770. lb | 48.0 ft | .0 ft |

Figure 25. Tractor-semitrailer (3-S2; GCW=82,270 lb; payload=51,970 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 65500. lb | 48.0 ft | .0 ft |

Figure 26. Tractor-semitrailer (3-S3; GCW=88,000 lb; payload=55,700 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 36270. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 34725. lb | 28.0 ft | 8.0 ft |

Figure 27. Double (2-S1-2; GCW=91,995 lb; payload=61,495 lb).

3,630 lb (1,647 kg) heavier than its counterpart in scenario 1. In this case, the bridge formula takes over as the dominant constraint and forces lighter axle loads than does the pavement rule.

The bridge formula is the more dominant constraint in the case of the tandem-axle double (figure 14) and only allows an extra 2,000 lb (907 kg) of total vehicle weight. The load distribution for the 111,500-lb (50,576 kg) vehicle is shown in figure 28. Since formula C is the dominant constraint, the remaining doubles developed in scenario 1 (figures 15 and 16) would be only 2,000 lb (907 kg) heavier under this set of constraints. The vehicle and axle layouts for the four vehicles developed in this scenario are summarized in table 4.

### *What kind of vehicles would be promoted*

As in scenario 1, LTL fleets do not stand to gain much from the constraints in this scenario. Besides encouraging the use of doubles to increase their volume capacity, the 2,000 lb (907 kg) weight allowance and removal of the weight cap might not affect LTL operators significantly.

For bulk haulers, however, the extra 2,000 lb (907 kg) provides an immediate reward of additional payload-carrying capacity. Though vehicle and axle layouts would be similar to the configurations in scenario 1, their GCW's would be higher by at least 2,000 lb (907 kg).

## Vehicle Performance

### *Performance summary*

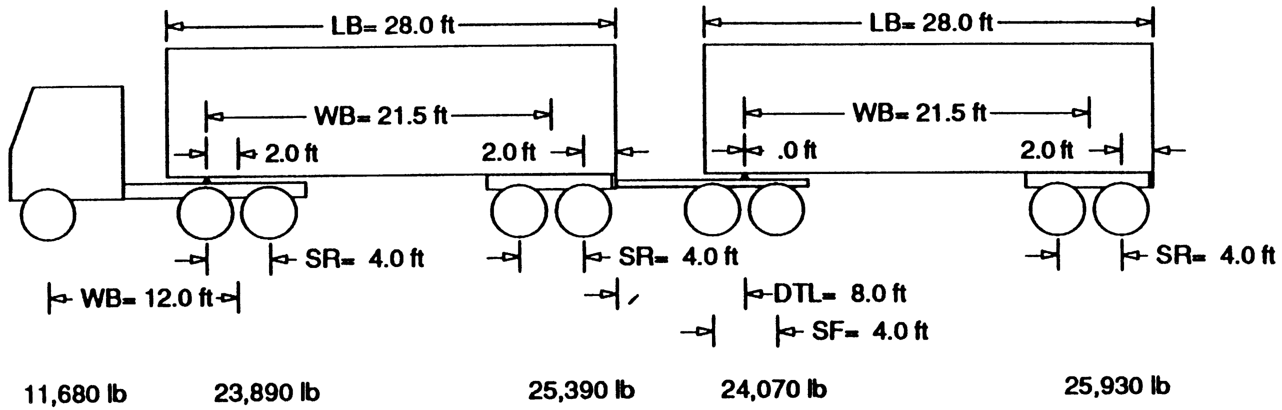
The performance measures of the four vehicles developed in this scenario are shown in table 5. The graphical representations of the tabulated results are shown in figures 29 through 36.

### *Safety and operational concerns*

Low-Speed Offtracking: Figure 29 displays the offtracking abilities of the four vehicles. Since the vehicles' axle layouts are the same in scenarios 1 and 2, their offtracking performance in low-speed turns is similar. The double-trailer configurations, with their short wheelbases and multiarticulated layouts, are clearly superior in their in-town maneuverability.

Friction Demand: The amount of friction required during tight turning is shown in figure 30. With no more than three axles in any suspension, the vehicles require lower levels of friction during tight-turns.

High-Speed Offtracking: The high-speed offtracking results for the vehicles are shown in figure 31. The figure indicates that the rear ends of these vehicles will not be more than




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 41000. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 41000. lb | 28.0 ft | 8.0 ft |

Figure 28. Double (3-S2-4; GCW=111,500 lb; payload=72,500 lb).

Table 4. Summary of example vehicles for scenario 2.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Tractor-semitrailer | 3-S2 | 30,300 lb | 82,270 lb | 51,970 lb | 3,672 | 53.5 ft | 5 |
| Tractor-semitrailer | 3-S3 | 32,300 lb | 88,000 lb | 55,700 lb | 3,672 | 53.5 ft | 6 |
| Double | 2-S1-2 | 30,500 lb | 91,995 lb | 61,495 lb | 4,284 | 67.0 ft | 5 |
| Double | 3-S2-4 | 39,000 lb | 111,500 lb | 72,500 lb | 4,284 | 67.0 ft | 9 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

Table 5. Summary of performance measures for example vehicles (scenario 2).

| | Tractor-semitrailer | | Double | |
|---|---|---|---|---|
| Vehicle Code | 3-S2 | 3-S3 | 2-S1-2 | 3-S3-5 |
| Gross Combination Weight (GCW) | 82,270 lb | 88,000 lb | 91,995 lb | 111,500 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | **17.34** | 16.23 | 14.05 | 12.47 |
| 2. Friction demand in a tight turn | 0.01 | 0.03* | 0.00 | 0.02* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.261* | 0.281* | 0.799* | 0.734* |
| 4. Braking efficiency (Loaded) - 0.2 g's | 0.887* | 0.853* | 0.885* | 0.904 |
| - 0.4 g's | 0.843 | 0.813* | 0.807* | 0.849 |
| 5. Braking efficiency (Empty) - 0.2 g's | **0.672** | **0.638*** | **0.615*** | **0.684** |
| - 0.4 g's | **0.645** | **0.613*** | **0.568*** | **0.642*** |
| 6. Rollover threshold (g's) | **0.370*** | **0.377** | **0.358*** | 0.417 |
| 7.a. Critical speed at 0.3 g's (mi/h) | **84.61*** | None | **24.72*** | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | **0.036*** | 0.114 | **< 0** | 0.117 |
| 8. Maximum rearward amplification | - | - | **1.504*** | **1.561*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

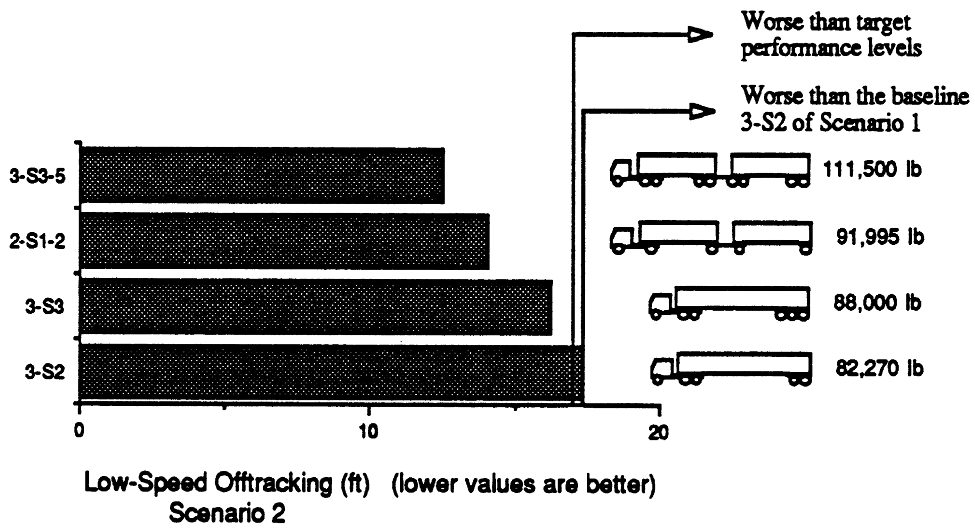



Figure 29. Low-speed offtracking, scenario 2.

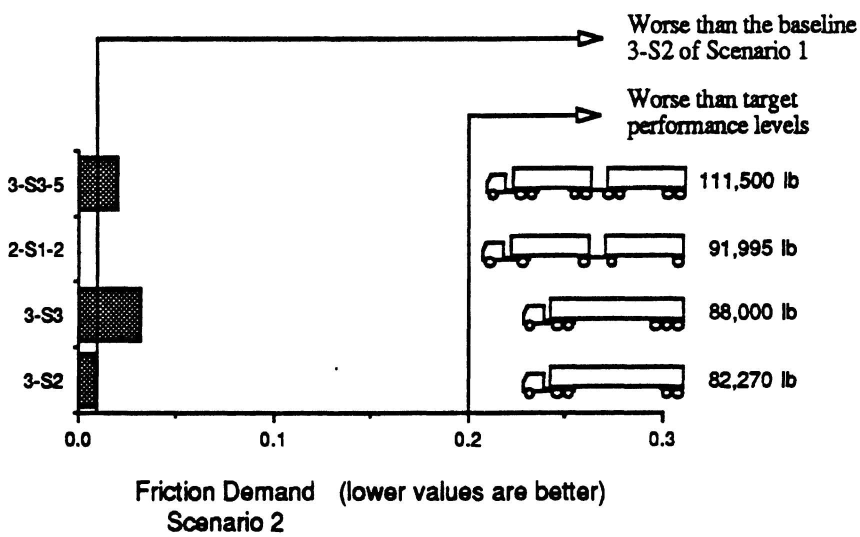



Figure 30. Friction demand, scenario 2.

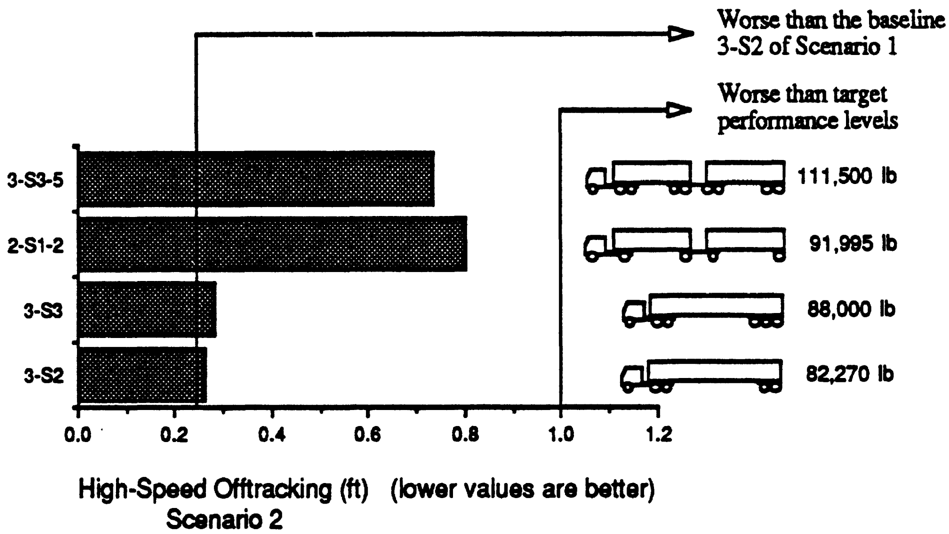



Figure 31. High-speed offtracking, scenario 2.

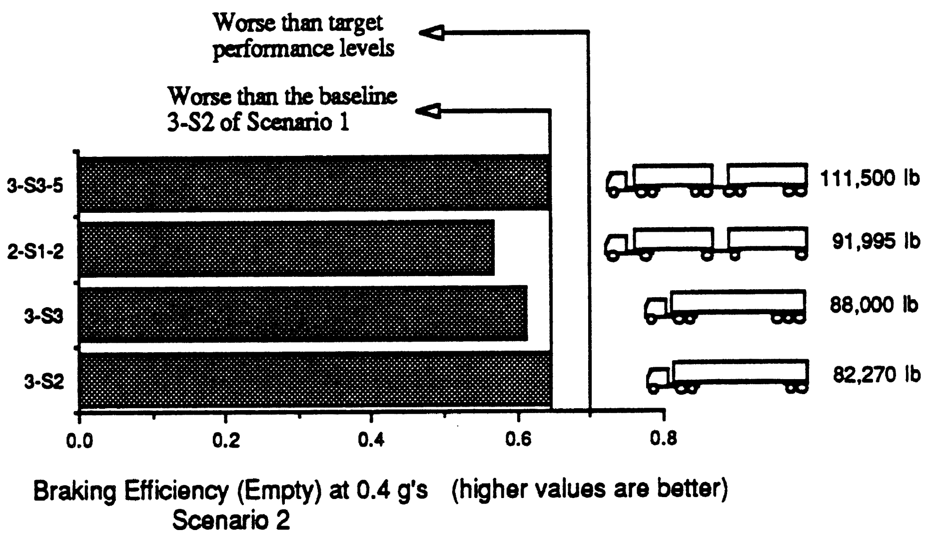



Figure 32. Braking efficiency, scenario 2.

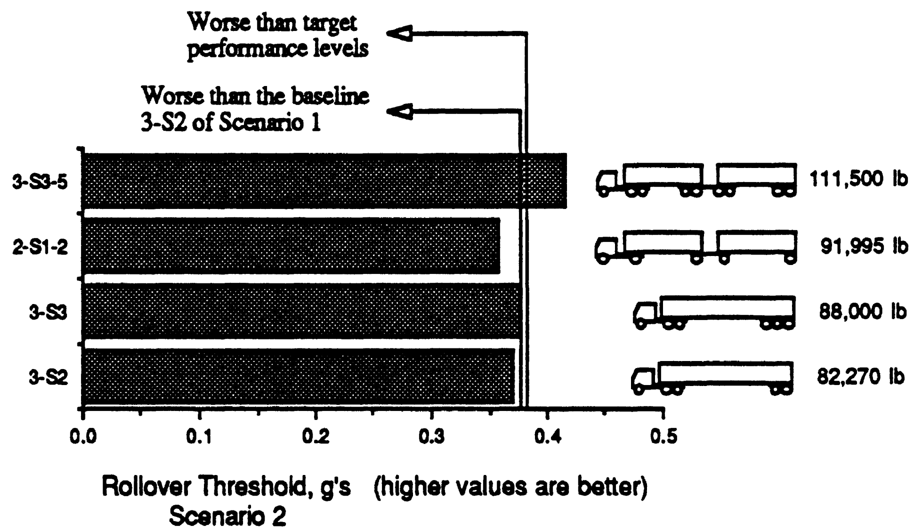



Figure 33. Rollover threshold, scenario 2.

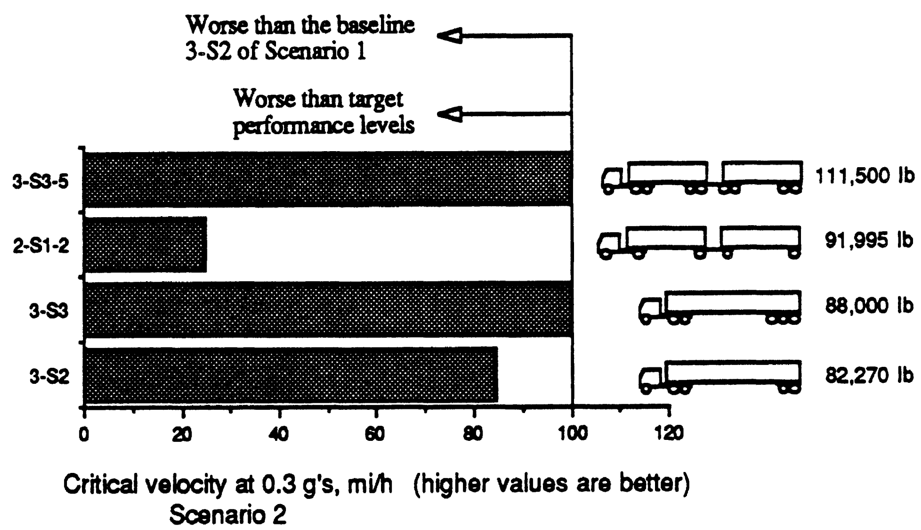



Figure 34. Critical velocity, scenario 2.

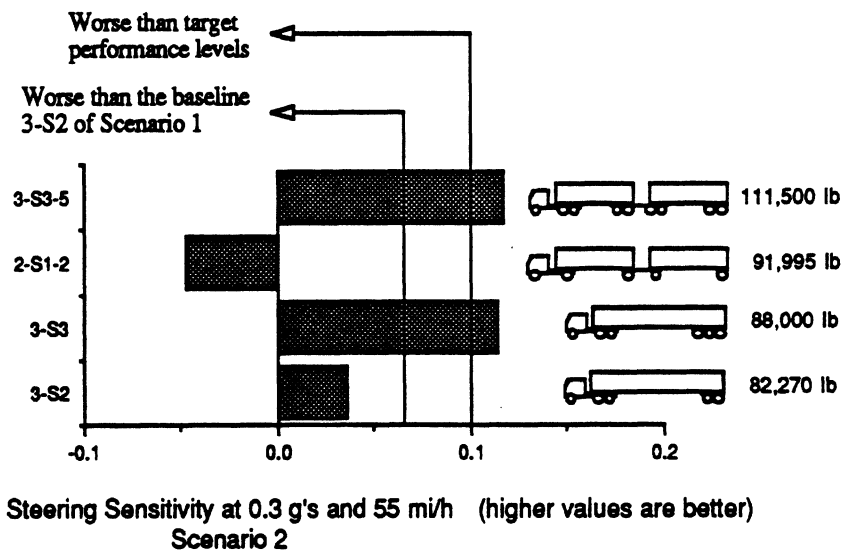



Figure 35. Steering sensitivity, scenario 2.

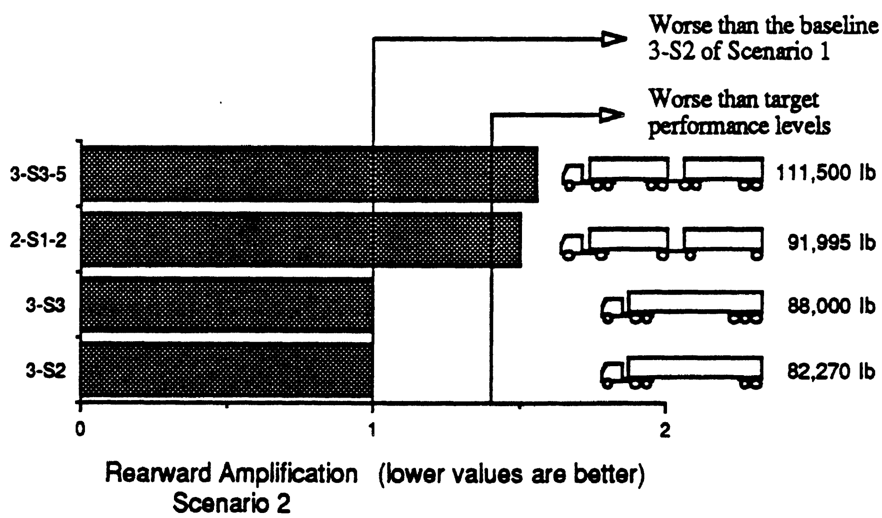



Figure 36. Rearward amplification, scenario 2.

0.8 ft (0.24 m) from the path of the front axle. Comparing scenarios 1 and 2, heavier axle loads in this scenario degrade the vehicles' high-speed offtracking performance slightly.

Constant Deceleration Braking: The braking efficiencies for the loaded and empty vehicles are listed in table 5. The heavier axle loads make a marginal improvement in the braking efficiencies of the loaded vehicles. Since the vehicle layouts are similar in scenarios 1 and 2, the braking efficiencies of the empty vehicles are identical. For this scenario, the vehicles' braking efficiencies at 0.4 g's are plotted in figure 32.

Steady Turn—Rollover: The results in figure 33 pertain to the rollover thresholds for the four vehicles. Compared with the corresponding vehicles in scenario 1, the vehicles in this scenario have lower levels of rollover threshold. For example, the "Western Double" (figure 26) and the five-axle TST (figure 25) have rollover thresholds less than 0.37 g's, which might be considered unacceptable in certain circumstances. Though the other two vehicles (figures 26 and 28) have rollover thresholds greater than 0.37 g's, their rollover immunity is poorer than the corresponding layouts in the previous scenario. The lower thresholds are due to the same proportion of roll stiffness resisting a higher amount of payload. In other words, the higher allowable GCW's result in a lower roll stiffness per pound of axle load.

Steady Turn—Handling: The critical speeds and the steering sensitivities for the four vehicles are shown in figures 34 and 35. The effect of the heavier load is evident in the case of the "Western Double," where the vehicle's critical speed is 25 mi/h (40 km/h). Even the three-axle tractor and tandem-axle semitrailer would be unstable at speeds higher than 85 mi/h (137 km/h). The steering sensitivities for the two vehicles (figure 35) indicate the relatively limited margin of safety in the steady turning maneuver.

Obstacle Evasion: Figure 36 displays the levels of rearward amplification that the vehicles experience under rapid steering reversals. In this scenario, a higher ratio of payload to the number of tires cause greater amounts of rearward amplification. Consequently, the heavier loads play a significant role in degrading the vehicles' evasive maneuvering capabilities.

# 6. SCENARIO 3 — NO WEIGHT CAP, FORMULA TTI, STAA LENGTHS

## Vehicle Design

*Definition of the constraints on vehicle design*

The constraints governing this scenario are

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | TTI |
| Length constraints: | STAA vehicles |

| | |
|---|---|
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

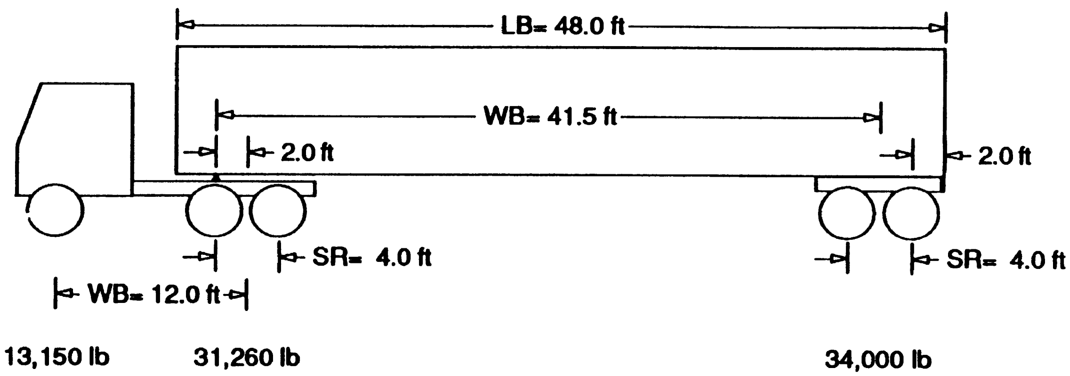
Formula TTI is a linear equation relating pavement loads to the distance between axle locations. The bridge formula has an inflection point at 56 ft (17 m) and 90,000 lb (40,823 kg) where the weight allowance for additional distance changes from 1000 lb (454 kg) to 500 lb (227 kg) per foot (0.3 m). Comparing formulas TTI and B on a length basis, formula TTI is more liberal at lengths less than 56 ft (17 m). While formula B provides approximately 500 lb (227 kg) for every additional foot (0.3 m), formula TTI allows an extra 1000 lb (454 kg). For example, a five-axle TST with an overall length of 56 ft (17 m) is allowed 83,000 lb (37,648 kg) under formula B. Under formula TTI, however, the same vehicle is allowed 90,000 lb (40,823 kg). At lengths over 56 ft (17 m), the two bridge formulas provide approximately the same weight allowance for additional length. It is important to note that formula B provides much higher weight allowances for additional axles. A seven-axle TST with the same overall length, that is, 56 ft (17 m), would be allowed 92,500 lb (41,957 kg) under formula B. The same vehicle, under formula TTI, would still be allowed only 90,000 lb (40,823 kg). Since the 2,000-lb (907-kg) tare weight of an extra axle would displace an equivalent amount of payload, vehicles developed under formula TTI would tend to have fewer axles.

With the greater incentive to use fewer axles, the pavement loading constraint becomes more important. Under formulas B and C, the weight allowance for extra axles forced individual pavement loads to get lighter. Consequently, in limiting axle loads, formulas B and C tended to be more restrictive than the pavement rule. Under formula TTI, however, the pavement rule is more restrictive, especially at lengths under 56 ft (17 m).

Like the previous two scenarios, vehicle configurations and trailer dimensions in this scenario are also restricted by the STAA. Since the bridge formula is altogether length dependent and trailer lengths are limited by the STAA, gross combination weights of TST configurations are fairly well constrained. Operators could use longer tractors, which are not limited by the STAA, to increase the vehicle's overall length and consequently their GCW's. Also, they could use tridem suspensions to avoid the constraints of the pavement rule. In the case of doubles, long tractors and dollies could be used to maximize the vehicles' total weight. With longer lengths, the pavement rule becomes less of a constraint and the bridge formula becomes the more dominant rule. Consequently, tridem-axle sets become less important and increasing vehicle length becomes the primary issue. In summary, the driving forces in this scenario are the length and bridge formula constraints. Accordingly, longer tractors and dollies, and fewer axles would be used in proposed vehicle configurations.

*Example vehicles*

Tractor-Semitrailers: The "baseline" five-axle TST, first presented in scenario 1, is still restricted to 78,410 lb (35,566 kg) in this scenario (figure 37). A forward-biased loading




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 41.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 57910. lb | 48.0 ft | .0 ft |

Figure 37. Tractor-semitrailer (3-S2; GCW=78,410 lb; payload=48,110 lb).

of the semitrailer could help increase the vehicle's GCW by reducing the influence of the pavement rule.

Using a tridem-axle suspension to circumvent the 34,000 lb (15,422 kg) tandem-axle restriction, a three-axle tractor and tridem-axle semitrailer (figure 38) is allowed to weigh 87,500 lb (39,689 kg). The same vehicle, under formula B (figure 9), was allowed to carry only 86,000 lb (39,009 kg). As a result, shorter vehicles (less than 56 ft (17 m)) with fewer axles are allowed to be more productive under formula TTI.

Increasing the length of the tractor to increase the vehicle's overall length, a 15-ft (4.6 m) three-axle tractor and a tridem-axle semitrailer (figure 39) is allowed a GCW of 89,975 lb (40,812 kg). Spreads of 5 ft (1.5 m) are used to increase the allowable load on the tridem suspension from 42,000 lb (19,050 kg) to 44,000 lb (19,958 kg). Another TST configuration with tridem suspensions on both the tractor and the semitrailer (figure 40) weighs 90,100 lb (40,869 kg). Though the seven-axle TST is heavier than the previous vehicle (figure 10), it is less productive since it carries a lighter payload. Since the bridge formula does not provide weight allowances for additional axles, the tare weight of the additional axle on the tractor displaces an equivalent amount of payload.

Doubles: The "Western Doubles," both with and without the 80,000-lb (36,287 kg) weight cap (figures 41 and 42), have the same load distribution as the corresponding vehicles in scenario 1 (figures 12 and 13). While the weight cap is the dominant constraint in figure 41, the pavement rule governs the load distribution in figure 42. Since the dominant constraint in both cases is other than the bridge formula, which is the only difference between scenarios 1 and 3, the vehicle and axle layouts for the "Western Double" would be the same as in the first scenario.

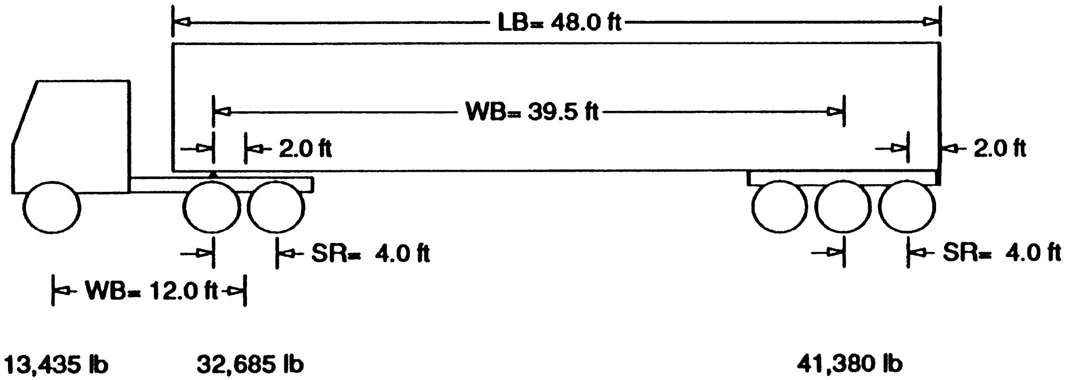
Using tandem-axles to escape the 20,000-lb (9,072 kg) limit on single axles, a nine-axle double-trailer configuration is shown in figure 43. With an overall length of 67 ft (20.4 m), the vehicle is limited to a total weight of 95,500 lb (43,318 kg). The same vehicle under formula B (figure 14) is allowed to weigh 109,500 lb (49,668 kg). It is clear that longer vehicles having more axles are more productive under formula B.

Using longer tractors and dollies to increase the allowable weight, a 14.5-ft (4.4 m) tractor and a 17.5-ft (5.3 m) dolly are used in the twin-trailer combination shown in figure 44. An overall vehicle length of 81 ft (24.7 m) results in a permissible weight of 102,500 lb (46,493 kg). Exploring the possibilities of extreme designs, a double with a 19-ft (5.8 m) tractor and 63-ft (19.2 m) dolly (figure 45) is allowed to carry 127,500 lb (57,833 kg). The last example is included to illustrate the wide range of design variations that are possible if size and weight regulations are not thoroughly analyzed.

The vehicle and axle layouts for the nine vehicles developed in this scenario are shown in table 6.

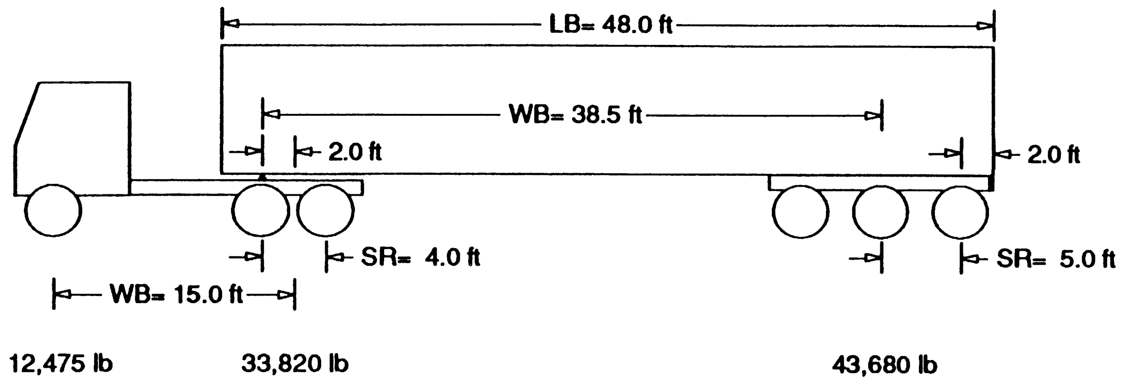
*What kind of vehicles would be promoted*

With the length constraint and the bridge formula being extremely restrictive in this scenario, the payoffs from removing the weight cap are not as great as in the first two situations. Though shifting from TST's to doubles would provide additional payload



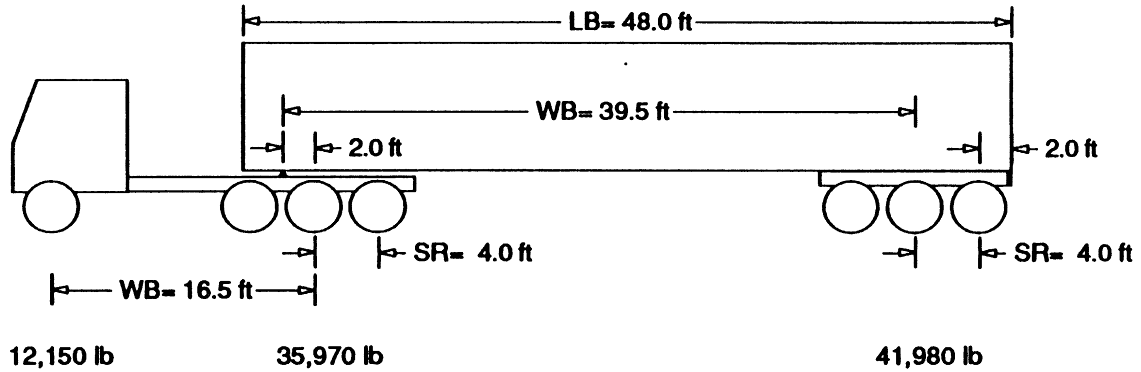

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 65000. lb | 48.0 ft | .0 ft |

Figure 38. Tractor-semitrailer (3-S3; GCW=87,500 lb; payload=55,200 lb).



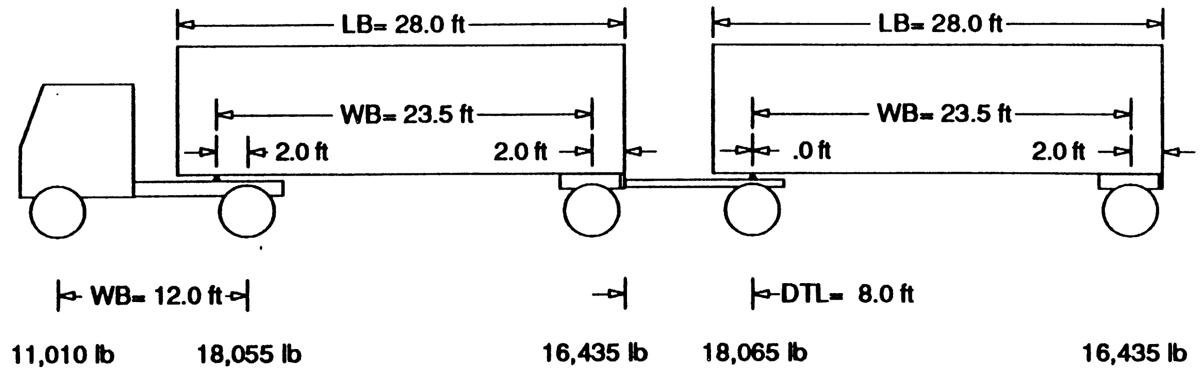

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 15.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 38.5 ft | 2.0 ft | .0 ft | 0. | 5.0 ft | 3. | 67473. lb | 48.0 ft | .0 ft |

Figure 39. Tractor-semitrailer (3-S3; GCW=89,975 lb; payload=57,675 lb).



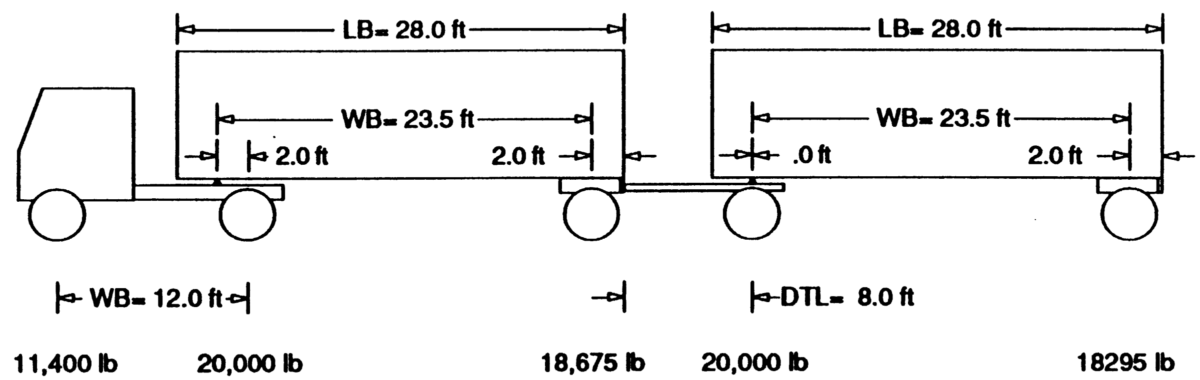

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 16.5 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 3. | 66100. lb | 48.0 ft | .0 ft |

Figure 40. Tractor-semitrailer (4-S3; GCW=90,100 lb; payload=56,300 lb).



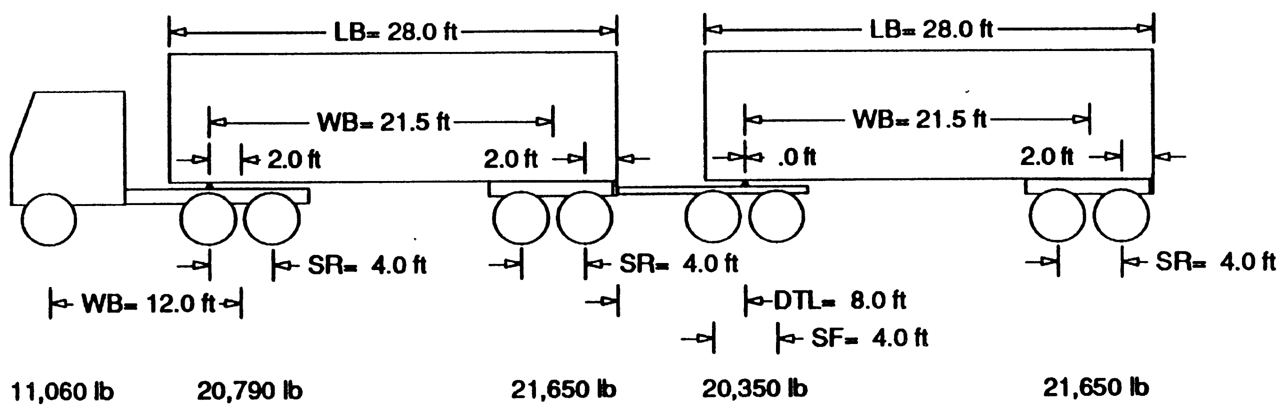

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 29500. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 29500. lb | 28.0 ft | 8.0 ft |

Figure 41. Double (2-S1-2; GCW=80,000 lb; payload=49,500 lb).



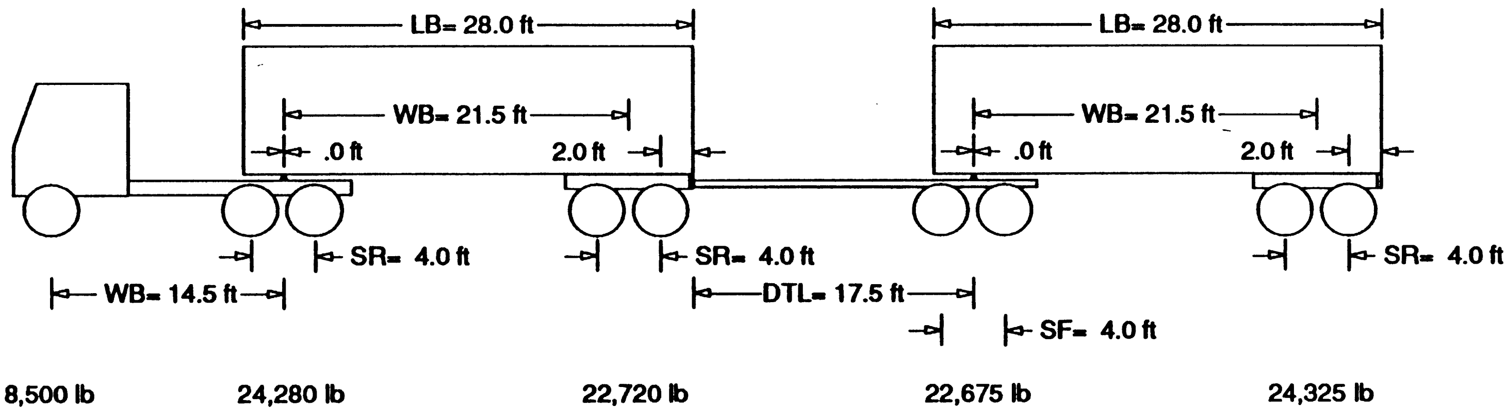

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 34079. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 33296. lb | 28.0 ft | 8.0 ft |

Figure 42. Double (2-S1-2; GCW=88,370 lb; payload=57,870 lb).



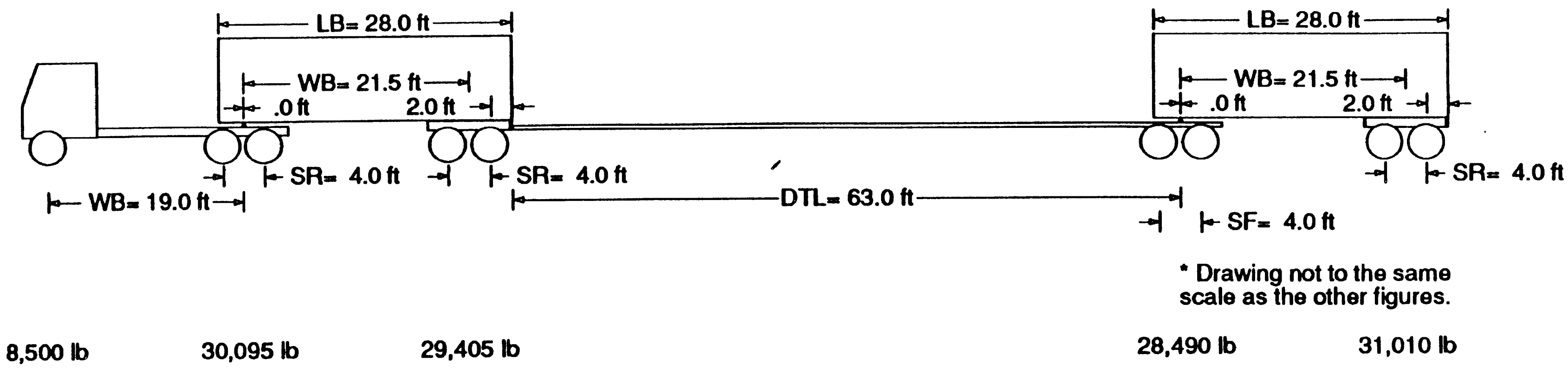

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 33000. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 33000. lb | 28.0 ft | 8.0 ft |

Figure 43. Double (3-S2-4; GCW=95,500 lb; payload=56,500 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 14.5 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 35000. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 38000. lb | 28.0 ft | 17.5 ft |

Figure 44. Double (3-S2-4; GCW=102,500 lb; payload=63,500 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 19.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 47500. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 50500. lb | 28.0 ft | 63.0 ft |

Figure 45. Double (3-S2-4; GCW=127,500 lb; payload=88,500 lb).

