Truck Size and Weight Study

Phase I: Working Papers 1 and 2 combined

Vehicle Characteristics Affecting Safety

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

There is no direct relationship between TS&W policy and safety. Vehicle characteristics are altered in response to TS&W policy, and vehicle characteristics also influence handling and stability. A wide variety of vehicle characteristics may satisfy a given TS&W policy, and a wide range of safety effects can result. This paper begins with a discussion of the recent history of TS&W policy, and the influence of past policy on safety. The technical relationships between vehicle characteristics and safety are summarized in Section 2. This material has been condensed from a rather large body of literature. Performance measures are introduced to describe (quantify) the capability of the vehicle in various maneuvers. The material in Section 2 summarizes the relationship of various vehicle characteristics and pertinent performance measures (roll threshold, rearward amplification, braking efficiency, and offtracking). This section also includes a summary of the literature addressing the relationship of these performance measures to the in-service accident experience. In general, performance in safety-related situations determines the safety impact of vehicle characteristics.

A related area of the literature, that is also covered in Section 2, addresses the influence of the operating environment on safety. Factors such as road type, rural versus urban areas, and daytime versus night are associated with substantial differences in the risk of accident involvement. The operating environment may be viewed as a demand for performance. This material is followed with a brief discussion of the problems in making policy inferences based on the in-service experience of limited vehicle populations. Differences in operating environment can overshadow the influence of vehicle characteristics, and are probably responsible for much of the past controversy over the safety of different configurations such as single- versus double-trailer combinations.

The information from the literature, summarized in section 2, relating performance measures and accidents is necessarily limited to past experience. Section 3 addresses the implications for future TS&W policy. The literature on the relationships between vehicle characteristics and performance measures is summarized in a series of axioms, and the role of gross combination weight, vehicle configuration, and length are addressed. Knowledge gaps and research needs are discussed in section 4. The concluding summary reduces the major themes to succinct statements. The overall conclusion is that the safety impact of TS&W policy can be assessed by evaluating vehicle performance in safety-related situations.

1. Recent History: The Influences of TS&W on Safety.

Safety has not been an explicit objective of TS&W policy to date. However, the evolution of trucks within the constraints of existing TS&W policy can have significant safety impacts. This section provides background on the historical relationship of TS&W policy and safety, and it synthesizes ideas presented in recent studies concerning the influences of heavy vehicle characteristics on control, stability, crashes, and safe operating performance.

TS&W rules were originally conceived as a means for road builders and road maintainers to use in developing and maintaining roads that would be strong enough to serve transportation demands. The basic premise was: if the vehicles used on these roads would conform to the TS&W rules, the roads could be expected to serve their transportation function for an economically reasonable period of time without wearing out.

Although not a conscious intent of the originators of the TS&W rules, the rules have had the effect of deciding certain basic properties of heavy vehicle design that influence control, stability, and safe operating performance as well as road maintenance and productivity. In order to maximize productivity (the amount of payload that could be carried), vehicle designers and vehicle specifiers (purchasers) looked for ways to create vehicles that fit the rules but, for economic reasons, tended to push those rules to their limits. An ideal truck was one that was convenient to use for its intended job, could carry a large payload so that fewer driver trips were required to perform the job, and could achieve the maximum bridge and pavement loading allowed by the TS&W rules. Although the market place has helped to ensure that productivity be considered, the direct influence of quantitative measures related to control, stability, and safe operating performance has not been as apparent in the development of TS&W rules.

Thus heavy trucks for general service in many locations are built to carry 20,000 pounds on single axles, 34,000 pounds on tandem axles, and with axles spaced to satisfy Bridge Formula B. Although these loading arrangements have an impact on safety, they were not developed with safety in mind. They were developed to ensure that the highways and bridges would be structurally adequate for the vehicles that are allowed to run on them.

These rules have been changed and modified from time to time and place to place to provide greater productivity to the trucking industry where it was deemed economically important to accept the need for stronger roads and bridges. For example, Michigan allows vehicles weighing over 164,000 pounds. These may have 11 axles with 8 of the axles restricted to no more than 13,000 pounds each in a typical configuration. This protects the pavements and provides a favorable ratio of pounds of payload delivered to equivalent single axle loads (ESALs) of pavement loading. To carry such heavy vehicles, Michigan designed bridges to HS25 standards. Certain Western states allow various types of so called "longer combination vehicles." These vehicles are productive and meet local TS&W rules. There is now debate as to whether these vehicles can be fit into wider usage in a way that would show reasonable concern for productivity, safety, traffic, road maintenance costs, driver requirements, and environmental conditions.

In some cases State agencies have considered other factors such as traffic flow, safety, and environmental conditions in setting special TS&W rules. For example, Oregon does not allow triples to operate when the environmental conditions are such that the roads are wet or slippery. After several large gasoline fires involving fatalities, Michigan initiated research studies on the control and stability of double tankers used to haul gasoline [1,2].[1] These studies showed that there were vehicle design features that accounted for the control and stability problems. As importantly, these studies showed that with improved vehicle designs these safety-related problems need not occur. In Michigan, the original double tanker configurations were ruled out, and new arrangements with special hitches and new designs of tankers were approved. In addition, during the transition period, double tankers were restricted from traveling into urban areas during time periods when traffic was congested.

1.1 Safety Quality Requires Safety Specificity

With regard to this paper, a very important point is involved here. If TS&W rules are to address safety, they need to be more than rules for sustaining our ability to maintain the infrastructure and more than rules for enhancing economic productivity. The solutions to the double tanker problem showed that heavy vehicles can be designed to provide levels of safe operating performance that are within the norm of current trucks. The weight and length provisions of the current TS&W rules do not determine whether vehicles will be able to operate safely. The point is, if designed properly, heavy vehicles can have safe operating characteristics that will meet quantifiable performance levels involving directional control, roll stability, tracking between the front and rear ends, and braking.

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[1]References listed at the end of the paper.

If TS&W policy is to embrace safety, there will be a need for new types of TS&W provisions to aid in developing vehicles with safe levels of operating performance. Such provisions would guide the development of larger and heavier vehicles that can be operated at safe performance levels and that can be economically achieved with the latest vehicle technology. Ideally, it would seem that a cooperative approach involving industry and government safety agreements would be a desirable solution.

Federal legislation in recent years has allowed the weight cap to go from 73,280 to 80,000 pounds, twin 28-foot double trailer combinations are allowed nationwide, and overall length, as influenced by tractor length, is not now allowed to restrict the use of 48-foot semitrailers. Weight is not the only issue with respect to productivity. Size or "cube" is also important in determining the amount of payload that can be delivered in one trip. Many finished goods are now lighter than they used to be so that more volume is desired even though the weight limit on productivity may not be challenged for many types of cargo. Most states now have rules allowing 53-foot trailers to operate routinely. Triple-trailer combinations are now allowed on some turnpikes and in some western states. It appears that length restrictions are being set by the forces of productivity since TS&W rules, based upon maintaining the quality of the infrastructure for an acceptable period of time, encourage spreading vehicle weight over a greater distance between less heavily loaded axles. As far as maintaining the infrastructure and productivity go, this may be as it should be, but these changes in TS&W rules have rarely been strongly influenced by quantitative considerations of traffic, safety, and highway geometric design—all matters that are worthy of consideration.

1.2 Recent Studies of Truck Size and Weight

There have been recent research studies performed in the U.S regarding the overall acceptability including control, stability, and safety of heavy vehicles. These studies have been supported by both U.S. and Canadian organizations. With the advent of the North American Free Trade Agreement (NAFTA), it is interesting to observe that the safety-related aspects of the inter-provincial rules in-place in Canada are based on work originally done for the Canadians by researchers in the U.S.[3]. The Canadians have acquired the technology as needed to use vehicle performance standards to make size and weight judgments. They are now leaders in advocating performance measures for use in ensuring acceptable performance of heavy vehicles in safety-related situations [4,5]. The Canadian approach has been to define a set of vehicle configurations that possess performance qualities selected to enhance highway safety as well as productivity and highway maintenance goals. They have offered economic incentives in terms of larger payloads for vehicle configurations that have properties that yield especially good performance in safety-related maneuvering situations.

The goal of establishing means for making safety-related evaluations of heavy trucks has been studied by NHTSA [6,7,8], FHWA [9], and TRB [10]. Each of these studies has contributed in its own way to the body of technology and knowledge now available for assessing the safety-related performance of heavy trucks and especially longer and heavier trucks.

1.2.1 The 216 Study

The UMTRI study [7] in support of the 216 report to Congress laid out a comprehensive plan for establishing performance based evaluations of heavy truck safety. (The later sections of the UMTRI report to NHTSA contained time and spending charts covering some 35 specific program areas and requiring an estimated 7 million 1986 dollars to complete in 10 years.) This program involved (1) the use of performance measures for quantifying vehicle performance in safety-related situations, (2) studies of the performance of the existing truck fleet, (3) evaluation of the links between crashes and truck performance, (4) studies of countermeasures to improve performance and mitigate crash potential, (5) the development of vehicle test procedures, and (6) evaluations of the costs and benefits of potential safety rules. Figure 1 diagrams the elements of the proposed program.

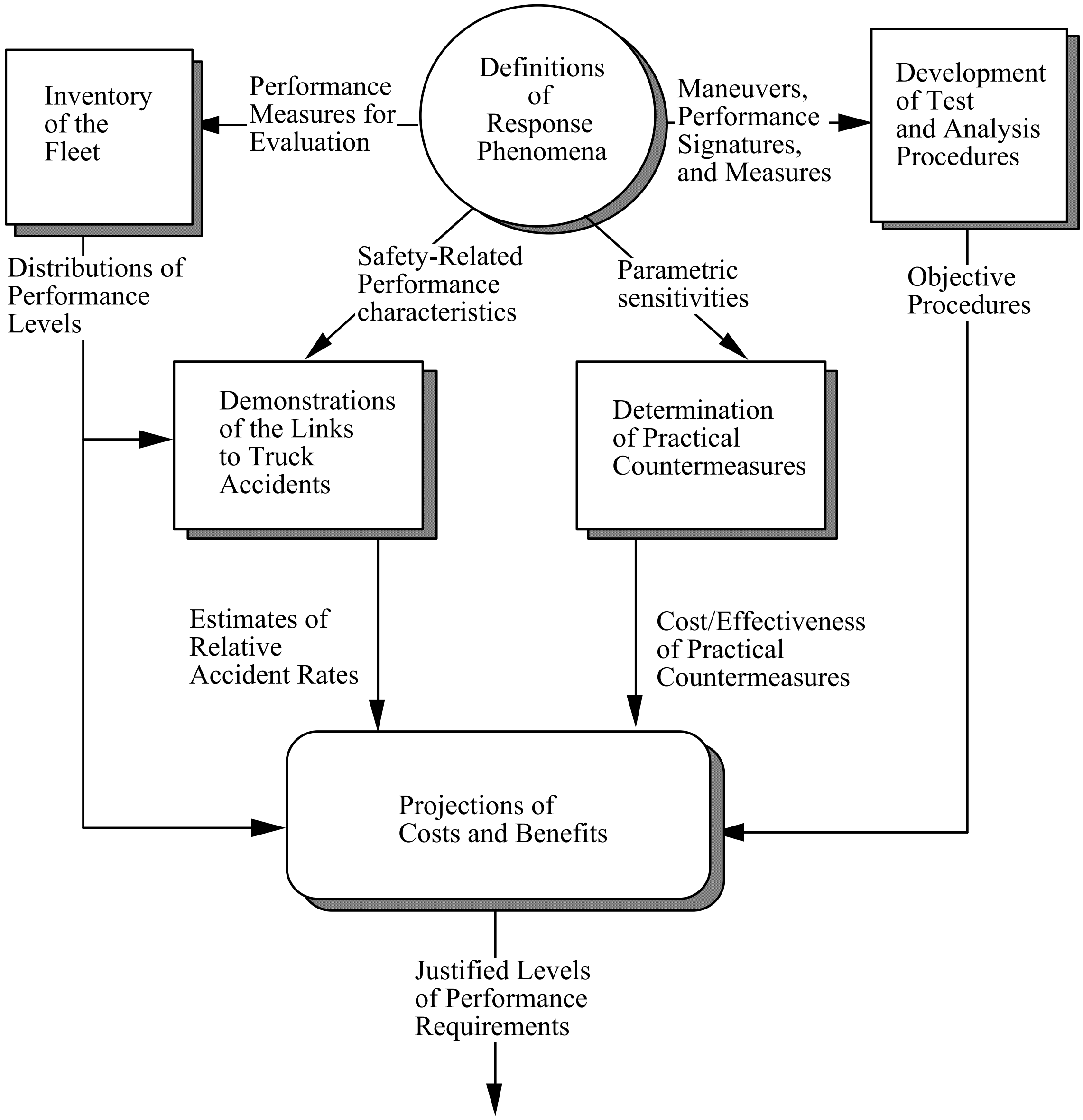


Figure 1. Information Base for Guiding Decisions on Safety-Related Performance

Some parts of this program have been addressed in the course of events. However, studies establishing the performance capabilities of the existing truck fleet have not been done. Efforts to develop countermeasures for current types of truck crashes have received some attention, but indirectly through attempts to promote antilock braking and other technological innovations. Test procedures have been developed for evaluating the threshold of roll stability and the rearward amplification of motion from the front to the rear of truck-full trailer, double-trailer, and triple-trailer combinations (Society of Automotive Engineers (SAE) J2180 [11], SAE J2179 [12]). In addition, test procedures for quantifying low speed offtracking have been demonstrated and they are very simple to arrange, for example see [10]. Procedures for evaluating the braking performance of heavy trucks have been available for some time and they have been in and out of government standards as Federal Motor Vehicle Safety Standard (FMVSS) 121, Air Brakes, underwent various modifications. It appears that a technological basis for evaluating vehicle performance exists, but there is work to be done in choosing practical levels of performance corresponding to reasonable application of the current state of knowledge in vehicle technology.