Table 6. Summary of example vehicles for scenario 3.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Tractor-semitrailer | 3-S2 | 30,300 lb | 78,410 lb | 48,110 lb | 3,672 | 53.5 ft | 5 |
| Tractor-semitrailer | 3-S3 | 32,300 lb | 87,500 lb | 55,200 lb | 3,672 | 53.5 ft | 6 |
| Tractor-semitrailer | 3-S3 | 32,300 lb | 89,975 lb | 57,675 lb | 3,672 | 56.5 ft | 6 |
| Tractor-semitrailer | 4-S3 | 33,800 lb | 90,100 lb | 56,300 lb | 3,672 | 58.0 ft | 7 |
| Double | 2-S1-2 | 30,500 lb | 80,000 lb | 49,500 lb | 4,284 | 67.0 ft | 5 |
| Double | 2-S1-2 | 30,500 lb | 88,370 lb | 57,870 lb | 4,284 | 67.0 ft | 5 |
| Double | 3-S2-4 | 39,000 lb | 95,500 lb | 56,500 lb | 4,284 | 67.0 ft | 9 |
| Double | 3-S2-4 | 39,000 lb | 102,500 lb | 63,500 lb | 4,284 | 81.0 ft | 9 |
| Double | 3-S2-4 | 39,000 lb | 127,500 lb | 88,500 lb | 4,284 | 131.0 ft | 9 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

volume, the change would only provide a marginal increase in payload weight capacity (see table 6). For example, while the TST shown in figure 39 is allowed to carry 57,675 lb (26,161 kg) of payload, the tandem-axle double, shown in figure 43, is allowed to carry only 56,500 lb (25,628 kg). Consequently, heavier permissible TST's provide less of an incentive to change from TST's to doubles.

From a higher payload volume standpoint, LTL fleets might find doubles to be a more attractive alternative to TST's. For liquid- and dry-bulk haulers, however, TST's would still be a viable option. Longer tractors and dollies could be used in the proposed designs to gain advantages in weight capacity.

## Vehicle Performance

*Performance summary*

Using the safety-related goals and the maneuvering situations discussed in section 2, the performance characteristics of the nine vehicles developed in this scenario are shown in table 7. The graphical representations of the tabulated results are shown in figures 46 through 53.

*Safety and operation concerns*

Low-Speed Offtracking: Figure 46 displays the offtracking abilities of the nine vehicles under consideration. The low-speed offtracking of the double with the 63-ft (19.2 m) dolly is extremely high. One might consider setting offtracking limits to augment the constraints for this scenario. With longer effective wheelbases (from having fewer axles) and longer tractors, the offtracking amounts for the TST's are almost as large as the "baseline" TST of scenario 1. The doubles (with the exception of the vehicle mentioned earlier) are better in this regard.

Friction Demand: Figure 47 contains the vehicles' friction requirements during tight turns. Unlike the vehicles of scenario 1, the vehicles in this scenario have no more than three axles in any suspension. Consequently, longer effective wheelbases and fewer axles allow the vehicles to make tight in-town turns, even on slippery surfaces.

High-Speed Offtracking: The high-speed offtracking results are shown in figure 48. Even though the longest vehicle in the group would never be built, that is, the double with the 63-ft (19.2 m) dolly, it is interesting to note that it has the least amount of offtracking. This is due to the extremely long dolly which tracks toward, instead of away, from the turn center at 55 mi/h (89 km/h). The rest of the vehicles have offtracking amounts less than 1 ft (0.3 m), which would be considered acceptable in this maneuver.

Constant Deceleration Braking: The braking efficiencies for the empty vehicles are shown in figure 49. The six-axle TST's (figures 38 and 39) and the "Western Doubles" (figures 41 and 42) perform poorly in the empty braking maneuver. As discussed in scenario 1, short wheelbases and single-axle suspensions reduce the braking efficiencies for the "Western Double." In the case of the six-axle TST, the three-axle suspension

Table 7. Summary of performance measures for example vehicles (scenario 3).

| | Tractor-semitrailer | | | | Double | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vehicle Code | 3-S2 | 3-S3 | 3-S3 | 4-S3 | 2-S1-2 | 2-S1-2 | 3-S2-4 | 3-S2-4 | 3-S2-4 |
| Gross Combination Weight (GCW) | 78,410 lb | 87,500 lb | 89,975 lb | 90,100 lb | 80,000 lb | 88,370 lb | 95,500 lb | 102,500 lb | 127,500 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | **17.34** | 16.23 | 16.38 | **17.30** | 14.05 | 14.05 | 12.47 | 15.28 | **36.43*** |
| 2. Friction demand in a tight turn | 0.01 | 0.03* | 0.05* | 0.03* | 0.00 | 0.00 | 0.02* | 0.02* | 0.02* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.242 | 0.280* | 0.349* | 0.297* | 0.718* | 0.772* | 0.727* | 0.838* | 0.168 |
| 4. Braking efficiency 1 (Loaded) - 0.2 g's / - 0.4 g's | 0.887<br>0.843 | 0.853*<br>0.812* | 0.875*<br>0.833* | 0.873*<br>0.859 | 0.882*<br>0.805* | 0.888<br>0.810* | 0.906<br>0.830* | 0.931<br>0.869 | 0.933<br>0.866 |
| 5. Braking efficiency 1 (Empty) - 0.2 g's / - 0.4 g's | **0.672**<br>**0.645** | **0.638***<br>**0.613*** | **0.645***<br>**0.620*** | 0.720<br>**0.694** | **0.615***<br>**0.568*** | **0.615***<br>**0.568*** | **0.684**<br>**0.642*** | **0.684**<br>**0.642*** | **0.684**<br>**0.642*** |
| 6. Rollover threshold (g's) | **0.376** | **0.377** | **0.378** | 0.407 | 0.382 | **0.365*** | 0.439 | 0.436 | 0.401 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | None | None | **54.34*** | **31.15*** | None | None | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | **0.065** | 0.115 | **0.092** | 0.144 | **< 0** | **< 0** | 0.124 | 0.105 | **0.065** |
| 8. Maximum rearward amplification | - | - | - | - | **1.445*** | **1.484*** | **1.562*** | **1.563*** | **1.594*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

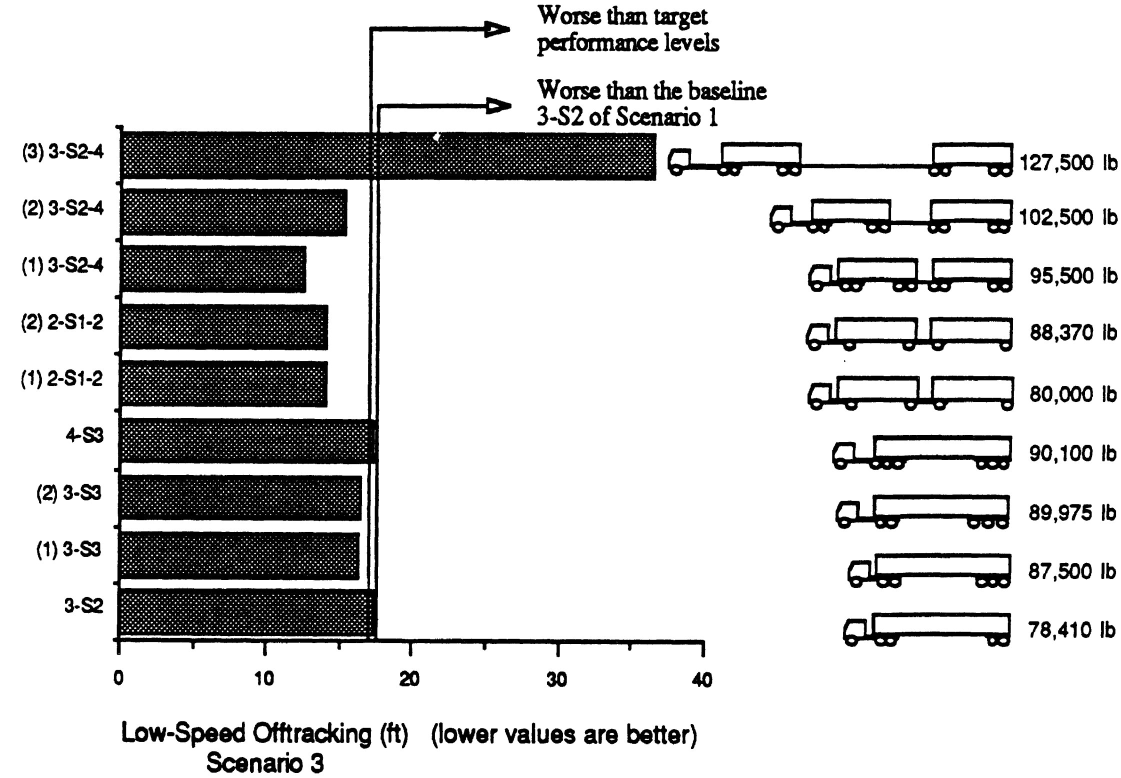



Figure 46. Low-speed offtracking, scenario 3.

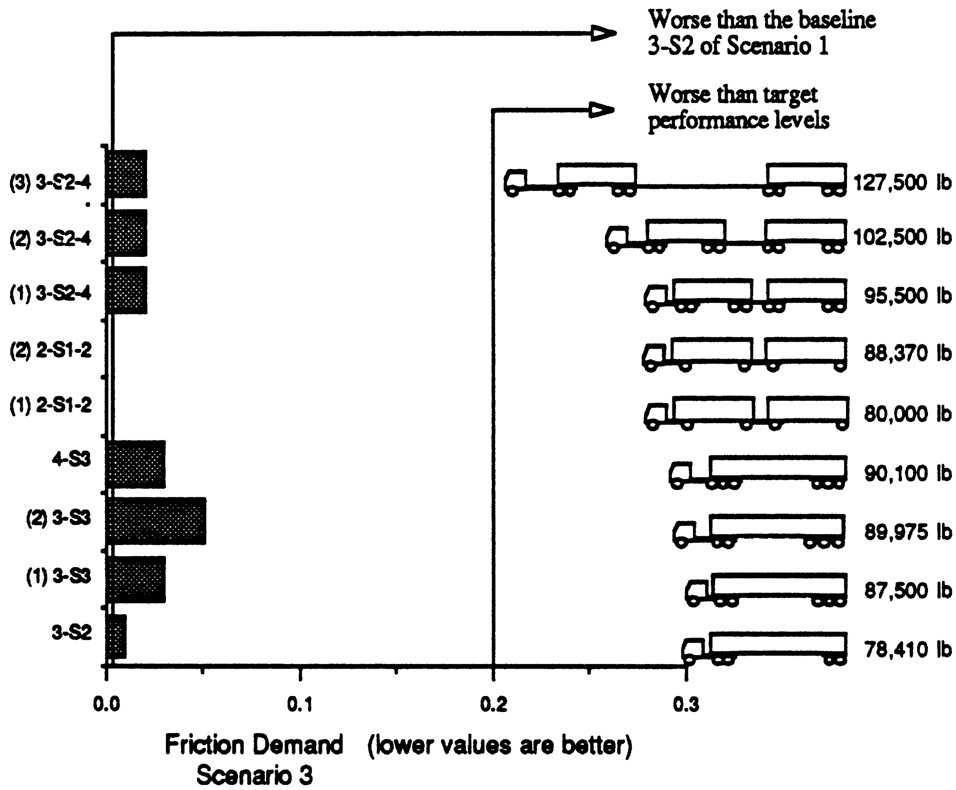



Figure 47. Friction demand, scenario 3.

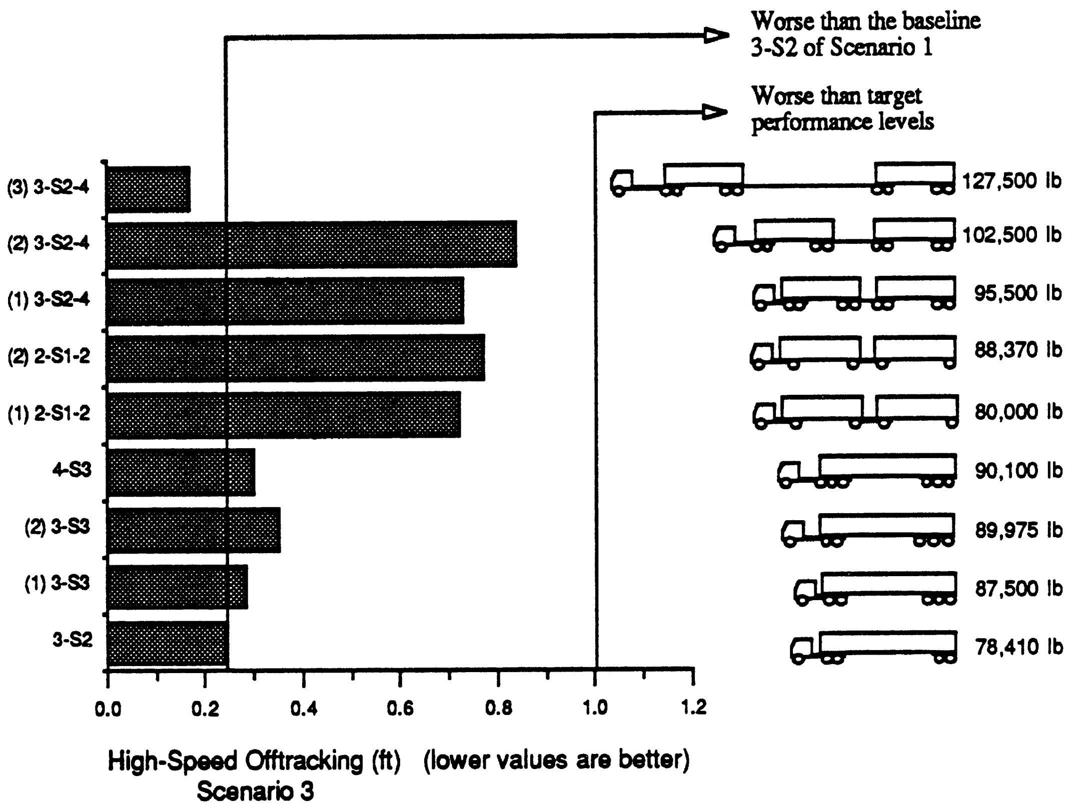



Figure 48. High-speed offtracking, scenario 3.

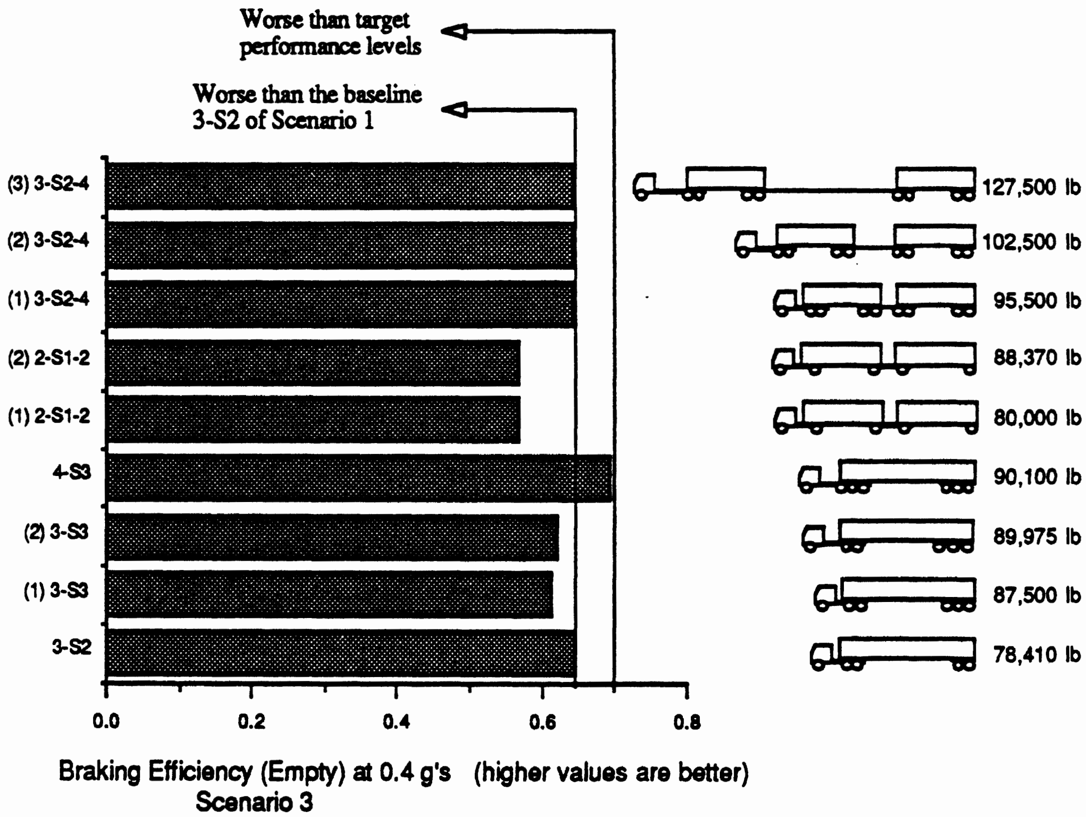



Figure 49. Braking efficiency, scenario 3.

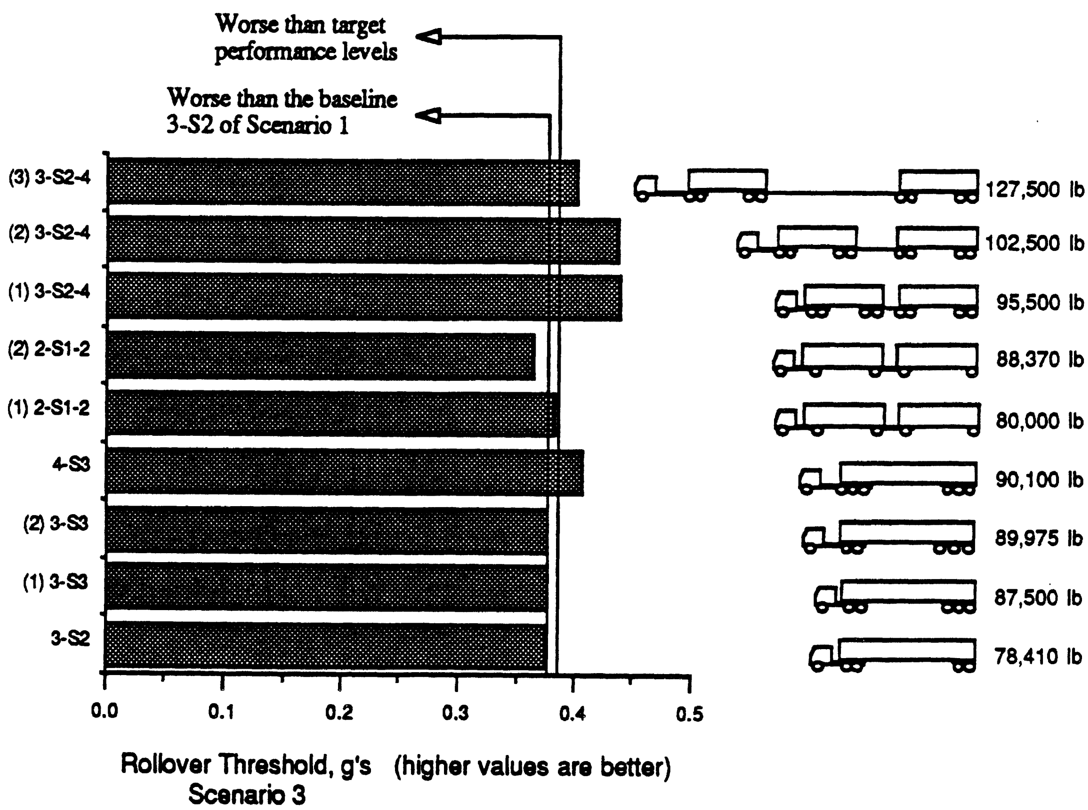



Figure 50. Rollover threshold, scenario 3.

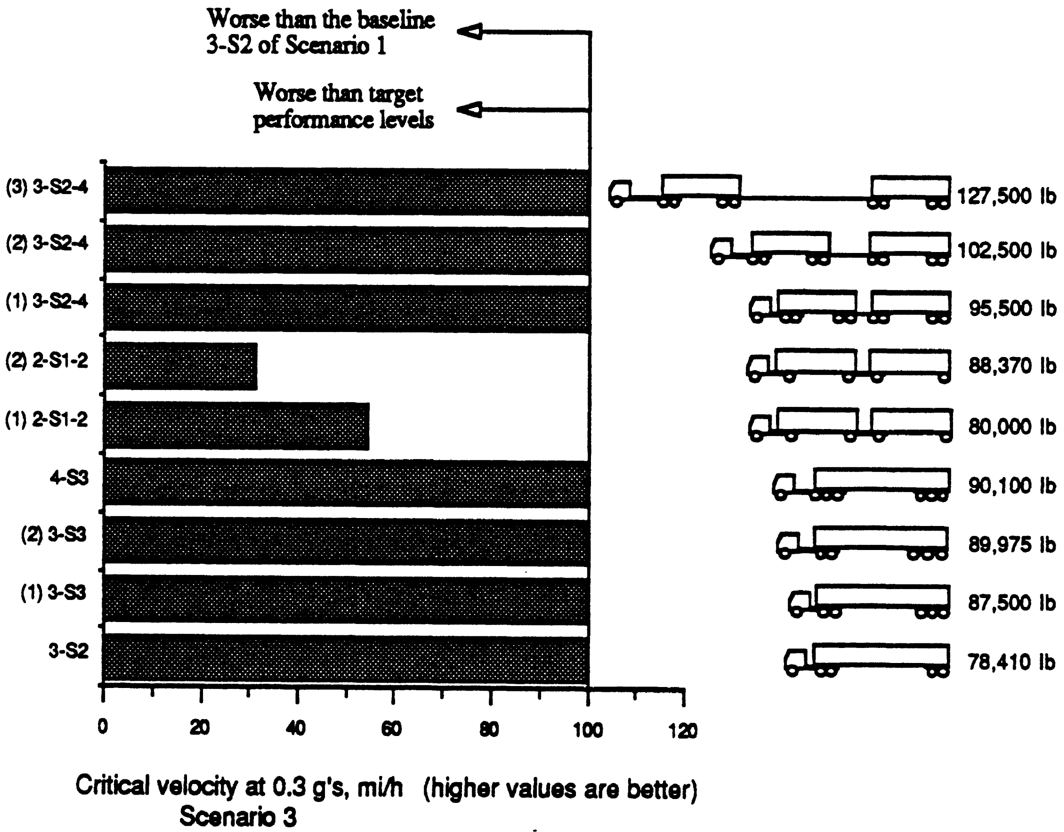



Figure 51. Critical velocity, scenario 3.

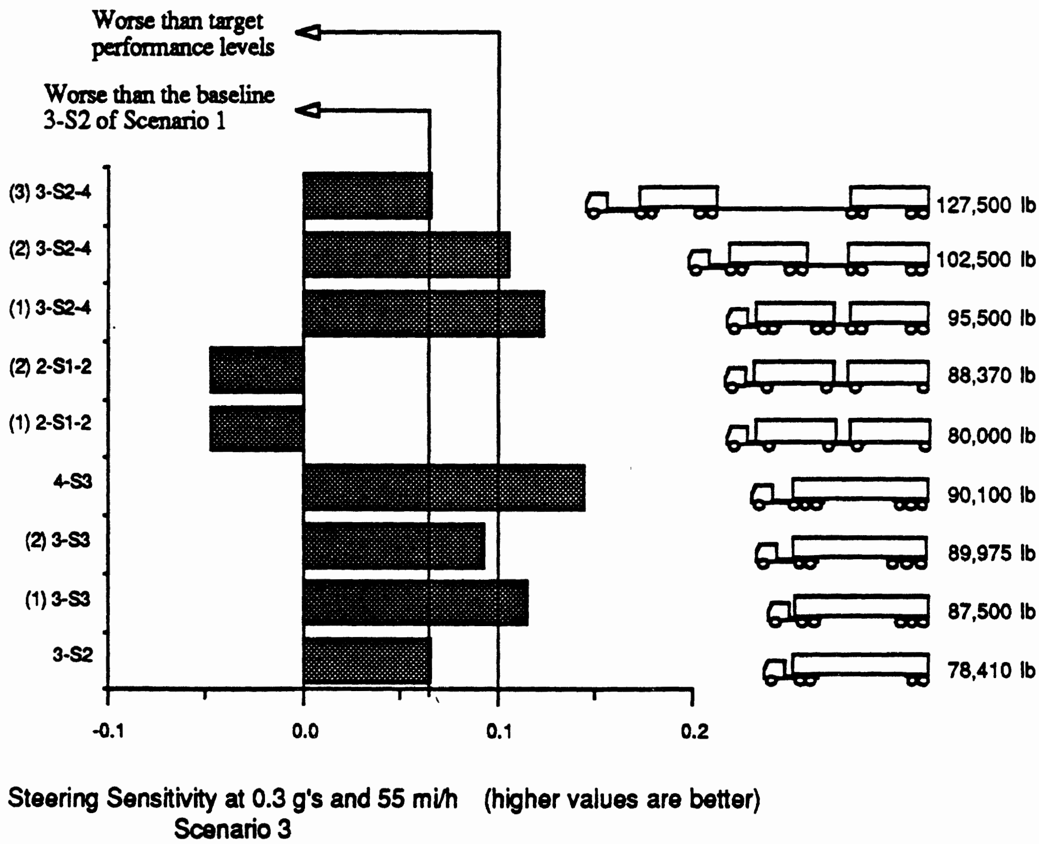



Figure 52. Steering sensitivity, scenario 3.

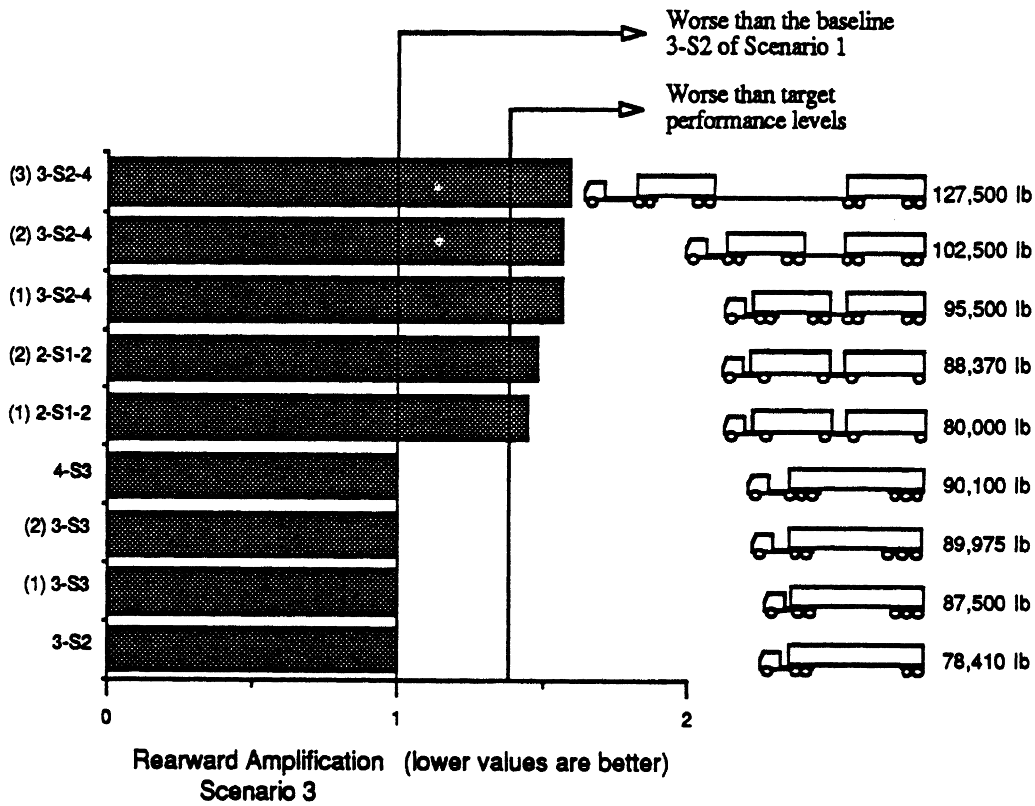



Figure 53. Rearward amplification, scenario 3.

generates too much braking force on the lightly loaded end of the semitrailer, resulting in premature "wheel-lock" on the trailer's axles. The TST in figure 40, with tridem suspensions on the tractor and trailer, is better than the other vehicles in this maneuver. In this situation, the braking force is balanced at both ends of the semitrailer, resulting in a better proportioning of the braking effort. In the loaded condition (items 4 and 5 in table 7), fewer axles with heavier loads improve brake proportioning and help postpone the possibility of wheel-lock.

Steady Turn—Rollover: The rollover thresholds for the proposed vehicles are shown in figure 50. Shorter vehicles, such as TST's, are allowed to be heavier under the TTI bridge formula. With fewer axles on these vehicles, the TST configurations have lower rollover thresholds. As in scenario 1, the "Western Doubles" continue to exhibit a low level of rollover threshold. In the case of the tandem-axle doubles, nine axles and lower GCW's (required by formula TTI) help increase the ratio of total roll stiffness to total weight. The higher roll stiffness per pound of axle load increases the rollover thresholds for these vehicles. Consequently, shorter vehicles, which are allowed to be heavier, would have lower levels of rollover threshold. Conversely, longer vehicles, which are forced to be lighter, would be more stable in roll.

Steady Turn—Handling: The handling characteristics for the nine vehicles are shown in figures 51 and 52. With the exception of the two "Western Double" layouts, the proposed vehicles in this scenario are fairly well behaved.

Obstacle Evasion: The rearward amplifications for the double-trailer combinations are displayed in figure 53. In this scenario, the bridge formula encourages doubles to have longer wheelbases and lighter trailer loads. Both these properties reduce rearward amplification, making the vehicles more stable in an evasive maneuver.

# 7. SCENARIOS 4&5 — USING FORMULAS C AND TTI INSTEAD OF FORMULA B

The vehicles in scenarios 4 and 5 are limited by an 80,000-lb (36,287 kg) gross weight cap. With the exception of the weight cap, scenario 4 is similar to the second scenario, where STAA vehicles are constrained by formula C and the "36/22" pavement rule. Scenario 5 is governed by formula TTI, the "34/20" pavement rule, the STAA length rule, and the 80,000-lb (36,287 kg) weight cap.

Unlike the first three scenarios, where the bridge formulas played a fairly significant role, their influence is less noticeable in scenarios 4 and 5. The gross weight cap is the most restrictive of all the constraints and reduces the effects of the respective pavement and bridge formula rules. In other words, proposed vehicles are limited to 80,000 lb (36,287 kg) before the other constraints can influence vehicle or axle layouts. Since examples of 80,000-lb (36,287 kg) TST's and doubles have been developed in previous scenarios, the results presented in earlier sections pertain to vehicles satisfying the constraints of these scenarios.

# 8. SCENARIO 6 — NO WEIGHT CAP, FORMULA B, AND AN OFFTRACKING LIMIT

## Vehicle Design

*Definition of the constraints on vehicle design*

The constraints governing this scenario are

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | B |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

With the elimination of the STAA constraint on lengths and vehicle types, the number of allowable configurations increases from tractor-semitrailers and doubles to the five "basic types"—straight trucks, tractor-semitrailers, truck-full trailers, doubles, and triples. The length constraint, in this scenario, is an "offtracking rule" which sets an outer limit on the low-speed offtracking of a vehicle. Under such a length constraint, the offtracking of a proposed vehicle design should be equivalent to that of a 12-ft (3.7 m) tractor pulling a semitrailer with a 40-ft (12 m) wheelbase.

Short wheelbases and more articulation joints reduce the low-speed offtracking of a vehicle. It is important to note that the wheelbase of a unit and its overall length are two distinct dimensions. For example, the overall length of a trailer is given by the "box-length," that is, the container length. Its wheelbase, however, is given by the distance between its kingpin and the center of its suspension. A 48-ft (15 m) semitrailer with a slider bogie could have wheelbase dimensions varying between 34 ft (10 m) and 42 ft (13 m) (assuming an 8 ft (2.4 m) travel for the slider attachment). Its overall length, obviously, remains the same. Since the offtracking constraint only restricts the wheelbases of the various units, there is no explicit limit on their overall lengths. With no restriction on overall length and using additional axles to reduce the wheelbase, a five-axle 53-ft (16 m) semitrailer could have an effective wheelbase of 40 ft (12 m). With a 12-ft (3.7 m) tractor, the tractor-semitrailer combination, with an overall length of approximately 65 ft (20 m), would still satisfy the offtracking constraint.

By providing additional weight allowances, formula B encourages longer lengths and extra axles in the vehicle layouts. As mentioned earlier, the bridge formula is more partial to adding axles than it is to increasing length. With the reinforcing trends of the two dominant constraints, that is, the length and bridge formula constraints, the incentive to add axles is overwhelming. For example, the five-axle 53-ft (16 m) semitrailer discussed earlier, would not only satisfy the offtracking constraint, but it would also get a weight allowance of 18,000 lb (8,165 kg) for the three additional axles. Even though lengths are governed by an offtracking rule, the effects of the two dominant constraints could result in extremely long multiaxle vehicles.

*Example vehicles*

Straight Trucks: Many States restrict the overall length of straight trucks to 40 ft (12 m). In this study, the straight truck is limited to 40 ft (12 m) in both the straight truck and truck-full trailer configurations. If many axles are used on the truck's rear suspension (to gain weight allowances), the short wheelbase and large spreads between the axles would make it almost impossible to turn the vehicle. A more acceptable five-axle design is presented in figure 54. The 6-ft (1.8 m) overhang, that is, the distance from the last axle to the rear end of the vehicle, is required to lighten the load on the steering axle.

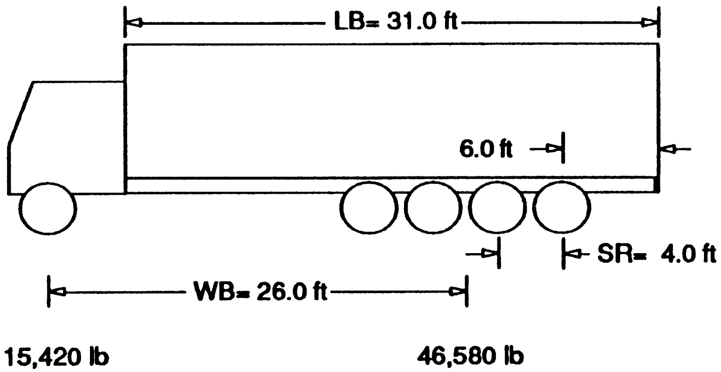
Tractor-Semitrailers: With a 41.5-ft (13 m) wheelbase on its semitrailer, the "baseline" TST, developed in scenario 1, does not satisfy the "offtracking rule." Since the semitrailer's suspension is critical in determining the vehicle's total weight, reducing the trailer's wheelbase, by moving the critical suspension forward, decreases the vehicle's GCW. The 76,310-lb (34,614 kg) vehicle is shown in figure 55.

Spreading a pair of axles has the same effect as adding an axle; it tends to reduce the effective wheelbase of the unit. For example, increasing a tandem spread from 4 ft (1.2 m) to 8 ft (2.4 m) reduces the unit's wheelbase by 2 ft (0.6 m). Spreading the axles, therefore, reduces the unit's wheelbase by a distance equal to half of the spread between consecutive axles. Using this effect in the next example (figure 56), a wide-spread tandem helps a five-axle TST satisfy the offtracking rule. With an 8-ft (2.4 m) spread between the axles, the wide-spread tandem can be considered as a pair of single axles, each with a weight capacity of 20,000 lb (9,072 kg). With the higher allowable weight on the critical set, that is, 40,000 lb (18,144 kg) instead of 34,000 lb (15,422 kg), the pavement rule's influence decreases and the vehicle is limited by the bridge formula to 81,500 lb (36,968 kg).

In the previous TST examples, the semitrailer's container length was limited to 48 ft (15 m). The vehicle's payload volume can be increased by using longer container length. A wide-spread tridem on a 52-ft (16 m) semitrailer is shown in figure 57. The vehicle satisfies the offtracking rule and is allowed to weigh 88,500 lb (40,143 kg).

An extreme application of the two dominant constraints produces the fourth TST design which is shown in figure 58. The 9-axle TST with a "bumper-to-bumper" length of 60 ft (18 m) is allowed to weigh 104,000 lb (47,174 kg). Although this vehicle is similar to the nine-axle TST developed in scenario 1 (see figure 11), it has a longer overall length and is, therefore, allowed to carry heavier loads.

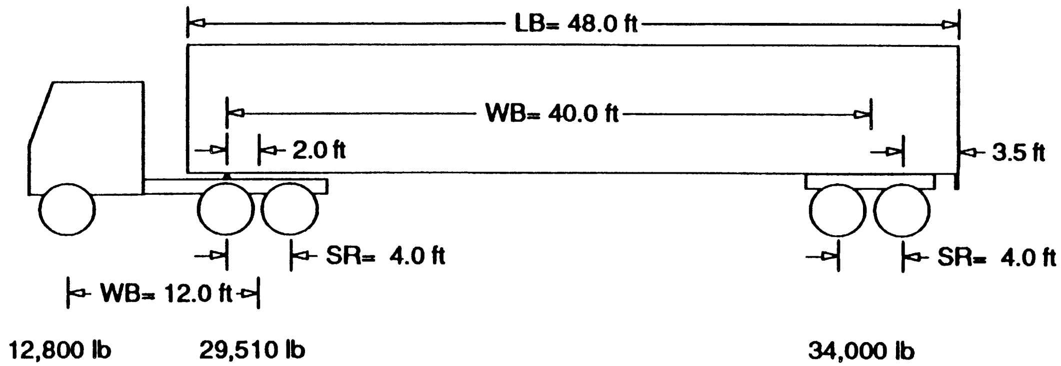
Truck-Full trailers: Using a 40-ft (12 m) straight truck to tow a 28-ft (8.5 m) full trailer, the five-axle vehicle is shown in figure 59. With the pavement rule restricting axle loads on the full trailer, the vehicle is limited to 86,930 lb (39,431 kg). The bridge formula also plays a role in this layout and restricts an intermediate group of axles, those containing the truck's rear suspension and the dolly's axle, to 54,000 lb (24,494 kg).





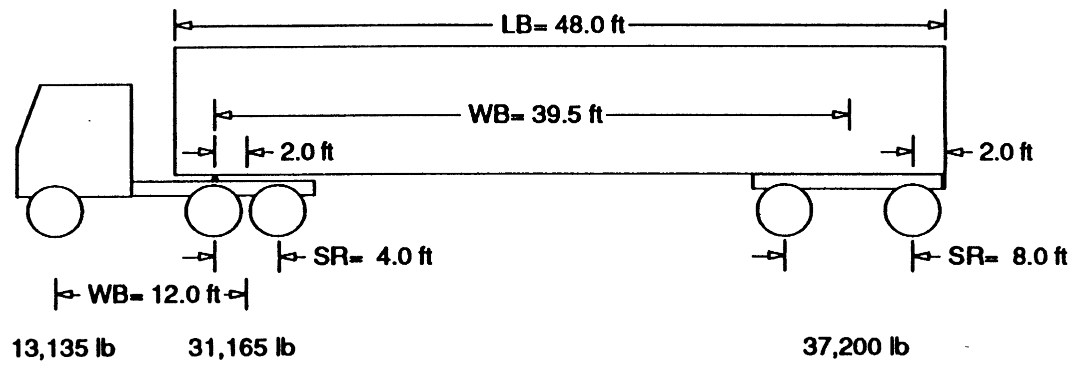

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 6.0 ft | .0 ft | 1. | 4.0 ft | 4. | 41000. lb | 31.0 ft | .0 ft |

Figure 54. Straight truck (5; GCW=62,000 lb; payload=35,490 lb).



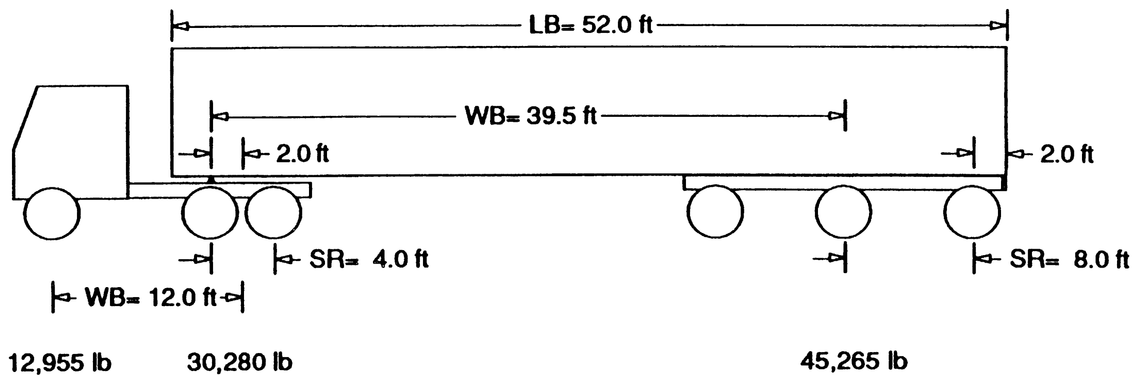

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 3.5 ft | .0 ft | 0. | 4.0 ft | 2. | 55810. lb | 48.0 ft | .0 ft |

Figure 55. Tractor-semitrailer (3-S2; GCW=76,310 lb; payload=46,010 lb).



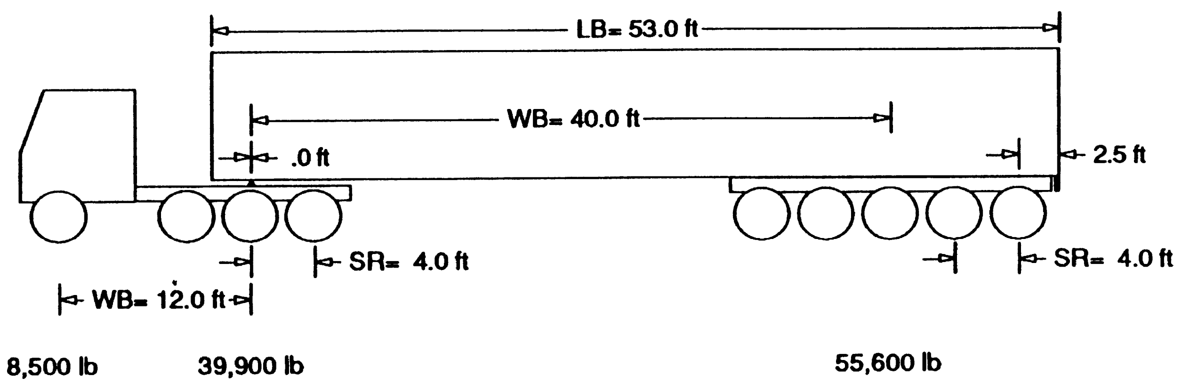

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 8.0 ft | 2. | 60995. lb | 48.0 ft | .0 ft |

Figure 56. Tractor-semitrailer (3-S2; GCW=81,500 lb; payload=51,200 lb).