The study [9] entitled "Safety Implications of Various Truck Configurations" had a theme pertinent to this synthesis. The idea behind the study was to create a set of TS&W scenarios based on selected current sets of existing and proposed bridge formulas and pavement loading constraints plus offtracking allowances and other length and weight constraints including ones that would be compatible with the use of International Standards Organization (ISO) shipping containers. The research then developed vehicle designs that would be highly productive for each TS&W scenario. Then the safety-related performance of hypothetical vehicles created to represent these new designs was predicted using analytic techniques and computer simulation. To the uninitiated, all of this may appear to be very tenuous, but the vehicle analyses and simulations were based upon a foundation of testing of complete vehicles and laboratory measurement of the mechanical properties of vehicle components that had gone on successfully for many years [13]. The results showed that one could create vehicles that had good safety-related performance or poor safety-related performance under the various scenarios. It was a straightforward matter to pick out and design for those types of vehicle combinations that would have acceptable safety-related performance in turning, tracking, and braking maneuvers.

1.2.2 The Turner Truck Study

The study [10] of the “Turner Truck” was prompted by a suggestion by Francis Turner, a former Federal Highway Administrator. Turner’s idea was to promote greater productivity with less pavement wear by allowing higher gross combination weights if the vehicle was to be equipped with enough axles such that the load per axle was greatly reduced from current axle loads. Experimental evidence shows that pavement wear and fatigue is a sensitive function of equivalent single axle loads (ESALs). Although there is room for assessing whether a 4th power law is a good approximation to use in evaluating the amount of pavement damage done by particular vehicles operating on particular roads, the fact remains that pavement damage increases dramatically with increases in axle loads. Given this sensitivity to axle loads, it follows that there are great advantages for increasing pavement life to be obtained by using many lightly loaded axles as compared to a few heavily loaded axles. (This is the same reasoning that caused highway engineers in Michigan to advocate the use of very heavy vehicles with many, lightly loaded axles.)

In 1988 and 1989, the TRB conducted a study of the Turner Truck [10]. Several prototype configurations of Turner Trucks were evaluated. These configurations included a 7-axle tractor semitrailer (4-S3), a 9-axle B-train double (3-S4-S2), a 9-axle A-train double(3-S2-4), and an 11-axle double (3-S3-5). Even though these vehicles were restricted to 15,000 pounds on single axles, 25,000 pounds on tandem axles, and 40,000 pounds on tridems, their GCWs were approximately 87,000 pounds for the 7-axle tractor semitrailer, 112,000 pounds for the B-double, 110,000 pounds for the 9-axle A-double, and 140,000 pounds for the 11-axle double. For the doubles the trailer box lengths were taken to be 33 feet which improved cubic capacity and allowed greater axle spreads which improved not only pavement loading but also reduced rearward amplification of vehicle motions compared to those of doubles with 28-foot trailers. These vehicles had low speed offtracking performance that was comparable to that of a typical tractor pulling a 48-foot STAA semitrailer.

Analyses and simulations were used to compare the performance of the prototype Turner Trucks with the performance of three current types of heavy trucks, specifically, a 5-axle tractor semitrailer, a 5-axle double, and a 9-axle turnpike double. The three current or baseline vehicles weighed 79,000, 80,000, and 130,000 pounds, respectively, and they all were restricted to 34,000 pound tandem axles and 20,000 pound single axles. The 5-axle tractor semitrailer and the 5-axle double met Bridge Formula B. The turnpike double had a typical loading configuration such that it represented typical bridge and pavement loading as currently applied by these vehicles. In general, the analyses and simulations showed that the prototype vehicles were predicted to have safety-related performances in turning, tracking, rollover immunity, and braking that were comparable to those of their baseline counterparts. As long as comparable suspensions, tires, and brakes were used, the prototype vehicles were better than the baseline vehicles in rollover immunity and steering sensitivity. Again the point is that one can design longer and heavier vehicles that perform as well or better than current heavy trucks.

The Turner Truck study also included an investigation of the relationships between performance levels and fatal accident rates. Although in hindsight it seems clear that vehicle performance in safety-related situations is a reasonable way to compare vehicles (and particularly new types of vehicles with older types of vehicles), that was a new idea at the time of the Turner Truck study. At the time there was an apparent dilemma. How could one evaluate new configurations of vehicles if these designs were not presently in use? Even if a relatively small number of new vehicles such as the 28-foot twins (the STAA doubles) was in use, there was not enough crash experience to evaluate whether their crash record was better or worse than that of currently used heavy trucks. It is clear that there is a fallacy in trying to reach conclusions based upon examining the crash record of new types of vehicles that represent only a small fraction of the overall heavy truck fleet. The solution used in the Turner Truck study was to estimate the performance characteristics of the vehicles in the accident record and to use those performance characteristics to evaluate crash risk. These relationships between performance characteristics and crash risk can then be used to evaluate the crash potential of new vehicle designs. Clearly these assessments can be made as soon as the vehicle's properties are known and long before these vehicles have been operated long enough to see the effect of their characteristics on the crash record. Figure 2 provides a diagram showing the process through which safety-related performance can be used in evaluating and improving vehicle designs.

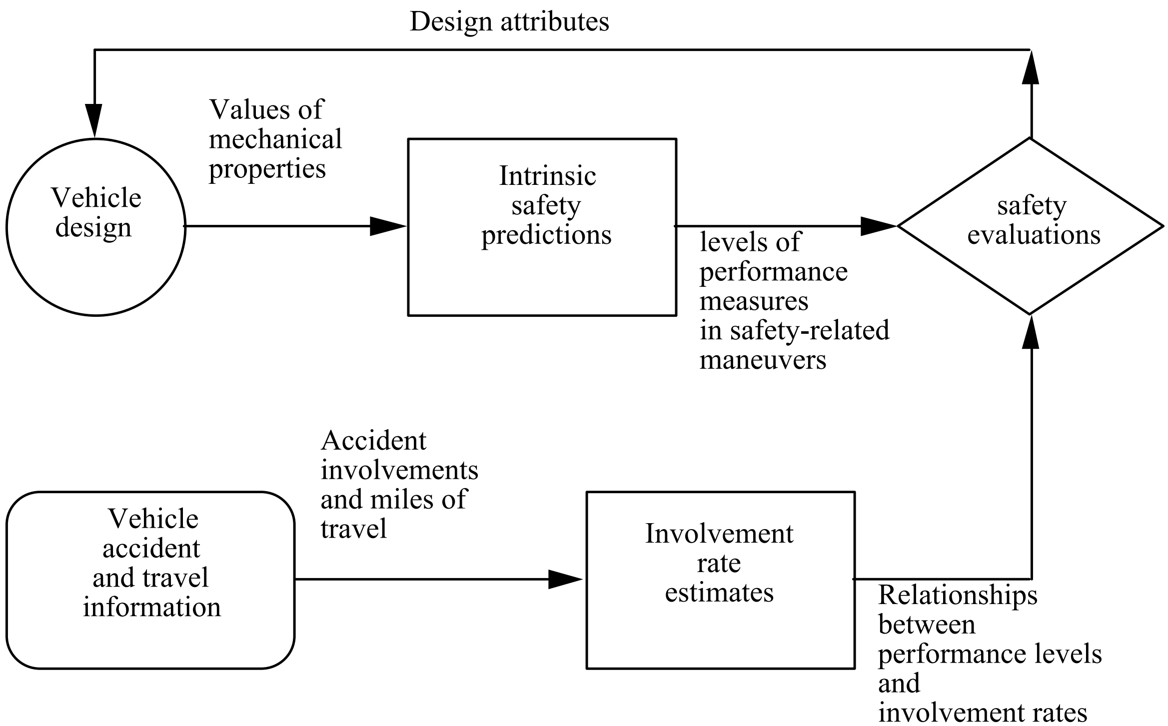
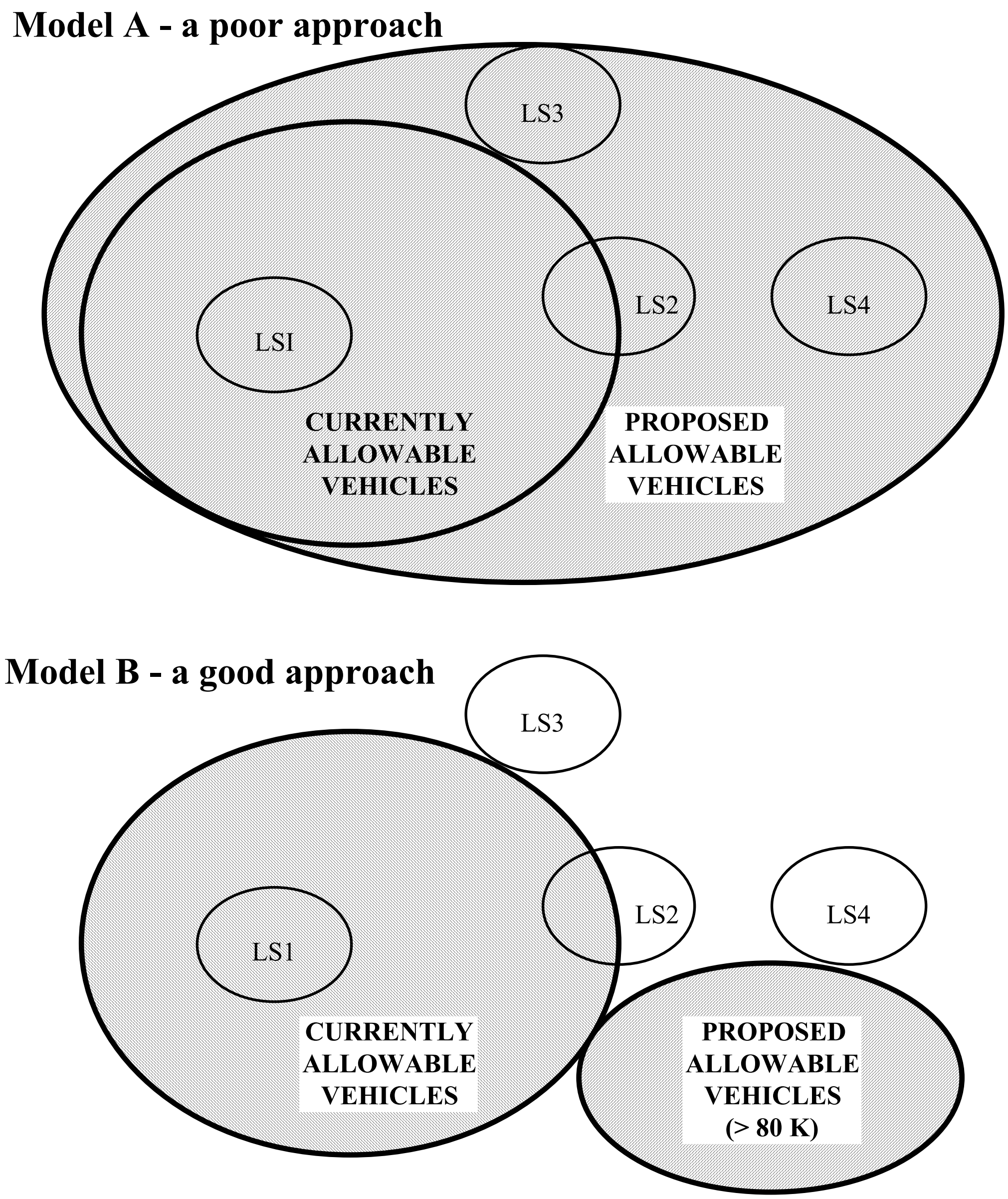


Figure 2. Handling and stability properties affecting safety.