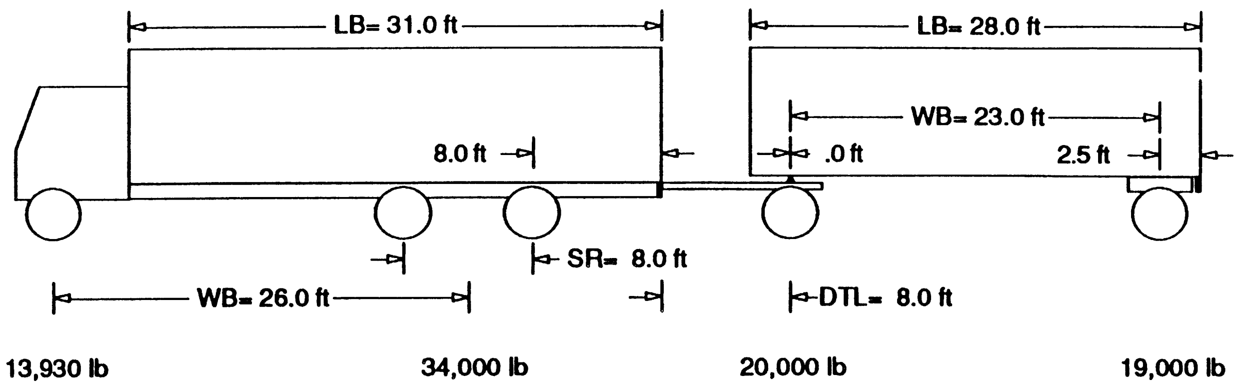

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 8.0 ft | 3. | 66000. lb | 52.0 ft | .0 ft |

Figure 57. Tractor-semitrailer (3-S3; GCW=88,500 lb; payload=55,190 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 2.5 ft | .0 ft | 0. | 4.0 ft | 5. | 76000. lb | 53.0 ft | .0 ft |

Figure 58. Tractor-semitrailer (4-S5; GCW=104,000 lb; payload=64,940 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 8.0 ft | .0 ft | 1. | 8.0 ft | 2. | 29930. lb | 31.0 ft | .0 ft |
| full trailer | 23.0 ft | 2.5 ft | .0 ft | 1. | .0 ft | 1. | 34000. lb | 28.0 ft | 8.0 ft |

Figure 59. Truck-full trailer (3-2; GCW=86,930 lb; payload=53,670 lb).

Using multiaxle suspensions and longer overall lengths, a 40-ft (12 m) straight truck, a 11.5-ft (3.5 m) dolly, and a 45-ft (14 m) trailer, make up the second truck-full trailer configuration shown in figure 60. The vehicle with an overall length of 88.5 ft (27 m), satisfies the "offtracking rule" and weighs 114,615 lb (51,988 kg). Again in this layout, the bridge formula restricts the same group of axles; those containing the dolly's and truck's rear suspensions.

Doubles: The "Western Double," first developed in scenario 1 (figure 13), satisfies the constraints of this scenario. Similarly, the tandem-axle double with STAA regulated trailers (figure 14) also satisfies this scenario's constraints. The layouts for these vehicles are presented again in figures 61 and 62.

Increasing the lengths of the trailers, a tandem-axle double with 35-ft (11 m) trailers is shown in figure 63. Due to its longer overall length, the vehicle is allowed to weigh 117,500 lb (53,297 kg). Another tandem-axle double, with a longer dolly and shorter trailers, is shown in figure 64. The vehicle has a smaller amount of payload volume capacity, but due to its longer overall length is allowed to be heavier than the vehicle in figure 63. Operators hauling dense cargo might find this vehicle design to be more productive than the layout in figure 63.

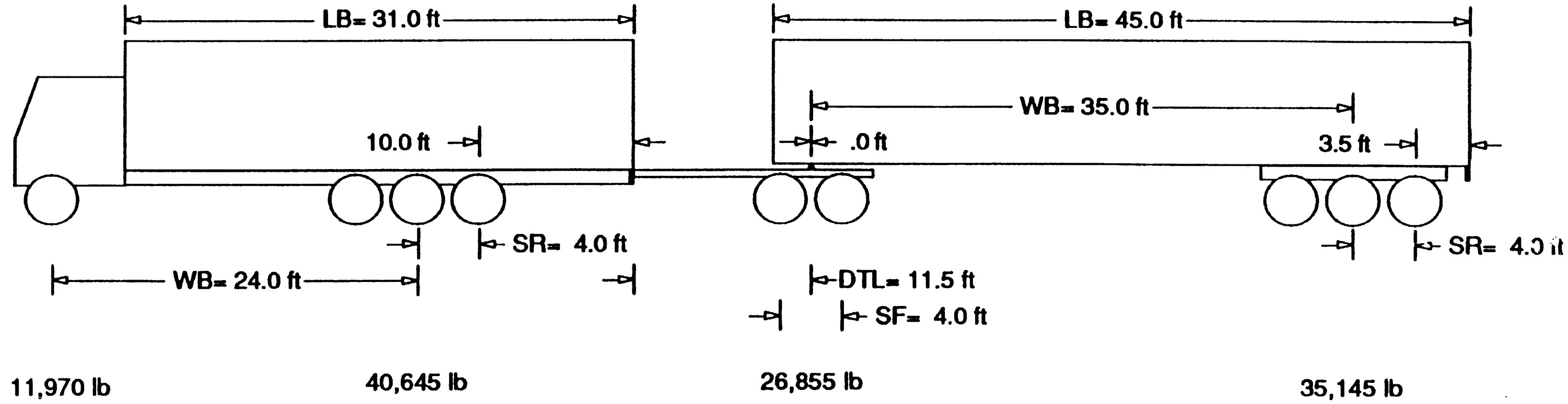
Triples: A triple-trailer configuration, with 28-ft (8.5 m) trailers, is shown in figure 65. With 21.5-ft (6.6 m) wheelbases and 4-ft (1.2 m) overhangs, the vehicle satisfies the "offtracking rule." The bridge formula allows the 98.5-ft (30 m) vehicle to weigh 116,850 lb (53,002 kg).

Exploring the possibilities of extreme designs, an example vehicle with three four-axle, 31-ft (9.5 m) trailers is shown in figure 66. Though the vehicle measures 128 ft (39 m) between extreme axles, the vehicle uses three- and four-axle suspensions to satisfy the "offtracking rule." With 22 axles on the vehicle, the bridge formula allows 215,500 lb (97,749 kg). To reiterate, such a vehicle would probably not be built, but it illustrates what could happen if the constraints are not thoroughly analyzed.

Information pertaining to the vehicles' productivity, such as available payload volume and weight, is summarized in table 8.

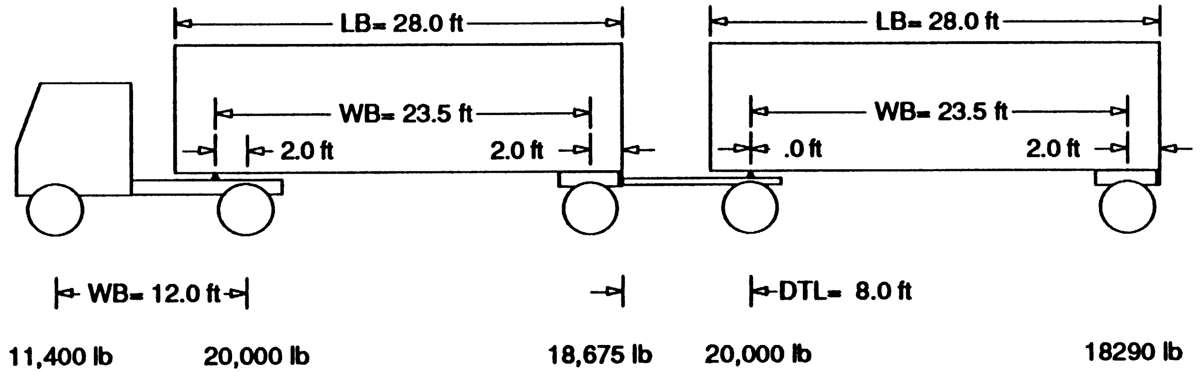
*What kind of vehicles would be promoted*

Since the constraints for this scenario are not sufficient to limit the range of design possibilities, vehicle layout variations are endless. Trailers could get longer, thereby, helping LTL haulers with increased payload volume. Bulk cargo haulers could benefit from the significant increases in GCW's. Accordingly, fleet operators would be encouraged to modify their fleets to take advantage of the substantial improvements in productivity. For example, TST's could use long multiaxle trailers and doubles could use long tandem-axle trailers to maximize volume and weight carrying capacities.



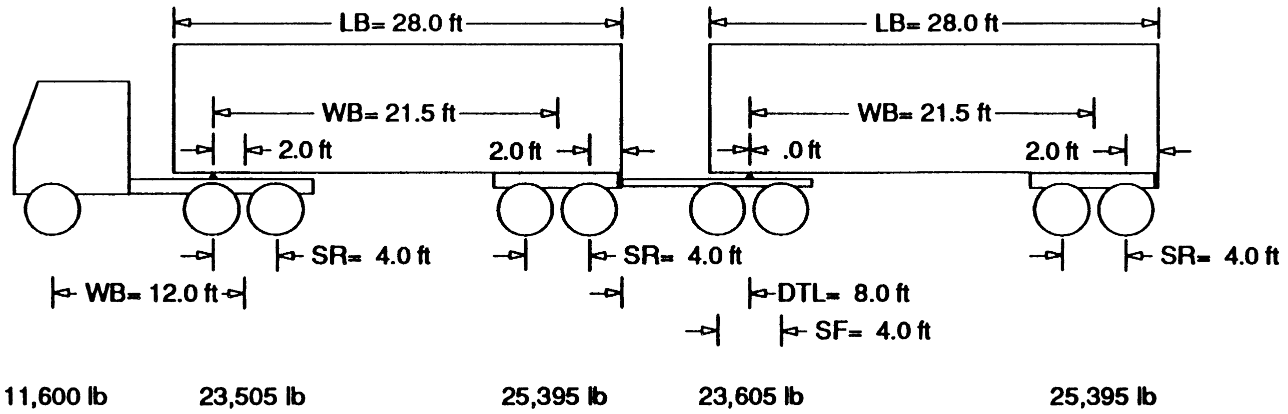

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 24.0 ft | 10.0 ft | .0 ft | 1. | 4.0 ft | 3. | 33115. lb | 31.0 ft | .0 ft |
| full trailer | 35.0 ft | 3.5 ft | 4.0 ft | 2. | 4.0 ft | 3. | 51000. lb | 45.0 ft | 11.5 ft |

Figure 60. Truck-full trailer (4-5; GCW=114,615 lb; payload=69,565 lb).



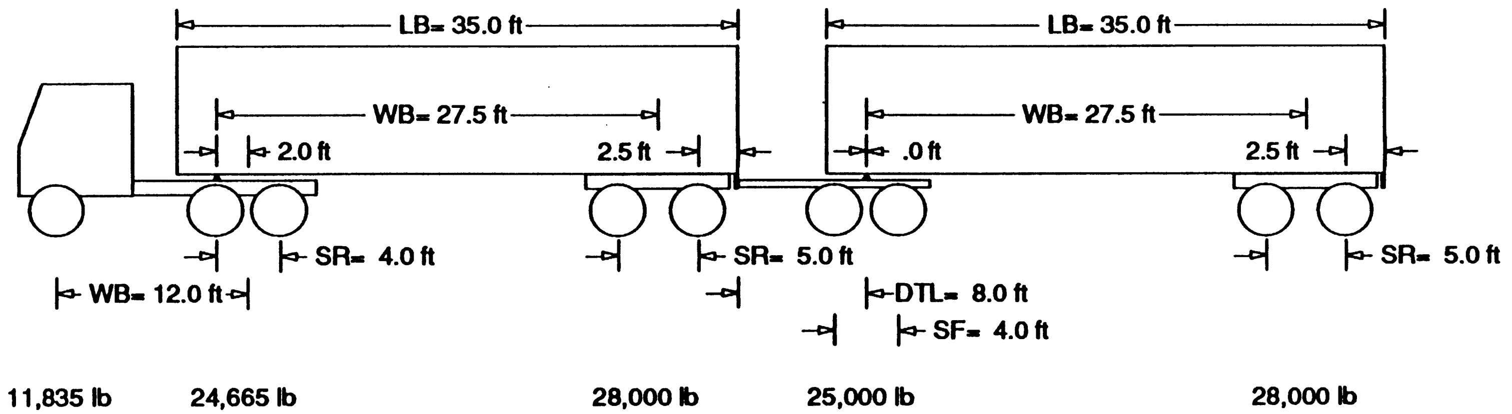

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 23.5 ft | 2.0 ft | .0 ft | 0. | .0 ft | 1. | 34075. lb | 28.0 ft | .0 ft |
| full trailer | 23.5 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 33290. lb | 28.0 ft | 8.0 ft |

Figure 61. Double (2-S1-2; GCW=88,365 lb; payload=57,865 lb).



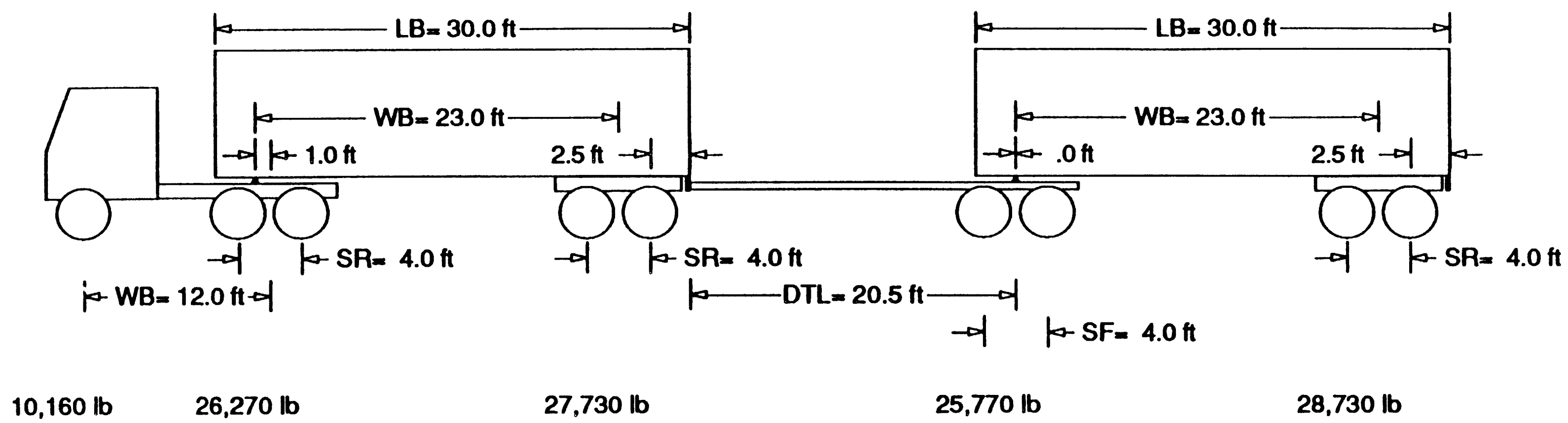

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 40000. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 40000. lb | 28.0 ft | 8.0 ft |

Figure 62. Double (3-S2-4; GCW=109,500 lb; payload=70,500 lb).



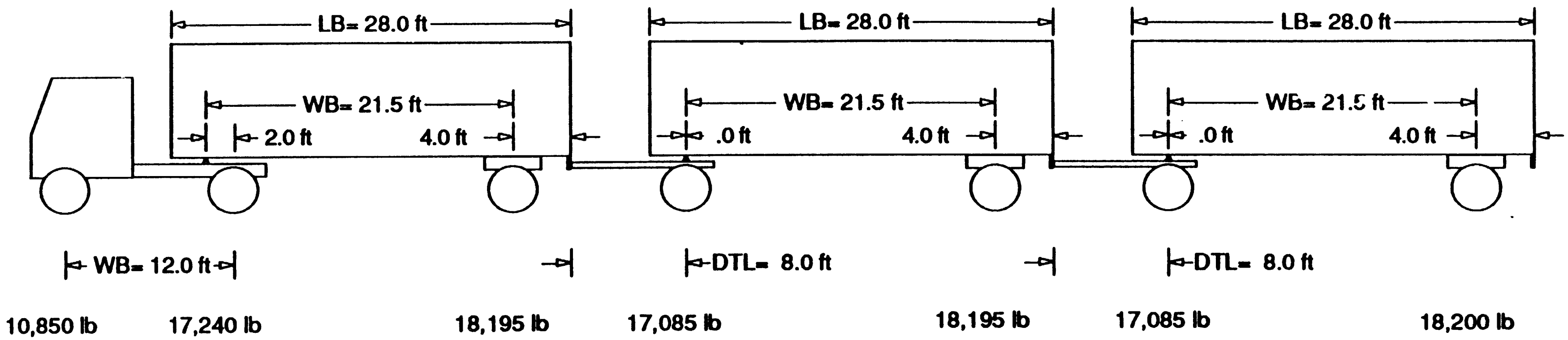

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 27.5 ft | 2.5 ft | .0 ft | 0. | 5.0 ft | 2. | 44000. lb | 35.0 ft | .0 ft |
| full trailer | 27.5 ft | 2.5 ft | 4.0 ft | 2. | 5.0 ft | 2. | 44000. lb | 35.0 ft | 8.0 ft |

Figure 63. Double (3-S2-4; GCW=117,500 lb; payload=74,960 lb).



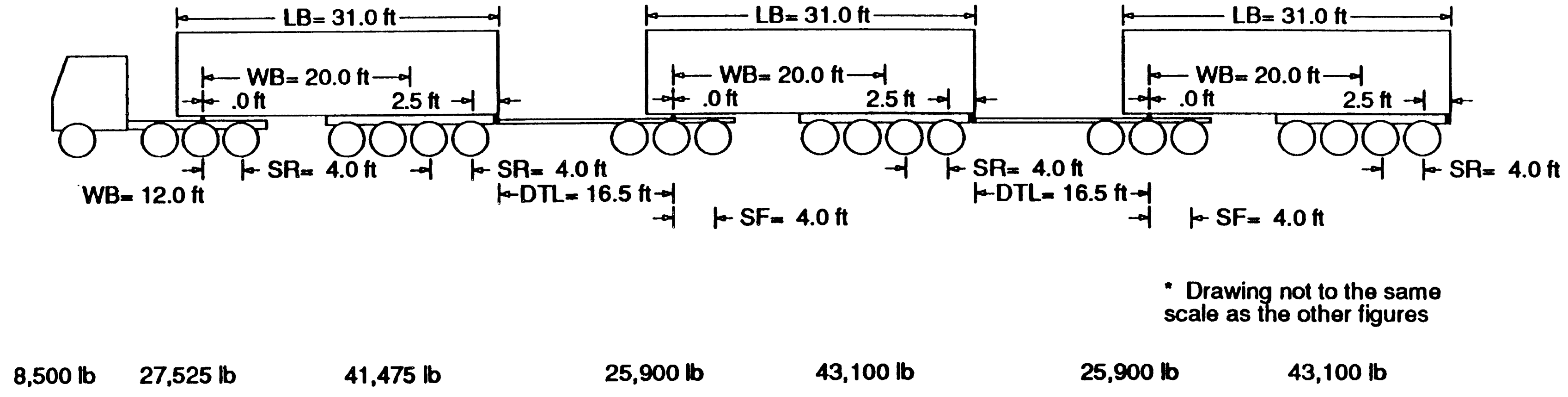

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 1.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 23.0 ft | 2.5 ft | .0 ft | 0. | 4.0 ft | 2. | 43660. lb | 30.0 ft | .0 ft |
| full trailer | 23.0 ft | 2.5 ft | 4.0 ft | 2. | 4.0 ft | 2. | 45500. lb | 30.0 ft | 20.5 ft |

Figure 64. Double (3-S2-4; GCW=118,660 lb; payload=78,640 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 4.0 ft | .0 ft | 0. | .0 ft | 1. | 30280. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 4.0 ft | .0 ft | 1. | .0 ft | 1. | 30280. lb | 28.0 ft | 8.0 ft |
| full trailer | 21.5 ft | 4.0 ft | .0 ft | 1. | .0 ft | 1. | 30285. lb | 28.0 ft | 8.0 ft |

Figure 65. Triple (2-S1-2-2; GCW=116,850 lb; payload=76,600 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 20.0 ft | 2.5 ft | .0 ft | 0. | 4.0 ft | 4. | 51500. lb | 31.0 ft | .0 ft |
| full trailer | 20.0 ft | 2.5 ft | 4.0 ft | 3. | 4.0 ft | 4. | 54000. lb | 31.0 ft | 16.5 ft |
| full trailer | 20.0 ft | 2.5 ft | 4.0 ft | 3. | 4.0 ft | 4. | 54000. lb | 31.0 ft | 16.5 ft |

Figure 66. Triple (4-S4-7-7; GCW=215,500 lb; payload=142,970 lb).

Table 8. Summary of example vehicles for scenario 6.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Straight truck | 5 | 26,510 lb | 62,000 lb | 35,490 lb | 2,372 | 32.0 ft | 5 |
| Tractor-semitrailer | 3-S2 | 30,300 lb | 76,310 lb | 46,010 lb | 3,672 | 52.0 ft | 5 |
| Tractor-semitrailer | 3-S2 | 30,300 lb | 81,500 lb | 51,200 lb | 3,672 | 53.5 ft | 5 |
| Tractor-semitrailer | 3-S3 | 33,310 lb | 88,500 lb | 55,190 lb | 3,978 | 57.5 ft | 6 |
| Tractor-semitrailer | 4-S5 | 39,060 lb | 104,000 lb | 64,940 lb | 4,055 | 60.0 ft | 9 |
| Truck-full trailer | 3-2 | 33,260 lb | 86,930 lb | 53,670 lb | 4,514 | 69.0 ft | 5 |
| Truck-full trailer | 4-5 | 45,050 lb | 114,615 lb | 69,565 lb | 5,814 | 88.5 ft | 9 |
| Double | 2-S1-2 | 30,500 lb | 88,365 lb | 57,865 lb | 4,284 | 67.0 ft | 5 |
| Double | 3-S2-4 | 39,000 lb | 109,500 lb | 70,500 lb | 4,284 | 67.0 ft | 9 |
| Double | 3-S2-4 | 42,540 lb | 117,500 lb | 74,960 lb | 5,355 | 80.5 ft | 9 |
| Double | 3-S2-4 | 40,020 lb | 118,660 lb | 78,640 lb | 4,590 | 84.0 ft | 9 |
| Triple | 2-S1-2-2 | 40,250 lb | 116,850 lb | 76,600 lb | 6,426 | 98.5 ft | 7 |
| Triple | 4-S4-7-7 | 72,530 lb | 215,500 lb | 142,970 lb | 7,115 | 128.0 ft | 22 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

## Vehicle Performance

### *Performance summary*

The performance characteristics of the vehicles developed in this scenario are summarized in table 9. The graphical representations of the various rows of the table are contained in figures 67 through 74.

### *Safety and operational concerns*

Low-Speed Offtracking: Figure 67 pertains to the low-speed offtracking performance of the proposed vehicles. Since the vehicles in this scenario are constrained by the "offtracking rule," their low-speed offtracking amounts would be within a controllable range. Though the multiaxle triple (figure 66) offtracks by more than the 18 ft (5.5 m), it is only slightly worse than the 17.34 ft (5.3 m) offtracking of the "baseline" TST in scenario 1.

Friction Demand: With more axles being used in the vehicle layouts, the in-town maneuverability of the proposed vehicles could suffer. Figure 68 contains the friction requirements of the vehicles developed in this scenario. The 40-ft (12 m) straight truck, with its short wheelbase and lightly loaded steering axle, could have trouble negotiating curves on slippery surfaces. This is evident in all the configurations that use the straight truck as their towing unit. Some of the TST configurations, especially those with the spread axles on their semitrailers, could also require high levels of tire/road friction. The extremely long triple, with its multiaxle suspensions, would also present a problem in this maneuver.

High-Speed Offtracking: With trailers getting longer, the high-speed offtracking of the proposed vehicles could pose a problem. Figure 69 contains the high-speed offtracking results for the 13 vehicles. The two triple-trailer configurations, with offtracking amounts greater than 1 ft (0.3 m), could have trouble negotiating entrance and exit ramps, especially at highway speeds. Though the remaining vehicles offtrack by less than 1 ft (0.3 m), the longer lengths degrade their performance in this maneuver.

Constant Deceleration Braking: The braking efficiencies for the empty vehicles are shown in figure 70. With the exception of the 22-axle triple, the empty vehicles perform rather poorly in this maneuver. With short-wheelbase trailers and fewer axles generating a braking force, the axles in the "Western Double" and the five-axle truck-full trailer (figure 59) are more prone to premature "wheel-lock." Though the same trailers are used in the single-axle triple, the extra braking effort produced by the third trailer's axles helps decelerate the vehicle more effectively prior to "wheel-lock," thereby improving the vehicle's braking efficiency. In this regard, the loaded vehicles perform slightly better, with most of the vehicles being more than 80 percent efficient in a 0.4 g's stop. However, the short wheelbase and the multiaxle suspension on the straight truck degrades its braking performance.

Steady Turn—Rollover: The use of extra axles in these layouts increases the vehicle's total roll stiffness. Figure 71 shows the relatively higher levels of rollover threshold. In

Table 9. Summary of performance measures for example vehicles (scenario 6).

| | Truck | Tractor-semitrailer | | | | Truck-full trailer | | Double | | | | Triple | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Code | 5 | 3-S2 | 3-S2 | 3-S3 | 4-S5 | 3-2 | 4-5 | 2-S1-2 | 3-S2-4 | 3-S2-4 | 3-S2-4 | 2-S1-2-2 | 4-S4-7-7 |
| Gross Combination Weight (GCW) | 62,000 lb | 76,310 lb | 81,500 lb | 88,500 lb | 104,000 lb | 86,930 lb | 114,615 lb | 88,365 lb | 109,500 lb | 117,500 lb | 118,660 lb | 116,850 lb | 215,500 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | 7.76 | 16.51 | 16.23 | 16.23 | 16.55 | 12.71 | **17.48*** | 14.05 | 12.47 | **17.09** | 16.64 | 16.98 | **18.25*** |
| 2. Friction demand in a tight turn | 0.19* | 0.01* | 0.04* | 0.15* | 0.10* | 0.13* | 0.13* | 0.00 | 0.02* | 0.03* | 0.02* | 0.00 | 0.15* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.430* | 0.296* | 0.346* | 0.387* | 0.393* | 0.872* | 0.890* | 0.771* | 0.732* | 0.751* | 0.848* | **1.242*** | **1.556*** |
| 4. Braking efficiency 1 (Loaded) - 0.2 g's | 0.825* | 0.860* | 0.851* | 0.925 | 0.889 | 0.921 | 0.842* | 0.888 | 0.905 | 0.871* | 0.944 | 0.940 | 0.910 |
| - 0.4 g's | 0.773* | 0.818* | 0.809* | 0.885 | 0.852 | 0.857 | 0.799* | 0.810* | 0.847 | 0.832* | 0.897 | 0.870 | 0.927 |
| 5. Braking efficiency 1 (Empty) - 0.2 g's | **0.662*** | **0.686** | **0.691** | **0.679** | 0.716 | **0.567*** | **0.688** | **0.615*** | **0.684** | 0.733 | 0.701 | **0.699** | 0.826 |
| - 0.4 g's | **0.626*** | **0.658** | **0.662** | **0.653** | **0.694** | **0.520*** | **0.660** | **0.568*** | **0.642*** | **0.696** | **0.660** | **0.647** | 0.788 |
| 6. Rollover threshold (g's) | **0.374*** | 0.381 | **0.370*** | 0.384 | 0.428 | **0.348*** | 0.389 | **0.365*** | 0.419 | 0.409 | 0.413 | 0.381 | 0.456 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | **81.61*** | None | None | **62.95*** | None | **31.19*** | None | None | None | **49.18*** | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | 0.264 | **0.072** | **0.033*** | **0.097** | 0.104 | **0.031*** | **0.073** | **< 0** | 0.118 | 0.110 | **0.087** | **< 0** | 0.107 |
| 8. Maximum rearward amplification | - | - | - | - | - | **2.207*** | 1.349* | **1.484*** | **1.569*** | 1.358* | **1.555*** | **2.794*** | **3.785*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

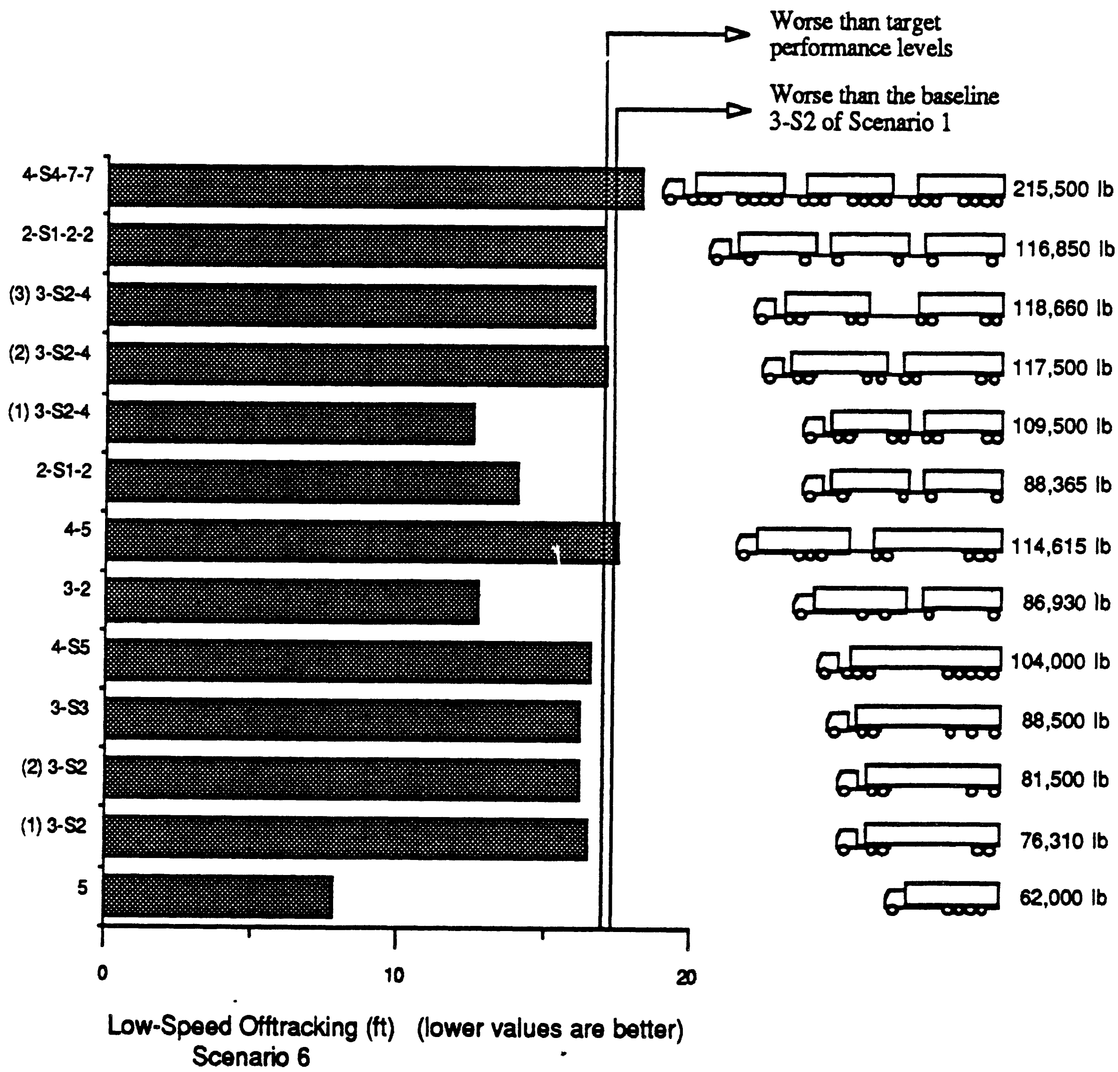



Figure 67. Low-speed offtracking, scenario 6.

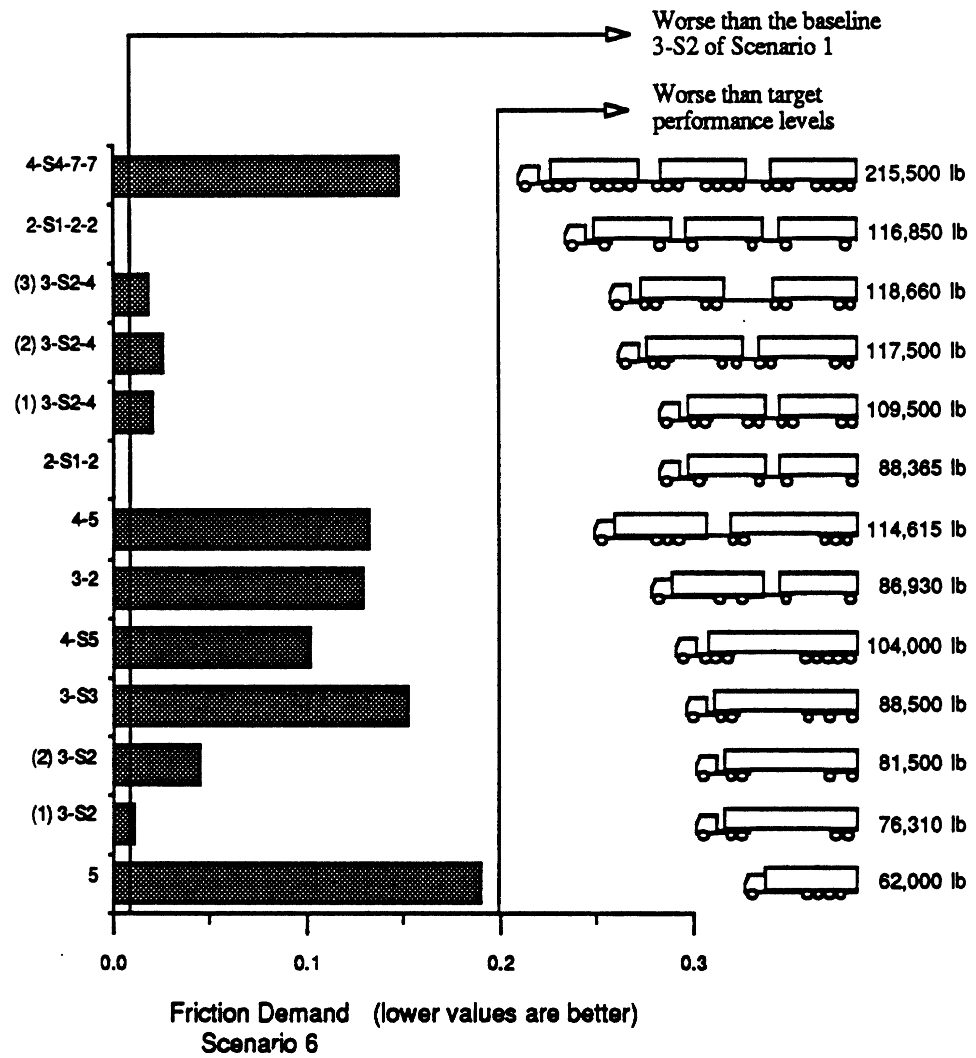



Figure 68. Friction demand, scenario 6.

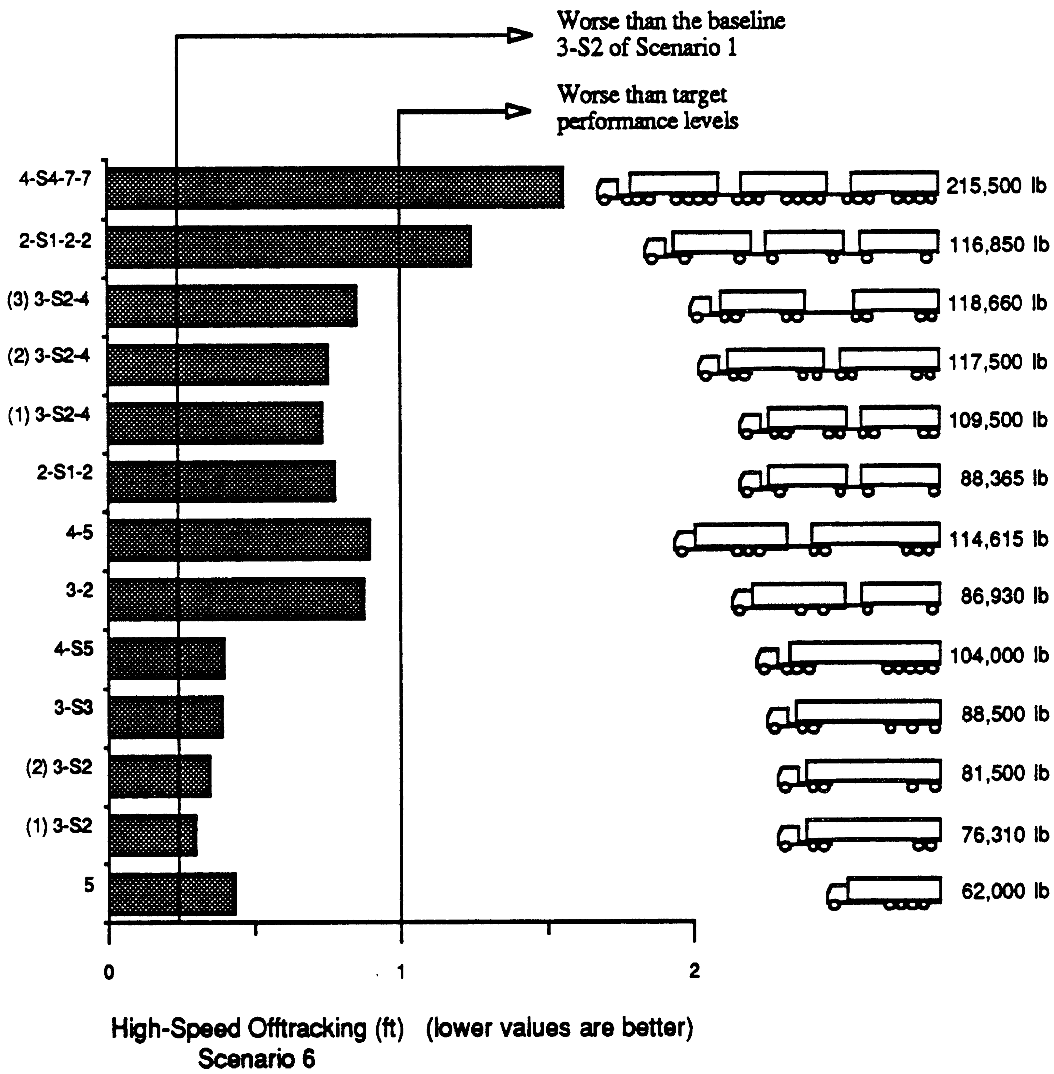



Figure 69. High-speed offtracking, scenario 6.

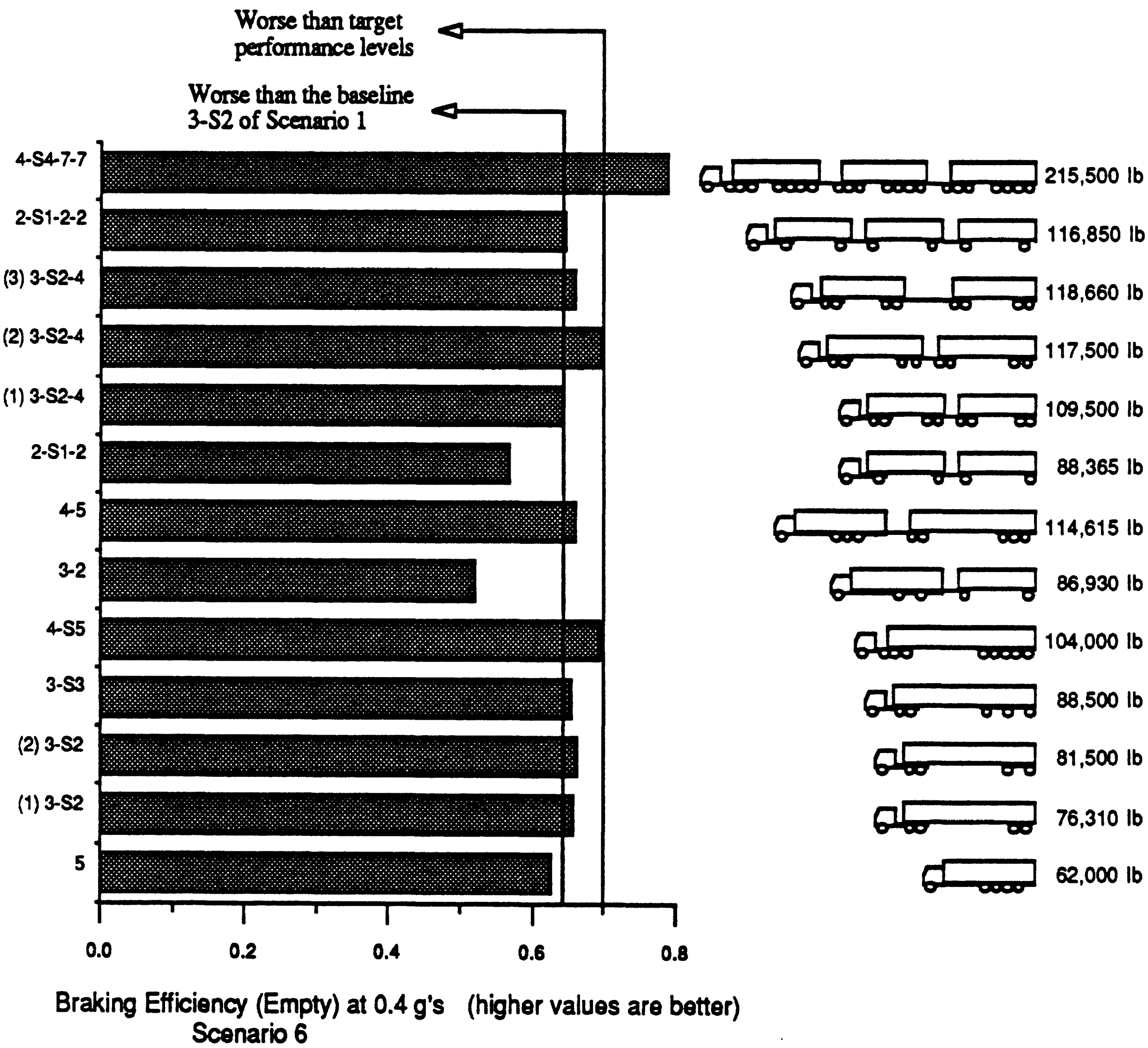



Figure 70. Braking efficiency, scenario 6.