There is a strong background of information on the influences of a vehicle's mechanical properties on vehicle performance in safety-related maneuvers, for example "Development Of Regulatory Principles For Straight Trucks And Truck-trailer Combinations" [4]. Pertinent information on the influences of TS&W variables were summarized in the Turner Truck study. The influences of TS&W properties on safety-related performance have become increasingly well understood. It is possible to predict the performance of new as well as current vehicle configurations. Given this capability, associations between vehicle designs and the crash record can be predicted.

An important, but sometimes misunderstood example, involves vehicle weight. Vehicle weight per se may not lead to a performance problem because performance depends upon the type of vehicle carrying the weight. If a vehicle’s weight was to be increased without changing the design of the vehicle to accommodate the additional weight, one would expect the crash record to degrade because the vehicle's safety-related performance would decrease. For example, if additional load is simply piled onto an existing vehicle, the rollover threshold would decrease because the center of gravity height would be increased and the center of gravity would move further outboard in a turn because the same suspension roll stiffness was attempting to balance a greater roll moment. On the other hand if a new vehicle with longer payload-space dimensions (lower c.g.) and more effective roll resistance was to be used to carry the new heavier load, the rollover threshold could be raised to a safer value than that of the current vehicle (even when the current vehicle is carrying a lighter load than the new vehicle). There needs to be careful consideration given to the influence of weight changes. Simply adding weight to existing vehicles is a poor idea, but new vehicles that are designed to carry more weight can well be safer than less productive, current vehicles. Figure 3, taken from the Turner Truck report [10], illustrates the basic concept of designing to achieve good safety-related performance as applied to heavier vehicles and considering not only rollover threshold but safety-related performance in braking and directional control as well.

The Turner Truck study also examined the influences of driver, road, and environmental factors. The in-service safety record of a vehicle is also influenced by the demands placed on the vehicle by the environment it is operated in. A safety problem doesn't arise until the driver is in a situation that requires more performance than the truck can provide. This topic is discussed further in Section 2.2.



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

1.3 Synthesis of Truck Operating Characteristics and Highway Design

In the last few years there have been a number of meetings addressing truck operating characteristics and reports assembling information on truck operating characteristics, especially as they apply to highway design, operations, and maintenance. Highway agencies tend to follow AASHTO Standards quite closely [14]. In these Standards there are numerous examples in which trucks play a role in setting geometric design conditions for roads. A recent ITE publication entitled “Geometric Design and Operational Considerations for Trucks” [15] covers many of the truck operating characteristics currently used in highway design. From a highway designers point of view, many of these design matters involve an element of safety in the sense that smooth flow of traffic with limited variation in speed and adequate sight distance are prerequisites for a safe roadway.

Currently TRB with AASHTO backing is supporting a synthesis of information on truck operating characteristics[16]. The performance evaluation information presented in that study is organized by the influence of vehicle characteristics and road design factors on situations involving turning, accelerating and braking, crash avoidance maneuvers, pavement loading, and congestion.

Turning at intersections, turning on ramps, and traveling on horizontal curves are considered in the section on turning situations. Offtracking toward the center of the turn is important during low speed turning. The vehicle factors that contribute to offtracking are the distances between axles (or axle sets) and articulation points. To the extent that property damage and pedestrian concerns are a safety problem, low speed offtracking may be considered a safety-related performance issue. At higher speeds there are concerns with directional control and rollover propensity. The curvature, superelevation, and expected truck speeds on ramps can lead to places where heavy trucks, having high centers of gravity and traveling a little faster than the intended speed of the roadway, may rollover. These high speed turning situations are all safety-related, and they show the need to coordinated TS&W properties with the geometric design of roadways.

With regard to longitudinal acceleration and deceleration, the acceleration capabilities of heavy trucks are important in meeting demands for moving expeditiously across rail crossings and through intersections as well as for sustaining speed on hills and accelerating from low speeds or from a stop on upgrades. Trucks with weight to power ratios of 300 pounds per horsepower (hp) and more can be traffic impediments and safety hazards because roads are often designed with the level of acceleration capability implied by 300 pound/hp or less. Clearly if trucks are allowed to get heavier without corresponding increases in power, they will be less capable in uphill situations as well as slower in crossing intersections, especially if they are not geared for low speed acceleration capability.

The acceleration characteristics of vehicles need to be coordinated with the sight distances available for crossing an intersection or railroad track. The truck driver needs to be able to see far enough to decide if it is safe to enter the intersection without causing vehicles that are approaching on the cross road to perform an unusual maneuver. Low acceleration capabilities increase the need for long sight distances.

Braking characteristics of trucks also need to be coordinated with highway design characteristics. Again, sight distances need to be long enough so that truck drivers can decide to stop when the situation requires it. If a heavy truck does not have enough brake torque capability to meet the demands for stopping within the available sight distance, there is a safety hazard. Clearly increases in weight need to be accompanied with increases in brake torque capability, especially if sight distances are not changed.

Another problematic situation for existing trucks as well as for new types of trucks is maintaining speed on downgrades. Given that the pounds of brake mass to pounds of vehicle mass is limited for trucks, there is a greater tendency for truck brakes to overheat than there is for car brakes. If trucks are allowed to carry heavier loads, there is a need to increase the thermal capacity of the brakes and/or restrict the vehicle to very slow speeds on downgrades. Since low speeds may represent a traffic hazard as well as a loss in productivity, greater thermal capacity is the preferred solution for heavier vehicles. In downhill descents it is important that all brakes do their fair share of the work and that brake adjustment and balance be carefully attended to.

It is pertinent to this discussion to observe that the lengths of trucks are not taken into account in designing roads with passing sight distances that are adequate for passing long trucks. The influences of truck lengths on passing requirements have been considered recently in Michigan [17]. Nevertheless, this subject warrants more study with the results to be used in evaluating whether certain roads are suitable for use in allowing long heavy trucks access to particular locations.

From NHTSA's point of regard and authority, the operating characteristics of trucks in crash avoidance situations is very important. As already described, there have been several studies pertaining to performance in safety-related situations involving rollover, obstacle avoidance (i.e., rearward amplification), rearend collisions, and running off the road. The draft TRB synthesis links vehicle/driver factors and highway factors to performance evaluation and achievement in all of these situations.

The sense of all of the recent studies covered here is that we know a lot about how to make large trucks operate safely. The problem seems to be one of figuring out reasonable policy for achieving safe operating performance along with productivity and endurance of the infrastructure. Even with a policy direction in place, however, there will be need for considerable effort to arrive at policies with a strong scientific foundation, appeal to truckers and the public sector, and a practical, pragmatic regard for the realities of delivering goods to consumers.

2. Technical Relationships Between TS&W Policy and Safety

The general approach here argues that performance measures can be used to evaluate the safety impact of proposed TS&W policy. Historically, TS&W policy alone does not sufficiently define the vehicle with regard to performance measures. A range of performance measures may be possible for a given TS&W policy, depending upon the way in which a truck is configured to comply with the policy and the highway environment in which the truck is operated. Safety could be incorporated in future TS&W policy by requiring that certain performance measures stay within acceptable bounds.

2.1 Performance Measures, Safety, and TS&W Policy

This material includes available evidence linking accidents and performance measures (mostly from the Turner Truck report [10]). Projections concerning the accident involvement rates of new types of vehicles, are based on the performance characteristics and accident records of existing vehicles. The keys to doing this are: (1) estimating vehicle performance in safety-related maneuvers and (2) developing relationships between vehicle performance and accident involvement rates. The methodology, previously diagrammed in Figure 2, illustrates how these key capabilities have been used in making safety evaluations and specifying desirable design attributes.

The upper part of Figure 2 (Section 1, p 9) contains a path running from vehicle design to safety evaluations. Given basic layouts of the vehicle configurations including the numbers of axles, the mechanical properties of these vehicles were specified in sufficient detail so that computer models could be used for predicting vehicle performance in safety-related maneuvers [18]. The levels of these performance measures in the safety-related maneuvers constitute predictions of "intrinsic safety" or "inherent safety" [19]. The terms "intrinsic" or "inherent" pertain to those aspects of safety that depend upon properties of the vehicle itself and the vehicle's ability to be forgiving of poor roads and/or poor drivers. The levels of performance measures pertaining to the safety-related maneuvers selected for this study constitute one of the inputs used in the safety evaluations presented herein (see the diamond shaped block in Figure 2 which appears in the previous section).

The other input to the safety evaluations comes from an analysis of accident and travel information on existing configurations. Only one usable source of suitable data was identified in the Turner Truck study—and in that source, truck involvements were limited to fatal accidents in the period from 1980 to 1984 [20]. Furthermore, the existing variables in the data base were not sufficient for directly establishing relationships between accident involvement rates and levels of vehicle performance. In order to establish those relationships, it was necessary to perform analyses to determine relationships between (1) the vehicle factors that exist in accident and travel databases, and (2) derived variables representing performance measures applicable to offtracking, braking, rollover, handling, and trailer "whipping" (rearward amplification). These derived variables were added to the accident and travel data files so that they could be used in computing involvement rates based on vehicle performance properties for truck configurations commonly in use.

The findings of the safety evaluations provide evidence supporting the following general conclusions:

- There are design attributes which, when applied to Turner Trucks, will limit the involvement risks for specific accident types to be comparable to or better than the accident involvement risks associated with current "baseline" vehicles.

- Based on the materials provided and discussions with manufacturers, the prototype vehicles can be equipped with engines and power trains that will make their hill climbing and acceleration capabilities comparable to those of current 80,000 pound Western doubles. As with Western doubles, due to the low ratio of drive axle load to gross combination weight (GCW), the prototype vehicles may have limitations with regard to climbing steep grades when the roadway is slippery.

- As expected, the building of a mock-up 9-axle Turner Double demonstrates that such a vehicle could be readily developed using existing hardware and that the performance of this vehicle would be as predicted in safety-related maneuvers.

- The simulation results (predicted performances) indicate that the prototype vehicles equipped with reasonable tires, brakes, and suspensions would be capable of meeting or exceeding minimum performance standards based on the performance capabilities of current vehicles, even though the prototype vehicles were longer and heavier than current vehicles.

- With care and ingenuity, accident and travel records can be used to establish relationships between performance levels and the risks of involvements in particular types of accidents. This is a new area of accident data analysis. The work in this study extends pioneering work regarding rollover [6,21] and jackknifing [22] and addresses other types of accidents.

Since most accident investigations and collections of accident or exposure data have paid little attention to assessing the performance capabilities of the heavy trucks involved, there are very few sources of information that can be used to link truck performance and handling properties to highway safety. However, vehicle dynamicists have forged ahead by defining what has been called "intrinsic" or "inherent" safety [23,24]. The basic notion underlying this approach is to examine vehicle performance in safety-related maneuvering situations leading to such events as rolling over, jackknifing, loss of directional stability, poor tracking, and poor braking.

Given that rollover and jackknifing are (1) easily recognized by accident investigators and (2) readily predicted by appropriate types of vehicle analyses, rollover and jackknifing accident involvements have been related to the accident record [6,21,22]. These studies show that rollovers are a major accident type for fully laden trucks and truck combinations and that jackknifes are most important for empty combinations. With regard to rollovers, important countermeasures are to keep centers of gravity as low as practical, to keep track widths of tires and springs as wide as practical, and to keep the center of gravity of the load from shifting sideways by using high roll stiffness in appropriate suspensions, preventing cargo shifting, and reducing slosh [25,26]. With regard to jackknifing, improvements in brake proportioning and antilock systems are recommended [9,27]. The problem is that the traditional approach to brake proportioning in the United States has been to design for fully laden axles without considering difficulties that can arise when the vehicle is empty or when load is transferred from the rear axles to forward axles due to high declarations. Heretofore, rollover has been the primary instance in which vehicle performance levels have been tied to information contained in the accident record. (For example, see Figure 4 illustrating how rollover thresholds were related to rollover accidents in reference [28].)

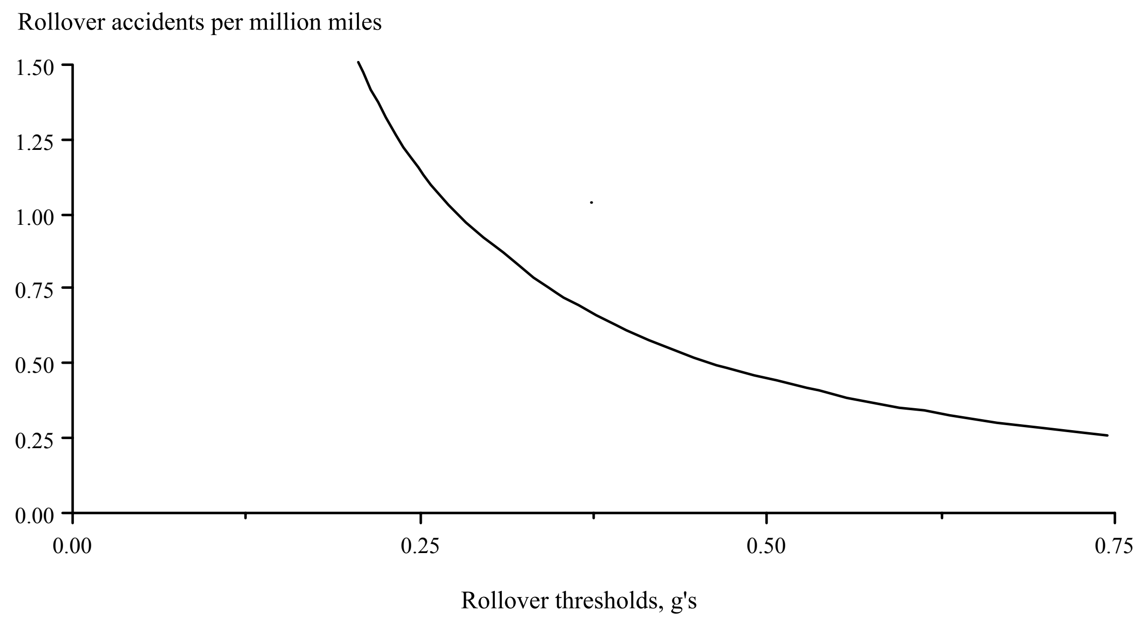


Figure 4. Rollover rate versus rollover threshold for a tractor with a van semitrailer. [28]

Now return to the vehicle dynamicist's point of view in which terms such as "active safety" or "pre-crash safety" are applied to accident avoidance situations. It is postulated that, if efforts to improve vehicles with respect to their accident avoidance capabilities are successful, the vehicles involved will appear less frequently in the accident record. The perspective taken here is that improved performance capabilities will lessen the likelihood that drivers will find themselves in situations that they cannot control or resolve satisfactorily.

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

- 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 selected for use in assessing vehicle performance relative to the practical goals listed above:

- Steady turn—rollover (Section 2.1.1)
- Obstacle evasion (rearward amplification, Section 2.1.2)
- Constant deceleration braking (Section 2.1.3)
- Low-speed offtracking (Section 2.1.4)
- High-speed offtracking (Section 2.1.5)

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 the benefits/costs are completely understood and connections with the accident record are not quantified for the current environment. However, examinations of the accident record have provided 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, judgments have been made regarding target performance levels. If one accepts these judgments and, also, recognizes that these analyses represent the performance of idealized vehicles that do not suffer from practical problems that occur in the trucking environment, then the relative differences in performance can be used in guiding changes that are expected to represent directions for improving both productivity and safety.

2.1.1 Roll Threshold

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. The results of these examinations indicate that the rollover of heavy tractor-semitrailers is very sensitive to their intrinsic rollover thresholds, especially where the rollover thresholds are less than 0.4 g. (See Figure 4 in Section 2.1.)

Test procedures and calculations can be used to examine the rolling performance of a vehicle during steady-turning maneuvers. The calculation procedures represent analytical equivalents of tilt-table experiments. The primary factors influencing roll are c.g. heights, axle track widths, spring and tire rates, spring spreads, roll center heights, and axle loads. The performance measure is the level of lateral acceleration at which rollover will occur.

A target performance level from the Turner Truck study:

The level of lateral acceleration which can be achieved without rolling over in a steady turn has been 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 a baseline tractor-semitrailer is 0.375g. (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 0.25g.)

Results pertaining to rollover illustrate (1) the distribution of rollover threshold in the fatal accident record for the current vehicle fleet (see Figure 5) and (2) rollover rate as a function of rollover threshold (see Figure 6). These results indicate that the current vehicles tend to have rollover thresholds in the 0.3g to 0.4g range and that the relative involvement ratio is large for vehicles in this range of rollover threshold. There are not enough cases in these fatal accident data to indicate the rollover rate for vehicles with rollover thresholds less than approximately 0.35g. The absence of vehicles in this range may be an indication that such vehicles are hard to operate safely and are rarely used unless the risk appears to be worth the desire to be productive. In any event, requiring heavy vehicles with rollover thresholds greater than 0.38g, when fully laden, will be comparable to the current fleet except that vehicles with intrinsically low values of rollover resistance (below 0.35g) would be avoided.

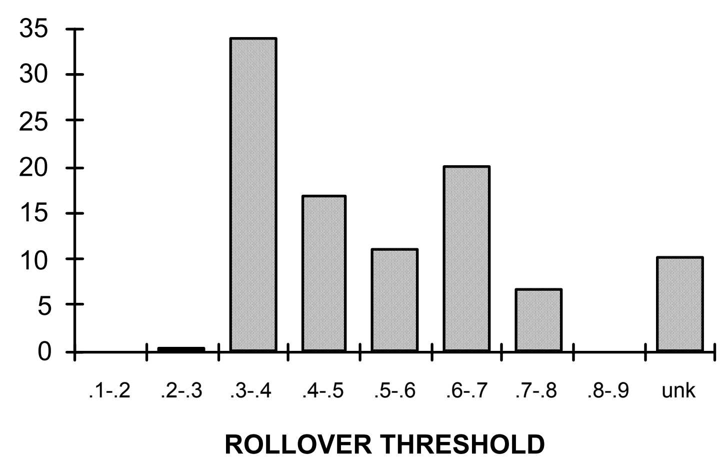


Figure 5. Distribution of travel by rollover threshold
for 5-axle van and tank singles and van doubles [10]

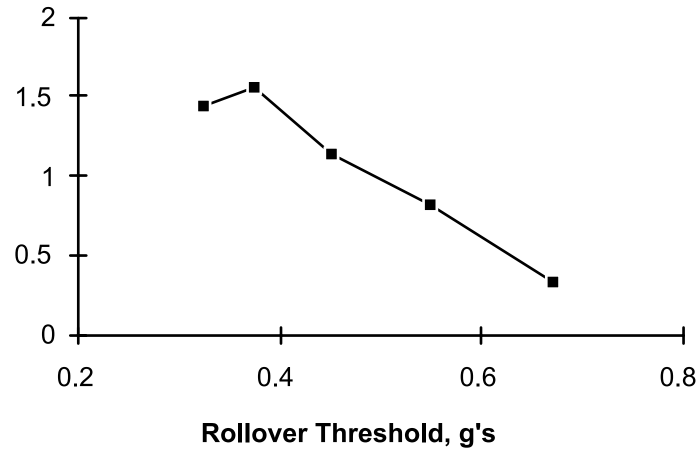


Figure 6. Relative risk by rollover threshold
fatal accident involvement of 5-axle van tractor semitrailers [10]

2.1.2 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.

In obstacle-avoidance maneuvers, multitrailer vehicles experience a "cracking-the-whip" phenomenon where the lateral accelerations of rear trailers are amplified considerably. (See Figure 7.) 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. Rearward amplification 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 [12]. The maximum amount of amplification is then used as the performance measure for this maneuver.

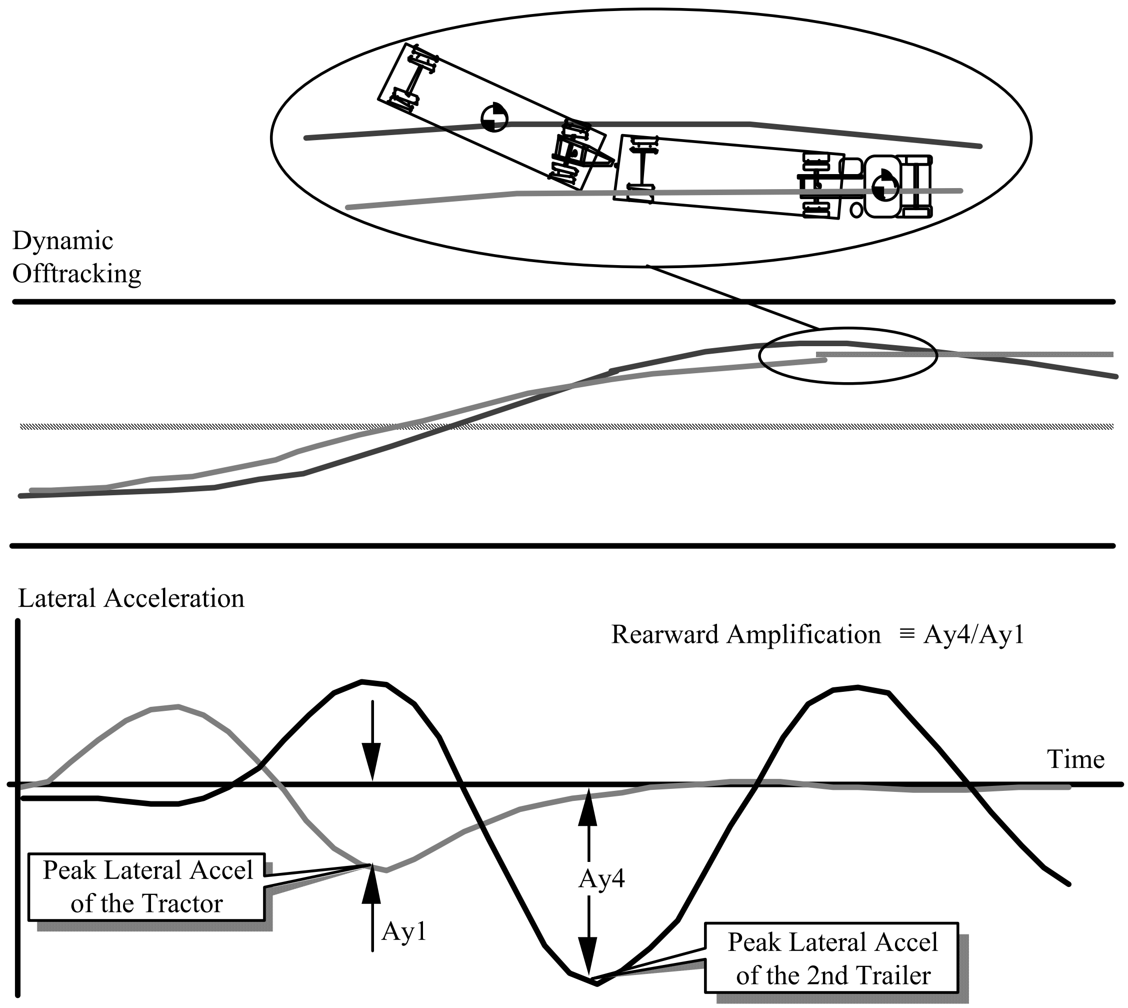


Figure 7. In a rapid obstacle avoidance maneuver, rearward amplification produces dramatic motion of the rear trailer, sometimes resulting in rollover.

A target performance level from the Turner Truck study:

A value of 2.0 has been chosen as a target level of rearward amplification [8]. This level can be reached by doubles combinations with stiff tires, relatively long trailers, and favorable hitch locations. Innovative dollies with special hitching arrangements and the use of semitrailer-semitrailer doubles (B-trains) are measures that can be used to control rearward amplification. For tractor-semitrailers, rearward amplification is approximately 1.0. Hence, the basic tractor-semitrailer does not encounter the same concerns with amplification-induced rollover or transient high-speed offtracking as vehicles with multiple articulation points. Nevertheless, a value of 2.0 has been chosen to represent a possible bound for vehicles with more than one articulation joint, since this value is typical of the performance of a Western double.

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

More than 30 percent of the five-axle doubles in the fatal file are estimated to have rearward amplification values greater than 2.4 (Figure 8). (Figure 8 is derived from [10] using results for an obstacle maneuver such as that specified in J2179 [12].) Associations between rearward amplification and single vehicle accidents, rollover accidents, and steering related accidents are shown in Figures 9, 10 and 11. These results show that vehicles with rearward amplification greater than 2.3 have much higher involvement ratios than vehicles with lower levels of rearward amplification. Examination of the details of the accident record show that many of the vehicles with rearward amplification greater than 2.3 have short trailers with lengths less than 27 feet and frequently with lengths in the 22 to 24-foot range. These vehicles have an accident record that is much worse than that of the Western 5-axle double which has a rearward amplification of 1.8 to 2.3 when fully laden.