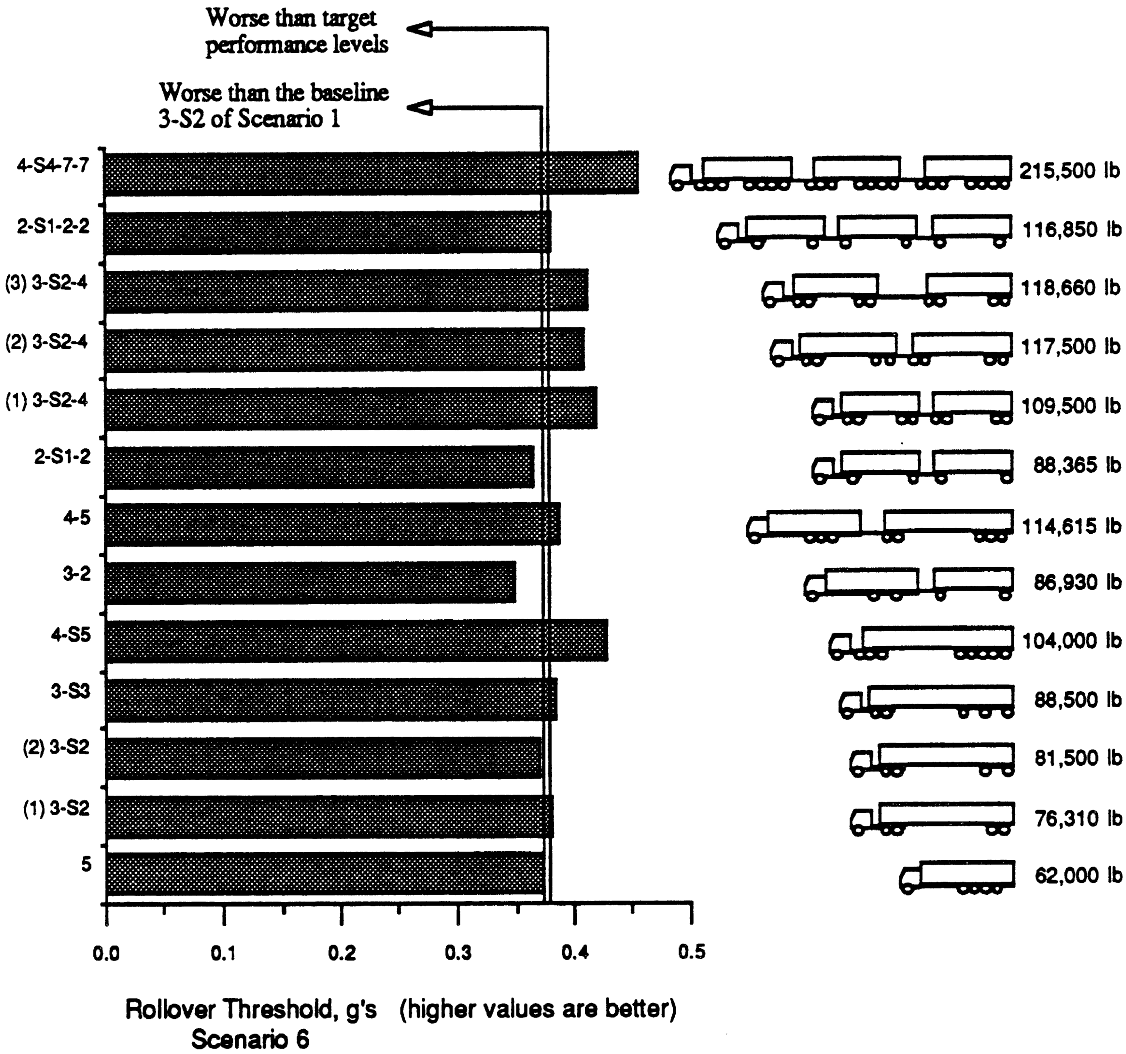



Figure 71. Rollover threshold, scenario 6.

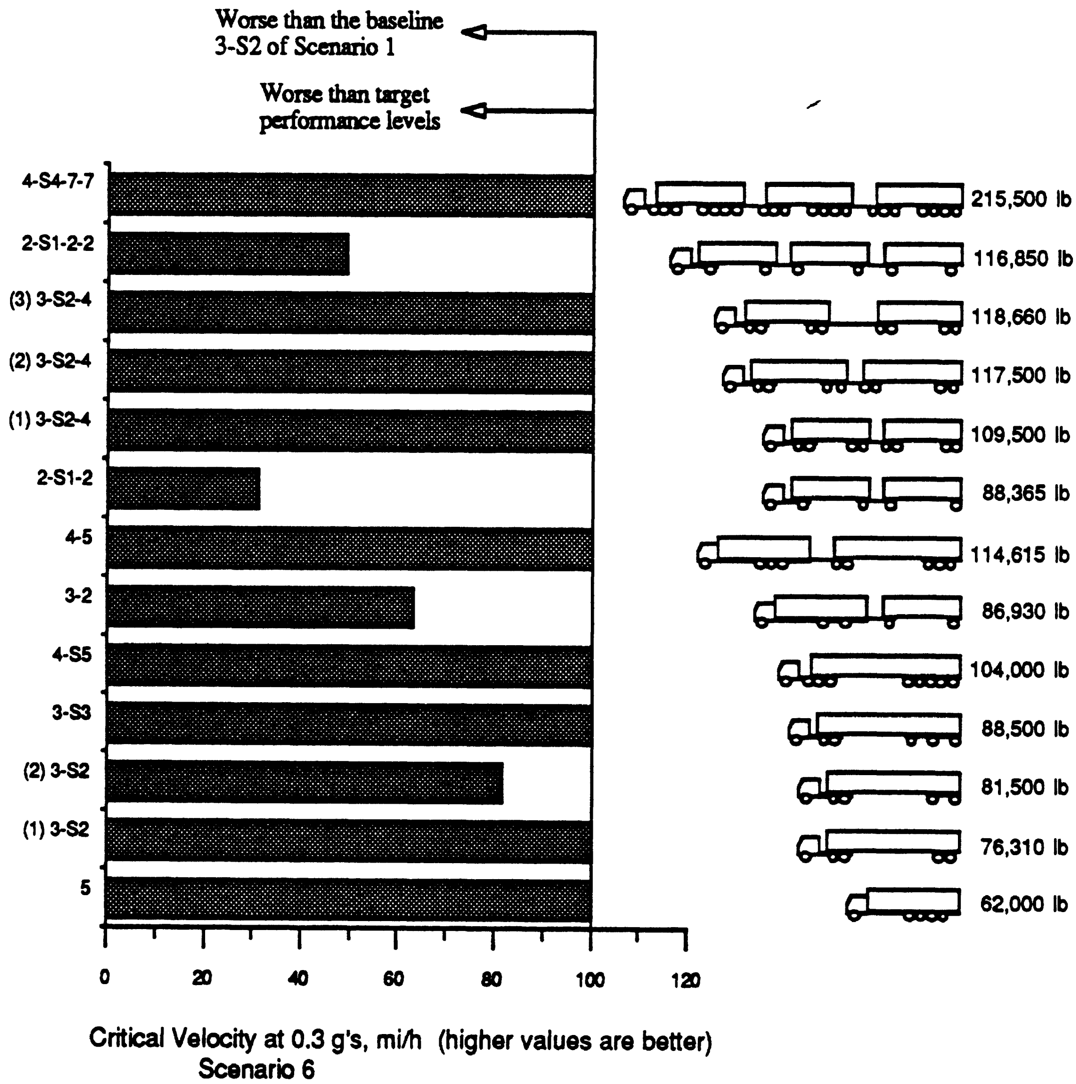



Figure 72. Critical velocity, scenario 6.

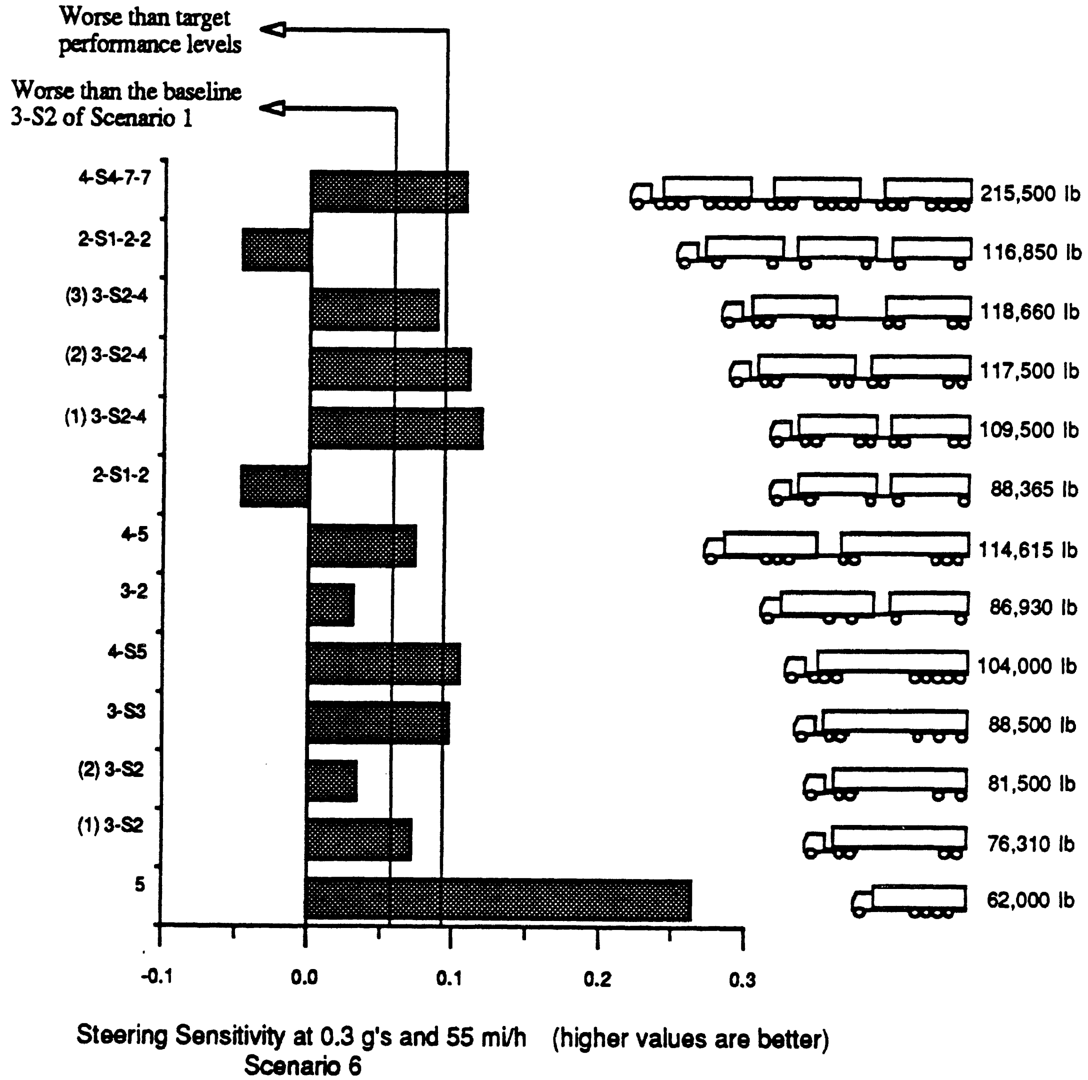



Figure 73. Steering sensitivity, scenario 6.

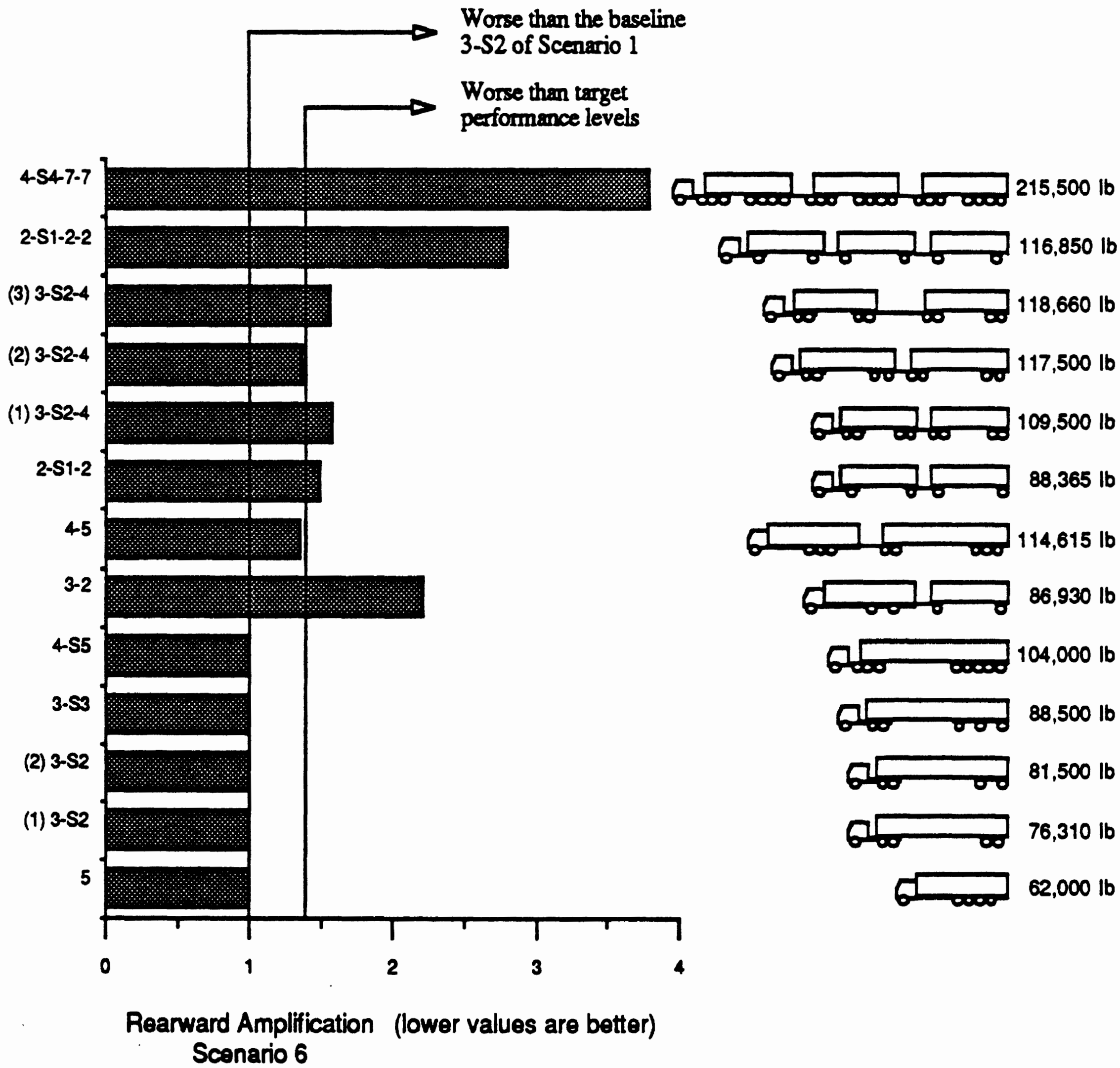



Figure 74. Rearward amplification, scenario 6.

this safety-related measure, the "Western Double" and the five-axle truck-full trailer continue to perform poorly. Also, the 81,500-lb (36,968 kg), five-axle TST (figure 56) has a rollover threshold lower than that of the "baseline" TST in scenario 1. Fewer axles resisting higher amounts of payload account for this trend. Otherwise, these vehicles remain relatively more stable in roll.

Steady Turn—Handling: The handling characteristics, that is, critical velocities and steering sensitivities, are displayed in figures 72 and 73. The vehicles with lower rollover thresholds are more difficult to handle in steady turns. For example, the 81,500-lb (36,968 kg) TST, discussed above, would be unstable at speeds over 82 mi/h (132 km/h). Also, the "Western Double" and the five-axle truck-full trailer have critical speeds of 31 mi/h (50 km/h) and 63 mi/h (101 km/h), respectively. Though the single-axle triple is fairly stable in roll, it would be difficult to handle at speeds over 49 mi/h (79 km/h). In this study, the load distribution on the two-axle tractor is partly responsible for the poor performance in this maneuver.

Obstacle Evasion: The rearward amplifications of the proposed vehicles are shown in figure 74. In the obstacle-avoidance maneuver, the triples would produce fairly high levels of rearward amplification. This is a result of the additional full trailer in the vehicle configuration. Short wheelbases, brought about by the need to reduce low-speed offtracking, increase the amount of rearward amplification. Consequently, the five-axle truck-full trailer (figure 59) performs poorly in such a maneuver. This "wheelbase-effect," therefore, helps doubles with long trailers be more controllable than similar vehicles with 28-ft (8.5 m) trailers.

# 9. VARIATIONS IN TIRES, BRAKES, AND SUSPENSIONS

As mentioned in the earlier scenarios, formula B has a decreasing weight return for every axle added to the vehicle. Consequently, many vehicles designed under formula B lead to relatively low individual axle loads. For example, in the previous section, the four-axle tractor and five-axle semitrailer (figure 58) carry only 11,120 lb (5,044 kg) on each of its semitrailer's axles. In the performance calculations, the vehicle's components, such as, brakes, suspensions, and tires, are selected based on axle loads of 17,000 lb (7,711 kg) for tandem axles and 20,000 lb (9,072 kg) for single axles. This results in an "over-compensation" by the components when axles are added to the vehicle layout. For example, in scenario 1, the multiaxle suspensions generate too much braking force and prematurely lock the wheels on some of the lightly loaded axles. Another result of this "overcompensation" is the improved rollover immunity due to added roll stiffnesses of the extra axles.

In this section, the performance calculations are based on components selected for the axle loads under consideration. In an attempt to emulate such a selection of components; parametric values for these components, such as brake gains for brakes, cornering stiffnesses for tires, and roll stiffnesses for suspensions, are adjusted according to the vehicle's load distribution. For example, scaling the components on the nine-axle TST (discussed above) with respect to a design load of 17,000 lb (7,711 kg) results in a 35 percent reduction from their original values. Five vehicles, selected from scenario 6 based on their low individual axle loads, are used as examples in this parameter variation study.

As a general rule, friction requirements and braking efficiencies improve with the load proportioning of the components. However, rollover threshold, high-speed offtracking, and rearward amplification are degraded by the scaling of the parameters. Handling, being a more complex issue, is more difficult to predict and depends upon the "front-to-rear" proportioning of the components.

*Safety and operational concerns*

The five vehicles selected for this analysis use multiaxle suspensions with relatively low individual axle loads. A representative vehicle is selected from each of the five "basic types" of configurations. The performance measures that are affected by the parameter variations are summarized in table 10. Vehicle codes and their GCW's are used to differentiate between the various vehicles and their axle layouts.

Friction Demand: Using "softer" tires instead of the "baseline" radials, the friction required during tight-turns decreases significantly. For example, the five-axle straight truck's (figure 54) tire/road friction requirements would decrease by almost 32 percent. The "softer" tires lessen the influence of large spreads between axles and reduce the turn-resisting moment of multiaxle suspensions. Consequently, a much lower level of tire/road friction is required to "scrub" these axles around a corner.

High-Speed Offtracking: "Softer" tires also require larger slip angles to resist the centrifugal motion of a vehicle in a high-speed turn. The lateral offsets of the various axles, that is, from the front axle, increase with increasing slip angles. Consequently, "softer" tires degrade the vehicle's high-speed offtracking performance. The almost 63% increase in the high-speed offtracking of the nine-axle double supports this tendency.

Constant Deceleration Braking: The scaling of brake parameters, with respect to the loaded vehicle's axle loads, is similar to the effects of a load-proportioning brake system. With higher brake forces on heavier axles and smaller brake forces on lighter axles, the probability of wheels locking up decreases substantially. The third and fourth items in table 10 contain the braking efficiencies of the empty and loaded vehicles with and without "load-proportioned" brakes. The improvements, especially in the case of the loaded vehicles, is fairly noticeable.

Steady Turn—Rollover: In the earlier scenarios, the addition of an axle increased the total roll stiffness of the vehicle. The two parameters that contribute to the vehicle's total roll stiffness are the vertical stiffness of the tires and the roll stiffnesses of the axles' suspensions. By scaling these parameters with respect to the lighter axle loads, the vehicle's rollover thresholds decrease. This is due to a lower amount of roll stiffness resisting the total weight of the vehicle. Though the vertical stiffnesses of the tires are not as significant as the roll stiffnesses of the suspensions, their combined effects degrade the vehicle's rollover immunity substantially. Though the reduction in the rollover threshold varies between 5 and 10 percent, these small perturbations cause significant safety implications.

Table 10. Summary of performance measures for parameter variations.

| Safety-related maneuver | Vehicle -> Vehicle Code -> Parameter Variation | Truck 5 | Tractor-semitrailer 4-S5 | Truck-full trailer 4-5 | Double 3-S2-4 | Triple 4-S4-7-7 |
|---|---|---|---|---|---|---|
| 1. Friction demand in a tight turn | None | 0.218 | 0.116 | 0.142 | 0.022 | 0.172 |
| | Tire cornering stiffness | 0.149 | 0.006 | 0.113 | 0.016 | 0.105 |
| 2. High-speed offtracking (ft) | None | 0.380 | 0.307 | 0.792 | 0.656 | 1.296 |
| | Tire cornering stiffness | 0.657 | 0.779 | 1.306 | 1.063 | 2.714 |
| 3. Braking efficiency 1 (Loaded) | None ; 0.2 g's | 0.825 | 0.889 | 0.842 | 0.905 | 0.910 |
| | ; 0.4 g's | 0.773 | 0.852 | 0.799 | 0.847 | 0.927 |
| | Brake gain; 0.2 g's | 0.879 | 0.957 | 0.949 | 0.915 | 0.924 |
| | ; 0.4 g's | 0.824 | 0.918 | 0.903 | 0.837 | 0.850 |
| 4. Braking efficiency 1 (Empty) | None ; 0.2 g's | 0.647 | 0.716 | 0.688 | 0.684 | 0.826 |
| | ; 0.4 g's | 0.595 | 0.694 | 0.660 | 0.642 | 0.788 |
| | Brake gain; 0.2 g's | 0.689 | 0.771 | 0.775 | 0.676 | 0.758 |
| | ; 0.4 g's | 0.634 | 0.748 | 0.747 | 0.634 | 0.719 |
| 5. Rollover threshold (g's) | None | 0.374 | 0.428 | 0.388 | 0.419 | 0.456 |
| | Suspension roll stiffness | 0.359 | 0.413 | 0.381 | 0.405 | 0.436 |
| | Tire vertical stiffness | 0.368 | 0.423 | 0.385 | 0.414 | 0.447 |
| | Roll & vertical stiffness | 0.354 | 0.407 | 0.377 | 0.399 | 0.426 |
| 6 Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | None | 0.304 | 0.126 | 0.188 | 0.149 | 0.140 |
| | Roll & vertical stiffness | 0.339 | 0.106 | 0.201 | 0.164 | 0.146 |
| | Tire cornering stiffness | 0.224 | 0.157 | 0.142 | 0.092 | 0.102 |
| | Roll, vertical & cornering stiffness | 0.254 | 0.134 | 0.152 | 0.106 | 0.109 |
| 7. Maximum rearward amplification | None | - | - | 1.326 | 1.510 | 3.261 |
| | Tire cornering stiffness | - | - | 1.446 | 1.804 | 6.143 |

Steady Turn—Handling: Vehicle handling is a more complex issue and depends primarily upon the vehicle's roll stability and its tire/load distribution. In addition to the roll stiffness parameters discussed above, the tire's sensitivity to load variations affects the vehicle's handling characteristics. The steering sensitivities, displayed in table 10, predict the margins of safety for the different vehicle configurations. In this maneuver, the tire's characteristics are critical in determining the vehicle's response in a steady-turning maneuver. Also, a decrease in the vehicle's roll resistance increases the possibility of yaw instabilities in this maneuver. With the exception of the TST configuration, the remaining vehicles would perform rather poorly with "softer" suspensions and tires. Addressing the anomaly in the TST configuration, the tractor carries a relatively light 8,500 lb (3,856 kg) load on its steering axle. Consequently, scaling the front axle's suspension and tire parameters, with respect to a design load of 12,000 lb (5,443 kg), results in a more controllable "understeer" situation. The "front-to-rear" load distribution, therefore, is important in determining the vehicle's handling characteristics in the steady turn.

Obstacle Evasion: With respect to rapid steering maneuvers, "softer" tires have a negative effect on the maneuvering performance of the vehicle. As mentioned earlier, "softer" tires require larger slip angles to generate the necessary forces to resist the lateral motion of the vehicle. Larger slip angles result in bigger offsets at the axles and lead to increased lateral displacements of the various units in a multiarticulated vehicle. This increase in lateral motion results in a higher amount of lateral acceleration, especially at the rear of the vehicle. This is evident in the seventh item of table 10 where the rearward amplification of the triple increases by 88 percent.

# 10. LOAD VARIATIONS

In addition to the parameter variations discussed in the previous chapter, the vehicles developed in scenario 6 are also subjected to a load variation study. The purpose of this evaluation is to reveal any safety-related difficulties arising from adverse loading conditions. In this study, the payload is placed forward (35 percent of container length) and rear (65 percent of container length) of the center of the trailer's container. To avoid overloading any of the axles, the amount of payload is reduced to 62.5 percent of its original value. The vehicle performance in braking, handling, and evasive maneuvers are calculated for the resulting matrix of loading states. The response time, defined as the time required for the towing unit to reach 90 percent of its steady-state lateral acceleration after crossing the "half-way" point in its steering maneuver, is also calculated for the various loading states.

Since the rearmost axles of a vehicle are most prone to locking up in a straight-line braking maneuver, heavier loads on these axles reduce the possibility of such an occurrence. The braking efficiencies would, therefore, improve with the payload located in the rear of the container instead of in the front. When compared with the forward loading situation, a rearward bias of the payload results in a lighter load on the tractor's drive axles, thereby, degrading the handling performance of the vehicle. From the rearward amplification viewpoint, the lighter payloads in the trailers decrease the vehicle's evasive maneuvering capabilities. In the partially loaded state, however, a rearward bias of the load would be more effective than a forward bias in decreasing the amount of rearward amplification.

*Safety and operational concerns*

Table 11 shows a summary of the performance characteristics for the load variations.

Constant Deceleration Braking: Due to the forward-pitching motion of a vehicle involved in a straight-line braking maneuver, the load on the rearmost axles of each unit tends to get lighter. With a forward bias of the payload, the loads on the critical axles, the rearmost ones, are reduced even further. With extremely light loads on these axles, the probability of a wheel locking up increases, thereby decreasing the braking efficiency. A rearward bias of the payload, however, increases the loads on the critical axles and reduces the rate at which the load is transferred to the leading axles of the vehicle. With heavier loads on the critical axles, a rearward bias of the payload improves the braking efficiency for the vehicle.

Steady Turn—Handling: As mentioned earlier, the vehicle's handling characteristics depend partly upon the "front-to-rear" load distribution on the towing unit. Since the tire's characteristics are load-sensitive, with its lateral force capabilities increasing with higher loads, heavy loads on the front axle and light loads on the rear axles would produce an "oversteer" condition in the towing unit. A rearward bias of the payload produces this effect, that is, it reduces the load on the rear axles of the towing unit. Consequently, a rearward bias of the payload reduces the vehicle's stability margin in a steady turn. This is evident in table 11 where the steering sensitivities decrease with a rearward-biased payload.

Obstacle Evasion: Since a rearward bias of the payload increases the loads on the rearmost axles of each unit, it increases the lateral force capabilities of the tires on those axles. "Stiffer" tires help decrease the lateral displacements of the various units and lead to smaller amounts of lateral acceleration. This reduces the amount of rearward amplification at the rear of the vehicle configuration. A forward bias of the payload would produce an opposite effect by "softening" the tires on the rearmost axles. This trend was discussed in the previous chapter where "softer" tires increased the amount of rearward amplification. Consequently, from the rearward amplification viewpoint, a rearward bias of the load would be more effective than a forward-biased load.

Response Times: The response time calculations are limited to TST's, truck-full trailers, and double-trailer configurations. Moreover, the calculations are restricted to vehicles with no more than four axles on their towing units. The response time is defined as the time taken for a vehicle to reach 90 percent of its steady-state lateral acceleration after it has performed 50 percent of its steering maneuver. Table 11 shows that a rearward bias of the payload increases the time taken for the vehicle to reach its steady state. Similar to the handling situation, the vehicle's response time depends upon the "front-to-rear" load distribution on the towing unit. In other words, light loads on the rear of the tractor reduce the lateral force capabilities of the tires on these axles. This effect would reduce the tractor's ability to generate the necessary lateral forces to execute the turning maneuver. Consequently, in a steady turn, a vehicle with a rearward-biased payload would take longer to reach its steady state than a vehicle with a forward-biased load.

Table 11. Summary of performance measures for load variations.

| Vehicle Configuration | Vehicle Code | Gross Combination Weight (GCW) | Payload Location | Braking Efficiency 0.2 g's | Braking Efficiency 0.4 g's | Handling Performance at 0.3 g's: Steering Sensitivity at 55 mi/h (radians/g) | Handling Performance at 0.3 g's: Critical Velocity (mph) | Rearward Amplification | Response Time (sec) |
|---|---|---|---|---|---|---|---|---|---|
| Straight truck | 5 | 48,691 lb | Front | 0.673 | 0.624 | 0.445 | - | - | - |
| | | | Rear | 0.910 | 0.861 | 0.177 | - | - | - |
| Tractor-semitrailer | 3-S2 | 59,056 lb | Front | 0.661 | 0.620 | 0.144 | - | - | 0.40 |
| | | | Rear | 0.632 | 0.590 | 0.076 | - | - | 0.48 |
| | 3-S2 | 62,297 lb | Front | 0.674 | 0.631 | 0.141 | - | - | 0.38 |
| | | | Rear | 0.615 | 0.573 | 0.061 | - | - | 0.46 |
| | 3-S3 | 67,804 lb | Front | 0.631 | 0.593 | 0.157 | - | - | 0.38 |
| | | | Rear | 0.633 | 0.604 | 0.068 | - | - | 0.52 |
| | 4-S5 | 79,648 lb | Front | 0.634 | 0.599 | 0.133 | - | - | - |
| | | | Rear | 0.711 | 0.701 | 0.078 | - | - | - |
| Truck-full trailer | 3-2 | 66,804 lb | Front | 0.575 | 0.500 | 0.291 | - | 2.67 | 0.59 |
| | | | Rear | 0.705 | 0.689 | 0.123 | - | 2.37 | 0.80 |
| | 4-5 | 88,529 lb | Front | 0.591 | 0.551 | 0.271 | - | 1.83 | - |
| | | | Rear | 0.653 | 0.654 | 0.142 | - | 1.94 | - |
| Double | 2-S1-2 | 66,667 lb | Front | 0.558 | 0.486 | Liftoff | - | 1.45 | 0.50 |
| | | | Rear | 0.717 | 0.699 | 0.058 | - | 1.37 | 0.76 |
| | 3-S2-4 | 83,064 lb | Front | 0.610 | 0.538 | 0.144 | - | 1.71 | 0.42 |
| | | | Rear | 0.624 | 0.611 | 0.091 | - | 1.47 | 0.51 |
| | 3-S2-4 | 89,390 lb | Front | 0.650 | 0.592 | 0.144 | - | 1.40 | 0.42 |
| | | | Rear | 0.596 | 0.567 | 0.085 | - | 1.24 | 0.50 |
| | 3-S2-4 | 89,168 lb | Front | 0.638 | 0.568 | 0.123 | - | 1.61 | 0.46 |
| | | | Rear | 0.665 | 0.690 | 0.084 | - | 1.44 | 0.50 |
| Triple | 2-S1-2-2 | 88,124 lb | Front | 0.604 | 0.526 | 0.088 | - | 2.79 | - |
| | | | Rear | 0.622 | 0.595 | 0.066 | - | 2.26 | - |
| | 4-S4-7-7 | 161,886 lb | Front | 0.695 | 0.627 | 0.134 | - | 4.68 | - |
| | | | Rear | 0.537 | 0.574 | 0.006 | 59.00 | 3.87 | - |

# 11. SCENARIO 7 — NO WEIGHT CAP, FORMULA TTI, AND AN OFFTRACKING LIMIT

## Vehicle Design

*Definition of the constraints on vehicle design*

The constraints governing this scenario are

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | TTI |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems;<br>20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

The constraints in this scenario are very similar to those discussed in scenario 6. With the exception of the bridge formula, the vehicles are governed by the same length and pavement rules. Also, the proposed vehicles are based on the five "basic types" of configurations, that is, straight trucks, tractor-semitrailers, truck-full trailers, doubles, and triples.

As discussed in scenario 3, formula TTI is a "length-to-weight" rule which does not provide allowances for additional axles. Instead, it encourages fewer axles with longer distances between axle locations. For lengths less than 56 ft (17 m), formula TTI provides a 1,000-lb (454 kg) weight allowance for every additional foot (0.3 m) of distance between consecutive axles. For example, increasing the distance between the tractor's and the trailer's axles would result in a higher permissible GCW for the vehicle. This increase in length, however, would increase the effective wheelbase of the trailer, thereby increasing the amount of low-speed offtracking. With the "offtracking rule" in effect, there is a greater incentive for the vehicle to have more articulation joints and shorter individual wheelbases. While the bridge formula encourages longer wheelbases, the length rule promotes the opposite effect. In restricting the vehicle, therefore, the length and bridge formula constraints tend to produce opposing trends.

In scenario 6, additional axles were used to shorten the wheelbases of long units. For example, an extra axle would reduce the unit's wheelbase by half of the spread between the axles. Further, formula B encouraged the use of extra axles by providing weight allowances for each additional axle. Under formula TTI, however, an extra axle would be unproductive since its tare weight would displace an equivalent amount of payload. Under the assumptions of the "offtracking rule," spreading the axles in a suspension produces the same effect as adding an axle to the suspension, that is, it reduces the unit's wheelbase. By moving the center of the suspension closer to the front of the unit, wide spreads between axles could help reduce the wheelbases of long units. Consequently, wide-spread axles can be used to optimize both length and bridge formula constraints.

In summary, the two dominant constraints in this scenario, formula TTI and the "offtracking rule," augment each other and encourage long vehicles with wide spreads between their axle placements. In other words, this scenario is very similar to scenario 6 where the constraints are not sufficient to prevent the development of extremely long vehicles.

*Example vehicles*

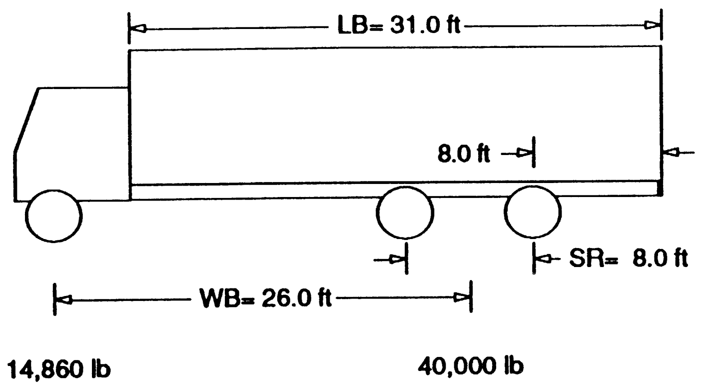
Straight Trucks: In the case of the straight truck, the 40-ft (12 m) overall length restriction is an indirect constraint on its load-carrying capacity. With no weight allowances for additional axles and accounting for 2-ft (0.6 m) offsets at the front and rear of the vehicle (a 2-ft (0.6 m) front-axle setback and a 2-ft (0.6 m) overhang), formula TTI allows a maximum GCW of 70,000 lb (31,752 kg) for the 36-ft (11 m) length. Since the pavement loading constraint is more restrictive than the bridge formula, especially for shorter vehicles, the vehicle's GCW is reduced even further. A proposed design, with wide-spread axles on the rear suspension (figure 75), is allowed to weigh 54,860 lb (24,884 kg). To avoid the axle-loading constraint of the pavement rule, a tridem-axle suspension is used in the second vehicle design shown in figure 76. The four-axle vehicle weighs 60,400 lb (27,397 kg) and is allowed to carry approximately the same payload weight as the five-axle straight truck in scenario 6 (figure 54).

Tractor-Semitrailers: The first two TST examples in scenario 6 (figure 55 and 56) also satisfy the constraints in this scenario. Their axle layouts and load distributions are repeated in figures 77 and 78. Since these vehicles are variations of STAA vehicles, they are included as examples in this scenario.

Increasing the vehicle's payload volume by using longer container lengths, a TST with wide-spread axles, on both tractor and trailer, is shown in figure 79. The vehicle, with a 50-ft (15 m) semitrailer, satisfies the offtracking rule and is allowed to weigh 85,900 lb (38,964 kg). Though the wide-spread tandems are treated as pairs of single axles, each with load-carrying capacities of 40,000 lb (18,144 kg), the pavement rule continues to be more restrictive than the bridge formula and limits the vehicle's total weight. Using tridem axles to assist in meeting the pavement rule, the same vehicle (figure 80) is allowed to weigh 89,455 lb (40,576 kg). The increase in the vehicle's GCW, however, is offset by a corresponding increase in the vehicle's tare weight. In other words, the additional axles displace an equivalent amount of payload and do not generate any appreciable gains in payload weight capacity.

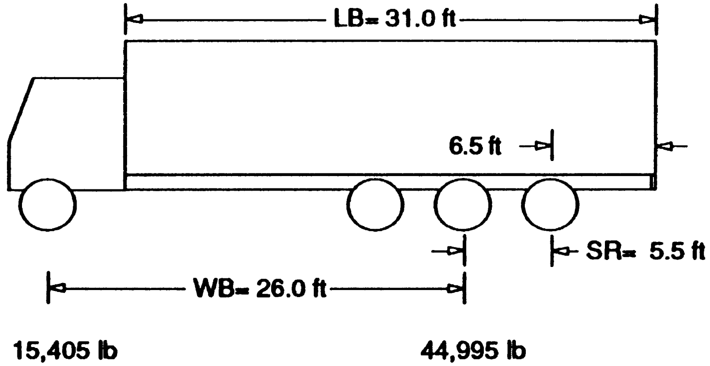
The fifth TST example is a vehicle design first proposed in scenario 6 (figure 57). The 52-ft (16 m) trailer with wide-spread tridem axles is shown again in figure 81. The vehicle satisfies the length and weight rules of this scenario and weighs 88,500 lb (40,143 kg).

Truck-Full trailers: Two truck-full trailer designs (figures 82 and 83) are presented in this scenario . Both vehicles use tandem axles on long dollies and trailers to be able to reach the higher gross combination weights. The first layout (figure 82) uses a 16.5-ft (5



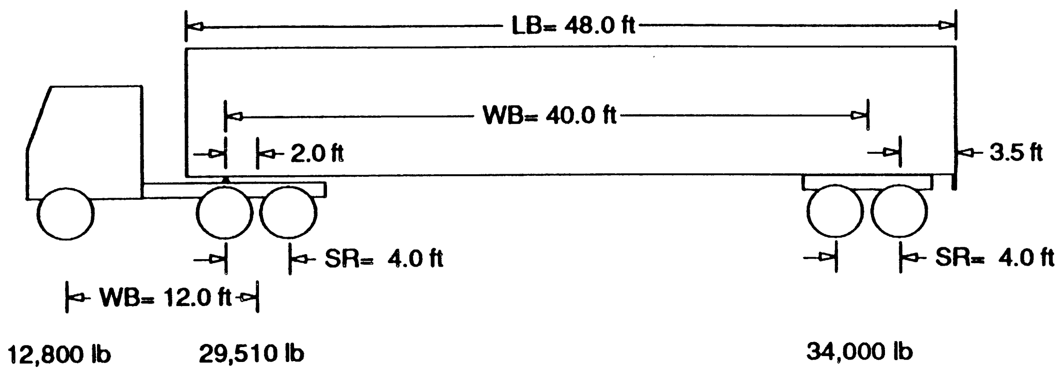

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 8.0 ft | .0 ft | 1. | 8.0 ft | 2. | 36860. lb | 31.0 ft | .0 ft |

Figure 75. Straight truck (3; GCW=54,860 lb; payload=31,350 lb).



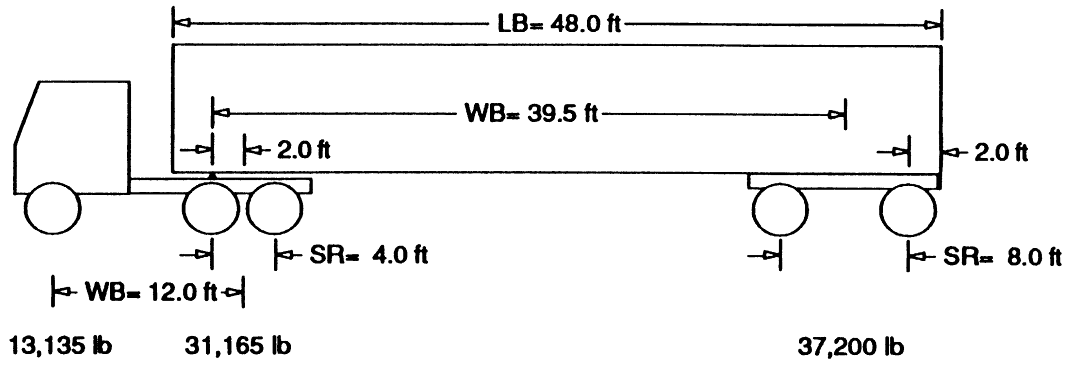

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 6.5 ft | .0 ft | 1. | 5.5 ft | 3. | 40900. lb | 31.0 ft | .0 ft |

Figure 76. Straight truck (4; GCW=60,400 lb; payload=35,390 lb).



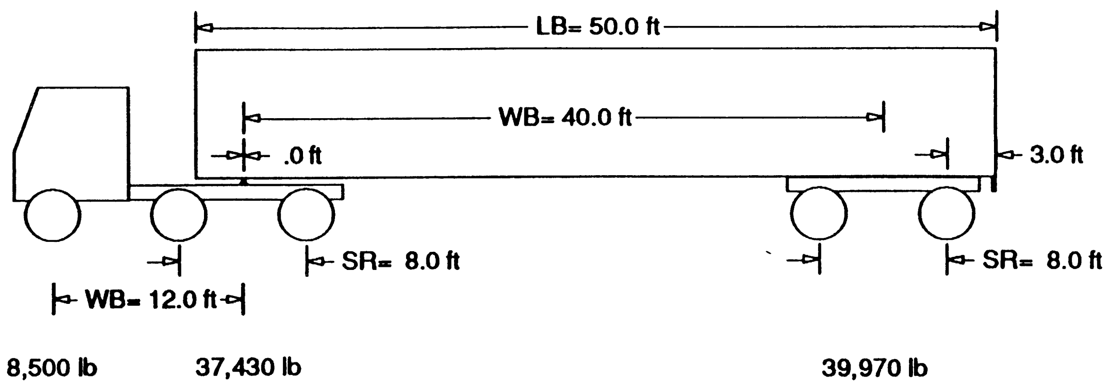

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 3.5 ft | .0 ft | 0. | 4.0 ft | 2. | 55810. lb | 48.0 ft | .0 ft |

Figure 77. Tractor-semitrailer (3-S2; GCW=76,310 lb; payload=46,010 lb).