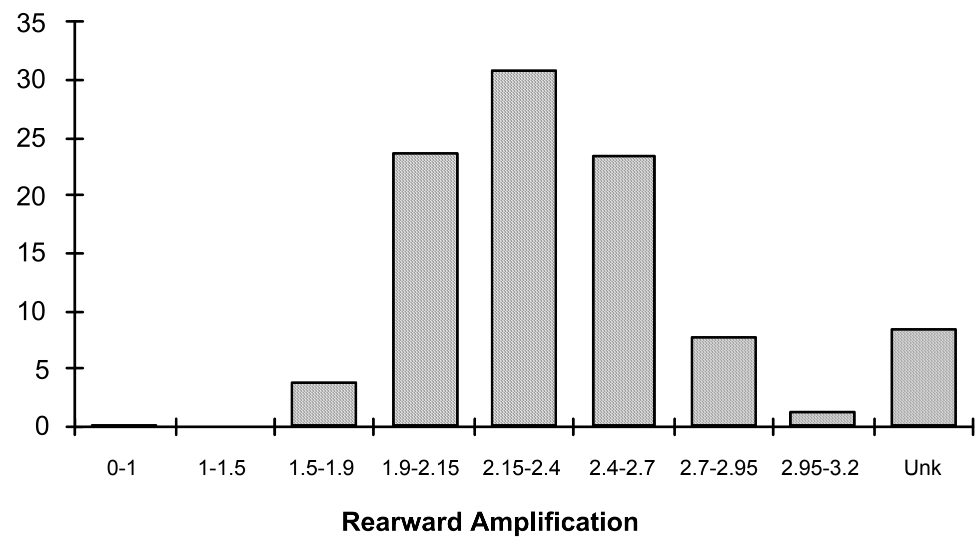


Figure 8. Distribution of travel by rearward amplification
for 5-axle double trailer combinations

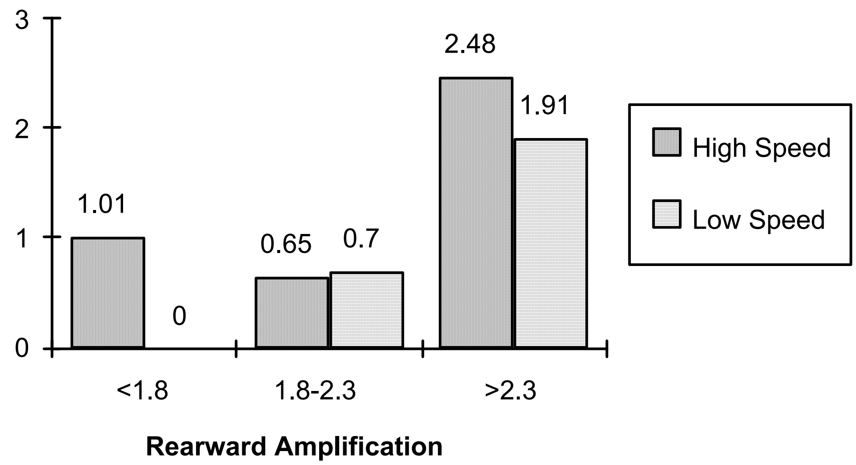


Figure 9. Relative risk of single-vehicle fatal accident involvement by rearward amplification for 5-axle double trailer combinations by road speed

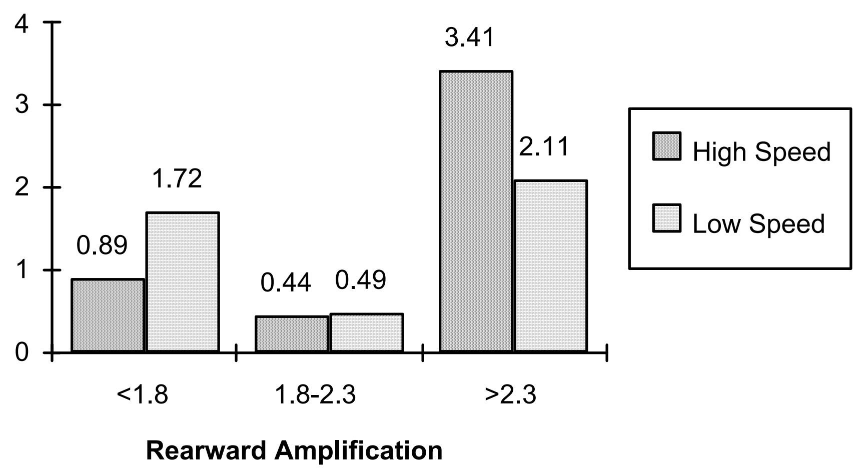


Figure 10. Relative risk of rollover fatal accident involvement by rearward amplification for 5-axle double trailer combinations by road speed

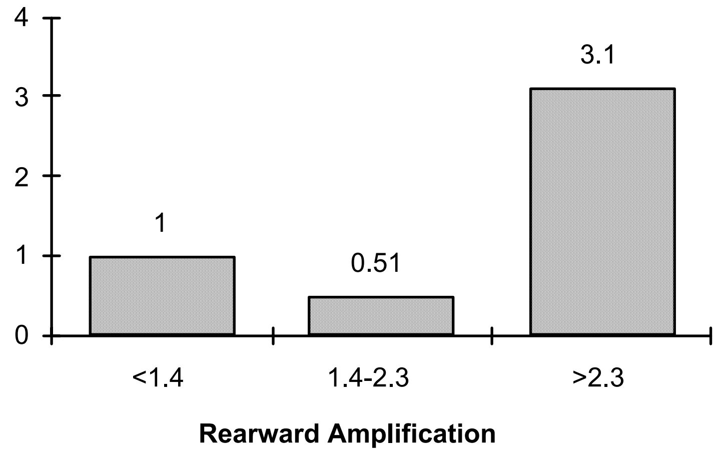


Figure 11. Relative risk of steering-related (sideswipe, ramp, or curve) fatal accident involvement by rearward amplification for 5-axle double-trailer combinations on high-speed roads

2.1.3 Braking

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

Testing or analysis procedures can be used to examine the proportioning of the braking system by determining the friction level required at each axle to prevent its wheels from locking up. The ratio of deceleration to the highest friction level required at any axle is the braking efficiency of the vehicle at that deceleration level. This simplified representation of the braking process is useful for illustrating braking arrangements and situations that will lead to poor deceleration performance. The braking efficiency of the vehicle at various levels of deceleration (for example, 0.2 g and 0.4 g) provide performance measures to use in evaluating braking capability. 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 performance level from the Turner Truck report:

A target of at least 0.7 has been selected. For the baseline five-axle tractor semitrailer (3-S2) with a full load, the braking efficiencies are 0.887 and 0.843 at 0.2 and 0.4 g, respectively. These excellent levels are attained because the braking systems on heavy trucks in the U.S. are proportioned in accordance with the gross axle weight ratings. When the 3-S2 is empty, the braking efficiencies are 0.672 and 0.645 at 0.2 and 0.4 g, respectively. These lower levels of efficiency are probably the cause of empty vehicles being overly involved in accidents in which the vehicle folds up ("jackknifes").

The distribution of braking efficiencies for existing heavy trucks shows a large percentage of vehicles with braking efficiencies in the range from 0.8 to 0.9 (Figure 12). However, approximately 26 percent of the vehicles are estimated to have braking efficiencies less than 0.7. Given the target performance level from the Turner Truck report, new heavy vehicles would have braking efficiencies greater than this portion of the existing vehicle fleet.

Figure 13 shows that jackknife rate decreases as braking efficiency increases. Vehicles with low braking efficiencies tend to have higher involvement ratios and involvements per mile of travel than those of vehicles with braking efficiencies greater than 0.7.

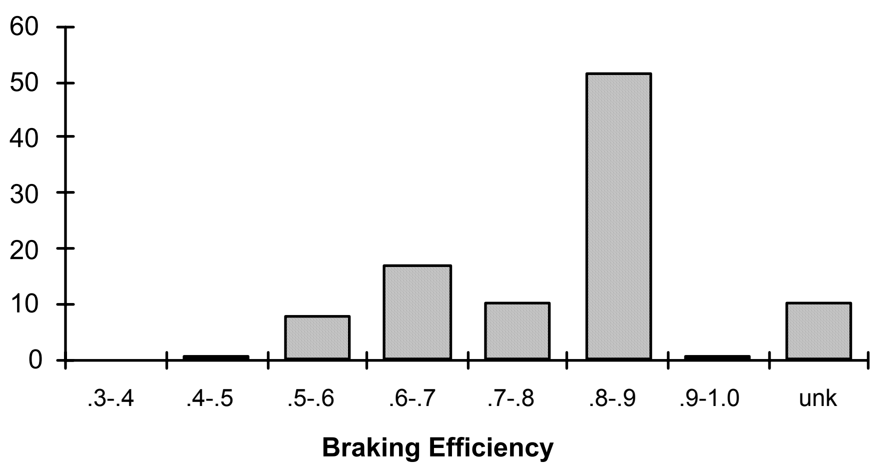


Figure 12. Distribution of travel by braking efficiency
for 5-axle single- and double-trailer tractor combinations [10]

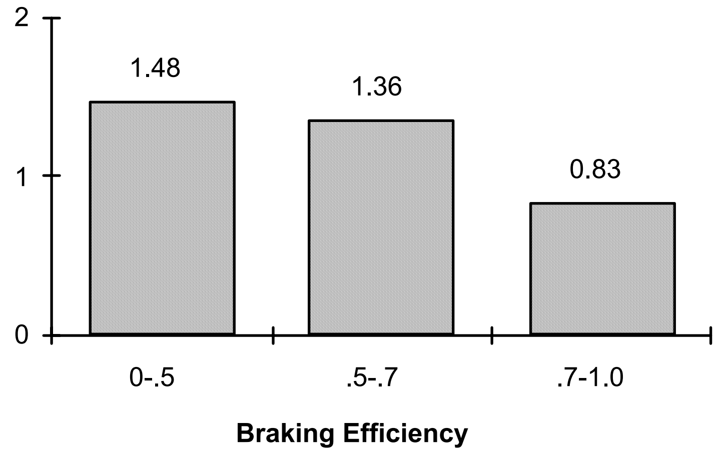


Figure 13. Relative risk of jackknife fatal accident involvements by braking efficiency for 5-axle single- and double-trailer tractor combinations [10]

2.1.4 Low Speed Offtracking

See Figure 14 which illustrates offtracking at an intersection. The rear of long vehicles may offtrack 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 test or 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 wheelbase and hitch locations, a computerized algorithm can be used to calculate the offtracking of the various units of the vehicle, if the vehicle is not available for testing. The maximum offtracking of the rear axle of the last unit is used to quantify the low-speed offtracking performance of the vehicle.

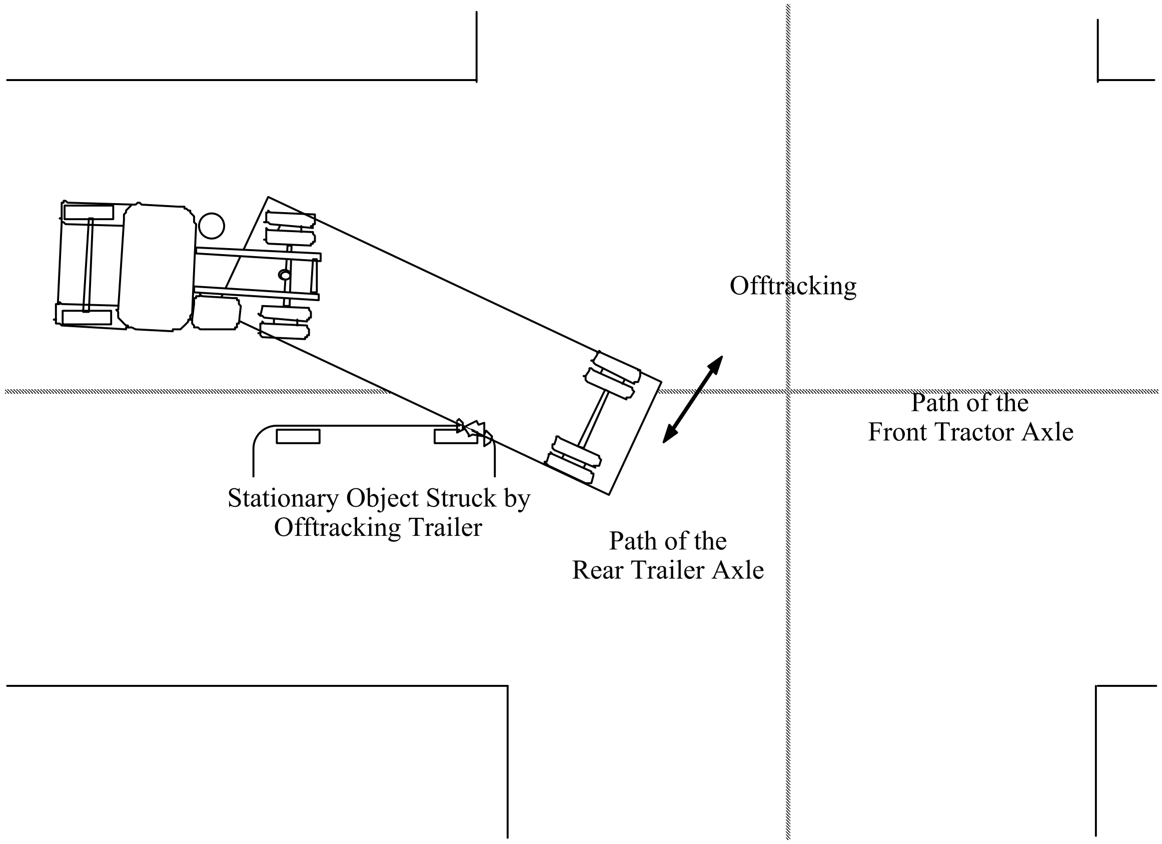


Figure 14. In low-speed offtracking, each axle tracks inboard of the preceding axle.

A target performance level:

For a 90-degree turn with a radius of 41 feet 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 feet inside of the path of the front axle. This compares with a calculated value of 17.34 feet for the baseline 3-S2.

Figure 15 indicates that approximately 20 percent of the vehicle fleet in 1984 had low speed offtracking that exceeded 17 feet. Today with the advent of longer semitrailers that percentage could be larger, but since longer semitrailers are often constrained to 41 feet from the king pin to the rear suspension the percentage of vehicles with offtracking greater than approximately 18 or 19 feet may not be much different than it was in 1984.

Figure 16 shows that the amount of offtracking appears to have only a mild effect on fatal accidents involving turning situations. However, this performance measure is more likely to be related to property damage accidents rather than fatalities.

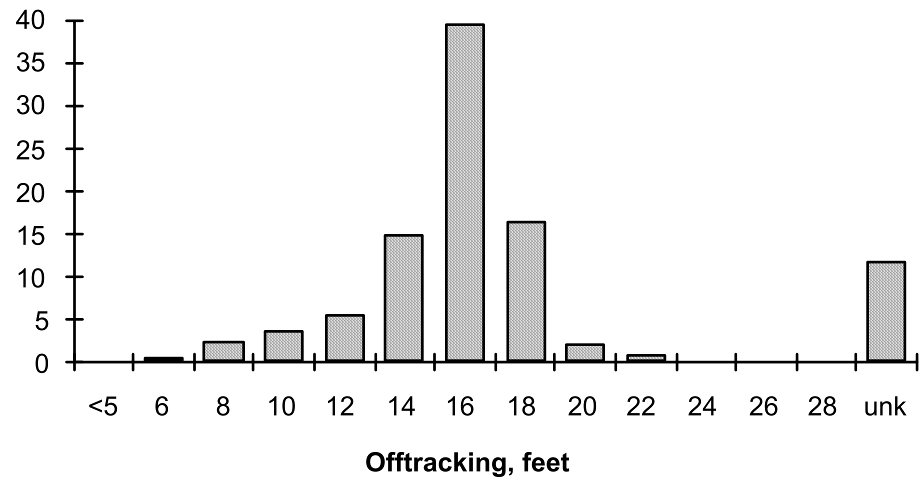


Figure 15. Distribution of travel by offtracking
for single- and double-trailer tractor combinations [10]

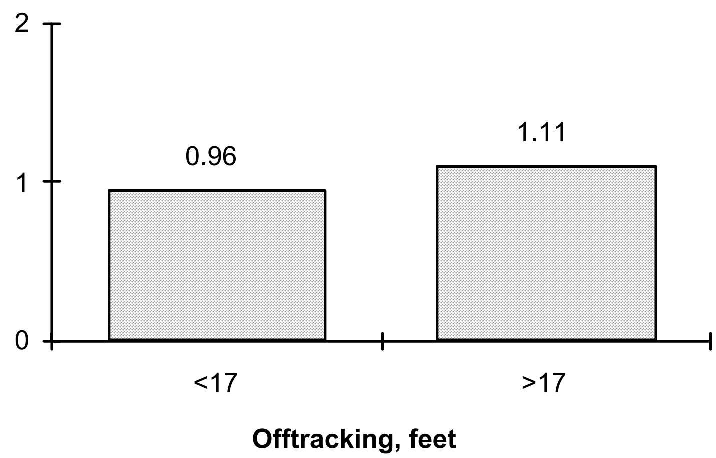


Figure 16. Relative risk of fatal accident involvement while turning by offtracking
for single-and double-trailer tractor combinations during the day [10]

2.1.5 High Speed Offtracking

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

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

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

A target performance level from the Turner Truck report:

The vehicle is envisioned to be in a steady turning situation on a radius of 1,200 feet and traveling at 55 mph. The selected target is for the center of the vehicle's last axle to track not more than 1 foot (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 feet. This level is based on ideas generated in Sweden where an 0.5 m offtracking limit was proposed. Generally, drivers do not come as close as 1 foot to curbs and other obstacles. Hence, this is probably the least critical of the intrinsic safety measures with vehicles like the baseline tractor-semitrailer being able to easily meet this goal.

2.2 Operating Environment as a Performance Demand

The previous material addresses the performance characteristic of the vehicle. However, that is only part of the equation. The other part is the demands placed on the vehicle by the environment it is operated in. A safety problem doesn't arise until the driver is in a situation that requires more performance than the truck can provide. For example, trucks operated in relatively flat Mid-Western States do not place the same demands on the braking system as when they are operated in mountainous States. A truck with a high friction demand may only have difficulty on wet, or slippery, pavements. To a limited extent, restrictions placed by some Western States on the operation of longer combination vehicles (LCVs) are intended to reduce the "demands." For the same reason, a vehicle that can be operated safely in the Western States, may not be suitable for the more congested Eastern States.

In a study of the X-car braking problem, Ervin [29] describes the relationship of the "demand" for road friction posed by the vehicle as a function of braking efficiency. Data from actual passenger car use shows the distribution of deceleration called for by drivers. This is shown in Figure 17 as the "100% braking efficiency" line. The line is labeled 100% because if the brakes were perfectly proportioned, each tire would be making the same friction demand on the road, and the x-axis indicates the necessary level of road friction to provide the level of deceleration called for. As shown in the figure, most stops require relatively low levels of road friction, well below the distribution of nominal road friction, shown as the distribution on the right in the figure. As long as friction demand called for by the driver is less than the available friction level from the road, none of the wheels will lock up, producing a skid.

Thinking about a truck application, if the braking efficiency is less than 100%, perhaps because the load distribution doesn't match the design axle distribution, or because the brakes are not all at the same adjustment, then some tires will be doing more of the braking than others. The tire doing the most braking will pose the highest friction demand on the pavement. This means that if the braking efficiency is only 50%, for example, a higher pavement friction is required for the same deceleration level. This is why one will sometimes see a lightly loaded axle lock up on dry pavement during a very mild stop.

This example is presented to illustrate that a vehicle can operate safely when the performance demands made by the driver are within the capability of the vehicle and roadway. As the performance level of the vehicle or roadway deteriorate, it becomes increasingly likely that the demands will exceed the available performance resulting in loss of control.

The operating environment is made up of different road classes (limited access vs. undivided, rural vs. urban) and these roads may be traveled in day and night. These different operating environments may also be thought of as a demand for vehicle performance. Campbell [20] and Blower [30] have measured accident rates for trucks in the different operating environments described by the various combination of limited access roads vs. other roads, rural vs. urban areas, and day vs. night. In general, each found that operating environment had a larger impact on the relative risk of accident involvement than did differences in vehicle configuration, at least when considering tractor-semitrailers vs. tractor-twin-trailer combinations. The differences in accident rates are large, as shown in Figure 18 for fatal accidents.

Overall, road type has the largest effect on risk of the factors shown in Figure 18. The driving task on limited access roads is relatively simple, at least when traffic is light, because traffic is one-way with controlled entry and exists and predictable horizontal curves and grades. Rural areas tend to have a higher risk of fatal and injury accidents, primarily due to the higher travel speeds. Urban areas have greater proportions of property-damage-only accidents. Nighttime is also associated with a greater risk of fatal and injury accidents than day. Drivers are more frequently fatigued than during the day, while sight distances are typically shorter, leaving less time to react and evade.

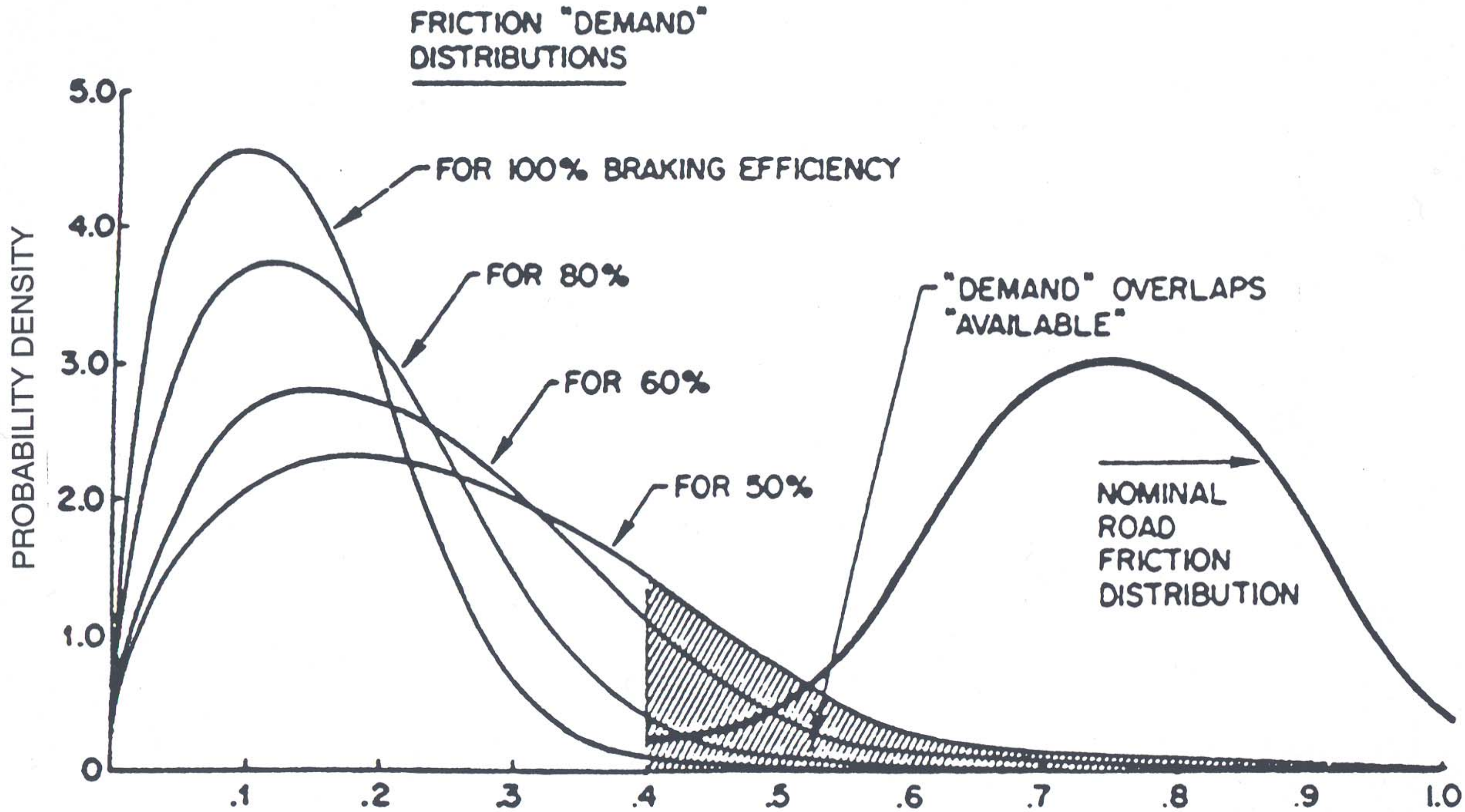
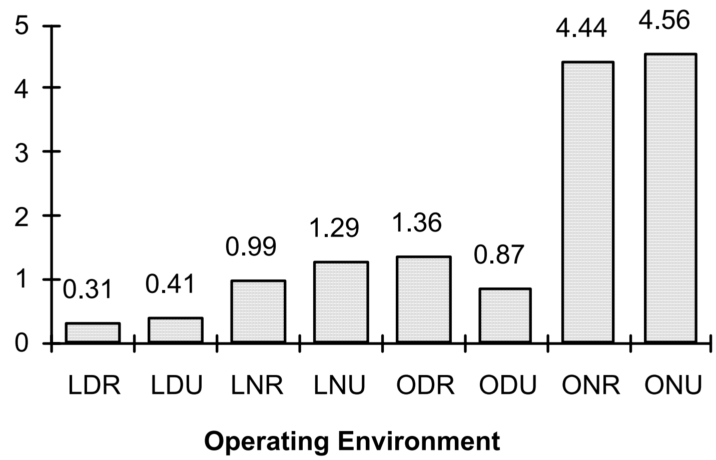