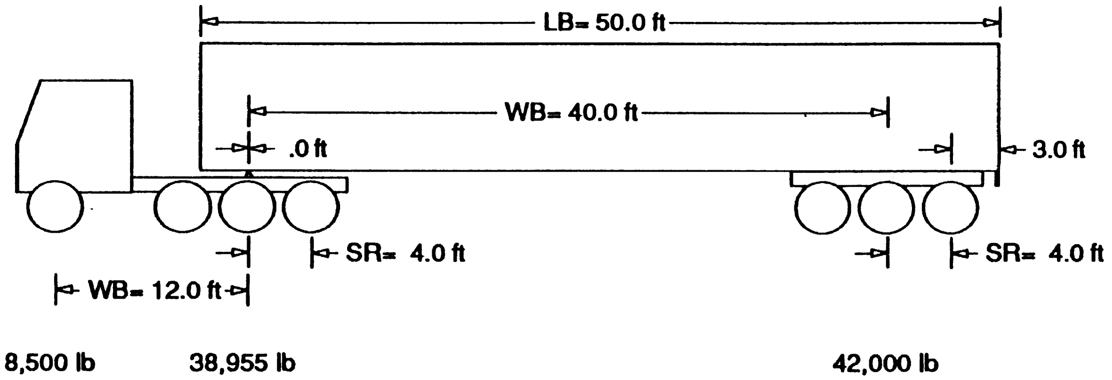

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 8.0 ft | 2. | 60995. lb | 48.0 ft | .0 ft |

Figure 78. Tractor-semitrailer (3-S2; GCW=81,500 lb; payload=51,200 lb).



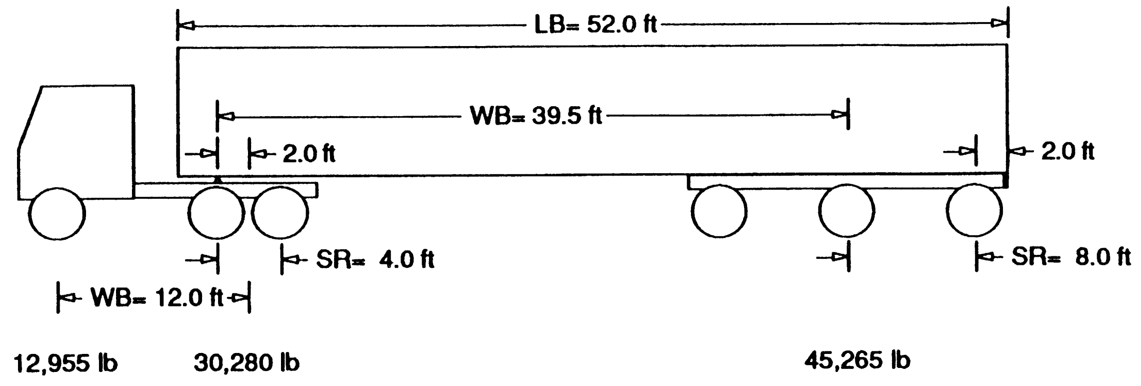

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 8.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 3.0 ft | .0 ft | 0. | 8.0 ft | 2. | 65400. lb | 50.0 ft | .0 ft |

Figure 79. Tractor-semitrailer (3-S2; GCW=85,900 lb; payload=55,095 lb).



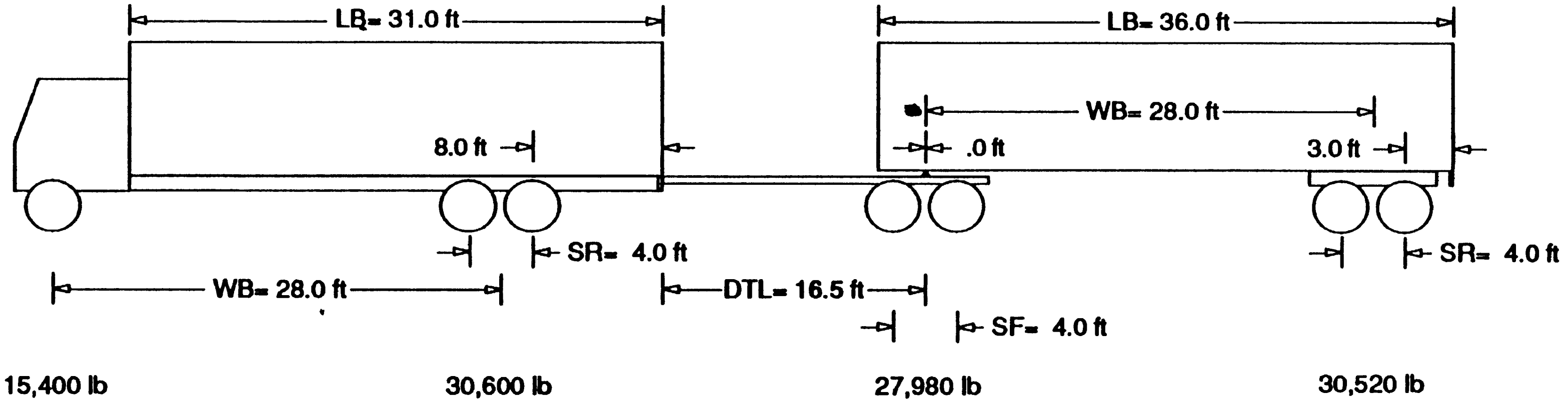

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 3.0 ft | .0 ft | 0. | 4.0 ft | 3. | 65455. lb | 50.0 ft | .0 ft |

Figure 80. Tractor-semitrailer (4-S3; GCW=89,455 lb; payload=55,150 lb).



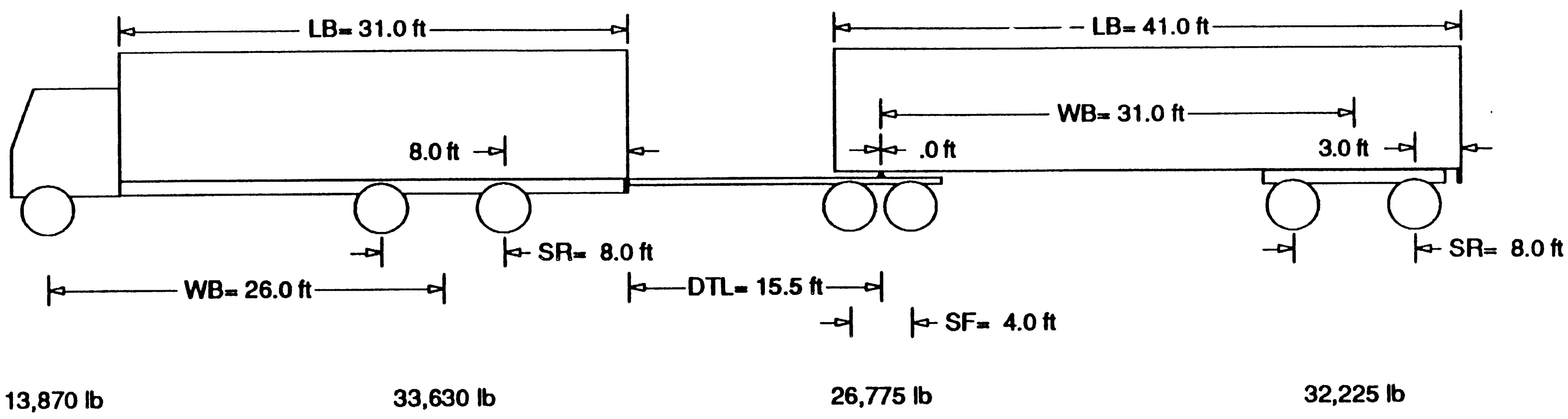

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 39.5 ft | 2.0 ft | .0 ft | 0. | 8.0 ft | 3. | 66000. lb | 52.0 ft | .0 ft |

Figure 81. Tractor-semitrailer (3-S3; GCW=88,500 lb; payload=55,190 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 28.0 ft | 8.0 ft | .0 ft | 1. | 4.0 ft | 2. | 28000. lb | 31.0 ft | .0 ft |
| full trailer | 28.0 ft | 3.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 49500. lb | 36.0 ft | 16.5 ft |

Figure 82. Truck-full trailer (3-4; GCW=104,500 lb; payload=65,219 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 8.0 ft | .0 ft | 1. | 8.0 ft | 2. | 29500. lb | 31.0 ft | .0 ft |
| full trailer | 31.0 ft | 3.0 ft | 4.0 ft | 2. | 8.0 ft | 2. | 50000. lb | 41.0 ft | 15.5 ft |

Figure 83. Truck-full trailer (3-4; GCW=106,500 lb; payload=65,957 lb).

m) dolly and a 36-ft (11 m) trailer to reach a GCW of 104,500 lb (47,400 kg). The second layout (figure 83) uses a 15.5-ft (4.7 m) dolly and a 41-ft (13 m) trailer to reach 106,500 lb (32,461 kg). Though the second vehicle uses a long dolly and trailer, it uses wide-spread axles to satisfy the "offtracking rule." With formula TTI becoming increasingly restrictive at lengths over 56 ft (17 m), the second vehicle is only allowed an additional 500 lb (227 kg) of payload weight. In addition to the restriction of the bridge formula, the increased tare weight of the longer vehicle is responsible for the reduction in payload-carrying capacity.

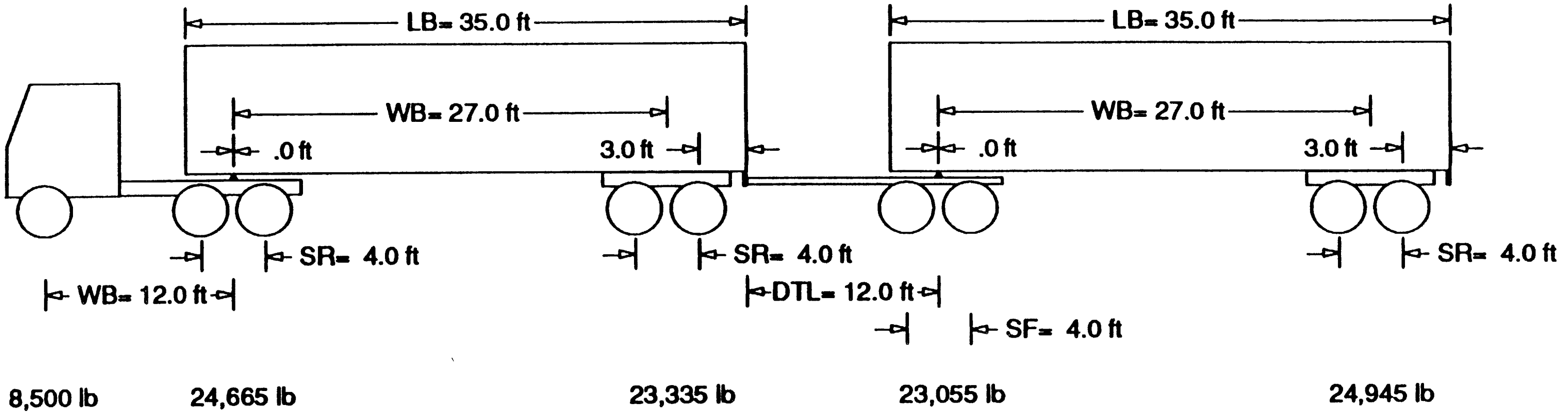
Doubles: Three double-trailer configurations, with varying trailer lengths, are presented in figures 84, 85, and 86. The vehicle configuration in figure 84 uses 35-ft (11 m) trailers and a 12-ft (3.7 m) dolly to achieve a GCW of 104,500 lb (47,400 lb). The second layout uses shorter trailers (31 ft (9.5 m)) but a longer dolly (23 ft (7 m)) to reach a higher weight of 106,000 lb (48,081 kg). Though the increase in the vehicle's GCW might not seem significant, the lower tare weight, resulting from shorter trailers, leads to a higher payload weight capacity. Operators hauling dense cargo might find this vehicle design to be more productive than the layout in figure 84. The third design uses even longer trailers (37 ft (11 m)) with wide-spread axles to reach a GCW of 107,000 lb (48,543 kg). As mentioned earlier, the wide-spread axles are used to shorten the wheelbases of the trailers. Though the vehicle has more volume available for cargo , the increased tare weight reduces its payload weight capacity.

Triples: A triple-trailer configuration, with STAA-regulated trailers, is shown in figure 87. The same vehicle was presented in scenario 6 (figure 65) and was allowed a GCW of 116,850 lb (53,002 kg). In this scenario, however, formula TTI restricts the vehicle's total weight to 111,500 lb (50,576 kg). Another layout, with shorter trailers (26 ft (7.9 m)), but with longer dollies (14 ft (4.3 m)), is shown in figure 88. The vehicle measures 106 ft (32 m) between extreme axles and is allowed to weigh 115,000 lb (52,163 kg).

Vehicle and axle layout information for the vehicles developed in this scenario is summarized in table 12.

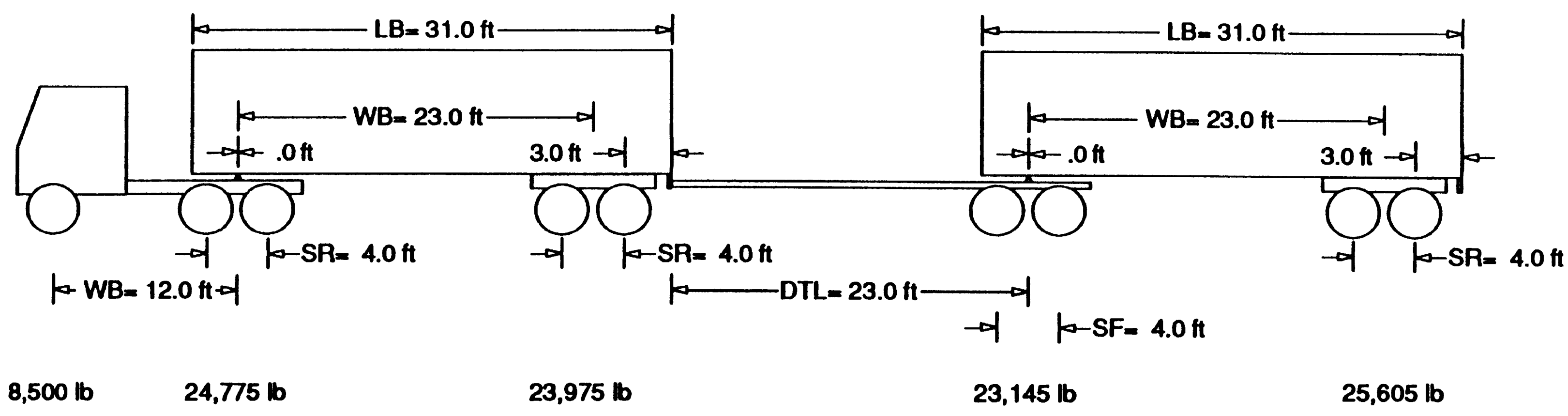
*What kind of vehicles would be promoted*

A wide variety of vehicles are possible in each of the five basic configurations. With no formal constraint on trailer lengths, LTL operators would benefit from being able to use longer trailers. For bulk haulers, however, the permissible GCW's are not as high as under formula B, especially for the longer doubles and triples. Consequently, haulers of heavy objects might still find TST's, with spread axles, to be a viable alternative. To reach the higher GCW's, longer trailers and dollies, with wide-spread axles on the various units, could become popular under the given set of constraints.



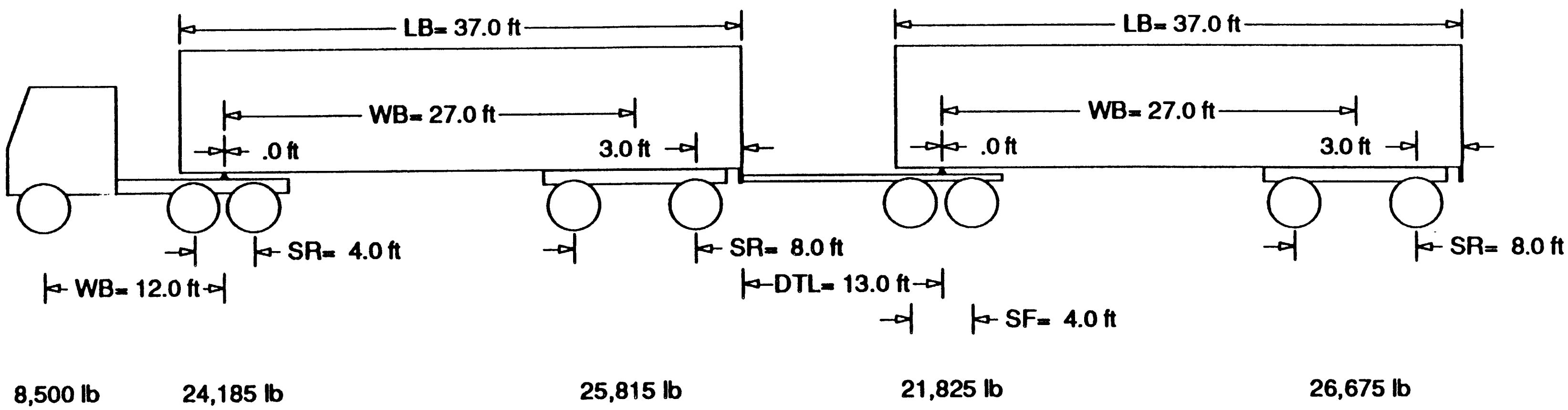

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 27.0 ft | 3.0 ft | .0 ft | 0. | 4.0 ft | 2. | 36000. lb | 35.0 ft | .0 ft |
| full trailer | 27.0 ft | 3.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 39000. lb | 35.0 ft | 12.0 ft |

Figure 84. Double (3-S2-4; GCW=104,500 lb; payload=61,962 lb).



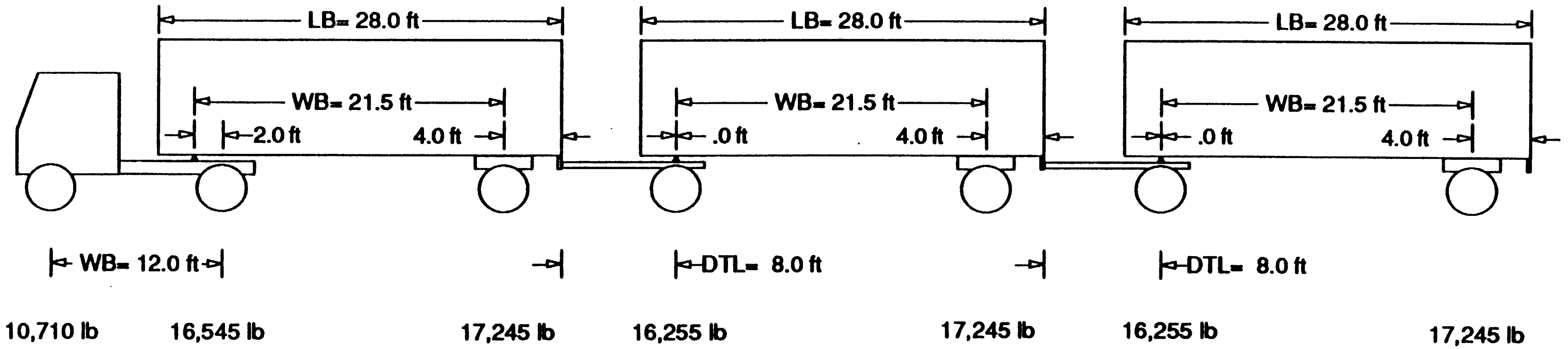

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 23.0 ft | 3.0 ft | .0 ft | 0. | 4.0 ft | 2. | 36750. lb | 31.0 ft | .0 ft |
| full trailer | 23.0 ft | 3.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 39750. lb | 31.0 ft | 23.0 ft |

Figure 85. Double (3-S2-4; GCW=106,000 lb; payload=65,481 lb).



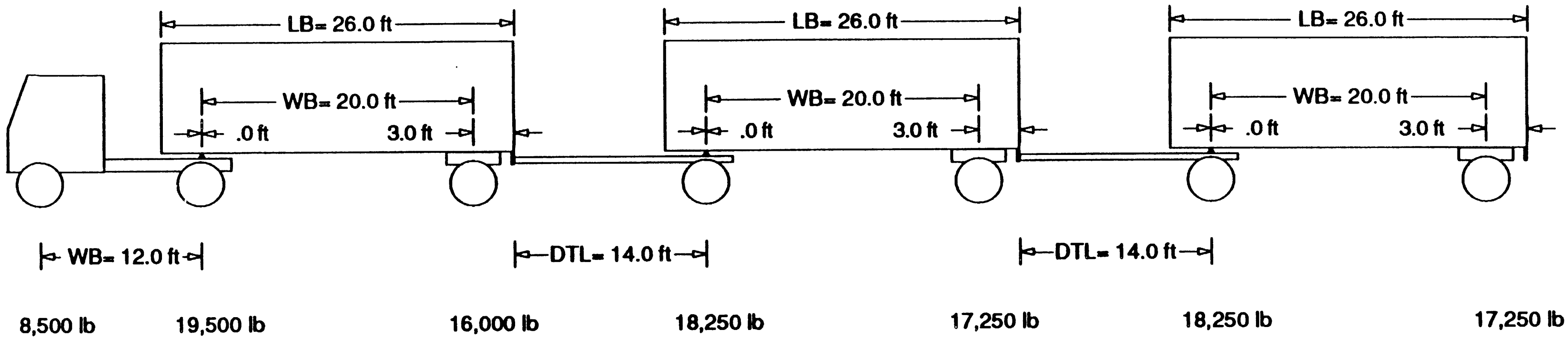

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 27.0 ft | 3.0 ft | .0 ft | 0. | 8.0 ft | 2. | 38000. lb | 37.0 ft | .0 ft |
| full trailer | 27.0 ft | 3.0 ft | 4.0 ft | 2. | 8.0 ft | 2. | 39500. lb | 37.0 ft | 13.0 ft |

Figure 86. Double (3-S2-4; GCW=107,000 lb; payload=63,452 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 21.5 ft | 4.0 ft | .0 ft | 0. | .0 ft | 1. | 28500. lb | 28.0 ft | .0 ft |
| full trailer | 21.5 ft | 4.0 ft | .0 ft | 1. | .0 ft | 1. | 28500. lb | 28.0 ft | 8.0 ft |
| full trailer | 21.5 ft | 4.0 ft | .0 ft | 1. | .0 ft | 1. | 28500. lb | 28.0 ft | 8.0 ft |

Figure 87. Triple (2-S1-2-2; GCW=111,500 lb; payload=71,243 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | .0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 20.0 ft | 3.0 ft | .0 ft | 0. | .0 ft | 1. | 28000. lb | 26.0 ft | .0 ft |
| full trailer | 20.0 ft | 3.0 ft | .0 ft | 1. | .0 ft | 1. | 30500. lb | 26.0 ft | 14.0 ft |
| full trailer | 20.0 ft | 3.0 ft | .0 ft | 1. | .0 ft | 1. | 30500. lb | 26.0 ft | 14.0 ft |

Figure 88. Triple (2-S1-2-2; GCW=115,000 lb; payload=76,257 lb).

Table 12. Summary of example vehicles for scenario 7.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Straight truck | 3 | 23,510 lb | 54,860 lb | 31,350 lb | 2,372 | 30.0 ft | 3 |
| Straight truck | 4 | 25,010 lb | 60,400 lb | 35,390 lb | 2,372 | 31.5 ft | 4 |
| Tractor-semitrailer | 3-S2 | 30,300 lb | 76,310 lb | 46,010 lb | 3,672 | 52.0 ft | 5 |
| Tractor-semitrailer | 3-S2 | 30,300 lb | 81,500 lb | 51,200 lb | 3,672 | 53.5 ft | 5 |
| Tractor-semitrailer | 3-S2 | 30,805 lb | 85,900 lb | 55,095 lb | 3,825 | 56.0 ft | 5 |
| Tractor-semitrailer | 4-S3 | 34,305 lb | 89,455 lb | 55,150 lb | 3,825 | 56.0 ft | 7 |
| Tractor-semitrailer | 3-S3 | 33,310 lb | 88,500 lb | 55,190 lb | 3,978 | 57.5 ft | 6 |
| Truck-full trailer | 3-4 | 39,281 lb | 104,500 lb | 65,219 lb | 5,126 | 84.5 ft | 7 |
| Truck-full trailer | 3-4 | 40,543 lb | 106,500 lb | 65,957 lb | 5,508 | 88.5 ft | 7 |
| Double | 3-S2-4 | 42,538 lb | 104,500 lb | 61,962 lb | 5,355 | 85.0 ft | 9 |
| Double | 3-S2-4 | 40,519 lb | 106,000 lb | 65,481 lb | 4,743 | 88.0 ft | 9 |
| Double | 3-S2-4 | 43,548 lb | 107,000 lb | 63,452 lb | 5,661 | 90.0 ft | 9 |
| Triple | 2-S1-2-2 | 40,257 lb | 111,500 lb | 71,243 lb | 6,426 | 98.5 ft | 7 |
| Triple | 2-S1-2-2 | 38,743 lb | 115,000 lb | 76,257 lb | 5,967 | 106.0 ft | 7 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

## Vehicle Performance

### *Performance summary*

The performance characteristics of the vehicles developed in this scenario are summarized in table 13. The graphical representations of the various rows of the table are contained in figures 89 through 96.

### *Safety and operational concerns*

Low-Speed Offtracking: Since the vehicles in this scenario are constrained by the "offtracking rule," their offtracking amounts would be equivalent to that of a 12-ft (3.7 m) tractor towing a 40-ft (12 m) semitrailer. The offtracking results of the proposed vehicles are shown in figure 89.

Friction Demand: Figure 90 contains the friction requirements of the proposed vehicles in this scenario. The straight truck examples, with their short wheelbases and wide-spread axles, would require relatively high levels of tire/road friction. Wide-spread axles in some of the other layouts, especially the six-axle TST in figure 81, and the double in figure 86, could reduce the vehicles' maneuverability on slippery surfaces.

High-Speed Offtracking: With a greater incentive to develop longer vehicles, the high-speed offtracking of these vehicles could suffer. Figure 91 contains the high-speed offtracking results for this scenario. Due to the longer lengths, the two triples have offtracking amounts greater than 1 ft (0.3 m). The remaining vehicles, especially the longer truck-full trailers and doubles, also have relatively high offtracking amounts.

Constant Deceleration Maneuver: Figure 92 pertains to the braking performance of the vehicles developed in this scenario. Fewer axles in the layouts improve the vehicles' braking performance. The straight-truck and truck-full trailer examples, however, perform rather poorly, especially in the empty state. In the case of the extremely long triple, short wheelbases on the trailers increase the amount of "rear-to-front" load transfer, thereby reducing the vehicle's braking efficiency. In the loaded state, the vehicles perform slightly better, with only the four-axle straight truck being less than 80 percent efficient in a 0.4 g's stop.

Steady Turn—Rollover: Figure 93 contains the rollover threshold results for this scenario. Again, fewer axles in the vehicle layouts decrease the total amount of roll stiffness in the proposed designs. This reduces the roll stability of the straight truck and truck-full trailer configurations. In the case of the TST's, extra axles, encouraged by the pavement rule, help increase the levels of roll stability. Since the bridge formula gets extremely restrictive at lengths over 56 ft (17 m), doubles and triples are limited to lower GCW's. Smaller amounts of payload, reacting with the roll stiffnesses of the axles, increase the rollover thresholds of the longer vehicles. Compared with the tandem-axle doubles, however, fewer axles in the triple-trailer combinations reduce the rollover thresholds for the proposed vehicles.

Table 13. Summary of performance measures for example vehicles (scenario 7).

| | Truck | | Tractor-semitrailer | | | | | Truck-full trailer | | Double | | | Triple | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Code | 3 | 4 | 3-S2 | 3-S2 | 3-S2 | 4-S3 | 3-S3 | 3-4 | 3-4 | 3-S2-4 | 3-S2-4 | 3-S2-4 | 2-S1-2-2 | 2-S1-2-2 |
| Gross Combination Weight (GCW) | 54,860 lb | 60,400 lb | 76,310 lb | 81,500 lb | 85,900 lb | 89,455 lb | 88,500 lb | 104,500 lb | 106,500 lb | 104,500 lb | 106,000 lb | 107,000 lb | 111,500 lb | 115,000 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | 7.76 | 7.76 | 16.51 | 16.23 | 16.55 | 16.55 | 16.55 | **17.59*** | **17.46*** | **17.39*** | **17.46*** | **17.45*** | 16.98 | **17.85*** |
| 2. Friction demand in a tight turn | 0.13* | 0.19* | 0.01* | 0.04* | 0.04* | 0.03* | 0.15* | 0.02* | 0.13* | 0.01* | 0.02* | 0.06* | 0.00 | 0.00 |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.521* | 0.451* | 0.296* | 0.346* | 0.439* | 0.322* | 0.393* | 0.835* | 0.944* | 0.806* | 0.865* | 0.909* | **1.207*** | **1.304*** |
| 4. Braking efficiency 1 (Loaded) | | | | | | | | | | | | | | |
| - 0.2 g's | 0.912 | 0.855* | 0.860* | 0.851* | 0.929 | 0.939 | 0.925 | 0.904 | 0.846* | 0.954 | 0.947 | 0.892 | 0.945 | 0.888 |
| - 0.4 g's | 0.851 | 0.799* | 0.818* | 0.809* | 0.948 | 0.909 | 0.885 | 0.851 | 0.854 | 0.907 | 0.896 | 0.900 | 0.864 | 0.817* |
| 5. Braking efficiency 1 (Empty) | | | | | | | | | | | | | | |
| - 0.2 g's | **0.685** | **0.663*** | **0.686** | **0.691** | 0.704 | 0.730 | **0.679** | **0.612*** | **0.668*** | 0.726 | 0.706 | 0.761 | **0.699** | **0.655*** |
| - 0.4 g's | **0.641*** | **0.624*** | **0.658** | **0.662** | **0.676** | 0.704 | **0.653** | **0.577*** | **0.634*** | **0.689** | **0.665** | 0.722 | **0.647** | **0.601*** |
| 6. Rollover threshold (g's) | **0.326*** | **0.350*** | 0.381 | **0.370*** | 0.382 | 0.423 | 0.428 | **0.339*** | **0.350*** | 0.432 | 0.430 | 0.427 | 0.389 | 0.381 |
| 7.a. Critical speed at 0.3 g's (mi/h) | **22.96*** | None | None | **81.61*** | **34.01*** | None | None | None | **66.59*** | None | None | None | **63.93*** | **47.81*** |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | **< 0** | 0.188 | **0.072** | **0.033*** | **< 0** | **0.083** | 0.104 | 0.152 | **0.040*** | **0.092** | **0.090** | **0.084** | **0.015*** | **< 0** |
| 8. Maximum rearward amplification | - | - | - | - | - | - | - | **1.733*** | **1.577*** | 1.368* | **1.542*** | **1.432*** | **2.733*** | **2.881*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

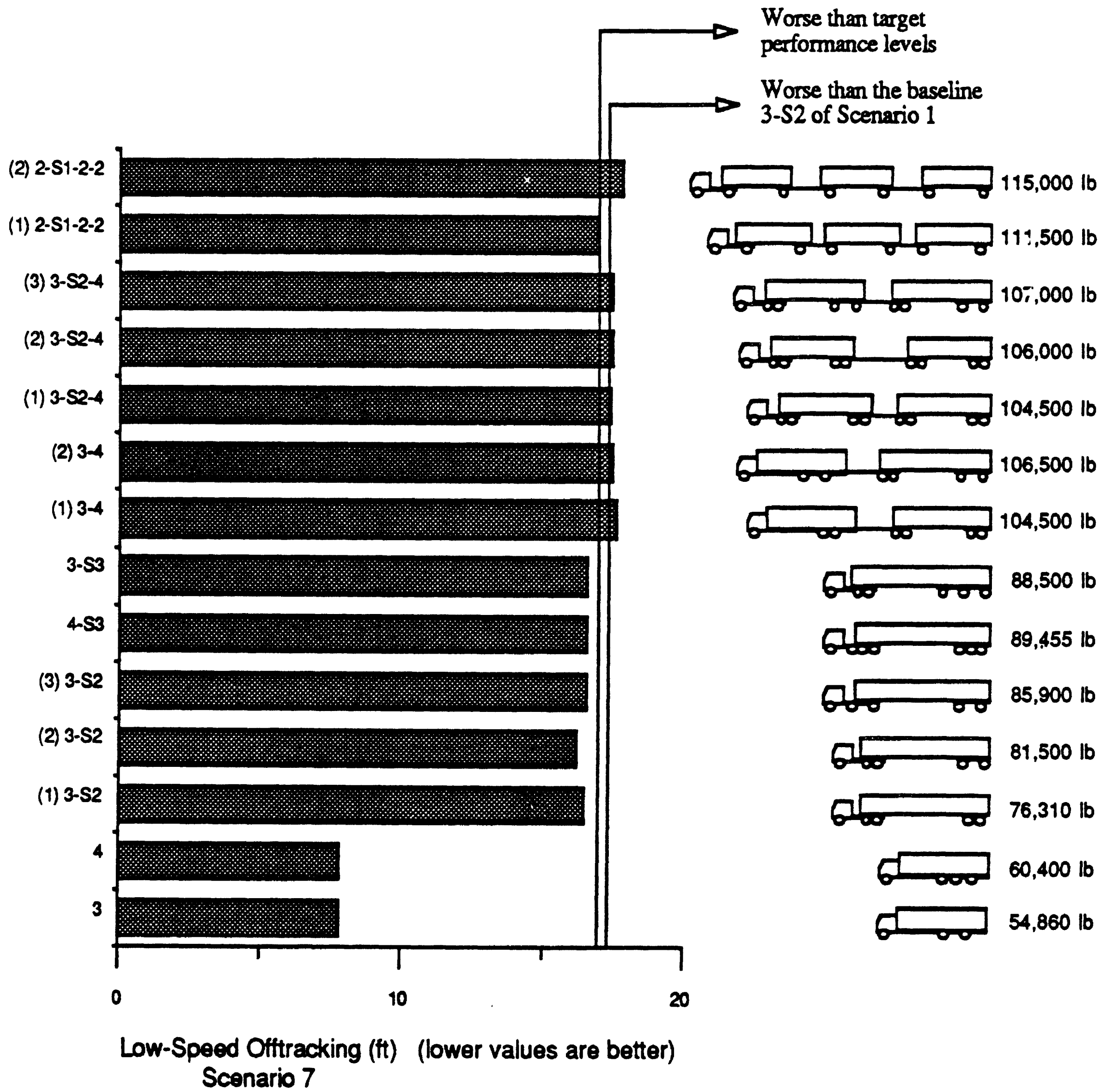



Figure 89. Low-speed offtracking, scenario 7.

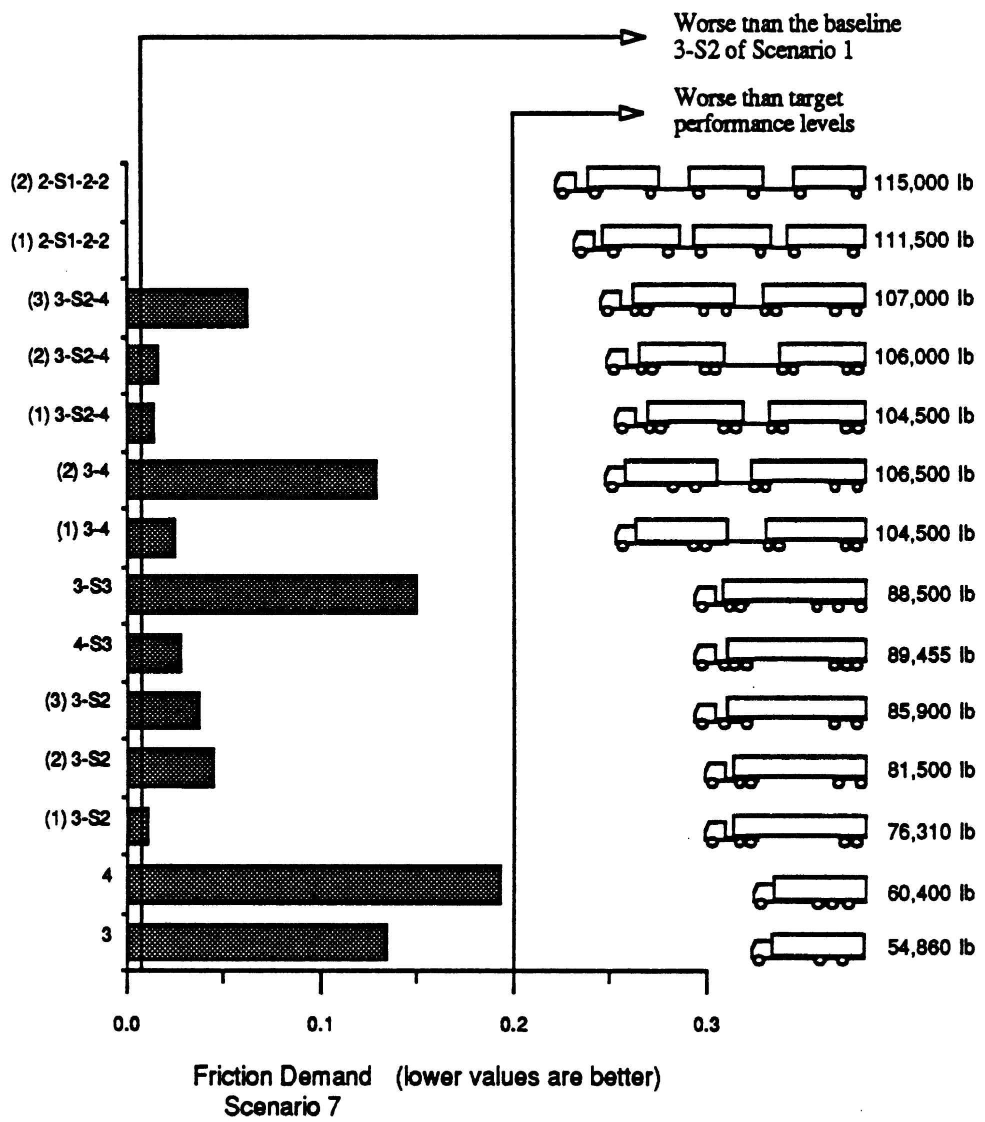



Figure 90. Friction demand, scenario 7.

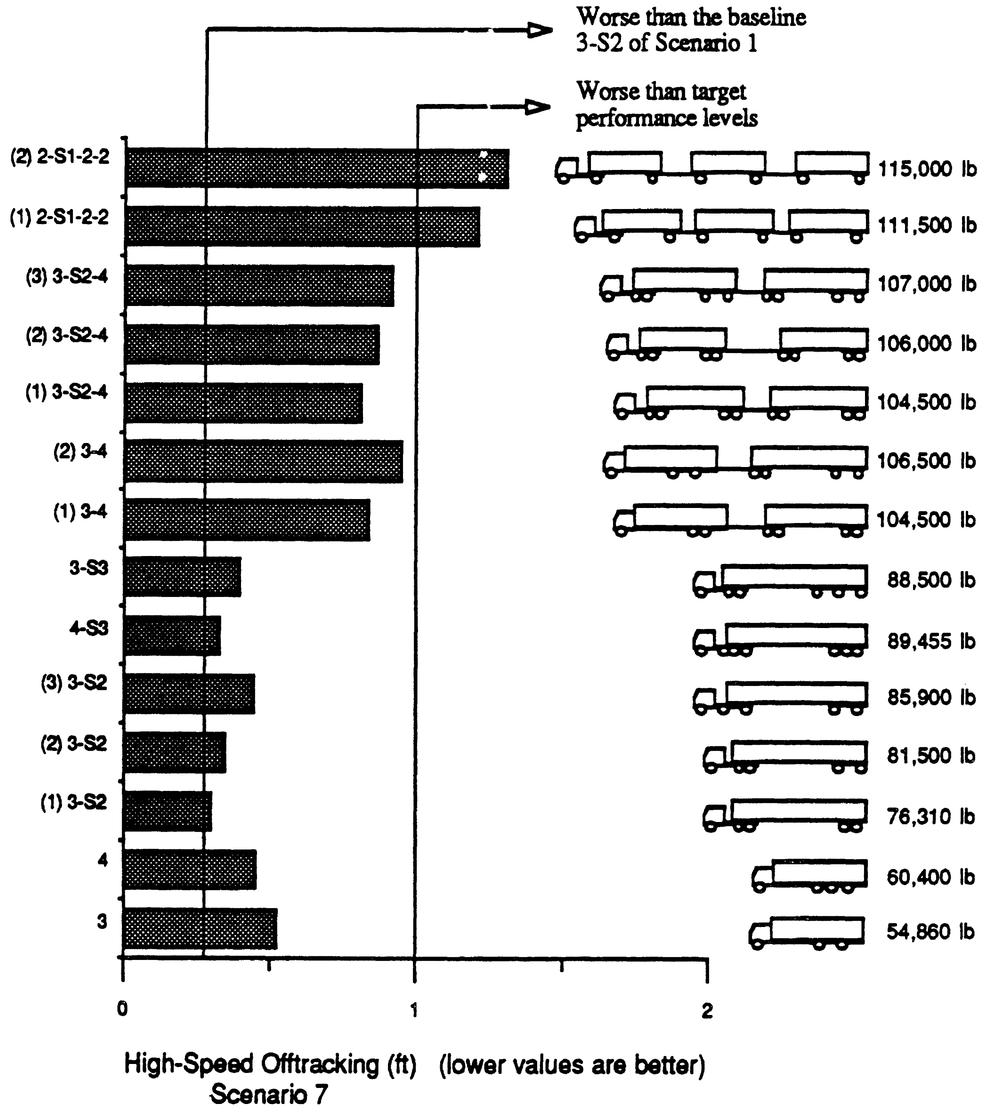



Figure 91. High-speed offtracking, scenario 7.