Figure 17. Overlap of Probability Distributions [29]



LDR--limited access road, day, rural
LDU--limited access road, day, urban
LNR--limited access road, night, rural
LNU--limited access road, night, urban
ODR--other road, day, rural
ODU--other road, day, urban
ONR--other road, night, rural
ONU--other road, night, urban

Figure 18. Relative risk of fatal accident involvement by operating environment for tractor semitrailer combinations [20]

In general, the operating environment has a larger influence on the risk of fatal accident involvement for a heavy truck than many of the vehicle characteristics. The operating environment can be viewed as one determinant of the performance demand placed on the vehicle. Thus, the operating environment must be considered when making projections of the accident experience for a new vehicle, and conversely, successful operation of a vehicle in one environment does not imply successful operation in different environments. This is the topic of the next section.

2.3 Why In-Service Safety Studies of Limited Vehicles are Generally Not Useful for Policy Decisions

Most states that allow non-standard vehicles (i.e., dimensionally bigger or heavier) to operate within their borders, typically also compensate for the perceived marginal or reduced performance of these larger vehicles by limiting the operational demands placed on the vehicle (i.e., by constraining the road types and/or conditions under which they may be operated) or by requiring higher level compensatory driver standards/skills than would otherwise be required for standard vehicle configurations. Thus, if there were differences in crash likelihood associated with vehicle types or configurations, they are often masked by the other confounding changes that accompany the vehicle design changes. Statistically segregating the effects of these different and subtle influences (i.e., vehicle, driver, and operating environment) becomes virtually impossible, especially in light of the second constraining reason.

With the exception of the studies cited previously, few motor vehicle accident data collection systems contain sufficiently detailed data elements to enable differentiation to be made among the crash involvement rate histories of various types or configurations of heavy vehicles. For example, since no state accident data collection system captures operating weight, it is impossible to differentiate, say, the crash involvement rates of vehicles operating at weights above the standard 80,000 pounds. limit prevalent in most states. This is a key question relative to the advisability of raising vehicle weight limits. Similarly, few data collection systems differentiate the various lengths of trailers used in doubles combinations, or identify triples combinations. Also, no mileage accumulation data are available for any of the different types of combination-unit vehicles to enable accident rate calculations (i.e., # accidents per 100 million miles of travel) to be made.

These problems/limitations are further compounded by the fact that few of these non-standard vehicles operate routinely in this country, or for that matter in Canada. As a result, few of them could be expected to become involved in crashes and, in fact, few are. Therefore, crash data analyses that can be conducted (i.e., those done using files from states in which the bigger/heavier vehicles are allowed to operate and which track their accident experiences) are statistically constrained by uncertainties that arise from extremely small sample sizes.

This creates two problems, the first of which is to simply find sufficient numbers of crash cases with which to work. For example, in the case of fatal triple trailer combination crashes, only thirteen are known to have occurred over the last 12 years, and only a few of these had any relevance to the fact that a triples combination was involved. Next, determining crash rate differences between non-standard vehicles and standard ones is hampered by the fact that large sample sizes are required. This is necessitated by the fact that, at worst, the differences are usually hypothesized or expected to be small (i.e., on the order of 10 percent differences or less), thereby necessitating large sample sizes in order to be able to state with statistical certainty that the small differences are, in fact, real. Typically, data are too sparse to meet this criteria.

Finally, it must be kept in mind that accident data are, by their nature, a history of past events. They can only provide retrospective insights. Often, however, attempts are made to use accident data prospectively to forecast what future trends in accident patterns might be if size and weights policies are modified. Doing so, is problematic, primarily because the conditions under which crashes occurred in the past are likely not to be the same as present or future conditions.

For example, there have been many attempts to forecast LCV accident frequencies and patterns if their use was expanded to more regions of the country. Because the extent of LCV use has been so limited, very little historical crash data are available. That which has been available has, for the most part, originated from individual motor carriers' internal files and reflects their experiences in regions of the country (primarily the West) where these vehicles are currently allowed to operate. These data portray generally positive results.

It should be kept in mind, however, that even if it is assumed these carriers' data are generally correct, the outcome is likely attributable to a number of controlling factors that might not be the same in the future. All these vehicles were operated under stringent controls exercised over the operation of the vehicles and stringent driver selection and training practices were required. Additionally, the reporting carriers have historically been, for the most part, large, well-established, financially-solvent, safety-conscious fleets, operating vehicles in sparsely populated regions of the country over limited access roads with very light traffic densities. It would likely be difficult to maintain this performance record under less well-controlled and more rigorous conditions, especially in denser traffic streams that might give rise to the need for these vehicles to attempt accident avoidance braking and/or steering maneuvers that could precipitate instabilities that lead to crashes.

3. Implications for Federal TS&W Policy

The study [3] that provided the foundation for the Canadian recommendations produced the following axioms [31] concerning the influences of size and weight variables on intrinsic safety:

- The addition of more trailers of the same configuration to a vehicle combination will result in an exponential increase in the rearward amplification response of the vehicle combination.
- Elimination of converter dollies (or fixed turntable dollies) from a vehicle combination, thereby constituting a "B-train," will categorically reduce rearward amplification relative to the original A-train configuration.
- Multitrailer combinations which are stiffly roll-coupled together will provide a high resistance to rollover in transient steering maneuvers as a result of phase lags in the response of successive units. This characteristic resistance will increase with the number of roll-coupled units in the combination.
- Given the common layout of trailers used in general freight transportation, the rearward amplification level reduces strongly with an increase in the trailer wheelbase dimension.
- An increase in the pintle overhang dimension will categorically produce an increase in rearward amplification.
- Increases in the gross weight of a given multi-articulated truck combination will result in a modest increase in the rearward amplification level.
- Rearward amplification does not exceed unity at speeds below approximately 30 mph but rises with a first-order dependence upon speed in the range of speeds normally associated with highway travel.

- The peculiar sensitivity of the rearward amplification phenomenon to the higher range of steer input frequencies suggests that strongly amplifying vehicles will pose the greatest hazard in congested, high-speed traffic.

- Vehicle configurations exhibiting a relatively high potential for rollover in rapid steering maneuvers (and under steady turning conditions, for that matter) are especially undesirable for the transportation of hazardous materials in bulk.

- Incremental increases in trailer wheelbase produce a first-order increase in low-speed offtracking. The rate of increase (feet of offtracking per foot of wheelbase) rises with the absolute value of the wheelbase such that modern semitrailers having wheelbase values near 40 feet produce approximately 0.6 feet of additional offtracking at intersections for each foot of additional wheelbase.

- Incremental increases in tractor wheelbase produce a modest increase in low-speed offtracking. The rate of increase (feet of offtracking per additional foot of tractor wheelbase) is on the order of 0.35 feet/foot for tandem axle tractors in common North American application.

- Because of characteristic differences in placement of axles and coupling points, A-, B-, and C-trains show modest differences in low-speed offtracking, for equivalent-bed-length trailers. Relative to the corresponding A-train, B-trains exhibit somewhat greater, and C-trains show somewhat less low-speed offtracking.

- The outside rear corner of a semitrailer may "swing out" into the path of opposing traffic during intersection turn maneuvers if the ratio, A/L, is sufficiently large where “A” is the distance from the king pin to the rear extremity of the vehicle and “L” is the distance from the king pin to the center of the rear suspension. Swing-out can reach a magnitude which approaches common inter-vehicular clearances when A/L approaches a value of approximately 1.5.

- Trailers with widely spread axle arrangements tend to promote tractor jackknife during tight-radius turning on slippery surfaces. Tractor jackknife can develop during intersection turns on slippery surfaces.

- Tractors having a widely-spread tandem axle set and relatively short wheelbase may not respond to further steering beyond some minimum radius turn, under low friction conditions. This problem worsens with wider spread, shorter wheelbase, and more rearward weight bias among the tractor axles.

- At increased levels of lateral acceleration, trailing axles tend to offtrack to the outside in a steady turn. The outboard offtracking response in a steady turn is maximized in vehicle combinations which are A) relatively long, overall but, B) articulated at multiple joints such that individual trailer length is relatively short.

- The paths of trailer tires can be even further displaced from those of the tractor under transient steering conditions. The extent of transient overshoots in the paths of trailing axles are greatest with long A-trains comprised of many short trailers.

3.1 Weight

Figure 19 shows the influence of weight on fatal accident rates for the current 80,000 pound tractor semitrailer. On the average, the involvement ratio (relative risk) is greater when the vehicle is fully laden than when it is partially loaded. This is as one would expect since the performance capabilities of this vehicle are less when it is fully laden than when it is partially laden. Certainly this vehicle is not intended to carry more than 80,000 pounds and the data indicate that allowing this vehicle to carry more load would not be beneficial to safety.

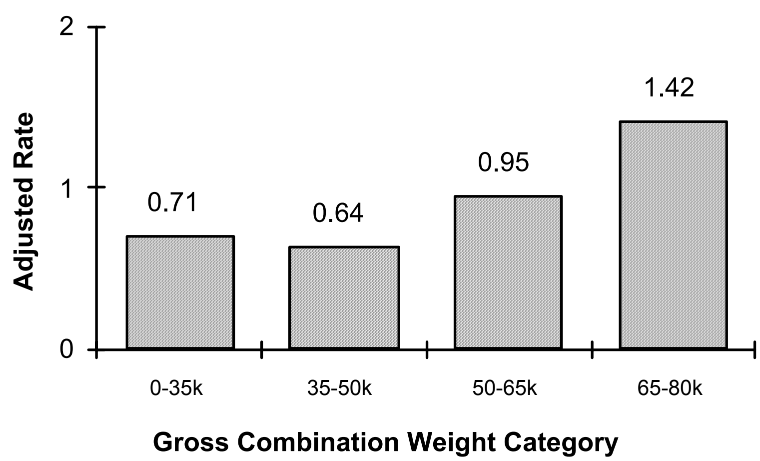


Figure 19. Overall fatal accident involvement rates versus GCW for non-empty van semitrailer combinations

Among all the vehicle characteristics reviewed in this discussion, weight shows the strongest association with fatal accident rates (accidents per mile traveled). For the vehicle characteristics discussed previously, a relationship with fatal accident rates was only evident when the analysis was restricted to specific accident types that were physically related to the vehicle characteristic, such as rollover accidents and roll threshold, or jackknife and braking efficiency. Gross combination weight (GCW) is the only vehicle characteristic showing a clear association with the *overall* fatal accident rate.

This finding is consistent with physical principles. Kinetic energy is proportional to weight (mass) times velocity squared. Damage, and the resulting harm, is related to the total energy that is dissipated in the collision. Conservation of momentum for impacts between two objects of disparate weight requires that the velocity change of the lighter vehicle (vehicle 1) is proportional to the relative speed at impact, V_c, times the ratio of the *heavier* vehicle (2) weight divided by the sum of the weights of the two colliding vehicles, as shown by the equation below.

$$\Delta V_1 = [\ W_2 / (W_1 + W_2)\ ] \times V_c$$

Velocity change during impact is the collision measure most strongly associated with the probability of injury [32]. Thus, when vehicles of disparate weight collide, there is an increase in the probability of injury (and fatality) in the lighter vehicle that is related to weight as shown above. Of course, these relationships are only approximations for collisions involving articulated vehicles. The general point is that the energy to be dissipated in a collision, and hence the damage done, increases with weight, and that the probability of injury increases with increasing disparity of weights in two-vehicle collisions.