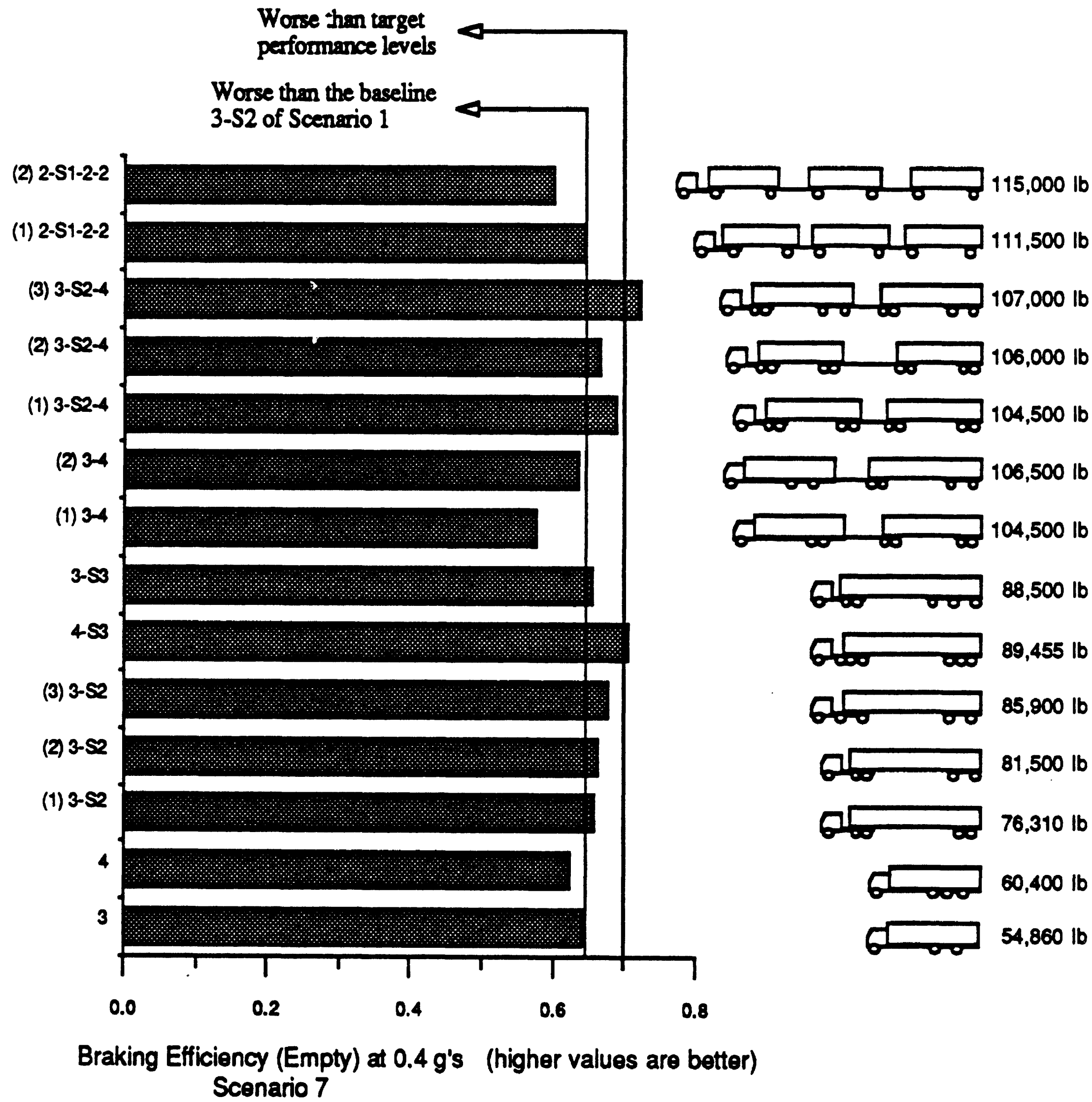



Figure 92. Braking efficiency, scenario 7.

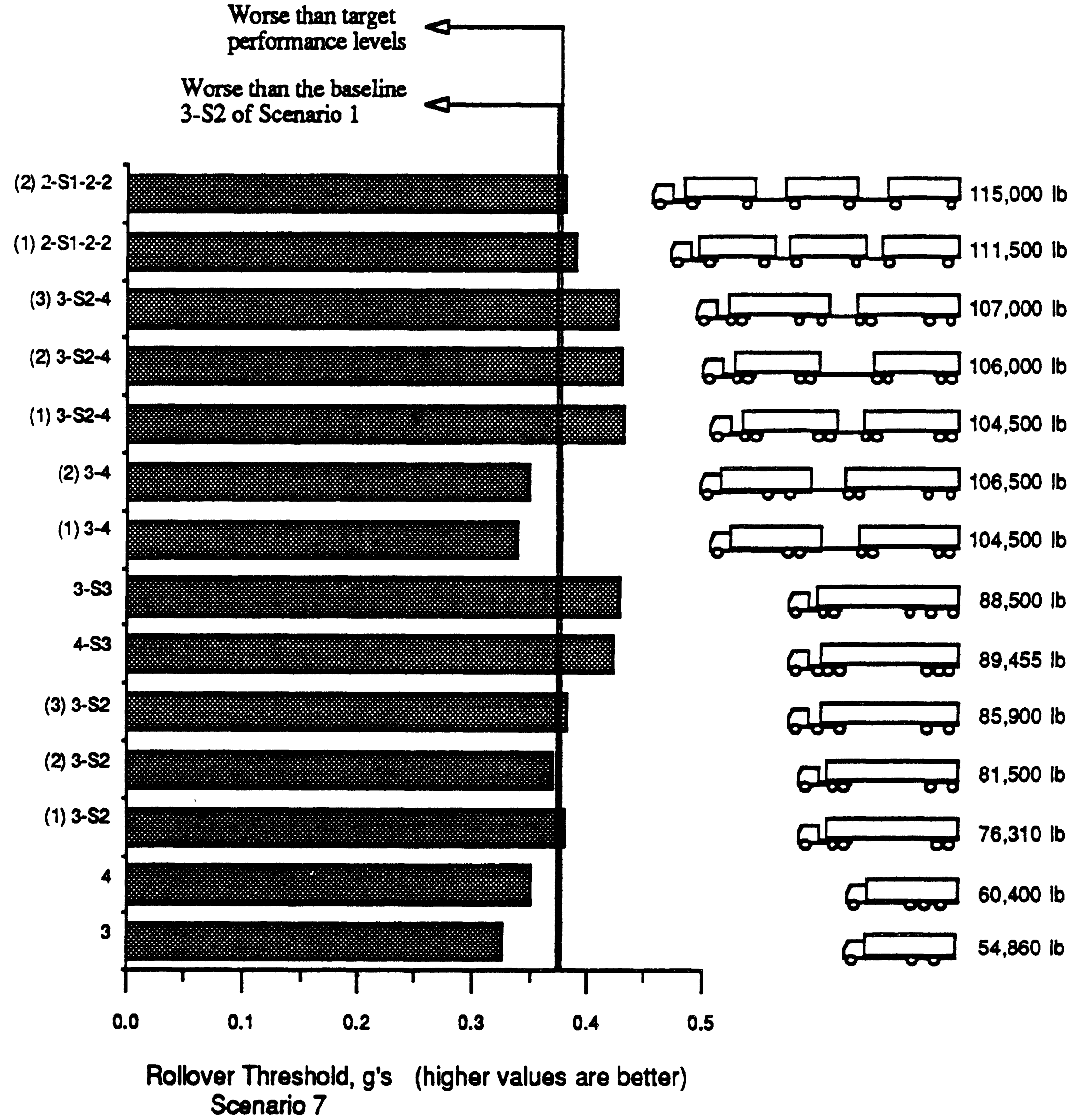



Figure 93. Rollover threshold, scenario 7.

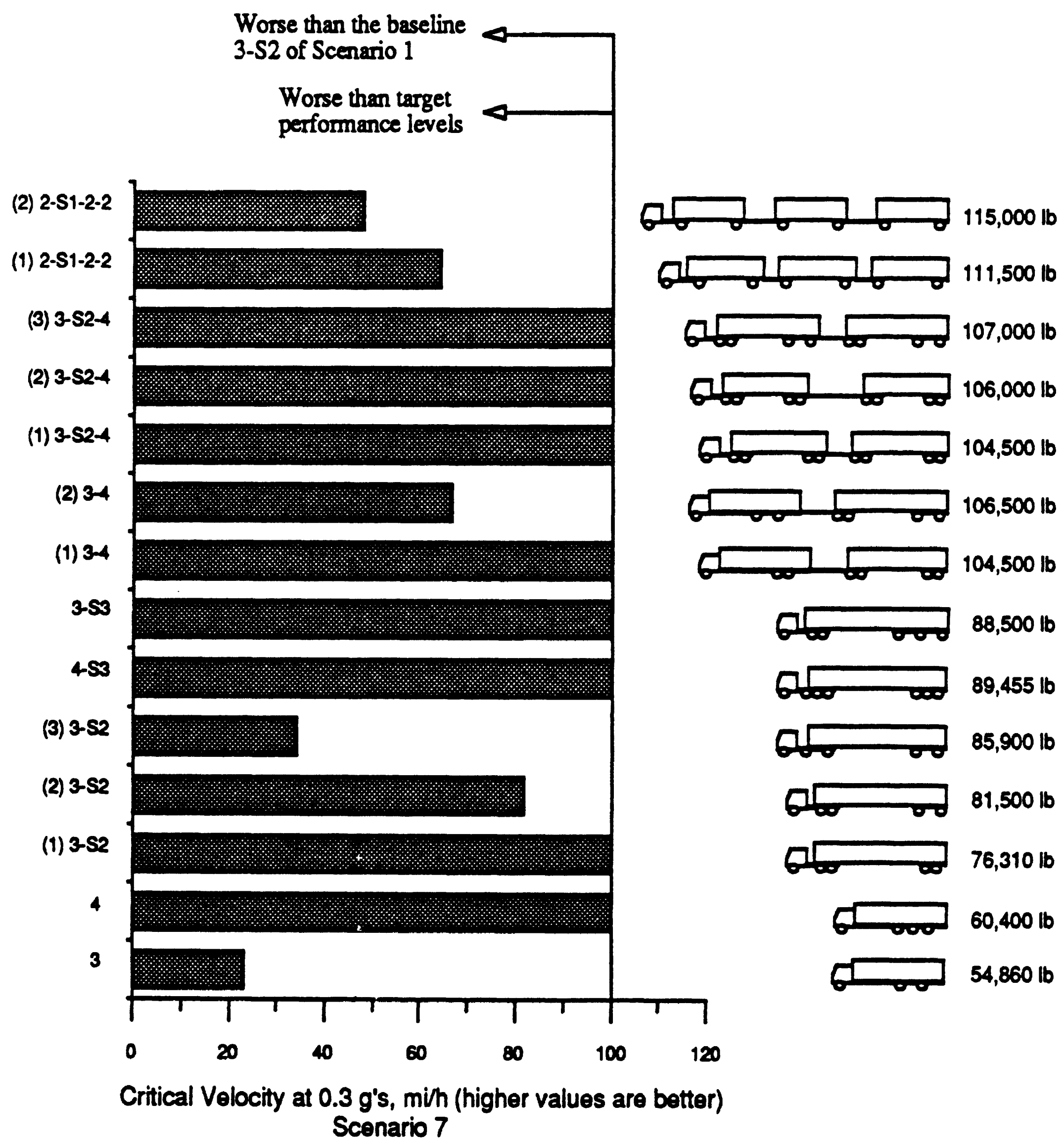



Figure 94. Critical velocity, scenario 7.

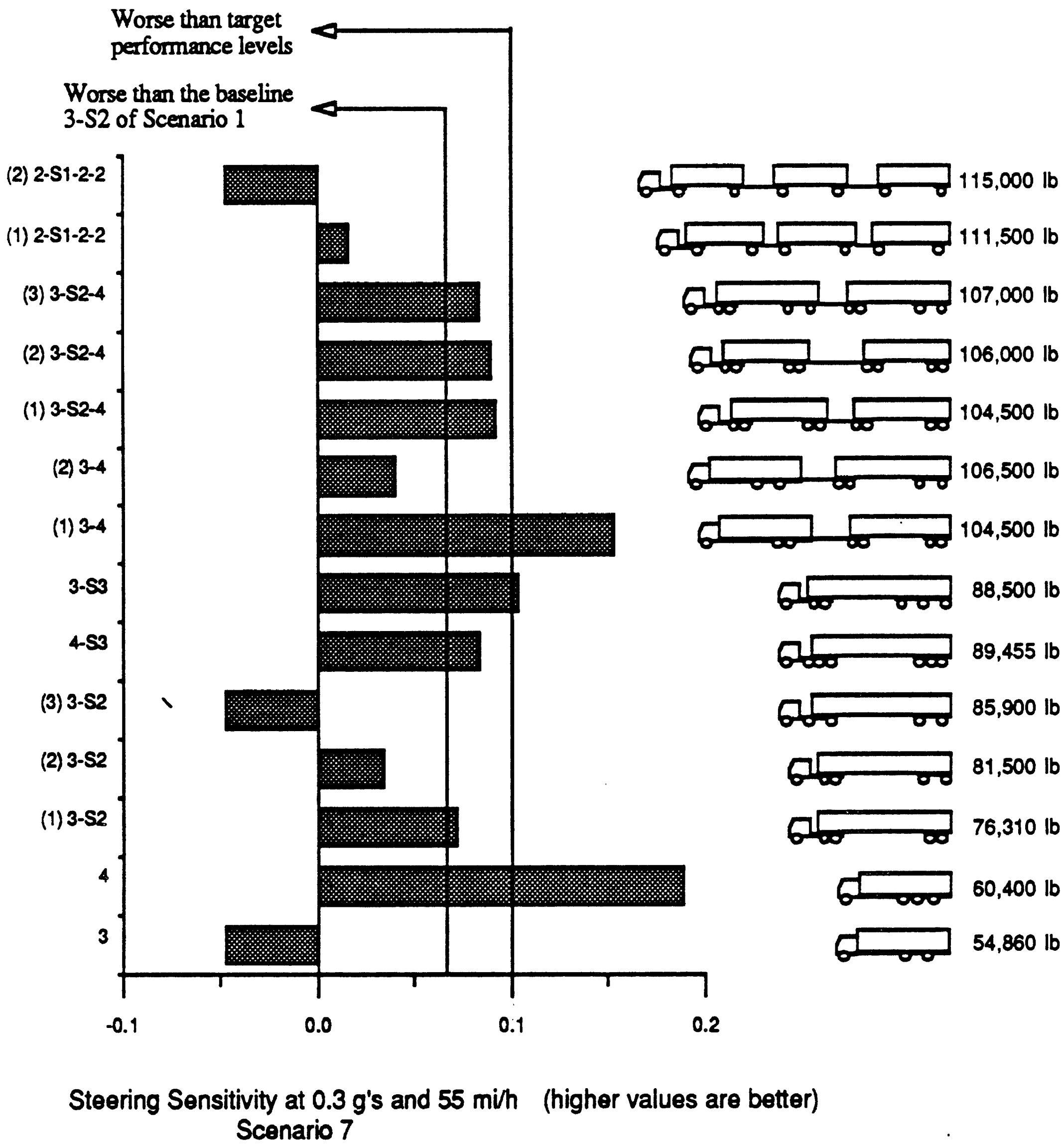



Figure 95. Steering sensitivity, scenario 7.

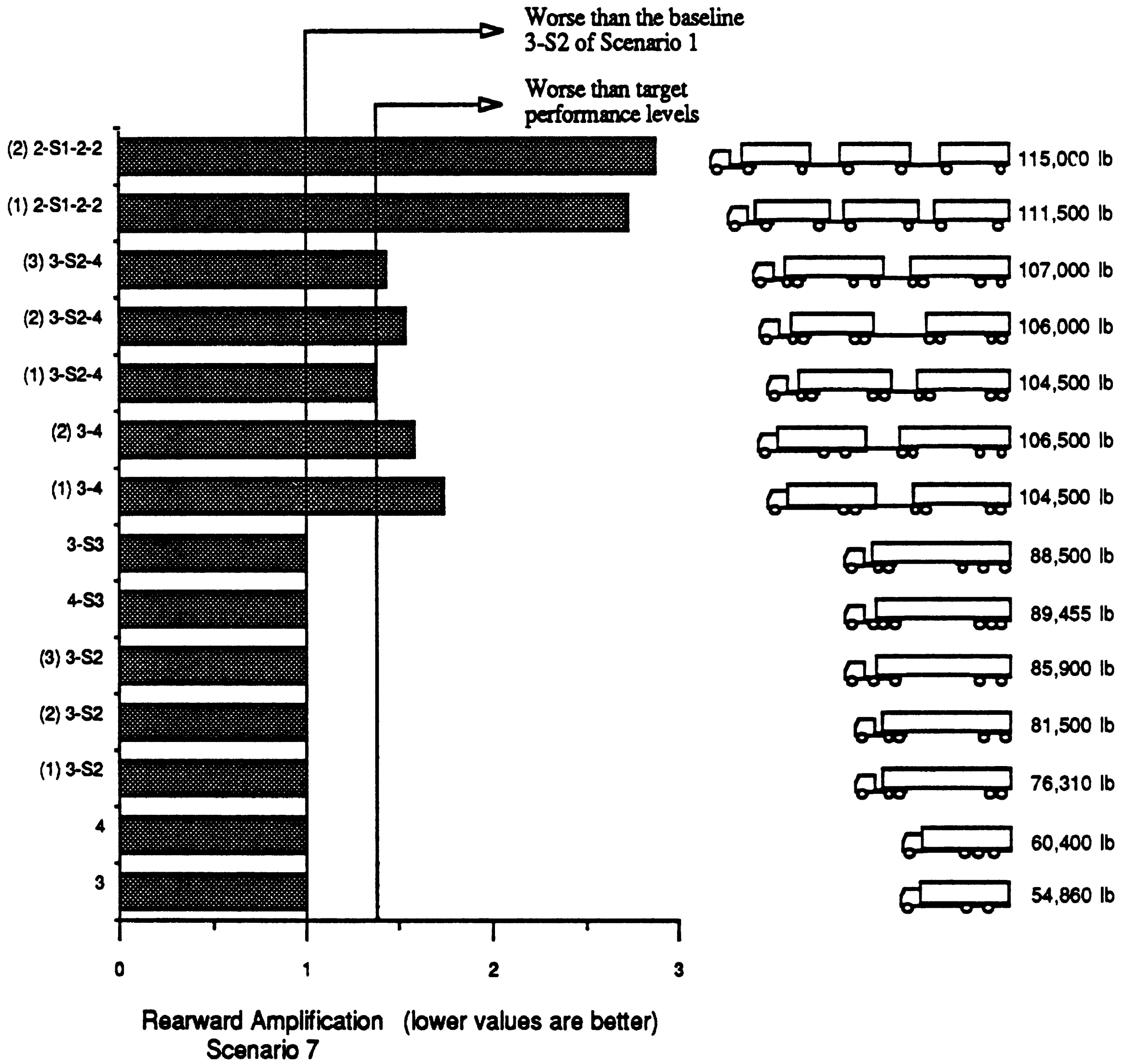



Figure 96. Rearward amplification, scenario 7.

Steady Turn—Handling: Figures 94 and 95 contain the critical velocities and the steering sensitivities for the 14 vehicles under consideration. As mentioned in section 9, the parameter variation study, vehicles with lower levels of roll stability are more difficult to handle in steady turns. Consequently, the two triple configurations, with critical velocities of 64 mi/h (103 km/h) and 48 mi/h (77 km/h) respectively, would be yaw unstable within the normal range of operation. Similarly, the five-axle TST, shown in figure 78, would also be difficult to handle.

With heavier allowable loads on wide-spread axles, the increased "side-to-side" load transfer on these axles could pose a problem during steady turns. With tire characteristics being load-sensitive, a greater amount of load transfer on drive axles could reduce their lateral-force capabilities and result in an "oversteer" condition. Vehicles with heavily loaded drive axles, therefore, are particularly vulnerable to yaw instabilities at high speeds. Configurations using trucks and tractors with heavily loaded drive axles, such as the truck layouts in figures 75 and 83, and the TST layout in figure 79, would be more difficult to handle at highway speeds. The smaller stability margins, due to reduced roll stability and/or heavily loaded drive axles, are evident in the critical velocities and steering sensitivities shown in figures 94 and 95.

Obstacle Evasion: Figure 96 contains the rearward amplifications for the vehicles in this scenario. The triples perform very poorly in this maneuver and the high levels of rearward amplification could induce the trailers to roll over. In addition to the extra trailer, short wheelbases and fewer axles are responsible for the large amounts of rearward amplification. The short wheelbase of the straight truck also accounts for the poor maneuverability of the truck-full trailer configurations. In the case of the doubles, however, longer wheelbases help reduce the amount of rearward amplification, thereby improving the vehicles' evasive maneuvering capabilities.

# 12. PAVEMENT LOADING CONSTRAINTS CORRESPONDING TO THE TURNER CONCEPT (SCENARIOS 8 — 11)

*Definition of the constraints on vehicle design*

The constraints governing this scenario are

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | B or TTI |
| Length constraints: | STAA or offtracking limit |
| Pavement loading restrictions: | 28,000 lb (12,701 kg) for tandems; 16,000 lb (7,258 kg) for singles. |

*Implications with respect to vehicle design*

Scenarios 8 through 11 address the Turner concept through the application of a more restrictive pavement rule. Under the Turner concept, tandem loads are reduced from 34,000 lb (15,422 kg) to 28,000 lb (12,701 kg) and single-axle loads are reduced from 20,000 lb (9,072 kg) to 16,000 lb (7,258 kg). In the case of multiaxle suspensions, those with more than two axles in a suspension, the pavement loads are constrained by the active bridge formula constraint.

Scenarios 8 and 9 are constrained by formula B and are limited by the STAA and the offtracking constraints, respectively. From the viewpoint of a trailer-length constraint, the STAA is more restrictive than the "offtracking rule." Consequently, most vehicles developed in scenario 8 would satisfy the constraints of scenario 9. In other words, scenario 8 is a subset of scenario 9. Similarly, scenarios 10 and 11 are constrained by formula TTI and are limited by the STAA and the "offtracking rule," respectively. Since most vehicles developed under the STAA rule would satisfy the "offtracking rule," scenario 10 is a subset of scenario 11. Accordingly, only scenarios 9 and 11 will be discussed.

With the exception of the pavement loading rule, the constraints in scenario 9 are very similar to those in scenario 6. Since formula B reduces the individual axle loads with every additional axle, that is, it provides a decreasing weight return for extra axles, the more restrictive "28/16" pavement rule becomes a nondominant constraint for multiaxle suspensions. In the case of single and tandem axles, however, the Turner concept could limit gross combination weights by becoming a dominant constraint. Using the vehicles developed in scenario 6 and applying the constraints of scenario 9, that is, the "28/16" pavement rule, the following table identifies the configurations that satisfy the Turner concept. The vehicles that satisfy the constraints in this scenario are distinguished by their bold face type. For the vehicles that violate the pavement rule, the suspension loads would have to be reduced.

| VEHICLE TYPES | CODE | GCW | COMMENTS |
|---|---|---|---|
| **Straight truck** | **5** | **62,000 lb** | |
| Tractor-semitrailer | 3-S2 | 76,310 lb | Trailer's tandem violates the pavement rule |
| Tractor-semitrailer | 3-S2 | 81,500 lb | Trailer's wide-spread single axles violate the pavement rule |
| Tractor-semitrailer | 3-S3 | 88,500 lb | Tractor's tandem violates the pavement rule |
| **Tractor-semitrailer** | **4-S5** | **104,000 lb** | |
| Truck-full trailer | 3-2 | 86,930 lb | All rear axles violate the pavement rule |
| **Truck-full trailer** | **4-5** | **114,615 lb** | |
| Double | 2-S1-2 | 88,365 lb | All rear axles violate the pavement rule |
| **Double** | **3-S2-4** | **109,500 lb** | |
| **Double** | **3-S2-4** | **117,500 lb** | |
| **Double** | **3-S2-4** | **118,660 lb** | |
| Triple | 2-S1-2-2 | 116,850 lb | All rear axles violate the pavement rule |
| **Triple** | **4-S4-7-7** | **215,500 lb** | |

With the exception of the pavement rule, the constraints in scenario 11 are similar to those in scenario 7. Formula TTI, unlike formula B, promotes single and tandem axles instead of multiaxle sets. In this scenario, therefore, the pavement rule plays a more significant role in the design of vehicle layouts. To avoid the restriction of the pavement rule, wide-spread singles (spread at least 8 ft (2.4 m) apart) could be used to replace tandems, thereby allowing pavement load on two axles to increase from 28,000 lb (12,701 kg) to 32,000 lb (14,515 kg). Using the vehicles developed in scenario 7 and applying the constraints of this scenario, that is, scenario 11, the following table uses a bold face type to identify the configurations that satisfy the pavement rule. For the vehicles that violate the pavement rule, the suspension loads would have to be reduced.

| VEHICLE TYPES | CODE | GCW | COMMENTS |
|---|---|---|---|
| Straight truck | 3 | 54,860 lb | Truck's wide-spread rear axles violate the pavement rule |
| **Straight truck** | 4 | 60,400 lb | |
| Tractor-semitrailer | 3-S2 | 76,310 lb | Trailer's tandem violates the pavement rule |
| Tractor-semitrailer | 3-S2 | 81,500 lb | Trailer's wide-spread single axles violate the pavement rule |
| Tractor-semitrailer | 3-S2 | 85,900 lb | All rear axles violate the pavement rule |
| **Tractor-semitrailer** | 4-S3 | 88,500 lb | |
| Tractor-semitrailer | 3-S3 | 88,500 lb | Tractor's tandem violates the pavement rule |
| Truck-full trailer | 3-4 | 104,500 lb | Truck's and trailer's rear suspensions violate the pavement rule |
| Truck-full trailer | 3-4 | 106,500 lb | Truck's and trailer's rear suspensions violate the pavement rule |
| **Double** | 3-S2-4 | 104,500 lb | |
| **Double** | 3-S2-4 | 106,500 lb | |
| **Double** | 3-S2-4 | 107,000 lb | |
| Triple | 2-S1-2-2 | 111,500 lb | All rear axles violate the pavement rule |
| Triple | 2-S1-2-2 | 115,000 lb | All rear axles violate the pavement rule |

# 13. SCENARIOS 12 AND 13

## Scenario 12 — no weight cap, formula C, and an offtracking limit

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | C |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 36,000 lb (16,329 kg) for tandems; 22,000 lb (9,979 kg) for singles. |

*Implications with respect to vehicle design*

With the exception of the bridge formula constraint, scenario 12 is very similar to scenario 6. The basic difference between the two bridge formulas is the additional 2,000-lb (907 kg) weight allowance provided by formula C. Aside from the vehicles being 2,000 lb (907 kg) heavier, the constraints in this scenario promote vehicles similar to those developed in scenario 6.

## Scenario 13 — 88k weight cap and formula B for a tractor-semitrailer

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | 88,000 lb (39,916 kg) |
| Bridge formula restrictions: | B |
| Length constraints: | STAA for a 3-S2 |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

In scenario 6, in the absence of a weight cap, we developed the "baseline" three-axle tractor and tandem-axle semitrailer (3-S2). Due to the water-level loading of the semitrailer, its suspension reached the 34,000-lb (15,422 kg) pavement limit before the vehicle reached 78,500 lb (35,607 kg). Moreover, in scenario 6, a TST was developed with wide-spread axles on an STAA-regulated semitrailer. The 3-S2 was limited to a weight of 81,500 lb (36,967 kg). In both situations, the pavement constraint played a more dominant role in restricting the vehicle to a lower gross combination weight. Consequently, an 88,000-lb (39,916 kg) weight cap would not cause a significant change in the layouts of 3-S2's.

# 14. DISCUSSIONS OF VEHICLES FOR HAULING INTERNATIONAL STANDARDS ORGANIZATION (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 given; it 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 is developed for each of the three bridge formulas.

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 during tight turns. 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 performance of the empty vehicles, however, continues to be a problem.

## Vehicle Design for Scenario 14

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

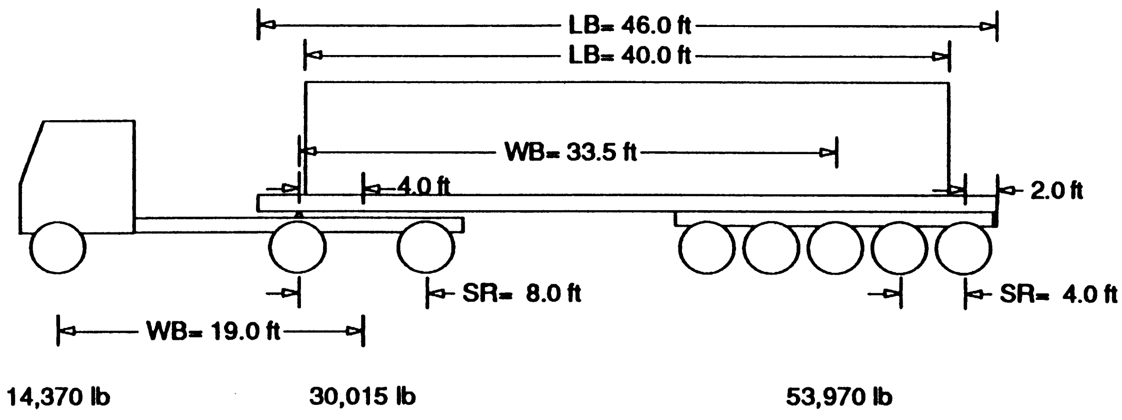
| | |
|---|---|
| Maximum weight cap: | ISO container |
| Bridge formula restrictions: | B |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems;<br>20,000 lb (9,072 kg) for singles. |

*Example vehicle*

Shipping containers are built resilient enough to withstand the rigors of sea travel. The chassis used for transporting these containers are, therefore, stripped down flat-bed trailers. The trailers are extremely light since the container's structure provides the necessary frame stiffness for the container-trailer unit.

Before exercising formula B, the tare weight of the TST combination must be included with the 67,200-lb (30,481 kg) payload. For example, a 55-ft (17 m) flat-bed trailer with four axles weighs approximately 13,650 lb (6,192 kg). With a 16,500-lb (7,484 kg) tractor, the total weight of the vehicle is 97,350 lb (44,157 kg). If the bridge formula calls for longer trailers or additional axles, the total weight of the vehicle would increase. In an attempt to minimize the tare weight of the vehicle, fewer axles and shorter trailers become more desirable.

Using the techniques discussed in scenario 6 for optimizing vehicle design, that is, adding axles to gain weight allowances and also to improve low-speed offtracking, a proposed vehicle design is shown in figure 97. A 19-ft (5.8 m) tractor pulling a five-axle flat-bed trailer, with an overall length of 46 ft (14 m), satisfies the constraints of this scenario.




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 19.0 ft | 4.0 ft | .0 ft | 1. | 8.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 33.5 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 5. | 71855. lb | 46.0 ft | .0 ft |

Figure 97. Tractor-semitrailer (3-S5; GCW=98,355 lb; payload=67,200 lb).

## Vehicle Design for Scenario 15

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | ISO container |
| Bridge formula restrictions: | C |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 36,000 lb (16,329 kg) for tandems; 22,000 lb (9,979 kg) for singles. |

*Example vehicle*

In earlier scenarios where formula C was a constraint (scenarios 2, 4, and 12), the only modification to vehicles developed under formula B was a weight allowance of 2,000 lb (907 kg). In this scenario, however, the difference in the two bridge formulas is interpreted in a different manner. The 2,000-lb (907 kg) weight allowance is converted into a length allowance (see discussion of formula C in section 2). A vehicle with a given amount of payload can be shorter under formula C than a vehicle with the same amount of payload under formula B.

Adapting the TST, developed in the previous scenario, to satisfy the constraints of this scenario, that is, formula C and the associated pavement rule, a shorter tractor (16 ft (7.3 m)) and a shorter trailer (44 ft (20 m)) is allowed to carry the given 67,200-lb (30,481 kg) payload (figure 98). With a lower tare weight, resulting from a shorter trailer, the vehicle has a lower gross combination weight.

## Vehicle Design for Scenario 16

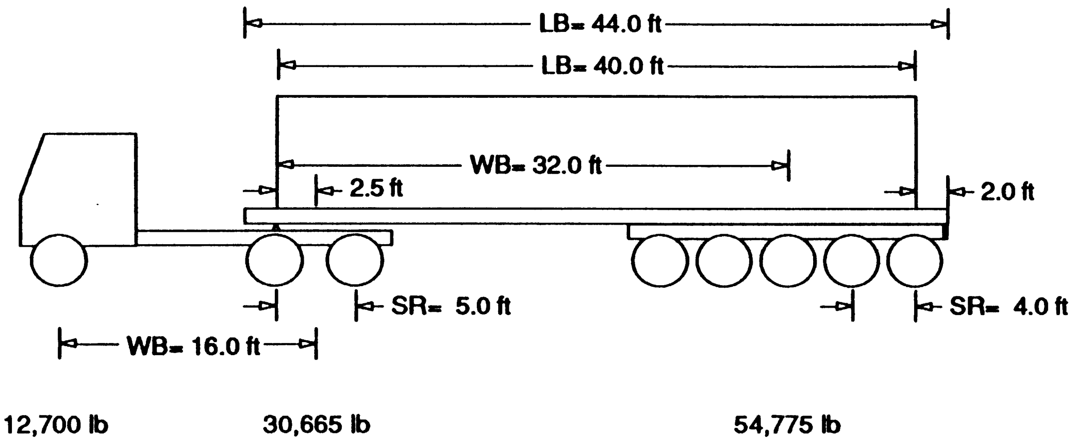
*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | ISO container |
| Bridge formula restrictions: | TTI |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles. |

*Example vehicle*

In the previous examples, figures 97 and 98, additional axles were used to gain weight allowances for the proposed vehicles. The extra axles also helped improve the vehicles' low-speed offtracking performance. Under formula TTI, however, with no weight allowance for extra axles, there is a greater incentive to reduce the tare weight of the vehicle




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 16.0 ft | 2.5 ft | .0 ft | 1. | 5.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 32.0 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 5. | 71640. lb | 44.0 ft | .0 ft |

Figure 98. Tractor-semitrailer (3-S5; GCW=98,140 lb; payload=67,200 lb).

by having fewer axles in the layout. With the 67,200-lb (30,481-kg) payload, formula TTI requires longer lengths between axle locations, thereby, increasing the overall lengths for the tractor and the trailer. Since longer units increase the tare weight of the vehicle, this produces an opposing effect in the design process. Consequently, the bridge formula is exceedingly restrictive in this scenario and could result in long TST's with wide spreads between axles.

A proposed design, with extremely wide spreads (8 ft (2.4 m) and 10 ft (3 m)) between axles is shown in figure 99. A 16.5-ft (5 m) tractor pulling a 52.2-ft (16 m) trailer would satisfy the constraints in this scenario. The ISO container would have to be placed closer to the front of the trailer so as to transfer some of the load from the trailer's suspension to the tractor's drive axles. This would reduce the vehicle's friction requirements during tight turns.

The vehicle and axle layouts for the three ISO transporters are shown in table 14.

## Vehicle Performance

*Performance summary*

The safety-related results for the three vehicles are shown in table 15. The graphical representations of the tabulated results are shown in figures 100 through 106.

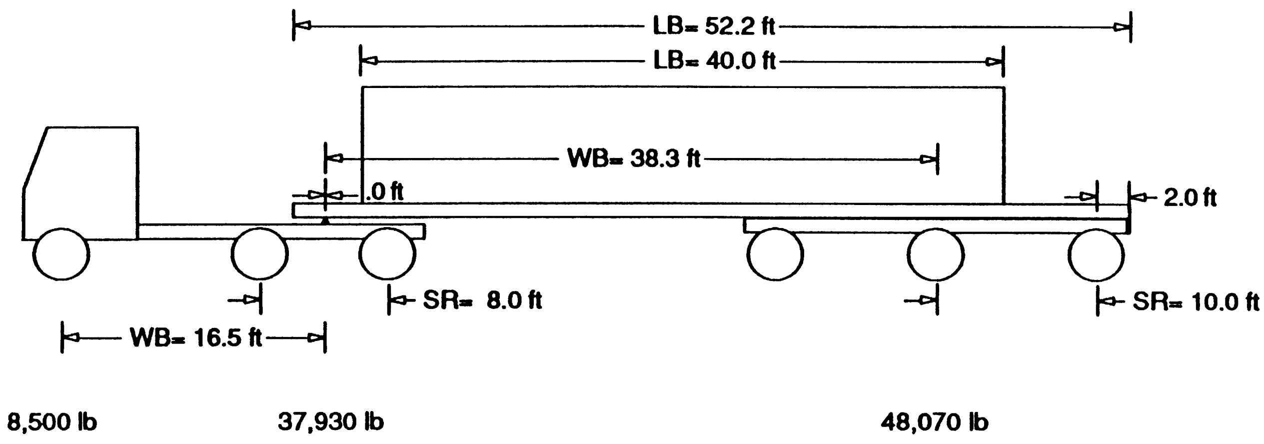
*Safety and operational concerns*

Low-Speed Offtracking: Figure 100 contains the low-speed offtracking amounts for the three ISO transporters. Since the vehicles are governed by the "offtracking rule," their performance in this maneuver is acceptable.

Friction Demand: Figure 101 pertains to the vehicles' friction requirements during tight turns. With five-axle suspensions being used in two cases and extremely wide-spread axles being used in the third, the friction requirements of the three vehicles are extremely high compared to the baseline 3-S2 of scenario 1.

High-Speed Offtracking: Figure 102 contains the high-speed offtracking results for the three vehicles. Being TST configurations with relatively short overall lengths, their high-speed offtracking amounts would be less than 0.5 ft (0.15 m). The lower amount of offtracking would help the vehicles negotiate entrance and exit ramps at highway speeds.

Constant Deceleration Braking: The fourth and fifth items in table 15 pertain to the braking performance of the three vehicles. The braking performance of the empty vehicles is shown in figure 103. Since the trailers are extremely light in these configurations, the braking performance of the empty vehicles would be very poor. The multiaxle suspensions in the first two examples (figures 97 and 98) tend to "overbrake" the vehicles and result in lower braking efficiencies. In the loaded state, however, the TTI vehicle, with fewer axles in its suspensions, would be better than the other two layouts.




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 16.50 ft | .0 ft | .0 ft | 1. | 8.0 ft | 2. | 0. lb | .00 ft | .0 ft |
| trailer | 38.25 ft | 2.0 ft | .0 ft | 0. | 10.0 ft | 3. | 72000. lb | 52.25 ft | .0 ft |

Figure 99. Tractor-semitrailer (3-S3; GCW=94,500 lb; payload=67,200 lb).

Table 14. Summary of container transporter examples.

| Example Vehicle | Vehicle Code | Tare Weight | Bridge Formula | GCW | Payload Weight | 1. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Tractor-semitrailer | 3-S5 | 31,155 lb | B | 98,355 lb | 67,200 lb | 56.5 ft | 8 |
| Tractor-semitrailer | 3-S5 | 30,940 lb | C | 98,140 lb | 67,200 lb | 53.5 ft | 8 |
| Tractor-semitrailer | 3-S3 | 27,300 lb | TTI | 94,500 lb | 67,200 lb | 64.8 ft | 6 |

1. Overall length is measured between extreme axles

Table 15. Summary of performance measures for container transporters.

| | Tractor-semitrailer | | |
|---|---|---|---|
| Bridge Formula | B | C | TTI |
| Vehicle Code | 3-S5 | 3-S5 | 3-S3 |
| Gross Combination Weight (GCW) | 98,355 lb | 98,140 lb | 94,500 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | 14.85 | 13.26 | 16.68 |
| 2. Friction demand in a tight turn | 0.16* | 0.16* | 0.20* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.442* | 0.471* | 0.413* |
| 4. Braking efficiency 1 (Loaded) | | | |
| - 0.2 g's | 0.799* | 0.812* | 0.910 |
| - 0.4 g's | 0.757* | 0.767* | 0.876 |
| 5. Braking efficiency 1 (Empty) | | | |
| - 0.2 g's | **0.647*** | **0.647*** | **0.650*** |
| - 0.4 g's | **0.622*** | **0.621*** | **0.625*** |
| 6. Rollover threshold (g's) | 0.392 | 0.399 | 0.384 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | **57.05*** |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | 0.229 | 0.161 | **0.006*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.

Entries in bold face type are judged to represent poor levels of performance relative to current technology.

Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

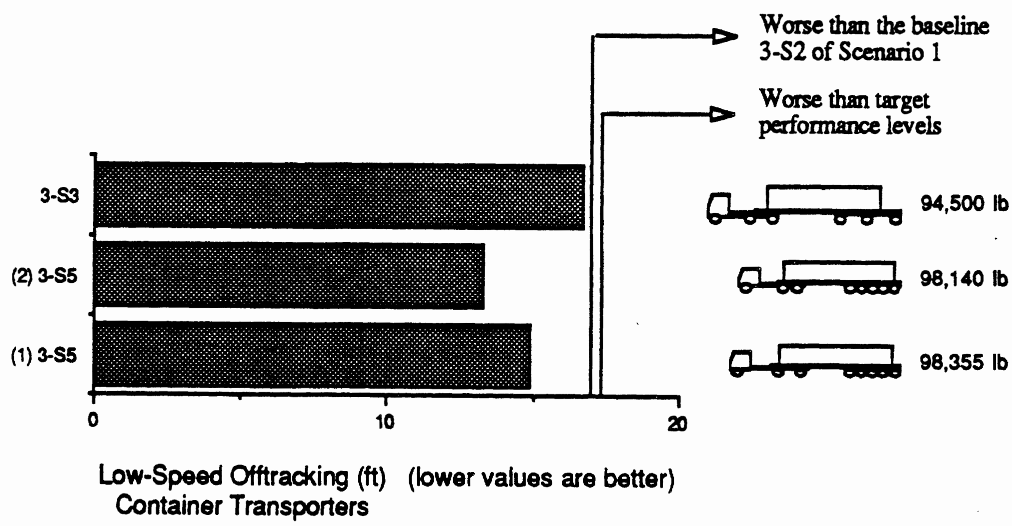



Figure 100. Low-speed offtracking, container transporters.

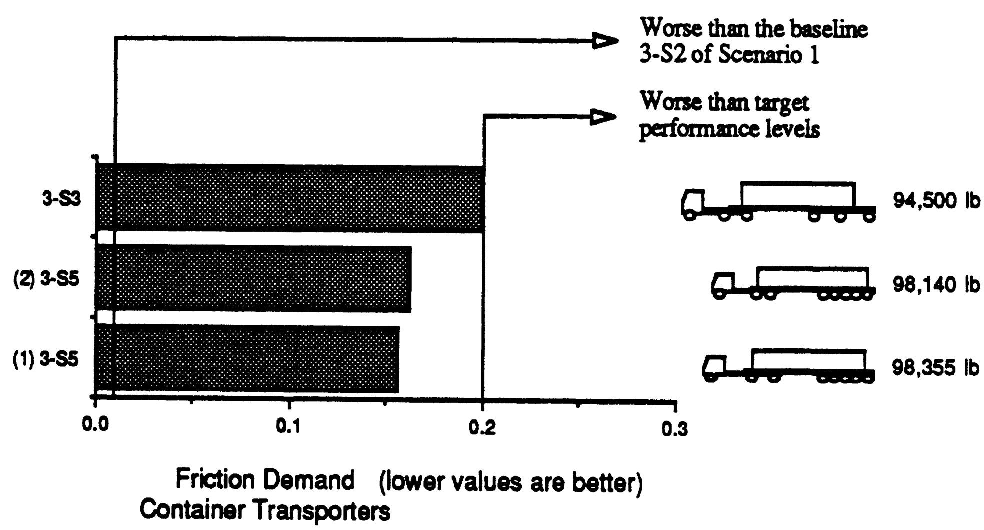



Figure 101. Friction demand, container transporters.

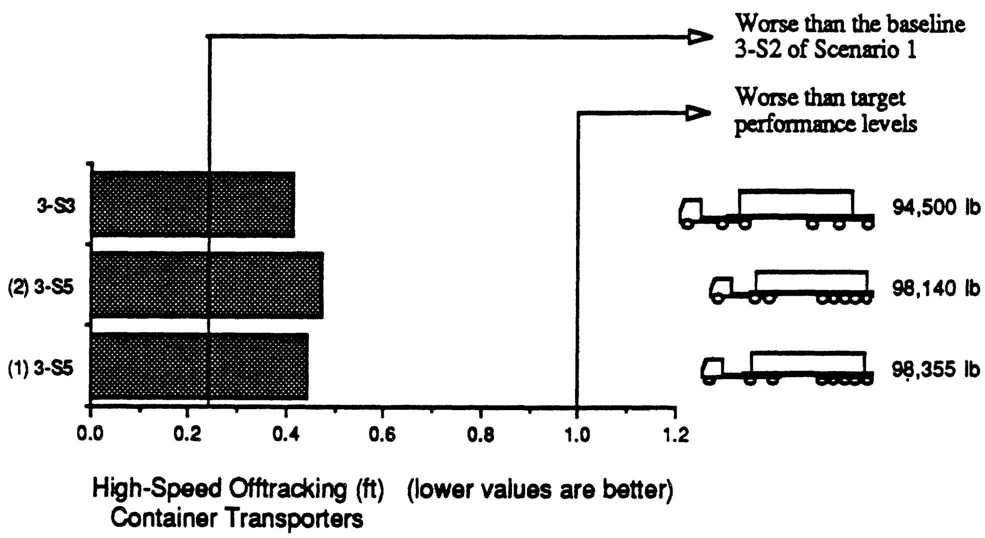



Figure 102. High-speed offtracking, container transporters.

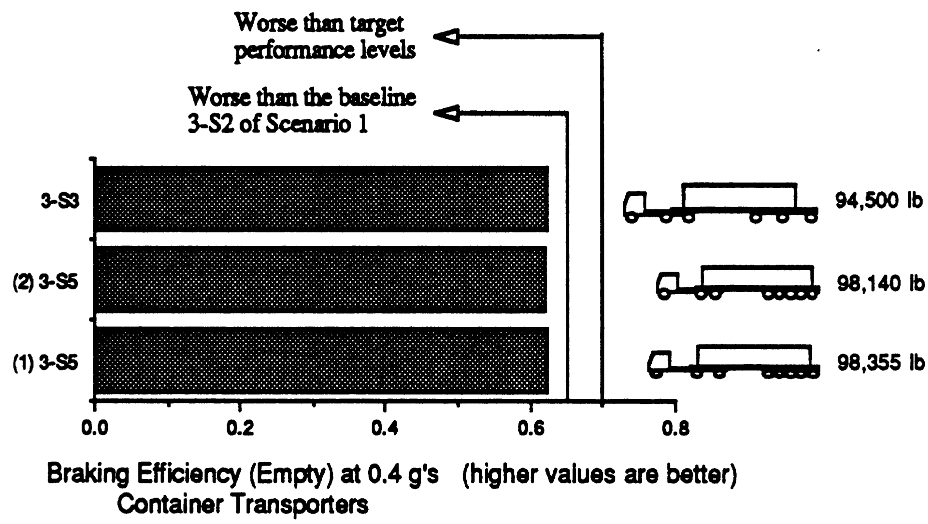



Figure 103. Braking efficiency, container transporters.

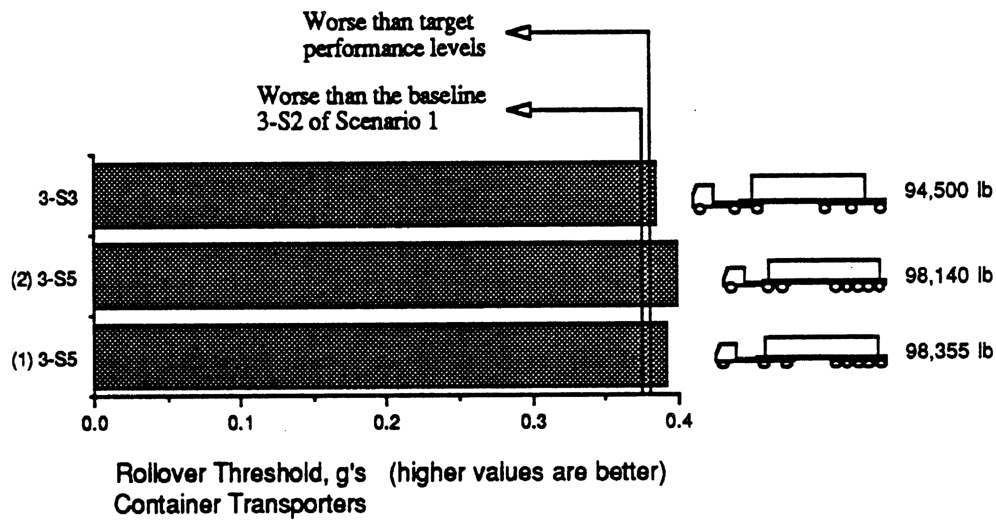



Figure 104. Rollover threshold, container transporters.

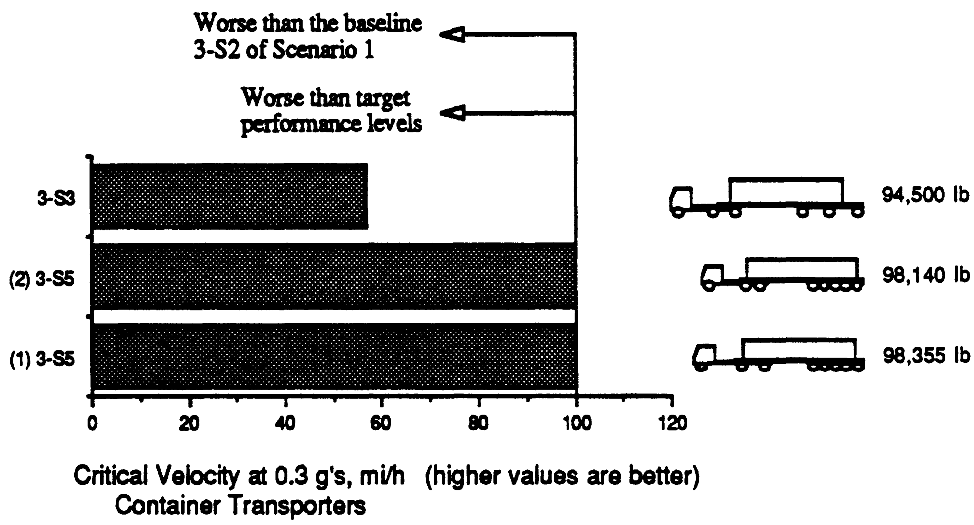



Figure 105. Critical velocity, container transporters.

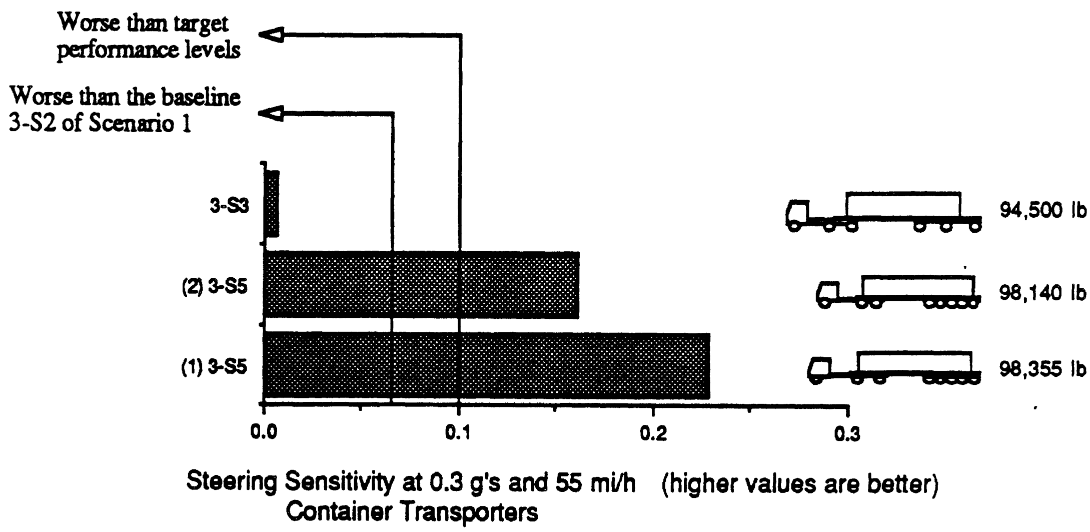



Figure 106. Steering sensitivity, container transporters.

Steady Turn—Rollover: Figure 104 contains the rollover thresholds for the proposed vehicles. The extra axles in the first two layouts help increase their rollover thresholds. Though the TTI vehicle has a slightly lower rollover threshold, it has a higher level of roll stability than the "baseline" TST in scenario 1.

Steady Turn—Handling: Figures 105 and 106 contain the margins of safety pertaining to vehicle handling. The first two ISO transporters would be fairly easy to handle even at highway speeds. Figure 106 shows the relatively high margins of safety for these two vehicles. The TTI vehicle, however, would be unstable at speeds over 57 mi/h (82 km/h) (figure 105). In this case, a poor "front-to-rear" loading distribution on the tractor is responsible for the lower levels of yaw stability.

# 15. SCENARIO 17 — 100K WEIGHT CAP, BRIDGE FORMULA B, AND AN OFFTRACKING LIMIT

## Vehicle Design

*Definition of the constraints on vehicle design*

The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | 100,000 lb (45,359 kg) |
| Bridge formula restrictions: | B |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems;<br>20,000 lb (9,072 kg) for singles. |

*Implications with respect to vehicle design*

Currently, vehicles are constrained by an 80,000-lb (36,28 kg) weight cap. With respect to vehicle design, the more restrictive weight cap reduces the influence of the bridge formula and other size and weight rules. Consequently, the weight cap has been very important in the development of prevailing vehicle and axle layouts. A removal of the weight cap could lead to another set of dominant constraints. These constraints could have an entirely different effect on the vehicle's design. For example, with the removal of the weight cap in scenario 6, the "offtracking rule" and the bridge formula become the dominant constraints. In scenario 6, the dominant constraints reinforce each other to allow a wide variety of long and extremely heavy multiaxle vehicles. If the weight cap is too high (as in scenario 6), then the weight cap becomes insignificant in the vehicle development scheme. Conversely, if the weight cap is too low, then the other constraints become immaterial. The amount of the weight cap, therefore, determines the point at which other size and weight constraints become less effective. For example, in the presence of a 100,000-lb (45,359 kg) weight cap, other size and weight constraints become insignificant at weights over 100,000 lb (45,359 kg).

In this scenario, the 100,000-lb (45,359 kg) weight cap is used to supplement the constraints of scenario 6. Consequently, for vehicle configurations with GCW's below the maximum weight cap, the "offtracking rule" and the bridge formula are the dominant constraints. For vehicle configurations that could get heavier than 100,000 lb (45,359 kg), the weight cap becomes the more limiting constraint. With a restriction on further increases in GCW, the weight cap reduces the incentive to add axles and/or increase trailer lengths.

For short vehicle configurations, such as straight trucks and tractor-semitrailers, vehicle design is influenced by the bridge formula and the "offtracking rule." However, for the truck-full trailers, doubles, and triples, the maximum weight cap becomes the more dominant constraint. Consequently, the resulting vehicles would have fewer axles and shorter overall lengths.

*Example vehicles*

Straight Trucks: Using the vehicles from scenario 6 as initial choices, the five-axle straight truck, shown in figure 54 and again in figure 107, satisfies the constraints of this scenario. Since the vehicle can only reach a GCW of 62,000 lb (28,123 kg), the 100,000-lb (45,359 kg) weight cap is immaterial.

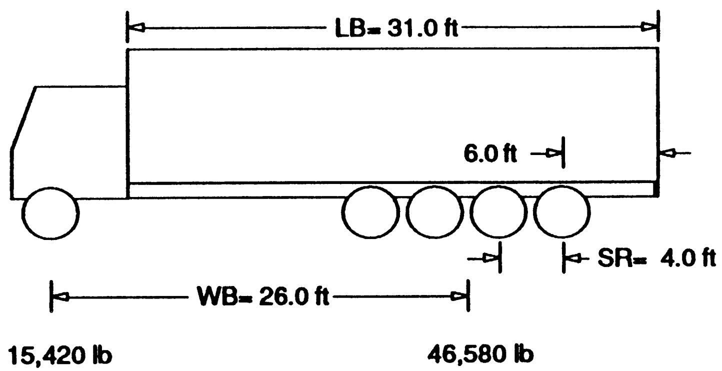
Tractor-Semitrailers: In the case of the TST, the "axle-effect" of formula B would have to be used to gain additional weight allowances. Consequently, a tandem-axle tractor and a five-axle, 55-ft (17 m) semitrailer is allowed to reach the weight cap of 100,000 lb (45,359 kg) (figure 108).

Truck-Full trailers: Using tandem axles in a truck-full trailer configuration, a vehicle with a 10-ft (3 m) dolly and a 33-ft (10 m) trailer is allowed to weigh 100,000 lb (45,359 kg) (figure 109). In this layout, though formula B allows a higher GCW, the weight cap is the more dominant constraint. Consequently, a shorter vehicle would still satisfy the constraints in this scenario.

Doubles: Adapting the tandem-axle double with 28-ft (8.5 m) trailers (figure 62) to operate under the weight cap, the same vehicle with lighter axle loads is shown in figure 110. Using longer trailers, a second double-trailer configuration, with 36-ft (11 m) trailers, is shown in figure 111. In both layouts, the maximum weight cap is the most dominant constraint. Unless payload volume is the motivating factor, the upper bound on weight capacity eliminates the need to add axles and/or increase trailer lengths. Moreover, by promoting lower tare weights, the weight cap encourages shorter trailers with fewer axles.

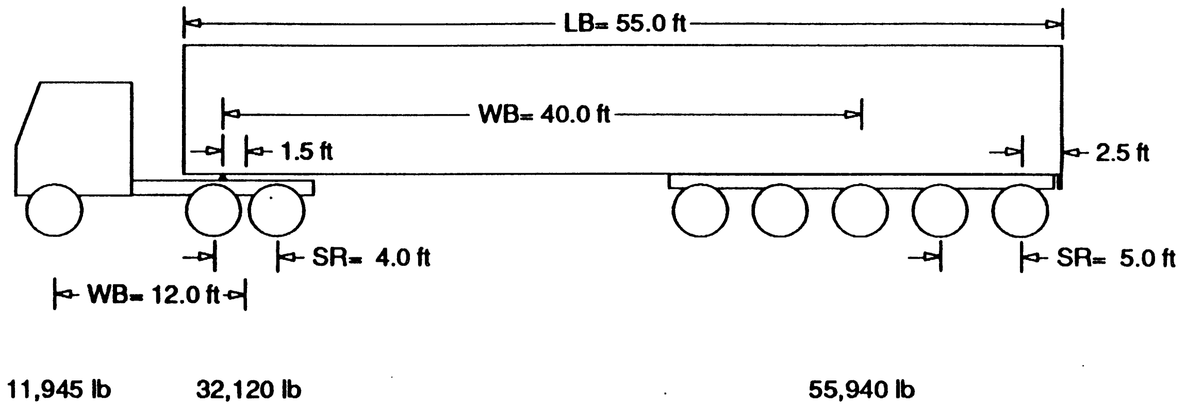
Triples: The triple with 28-ft (8.5 m) trailers, shown in figure 65, is modified to operate under the 100,000-lb (45,359 kg) weight cap. The vehicle, with slightly lower axle loads, is shown in figure 112. Again, in this layout, the maximum weight cap is the more dominant constraint.

Productivity information pertaining to the five vehicle and axle layouts is summarized in table 16.



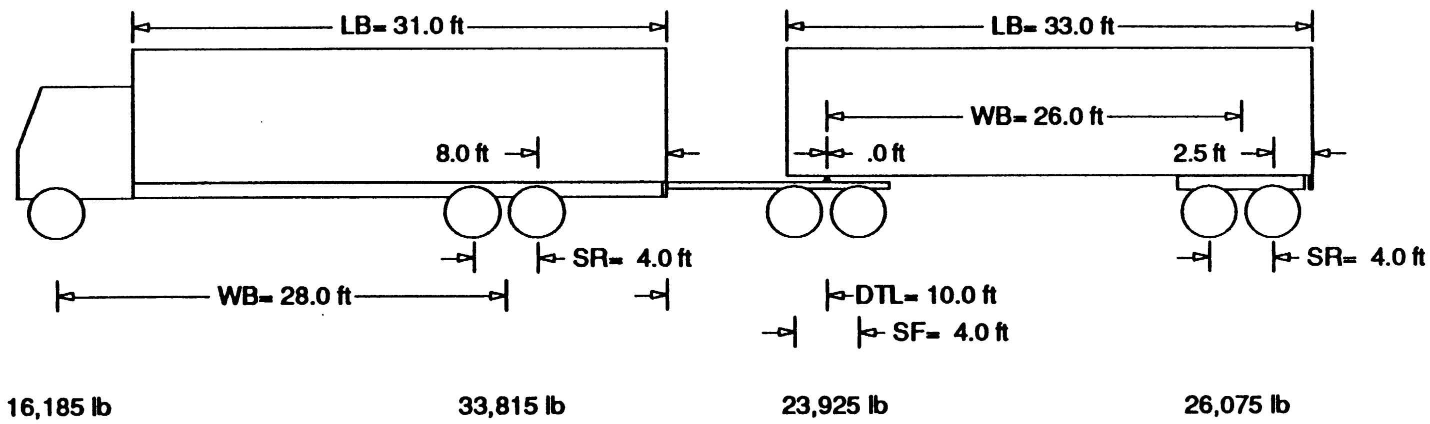

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 26.0 ft | 6.0 ft | .0 ft | 1. | 4.0 ft | 4. | 41000. lb | 31.0 ft | .0 ft |

Figure 107. Straight truck (5; GCW=62,000 lb; payload=35,490 lb).



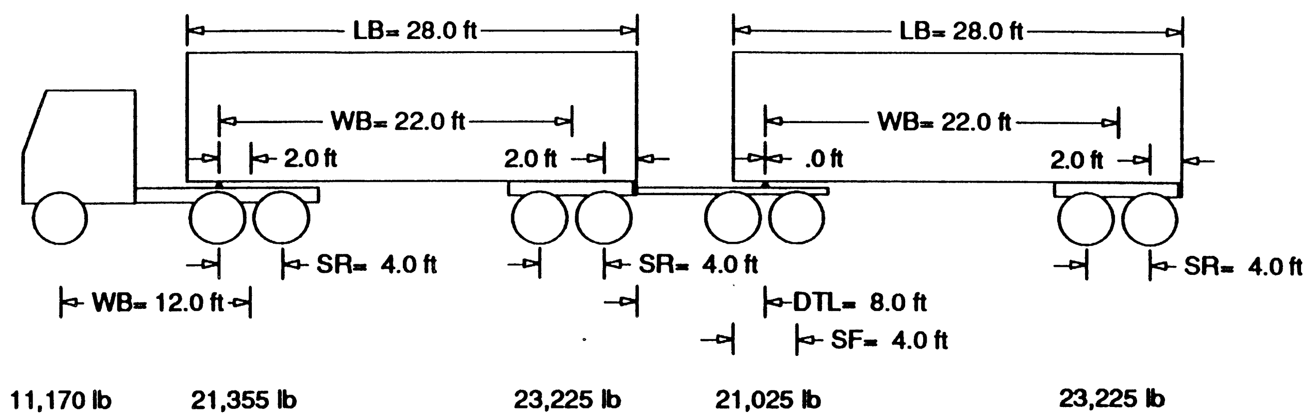

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 1.5 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 40.0 ft | 2.5 ft | .0 ft | 0. | 5.0 ft | 5. | 73500. lb | 55.0 ft | .0 ft |

Figure 108. Tractor-semitrailer (3-S5; GCW=100,000 lb; payload=61,933 lb).



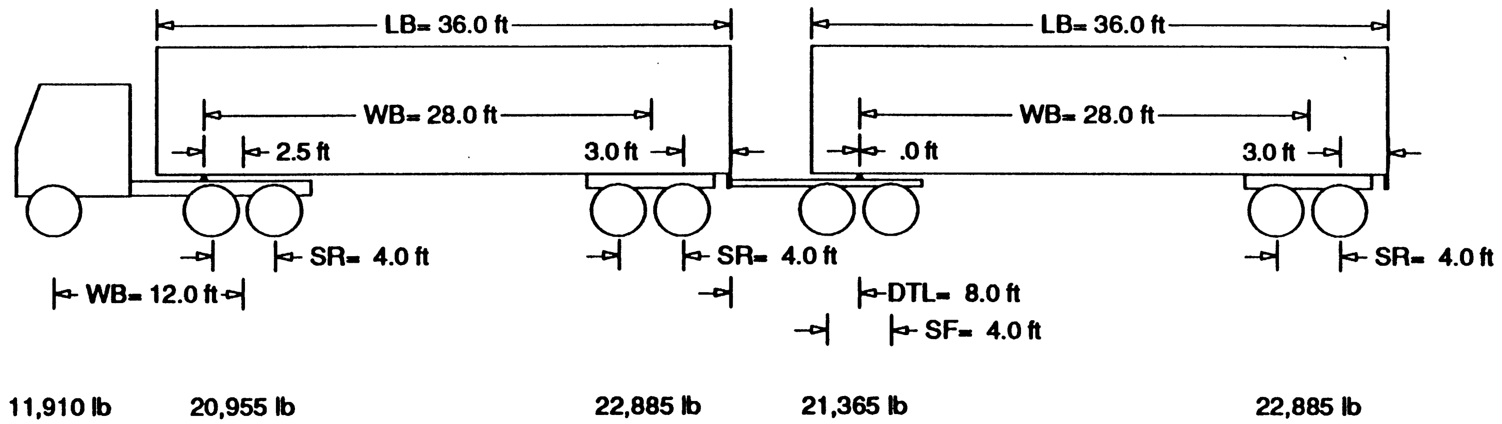

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 28.0 ft | 8.0 ft | .0 ft | 1. | 4.0 ft | 2. | 32000. lb | 31.0 ft | .0 ft |
| full trailer | 26.0 ft | 2.5 ft | 4.0 ft | 2. | 4.0 ft | 2. | 41000. lb | 33.0 ft | 10.0 ft |

Figure 109. Truck-full trailer (3-4; GCW=100,000 lb; payload=61,476 lb).



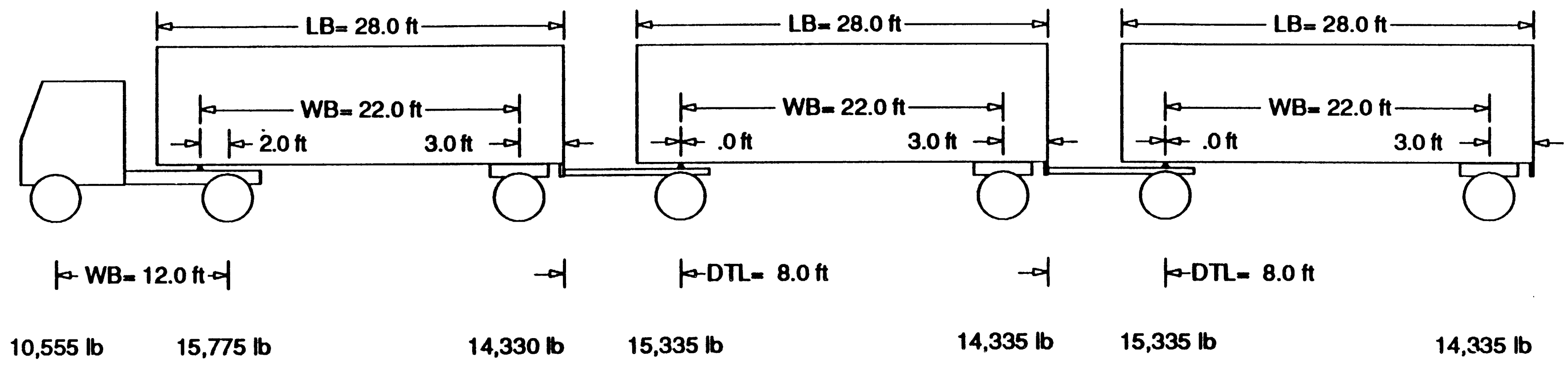

| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 22.0 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 2. | 35250. lb | 28.0 ft | .0 ft |
| full trailer | 22.0 ft | 2.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 35250. lb | 28.0 ft | 8.0 ft |

Figure 110. Double (3-S2-4; GCW=100,000 lb; payload=60,995 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.5 ft | .0 ft | 1. | 4.0 ft | 2. | 0. lb | .0 ft | .0 ft |
| trailer | 28.0 ft | 3.0 ft | .0 ft | 0. | 4.0 ft | 2. | 35250. lb | 36.0 ft | .0 ft |
| full trailer | 28.0 ft | 3.0 ft | 4.0 ft | 2. | 4.0 ft | 2. | 35250. lb | 36.0 ft | 8.0 ft |

Figure 111. Double (3-S2-4; GCW=100,000 lb; payload=56,957 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 12.0 ft | 2.0 ft | .0 ft | 1. | .0 ft | 1. | 0. lb | .0 ft | .0 ft |
| trailer | 22.0 ft | 3.0 ft | .0 ft | 0. | .0 ft | 1. | 24660. lb | 28.0 ft | .0 ft |
| full trailer | 22.0 ft | 3.0 ft | .0 ft | 1. | .0 ft | 1. | 24665. lb | 28.0 ft | 8.0 ft |
| full trailer | 22.0 ft | 3.0 ft | .0 ft | 1. | .0 ft | 1. | 24665. lb | 28.0 ft | 8.0 ft |

Figure 112. Triple (2-S1-2-2; GCW=100,000 lb; payload=59,743 lb).

Table 16. Summary of example vehicles for scenario 17.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Straight Truck | 5 | 26,510 lb | 62,000 lb | 35,490 lb | 2,372 | 32.0 ft | 5 |
| Tractor-semitrailer | 3-S5 | 38,067 lb | 100,000 lb | 61,933 lb | 4,208 | 60.5 ft | 8 |
| Truck-full trailer | 3-4 | 38,524 lb | 100,000 lb | 61,476 lb | 4,896 | 76.0 ft | 7 |
| Double | 3-S2-4 | 39,005 lb | 100,000 lb | 60,995 lb | 4,284 | 68.0 ft | 9 |
| Double | 3-S2-4 | 43,043 lb | 100,000 lb | 56,957 lb | 5,508 | 80.5 ft | 9 |
| Triple | 2-S1-2-2 | 40,257 lb | 100,000 lb | 59,743 lb | 6,426 | 98.0 ft | 7 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

*What kind of vehicles would be promoted*

LTL operators would still gain substantially from the constraints of this scenario. With no restrictions on trailer length, they are free to maximize their payload-carrying volume by stretching their trailers. Bulk cargo haulers, however, would be limited by the 100,000-lb (45,359 kg) weight cap. With the exception of the straight truck and the tractor-semitrailer, which need multiaxle suspensions to reach the gross weight cap, designs for the remaining vehicle configurations would need little or no modification.

## Vehicle Performance

*Performance summary*

The performance characteristics for the vehicles developed in this scenario are summarized in table 17. The graphical representations of the various rows of the table are contained in figures 113 through 120.

*Safety and operational concerns*

Low-Speed Offtracking: Figure 113 contains the low-speed offtracking amounts for the five vehicles developed in this scenario. With the "offtracking rule" in effect, the proposed vehicles would have acceptable levels of low-speed offtracking.

Friction Demand: The vehicles' friction requirements are shown in figure 114. With the exception of the straight truck and the TST configurations, the remaining vehicles have relatively low friction requirements. The straight truck and the TST, however, use multiaxle suspensions which degrade the vehicles' low-speed cornering performance, especially on slippery surfaces.

High-Speed Offtracking: Figure 115 contains the high-speed offtracking results for the proposed vehicles in this scenario. The triple continues to exhibit rather high levels of high-speed offtracking. The remaining vehicles have relatively lower amounts of high-speed offtracking.

Constant Deceleration Braking: The fourth and fifth items in table 17 pertain to the braking performance of the proposed layouts. Figure 116 contains the braking efficiencies for the empty vehicles executing a 0.4 g stop. As mentioned earlier, multiaxle suspensions tend to "overbrake" the vehicle during a constant deceleration maneuver. Consequently, the braking performances of the straight truck and the tractor-semitrailer are fairly poor. Moreover, short wheelbases and fewer axles degrade the braking efficiencies of the empty truck-full trailer and triple. In the case of the truck-full trailer, however, the loaded vehicle continues to be inefficient in the braking maneuver.

Steady Turn—Rollover: The use of extra axles in these layouts increases the vehicles' roll stiffness. Also, lower GCW's for some of the longer vehicles help increase their levels of roll stability. Figure 117 contains the rollover thresholds for the five vehicles developed in this scenario. With the exception of the proposed truck-full trailer configuration, the

Table 17. Summary of performance measures for example vehicles (scenario 17).

| | Truck | Tractor-semitrailer | Truck-full trailer | Double | | Triple |
|---|---|---|---|---|---|---|
| Vehicle Code | 5 | 3-S5 | 3-4 | 3-S2-4 | 3-S2-4 | 2-S1-2-2 |
| Gross Combination Weight (GCW) | 62,000 lb | 100,000 lb | 100,000 lb | 100,000 lb | 100,000 lb | 100,000 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | 7.76 | 16.53 | 15.35 | 12.84 | **17.47*** | **17.56*** |
| 2. Friction demand in a tight turn | 0.19* | 0.20* | 0.03* | 0.02* | 0.02* | 0.00 |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.430* | 0.428* | 0.793* | 0.726* | 0.715* | **1.073*** |
| 4. Braking efficiency 1 (Loaded) - 0.2 g's | 0.825* | 0.822* | 0.787* | 0.897 | 0.867* | 0.876* |
| - 0.4 g's | 0.773* | 0.787* | 0.747* | 0.854 | 0.826* | 0.797* |
| 5. Braking efficiency 1 (Empty) - 0.2 g's | **0.662*** | **0.672** | **0.590*** | **0.691** | 0.731 | **0.673** |
| - 0.4 g's | **0.626*** | **0.649** | **0.553*** | **0.649** | **0.695** | **0.622*** |
| 6. Rollover threshold (g's) | **0.374*** | 0.397 | **0.326*** | 0.433 | 0.427 | 0.403 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | **68.59*** | None | None | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | 0.264 | 0.119 | **0.046*** | 0.121 | 0.132 | **0.060*** |
| 8. Maximum rearward amplification | - | - | **1.967*** | **1.531*** | 1.332* | **2.373*** |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor.

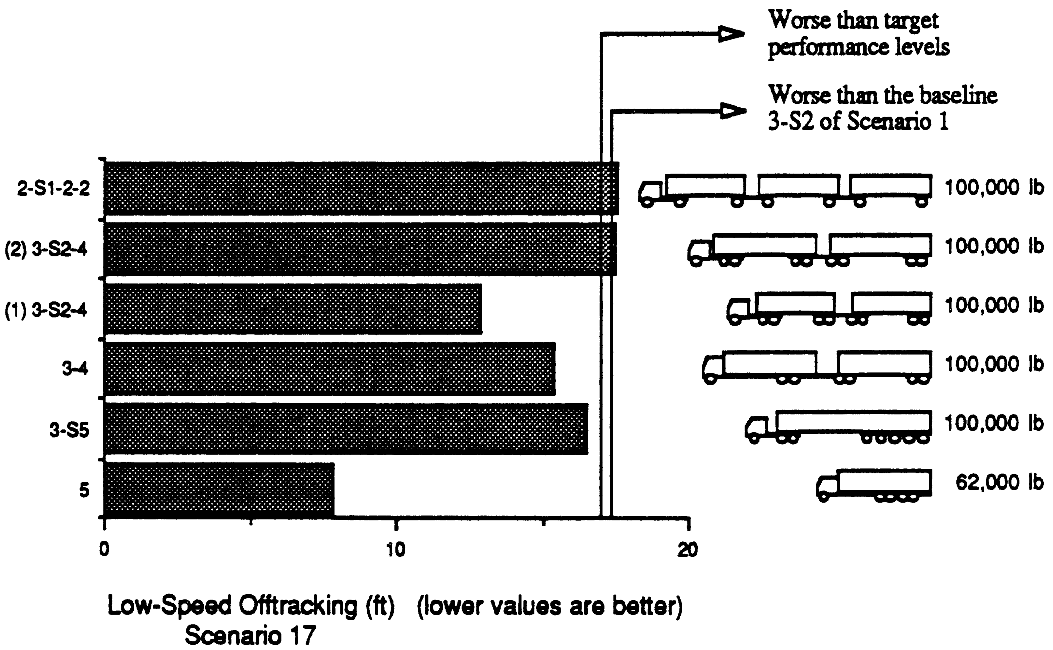



Figure 113. Low-speed offtracking, scenario 17.

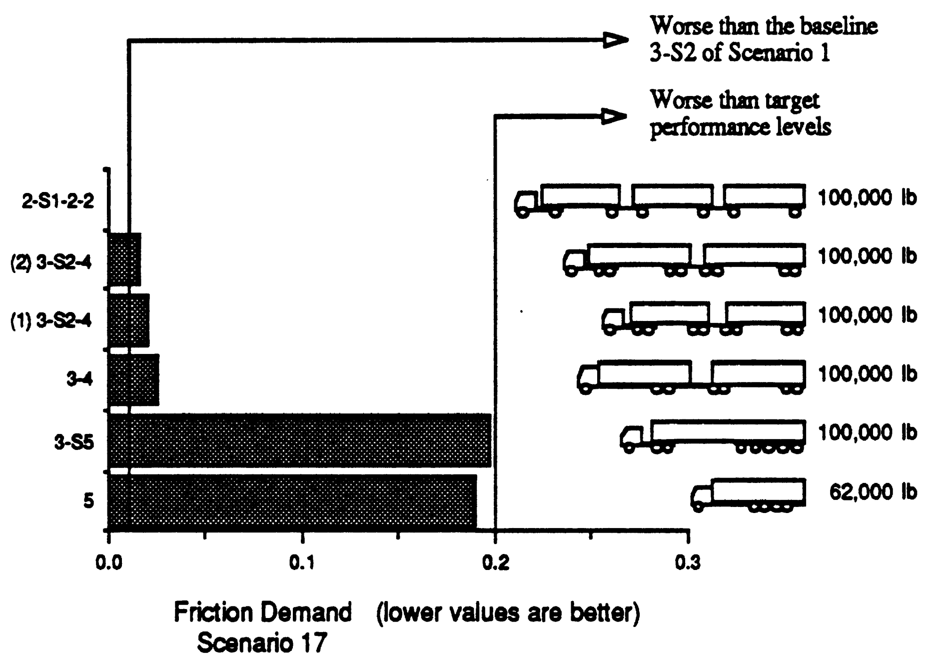



Figure 114. Friction demand, scenario 17.

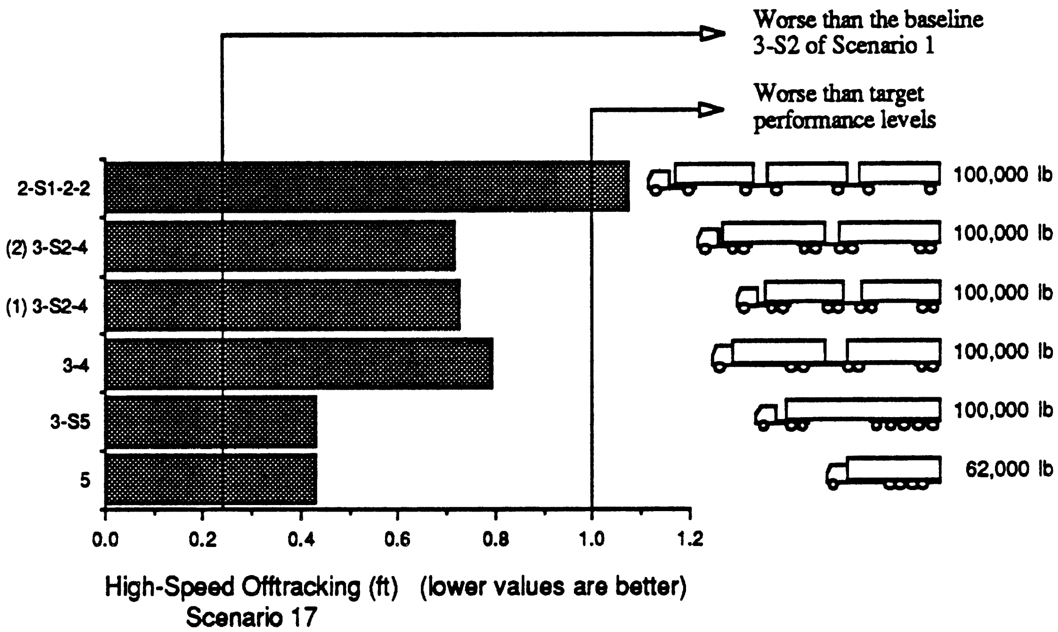



Figure 115. High-speed offtracking, scenario 17.

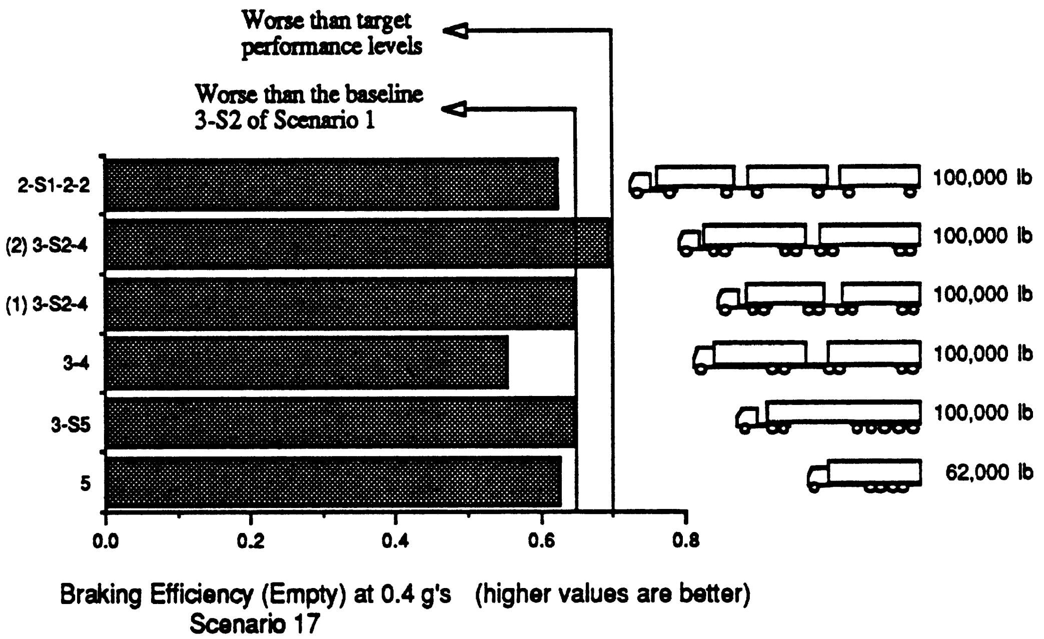



Figure 116. Braking efficiency, scenario 17.

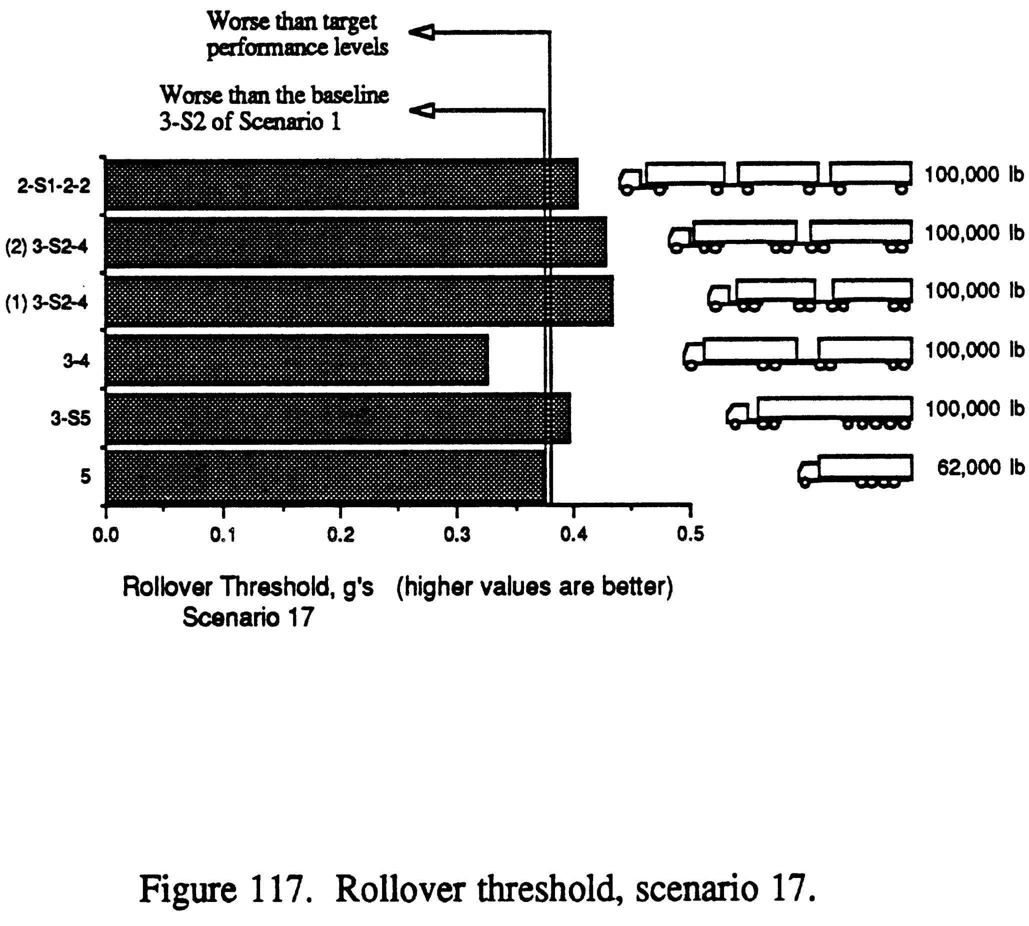



Figure 117. Rollover threshold, scenario 17.

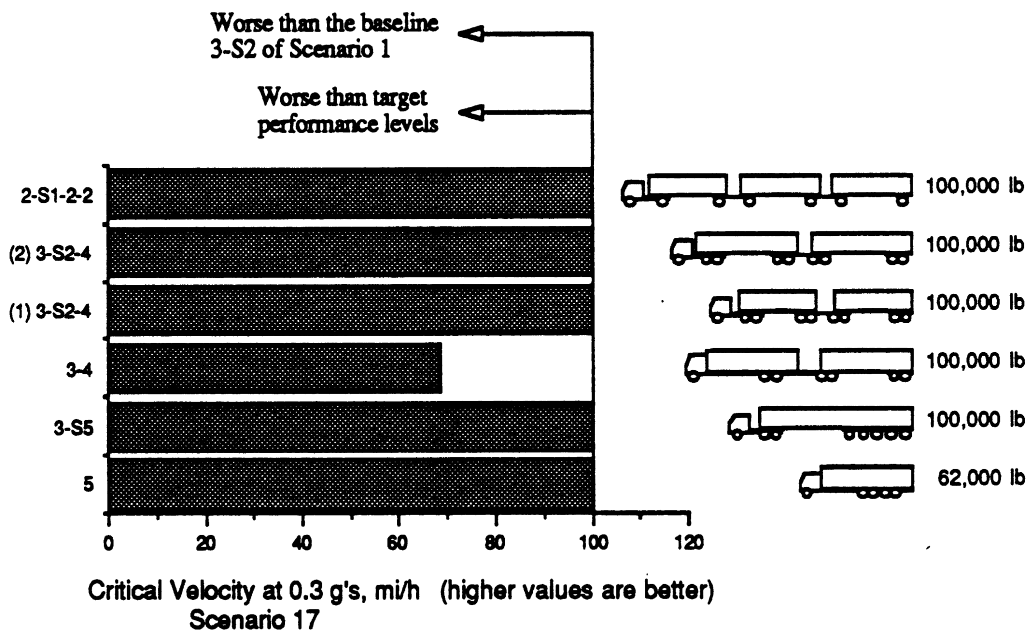



Figure 118. Critical velocity, scenario 17.

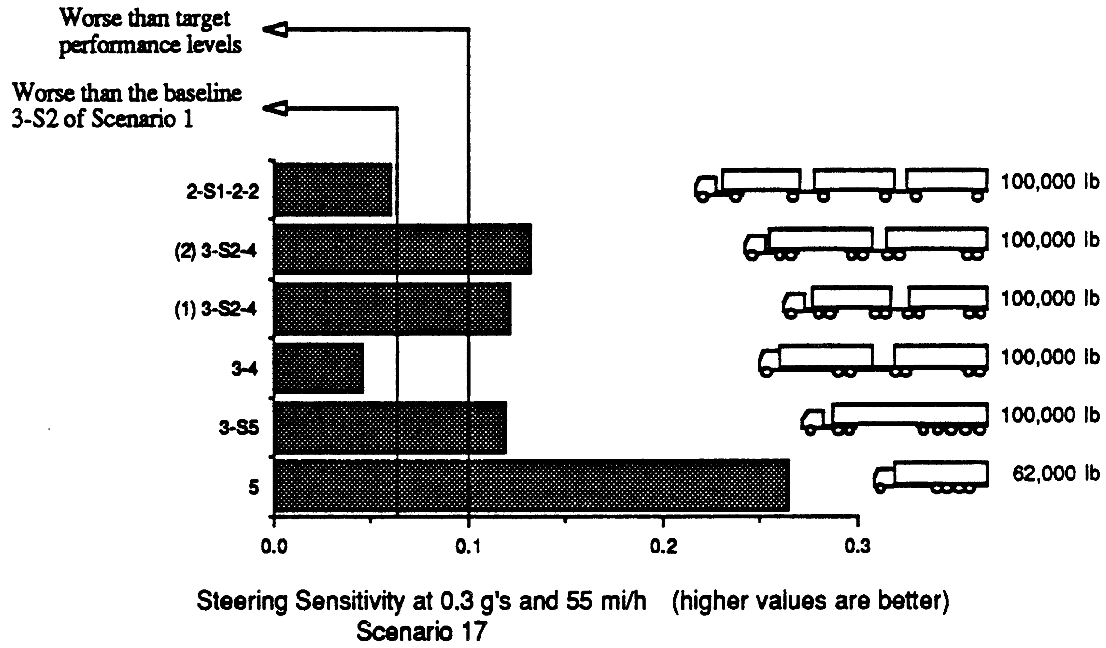



Figure 119. Steering sensitivity, scenario 17.

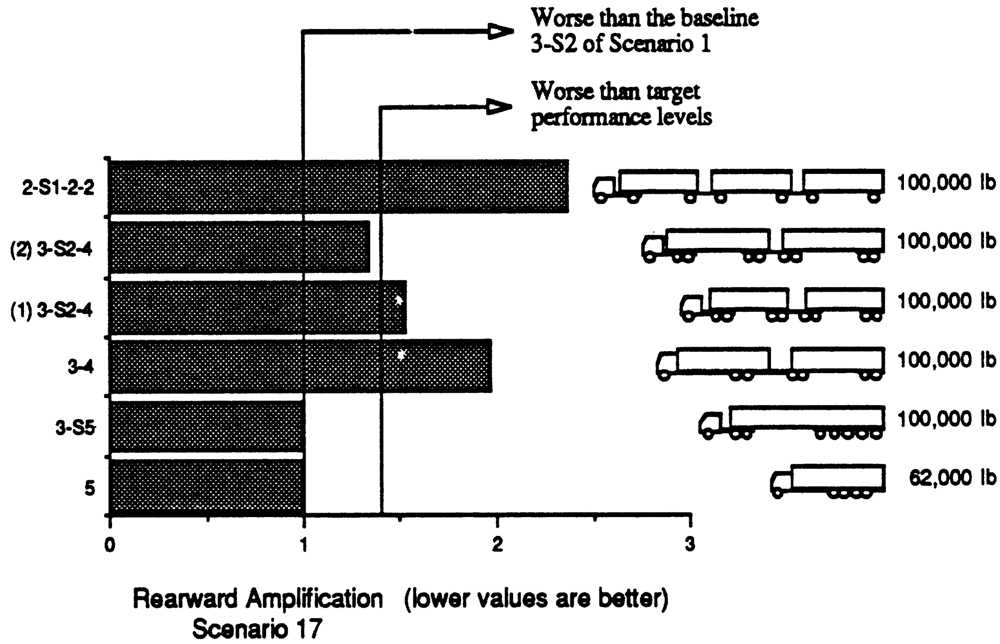



Figure 120. Rearward amplification, scenario 17.

remaining vehicles would be relatively stable in roll. In the case of the truck-full trailer, heavier loads and fewer axles on the towing unit reduce the vehicle's rollover threshold.

Steady Turn—Handling: Figures 118 and 119 contain the critical velocities and the steering sensitivities for the proposed vehicles in this scenario. With the exception of the truck-full trailer configuration, the remaining vehicles have relatively high margins of safety in the steady-turning maneuver. As mentioned earlier, the truck-full trailer has a lower rollover threshold which leads to an increased level of yaw instability at highway speeds. In fact, the vehicle would be yaw unstable at speeds over 69 mi/h (111 km/h).

Obstacle Evasion: Figure 120 displays the levels of rearward amplification generated by the multiarticulated vehicles in this scenario. Short wheelbases, in the truck-full trailer, and the triple, cause high levels of rearward amplification. The double-trailer configurations are better in this regard. In the second double-trailer layout (figure 111), longer trailers improve the vehicle's evasive maneuvering skills.

# 16. SCENARIO 18 — TWIN STEERING AXLES

## Vehicle Design

*Definition of the constraints on vehicle design*

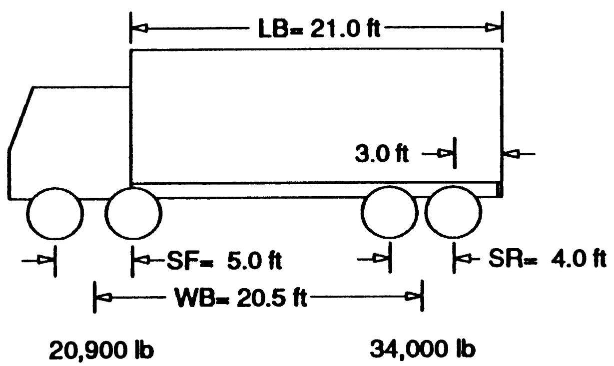
The constraints governing this scenario are:

| | |
|---|---|
| Maximum weight cap: | None |
| Bridge formula restrictions: | B |
| Length constraints: | 12 ft (3.7 m)/40 ft (12 m) offtracking limit |
| Pavement loading restrictions: | 34,000 lb (15,422 kg) for tandems; 20,000 lb (9,072 kg) for singles |
| Vehicle Types: | Twin-steer vehicles |

*Example vehicles*

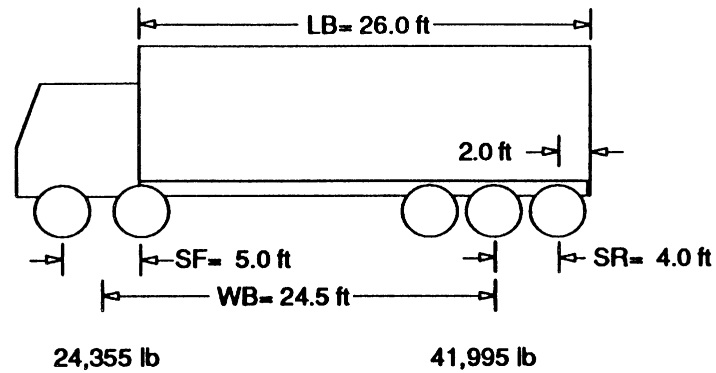
From the standpoint of improved safety, especially after front tire blowouts, twin-steer vehicles are generating public interest. Besides the unique twin-steer design, the vehicles are governed by the same set of constraints as in scenario 6, that is, the "offtracking rule," formula B, and the "34/20" pavement rule.

Straight Trucks: Two proposed straight truck designs are presented in this scenario. The first layout is a 30-ft (9.1 m), four-axle vehicle which is allowed a GCW of 54,900 lb (24,902 kg) (figure 121). Due to the tandem axles on the rear of the vehicle, the pavement rule becomes a limiting constraint. Consequently, the front suspension of the vehicle is limited to a load of approximately 21,000 lb (9,525 kg). The second layout involves a 35-ft (11 m), five-axle vehicle with a GCW of 66,350 lb (30,096 kg) (figure 122). In this layout, the bridge formula limits the rear tridem to 42,000 lb (19,051 kg). However,




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 20.5 ft | 3.0 ft | 5.0 ft | 2. | 4.0 ft | 2. | 35400. lb | 21.0 ft | .0 ft |

Figure 121. Straight truck (4; GCW=54,900 lb, payload=32,415 lb).




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| truck | 24.5 ft | 2.0 ft | 5.0 ft | 2. | 4.0 ft | 3. | 45350. lb | 26.0 ft | .0 ft |

Figure 122. Straight truck (5; GCW=66,350 lb, payload=41,102 lb).

the tridem axle suspension helps circumvent the pavement rule and increases the load on the front suspension to approximately 24,500 lb (11,113 kg). Compared with the 40-ft (12 m),five-axle straight truck of scenario 6, the higher front suspension load results in a higher total weight for this layout.

Tractor-Semitrailers: A tractor-semitrailer with twin-steer front axles is shown in figure 123. The vehicle with a five-axle tractor and a four-axle semitrailer reaches a total weight of 101,500 lb (46,040 kg). Though the bridge formula allows the nine-axle vehicle a total weight of 105,000 lb (47,627 kg), the location of the second steering axle reduces its axle load. In other words, with the tractor's fifth wheel located so close to its rear suspension, most of the trailer's kingpin load is supported by the tridem axles. Moreover, the bridge formula limits the trailer's suspension to 50,000 lb (22,680 kg). Consequently, a different axle layout could lead to higher vehicle weights. For example, wider spreads between the trailer's axles and a bigger fifth wheel offset could lead to a higher GCW.

A summary of the three layouts is shown in table 18.

## Vehicle Performance

### *Performance summary*

The safety-related items for the twin-steer vehicles are shown in table 19. The graphical representations of these performance characteristics are shown in figures 124 through 129.

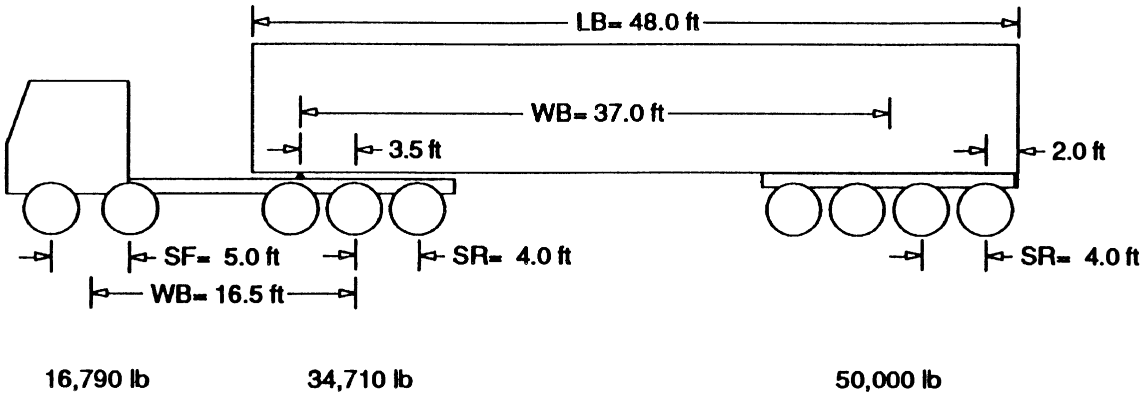
### *Safety and operational concerns*

Low-Speed Offtracking: Figure 124 contains the low-speed offtracking amounts for the vehicles developed in this scenario. Since all three vehicles are relatively short and have multiaxle suspensions, their offtracking amounts are less than the "baseline" TST.

Friction Demand: The friction requirements of the proposed vehicles are shown in figure 125. Though one might expect high friction requirements in the case of the nine-axle TST, the three drive axles on the tractor help improve the vehicle's maneuverability on slippery surfaces.

High-Speed Offtracking: Figure 126 contains the high-speed offtracking amounts for the twin-steer vehicles. With offtracking amounts less than 0.35 ft (0.1 m), the proposed vehicles perform fairly well in this maneuver.

Constant Deceleration Braking: The vehicle's braking performance is shown in the fourth and fifth items of table 19. The braking efficiency of each empty vehicle is shown in figure 127. The extra front axle improves the vehicles' braking performance significantly. In fact, the empty TST has efficiency levels comparable to some of the loaded vehicles developed in earlier scenarios. With the "rear-to-front" load transfer resulting in heavier loads on the front axles, the additional braking effort of the extra axle increases the vehicle's braking efficiency.




| Unit Type | Wheelbase WB | Pintle Hitch/ 5th Wh OS | Front spread SF | Front axles NF | Rear spread SR | Rear axles NR | Trailer load PL | Box length LB | Dolly tongue DTL |
|---|---|---|---|---|---|---|---|---|---|
| tractor | 16.5 ft | 3.5 ft | 5.0 ft | 2. | 4.0 ft | 3. | 0. lb | .0 ft | .0 ft |
| trailer | 37.0 ft | 2.0 ft | .0 ft | 0. | 4.0 ft | 4. | 74000. lb | 48.0 ft | .0 ft |

Figure 123. Tractor-semitrailer (5-S4; GCW=101,500 lb, payload=64,200 lb).

Table 18. Summary of example vehicles for scenario 18.

| Example Vehicle | Vehicle Code | Tare Weight | GCW | 1. Payload Weight | Payload Volume (cubic feet) | 2. Overall Length | Number of Axles |
|---|---|---|---|---|---|---|---|
| Straight truck | 4 | 22,485 lb | 54,900 lb | 32,415 lb | 1,607 | 25.0 ft | 4 |
| Straight truck | 5 | 25,248 lb | 66,350 lb | 41,102 lb | 1,989 | 31.0 ft | 5 |
| Tractor-semitrailer | 5-S4 | 37,300 lb | 101,500 lb | 64,200 lb | 3,672 | 58.5 ft | 9 |

1. Payload weight (excludes trailer weight) is estimated from a water level loading situation
2. Overall length is measured between extreme axles

Table 19. Summary of performance measures for example vehicles (scenario 18).

| | Truck | | Tractor-semitrailer |
|---|---|---|---|
| Vehicle Code | 4 | 5 | 5-S4 |
| Gross Combination Weight (GCW) | 54,900 lb | 66,350 lb | 100,000 lb |
| 1. Maximum transient (low-speed) offtracking (ft) - 41 ft and 90° | 5.15 | 7.02 | 15.91 |
| 2. Friction demand in a tight turn | 0.03* | 0.07* | 0.08* |
| 3. High-speed offtracking (ft) - 1200 ft at 55 mi/h | 0.302* | 0.298* | 0.346* |
| 4. Braking efficiency 1 (Loaded) | | | |
| - 0.2 g's | 0.939 | 0.845* | 0.935 |
| - 0.4 g's | 0.845 | 0.776* | 0.921 |
| 5. Braking efficiency 1 (Empty) | | | |
| - 0.2 g's | **0.699** | **0.677** | 0.732 |
| - 0.4 g's | **0.637*** | **0.631*** | 0.707 |
| 6. Rollover threshold (g's) | **0.338*** | **0.328*** | 0.414 |
| 7.a. Critical speed at 0.3 g's (mi/h) | None | None | None |
| 7.b. Steering sensitivity at 0.3 g's and 55 mi/h (radians/g) | 0.136 | 0.332 | 0.300 |

Entries with asterisks indicate performance measures that are worse than those of the 3-S2 of Scenario 1. The 3-S2 in Scenario 1 is used as a basis for comparison.
Entries in bold face type are judged to represent poor levels of performance relative to current technology.
Entries in bold face and with asterisks are both worse than the 3-S2 (Scenario 1) and poor

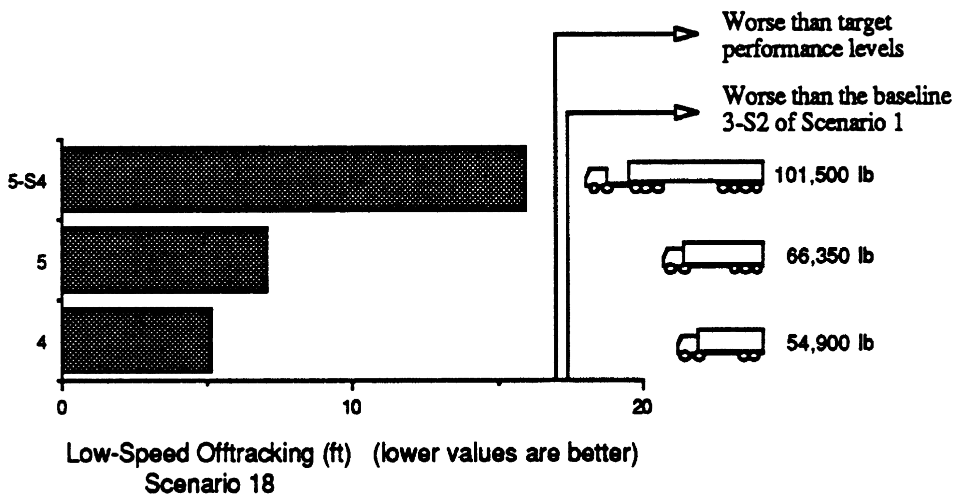



Figure 124. Low-speed offtracking, scenario 18.

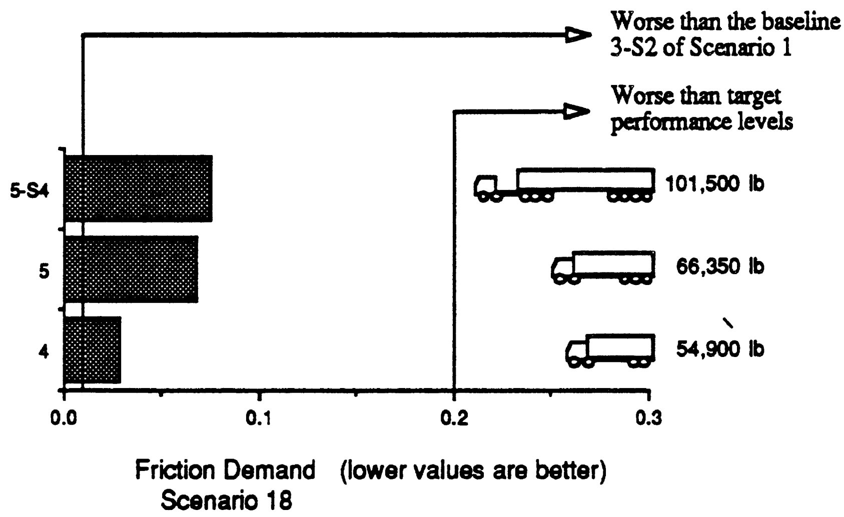



Figure 125. Friction demand, scenario 18.

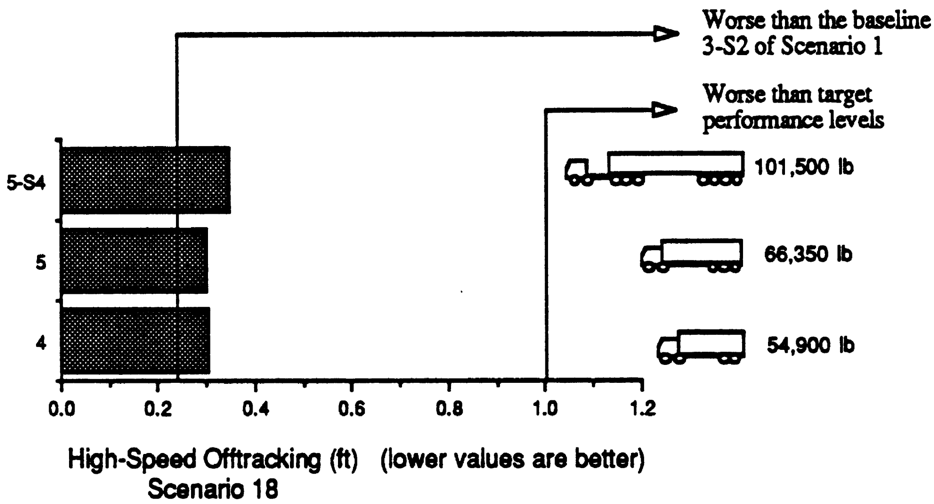



Figure 126. High-speed offtracking, scenario 18.

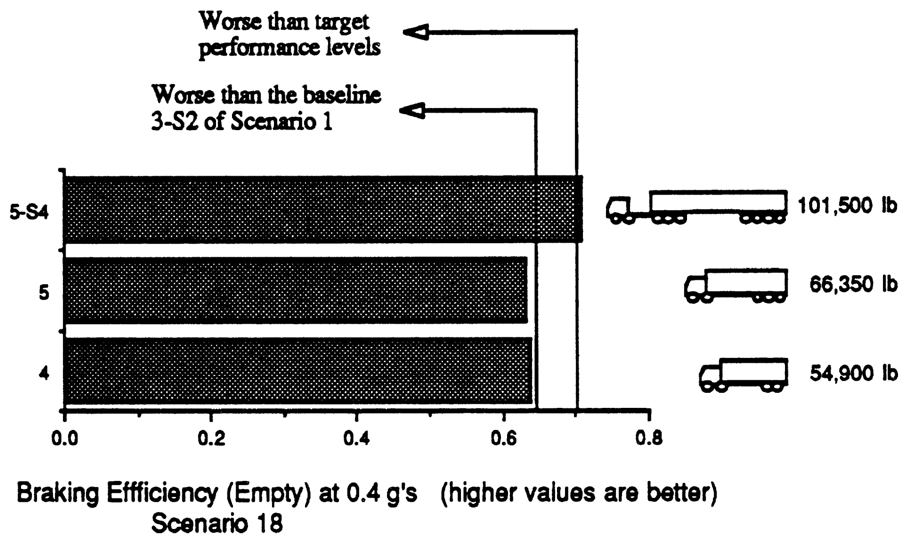



Figure 127. Braking efficiency, scenario 18.

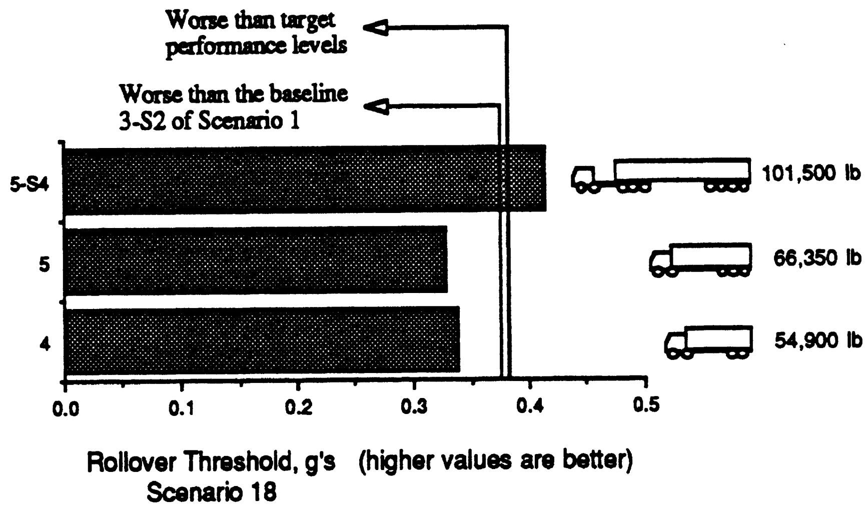



Figure 128. Rollover threshold, scenario 18.

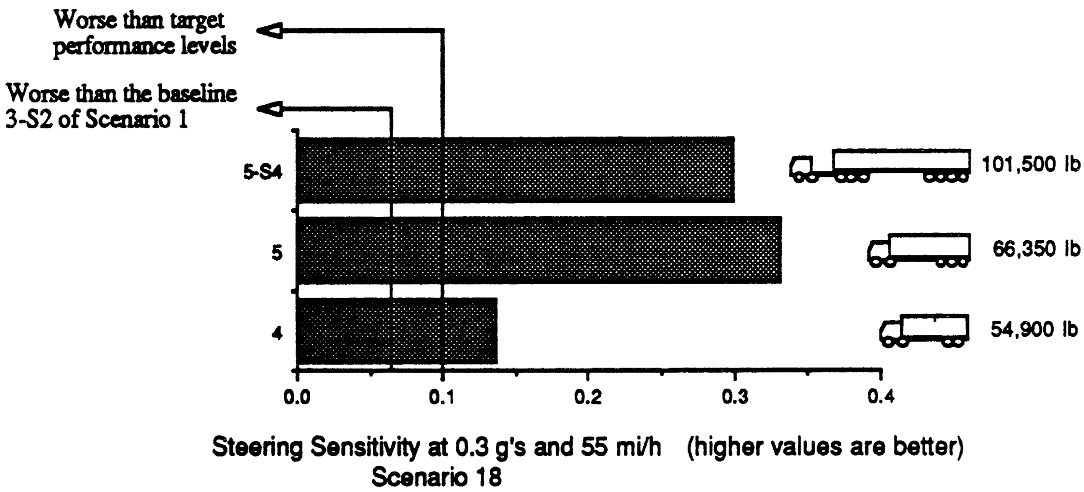



Figure 129. Steering sensitivity, scenario 18.

Steady Turn—Rollover: The rollover thresholds for the three vehicles are shown in figure 128. Fewer axles and heavier loads in the straight truck configurations reduce their rollover thresholds. Conversely, nine axles increase the TST's total roll stiffness and improve the vehicle's roll stability.

Steady Turn—Handling: Figure 129 displays the steering sensitivities for the three vehicles in a steady-turning maneuver. The extra front axle tends to improve the margin of safety in this maneuver. Consequently, with critical velocities greater than 100 mi/h (161 km/h), the vehicles maintain their yaw stability in the range of normal operation.

# 17. CONCLUSIONS FROM THE 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. Given that size and weight regulations are to a large extent results of political processes, they represent judgements based on many aspects of the influences of truck transportation on society. The compromises that could result in future proposals for changes in size and weight rules may lead to scenarios that have not been addressed specifically in this study. 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 80,000-lb (36,287 kg) weight cap has been very important in the development of currently prevalent vehicle configurations and axle arrangements. A removal of the weight cap could lead to different vehicle and axle layouts which would be more productive under the new set of rules.

The length provisions of the Surface Transportation Assistance Act (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 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 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 a five-axle TST.) 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 (36,287 kg) 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 (17 m) of cargo length (two 28-ft (8.5 m) "boxes" on the semitrailers) while the TST has 48 ft (15 m) 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 (36,287 kg) to approximately 88,000-lb (39,917 kg). 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 (36,287 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 a 3-S2-4 double, formula B would allow the 3-S2-4 vehicle to have a GCW equal to approximately 109,000 lbs (49,442 kg). Furthermore, the use of tridems on the double's semitrailers could lead to a practical vehicle (a 3-S3-5) that would be legally allowed to have a GCW of 122,500 lb (55,566 kg). These vehicles (the 3-S2-4 and the 3-S3-5) would be very attractive to the trucking industry because of their 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 it is a cause of 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 (36,287 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 braking 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 may cost more, 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 closing 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 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 practise. 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 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 5 and 6 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 lbs 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 rollover 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.

## 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-axles sets. The more lenient pavement rule often helps vehicles with biased load distributions reach higher gross combination weights without exceeding axle load limits.

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 directional 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 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 directional 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, multiaxle concrete 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 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 (36,287 kg) cap. The main effect of using formula C is that it would make it easier to reach the 80,000-lb (36,287 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 (36,287 kg), it would allow slightly shorter two-axle semitrailers to be used in TST's carrying 80,000 lb (36,287 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 (36,287 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; 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 multiarticulated 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 less 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 of figure 63 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 practised in other countries and has been adopted here with regard to the 65 mi/h (104 km/h) speed limit in some jurisdictions.)

## 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 scenaric 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; 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. The vehicle pictured in figure 84 is an example of a productive double that has a relatively low level of rearward amplification. 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. (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.

## Pavement loading constraints corresponding to the Turner concept (scenarios 8 through 11)

These scenarios are examples of situations in which single-axle loads are limited to 16,000 lb (7200 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 (32,300 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 (see figure 63) 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 illustrated in figure 84 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.

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 nearly unacceptable. With the exception of a possible directional 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 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 designs presented in figures 97, 98,and 99 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 five-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 (see figure 111) 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 portrayed in figures 63 and 84 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. [18]

## 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 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 three vehicles are improved significantly. In addition to improving the braking performance, the extra front axle tends to improve the vehicle's directional 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 loads that they are carrying.

On the other hand, the TST with nine axles has enough roll stiffness to have a relatively high level of predicted rollover immunity. In hind-sight, 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.

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

## What are the fundamental finaings 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 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 section 3. The material in section 3 was tailored to the implications of specific size and weight allowances. Table 20, 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 20 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,

Table 20. 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 |

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

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 20. **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 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.[16] 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 20 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 130 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 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 130 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 131 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.

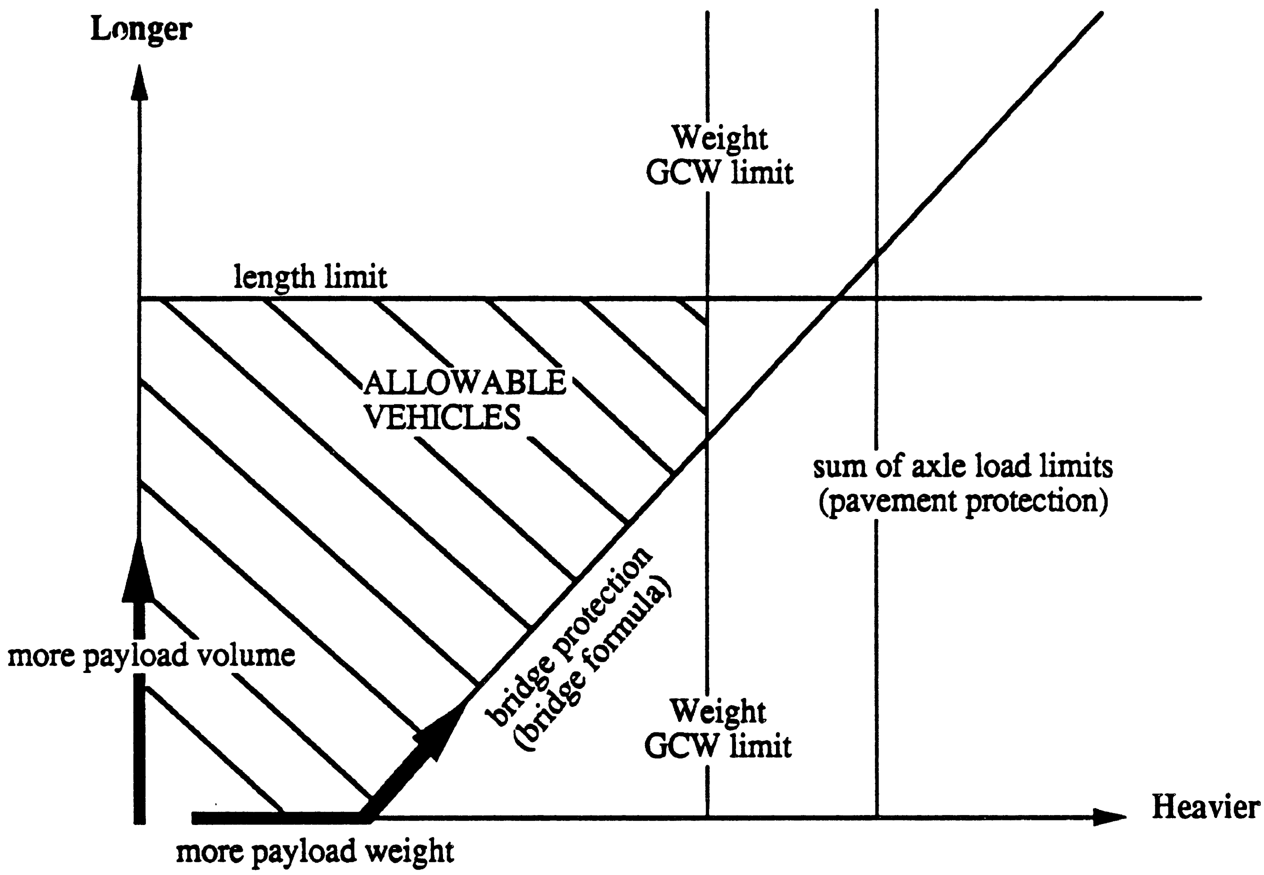



Figure 130. The range of allowable vehicles as constrained by size and weight rules.

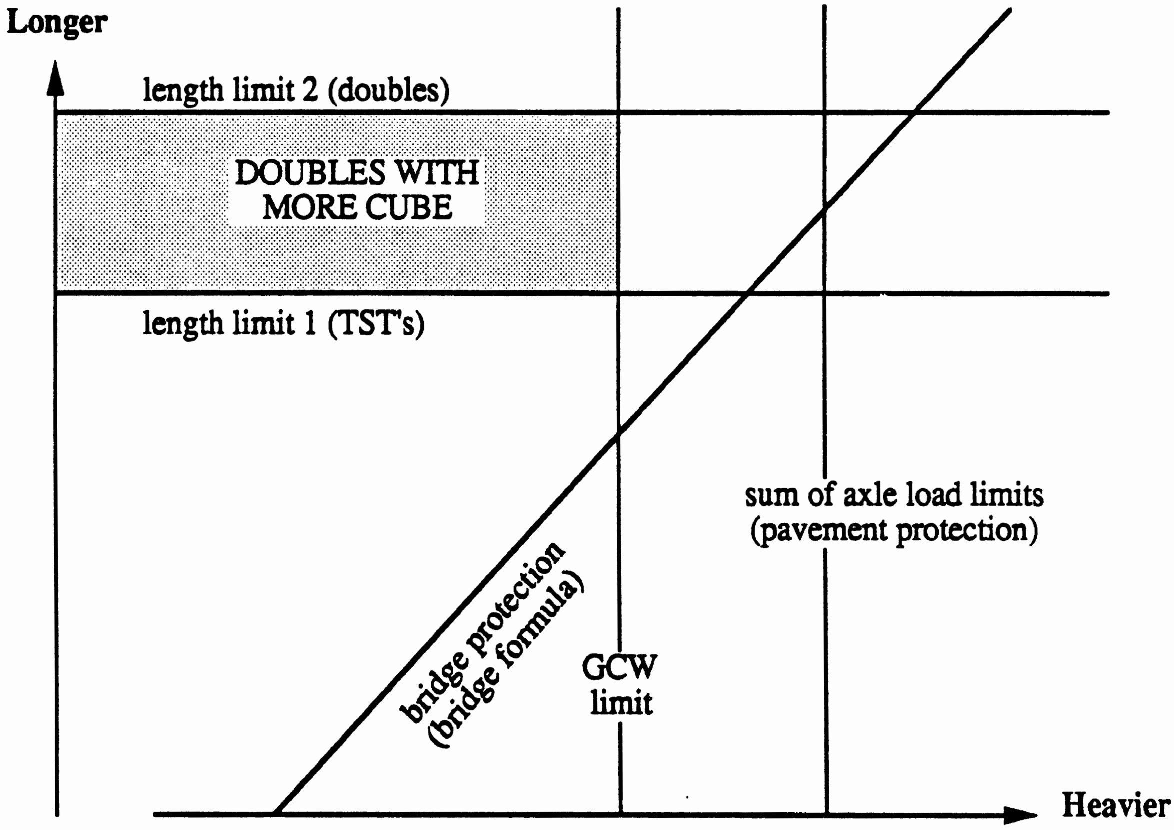



Figure 131. Different length constraints for doubles and tractor semitrailers (TST).

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 tthere 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 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 130. 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.

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 130, 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 130, 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 130 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 130.)

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 that 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:

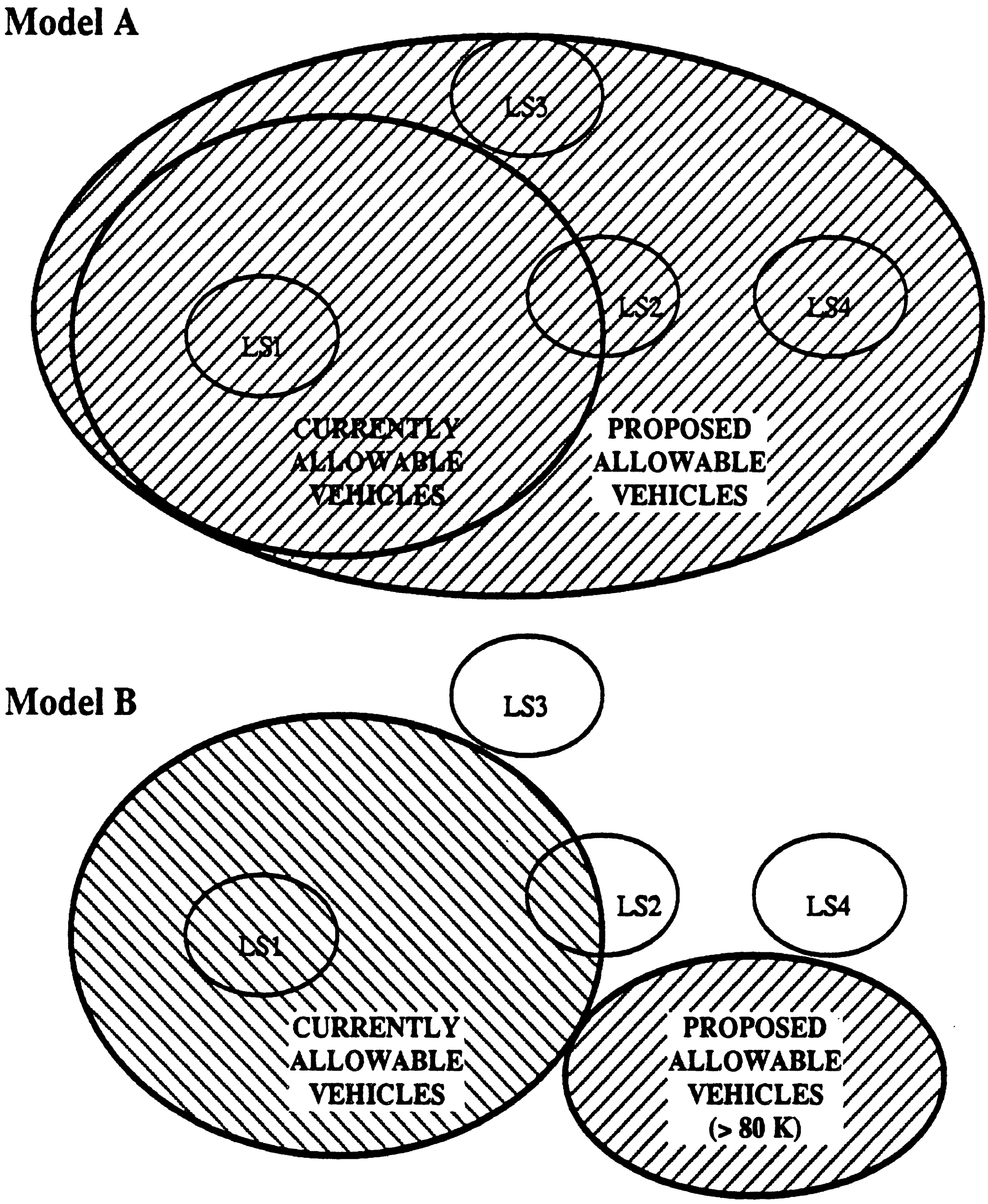
- Rollover immunity would be degraded. Reductions in the vertical stiffnesses of the tires and the roll stiffnesses of the suspensions would lower rollover thresholds to levels of turning that are significantly less than those obtainable using current tire and suspension stiffnesses.
- The level of tire 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 132 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 132 represent subsets of vehicles with poor levels of intrinsic safety. Ideally, as illustrated figuratively in model B of figure 132, 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




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

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.

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.

# 19. RECOMMENDATIONS

The fundamental conclusions derived from this study have just been presented in section 18. 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 section 18.)

- 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 (inherent) 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 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 travelling 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 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 section 18.

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