Many of the individual vehicle handling and stability characteristics are also related to weight. Empty vehicles have low levels of braking efficiency (because brakes are proportioned by axle for the fully loaded condition), and low levels of braking efficiency are related to an increased risk of jackknifing, as discussed in Section 2.1.3. However, the rest of the handling and stability characteristics discussed in Section 2 generally deteriorate with increasing weight. So one would expect the fully loaded vehicle to generally correspond to a worst case situation with regard to handling and stability characteristics. Consequently, the general shape of the relationship shown in Figure 19 is not inconsistent with our understanding of handling and stability characteristics.

The analysis for Figure 19 was restricted to tractors pulling a non-empty van semitrailer. The objective of this restriction was to identify a large group of similar trucks. The adjustment procedure that was employed requires a large sample size. The fatal accident rates shown in Figure 19 have been adjusted in an effort to better reflect the influence of gross combination weight. The relationship of operating environment to accident risk has already been discussed in Section 2.2. As one might expect, there are differences in the operating environment for lightly loaded as compared to fully loaded trucks. The lightly loaded trucks tend to operate more in urban areas, during the day, and off the interstate roads. In comparison, fully-loaded trucks are more likely to operate on rural interstate roads with a greater proportion of nighttime travel. These differences follow from the nature of pickup and delivery operation as compared to over the road. Since these operational factors have been shown to have a strong influence on fatal accident rates, the actual accident rates reflect the influence of these operational factors, as well as the effect of weight. The adjusted rate procedure is intended to provide a comparison that compensates for the influence of the operational factors, better illustrating the weight effect.

The first step in the adjustment procedure is to calculate accident rates for each operating environment and each weight group. This is where the large sample is needed. The actual accident rate for each weight category may be thought of as a weighted sum of the rates for each operating environment, where the weighting factor is the proportion of travel in that operating environment. The lack of comparability across the weight groups arises because these travel proportions differ across the weight categories. The adjusted rates process assumes that the distribution of travel among the differing operating environments is the same for each weight group. In this case, the travel distribution for the aggregate of all four weight groups was used as the basis for adjustment. So the adjusted rates are not the actual experience of each weight group, but they are the accident rates that would be expected if trucks in each weight group accumulated the same travel in each operating environment. Thus, the adjusted rates provide a view of the influence of weight that is not clouded by the influence of differences in operating environment.

Comparison of the unadjusted rates and the adjusted rates shows that the adjustment process did not alter the result very much. The overall pattern of rates is essentially unchanged. The adjustment process tended to lower the rate at lower weights and increase the rate at higher weights, so that the influence of weight is somewhat stronger after the adjustment is made.

Limitations of this result should also be discussed. The analysis was limited to the most common truck, a tractor pulling a single van semitrailer (excluding empty trailers). There was not enough data to look at the effect of weight in different configurations. Only fatal accident rates were analyzed. And at this point, the 1986 data is rather dated. As far as the authors know, this result has not been replicated in an independent study. Several changes have occurred in the trucking industry that might be relevant, including greater use of antilock brakes and automatic slack adjusters, plus a dramatic increase in roadside vehicle inspections brought about by the Motor Carrier Safety Assistance Program. These changes might be expected to alter actual rates somewhat, but the basic trend of increasing risk with increasing weight (for a given vehicle) cannot be eliminated because there will always be a greater safety margin for the partially loaded vehicle as compared to the fully loaded vehicle.

However, vehicles like the Turner Truck and many of the current LCVs are designed for the load they carry. As already indicated in Figure 3, a basic idea behind size and weight rules could be to require provisions to avoid using vehicles that are not designed for the loads they carry and the operational situations they encounter. Predicting the relationship of accident rates to gross combination weight for a new design is something else. It would be completely inappropriate to "extend" the relationship in Figure 19 out to the rated capacity of the new vehicle. One can compensate for the increased weight by designing vehicles to minimum levels of handling and stability characteristics. Such compensation would have the effect of shifting the curve to the right.

3.2 Configuration

A number of quantities, pertaining to the geometric layout of truck configurations, influence safety-related performance. Table 1 summarizes these influences for a number of important vehicle properties. It is interesting to observe that the items that improve low-speed offtracking tend to degrade rearward amplification. There is a basic tradeoff here, and TS&W rules need to be structured to achieve acceptable performance in both types of safety-related performance.

Table 1. Influences of Configurational Properties on Safety-Related Performance.

CHANGE IN DESIGN FEATURES	Safety-Related Performance Measures				
	Low-Speed Offtracking	High-Speed Offtracking	Constant Deceleration Braking *braking efficiency*	Steady Turn Rollover *rollover threshold*	Obstacle Evasion *rearward amplification*
Increasing the number of articulation points	S I	M D	?	N A	S D
Longer wheelbase	S D	M I	M I	N A	S I
Longer overhangs to rear hitches	M I	M D	N A	N A	S D
Increasing the number of axles	M I	M D	S D	S I	S D
Increasing axle spreads	M I	M D	N A	N A	S D
Increasing axle loads	N A	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

3.3 Length

Currently length constraints are not generally decided by objective measures of safety-related performance. Performance measures related to offtracking, rearward amplification (obstacle evasion), passing, and crossing intersections are pertinent to vehicle length considerations. Both the vehicle's capabilities and the demands of the roads and traffic are relevant for deciding on acceptable vehicle and roadway properties.

3.4 Axle Loads and Placement

Axle loads and placement have been considered in Section 3.2 on configuration (See Table 1). In general, safety related-performance in high-speed situations is improved by constraining axles to reasonable loads, keeping axle loads fairly uniform, and spreading suspensions (axle sets), and spreading kingpin to axle distances on semitrailers.

4.0 Knowledge Gaps and Research Needs

Research needs were described in an 1986 UMTRI report [7], and are illustrated in Figure 1 (on page 5). From the discussion in this paper, it follows that part of the evaluation of a proposed TS&W policy would be an evaluation of the performance measures, or intrinsic safety, of any new vehicles that would result from the policy. Alternatively, the new TS&W policy could incorporate minimum performance levels for specified measures. The Canadian approach is simpler, in that only specific vehicles are allowed. This limits the scope of the evaluation of performance measures.

Test procedures have been developed for roll threshold and rearward amplification [11,12]. However, some consensus must be reached as to appropriate minimum levels. A related issue is the distribution of performance levels in the existing truck fleet. Information on the range of levels in the current fleet might provide a perspective for specifying minimum values for new vehicles. In the Turner Truck study [10], performance measures were estimated from the physical descriptions of the trucks obtained in a travel survey based on a nationally representative sample. However, this information was collected in 1986. Consequently, one research area might be to look at ways to determine performance measures for the existing national fleet.

The information relating accident risk to the performance measures cited in this paper also dates to 1986. Another research need is to update and corroborate these relationships. It is the view of these authors, that the general nature (direction) of these relationships follows from physical principles, hence the use of the term "intrinsic safety." However, the resulting magnitude of the effect, and also the relationship to operating environment must be determined from actual operating experience. Also, some performance measures appear to be more important than others, at least in terms of the accident experience. Another shortcoming of the studies cited [10,20] is that they are limited to fatal accidents. While the fatal accident experience is important, some of the performance measures are more likely to be evident in less severe accidents. For example, Blower [30] observed that the day/night difference in accident rates is much stronger for fatal accidents than for injury or property damage accidents. In general, a better understanding of the relationships between the performances measures, operating environment, and the in-service accident experience is needed. Such information is necessary for cost/benefit studies as well.

5. Concluding Summary

- A vehicle can operate "safely" when its level of performance is sufficient to meet the demand presented by the combination of driver, roadway, and environment.

- The truck safety problem is a consequence of the discrepancy in performance levels and mass of cars and trucks. The discrepancy in performance means that trucks cannot start, stop, or maneuver nearly as quickly as cars. The discrepancy in weight produces a greatly elevated probability of injury or death when cars and trucks collide.

- Previous TS&W policies were not specifically set to maintain safety because there was no provision to maintain performance levels when the trucking industry developed vehicles to take advantage of the policy.

- It is generally not feasible to assess the safety impact based on the experience of a small number of vehicles in specialized operations. Most data systems cannot even identify these vehicles. Performance measures are a better indicator of the relative safety of different trucks.

- Increasing the allowable weight on existing trucks without modification or redesign will certainly degrade safety. The magnitude of the degradation depends on combination of driver, roadway, and environmental conditions the heavier vehicles operate in.

- New truck designs (i.e. the Turner Truck) could provide increased productivity without degraded safety *if* the designs ensured that minimum performance levels were maintained, and/or operating restrictions (roads, driver qualification, speed, etc.) effectively limited the demand levels to the capability of the vehicle.

- Maintenance is a final factor to consider. The material above all speaks to the vehicle as designed. Some performance measures are affected by wear, particularly braking. Another consideration is the extent to which performance will be degraded by normal wear.

References

1. Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers. R.D. Ervin, et al. Final Report. Michigan Office of Highway Safety Planning. Contract No. MPA-78-002A. University of Mighigan Transportation Research Institute. Report No. UMTRI-78-18. 1978.

2. Analysis of the Directional Reaponse Characteristics of Double Tankers. C. Mallikarjunarao and P.S. Fancher. Society of Automotive Engineers. Paper No. 781064. 1978.

3. Influence of Weights and Dimensions on the Stability and Control of Heavy-Duty Trucks in Canada.. Ervin, R.D. and Guy, Y. Final Rept., Sponsored by Canroad Transportation Research Corp., University of Mighigan Transportation Research Institute. UMTRI-86-35. July 1986.

4. Development Of Regulatory Principles For Straight Trucks And Truck-trailer Combinations. J.R. Billing and C.P. Lam. Heavy Vehicles and Roads, Technology, safety, and Policy. Proceedings of the third international symposium on heavy vehicle weights and dimensions. 1992

5. Recommended Regulatory Principles for Interprovincial Heavy Vehicle Weights and Dimensions. CCMTA/RTAC Vehicle Weights and Dimensions Study. Implementation Committee Report. 1987.

6. Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks. R.D. Ervin, et al. Final Report. Contract No. FH-11-9577. Report No. FHWA/RD-83/029. University of Michigan Transportation Research Institute. 1986.

7. Heavy Truck Stability: Synthesis/Program Plan Development. P.S. Fancher, et al. Final Report. Contract No. DTNH22-84-D-07080. University of Michigan Transportation Research Institute. Report No. UMTRI-86-3. 1986.

8. Heavy Vehicle Size and Weight--Test Procedures for Minimum Safety Performance Standards. C.B Winkler, P.S. Fancher, Z. Baraket, S. Bogard, G. Johnson, S. Karamihas and C.Mink. Final Report. Contract No. DTNH22-87-D-17174. University of Mighigan Transportation Research Institute. Report No. DOT-HS-807-855 1992.

9. Safety Implications of Various Truck Configurations. P.S. Fancher and A. Mathew. Final Report. Contract No. DTFH61-85-C-00091. University of Michigan Transportation Research Institute, Report No. FHWA-RD-89-018. 1988.

10. Turner Truck Handling and Stability Properties Affecting Safety, Volumes I and II. P.S. Fancher, A. Mathew, K. Campbell, D. Blower and C. Winkler. Final Report. Transortation Research Board Contract No. HR2-16A. University of Michigan Transportation Research Institute. UMTRI-89-11. 1989.

11. A Tilt Table Procedure for Measuring the Static Rollover Threshold for Heavy Trucks. Society of Automotive Engineers Recommended Practice J2180. 1992.

12. A Test for Evaluating the Rearward Amplification of Multi-Articulated Vehicles. Society of Automotive Engineers Recommended Practice J2179. 1992.

13. Research into the Dynamic Performance of Heavy Trucks. Engineering Research Division. University of Mighigan Transportation Research Institute. 1988.

14 A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials. 1990.

15. Geometric Design and Operational Considerations for Trucks. Institute of Transportation Engineers. An ITE Informational Report by Technical Committee 5B-28. 1992. .

16. Truck Operating Characteristics Synthesis of Information. P.S. Fancher and T.D. Gilespie. National Cooperative Highway Research Program (NCHRP) Project 20-5. Topic 22-12. University of Michigan Transportation Research Institute. 1994.

17. Effect of Large Trucks on Traffic Safety and Operations. Z. Bareket and P.S. Fancher. Final Report. Michigan Department of Transportation Contract No. 92-0578. Report No. UMTRI-93-19. 1993

18. A Vehicle Dynamics Handbook for Single-Unit and Articulated Heavy Trucks. Fancher, P.S. and Mathew, A. Final Rept., Contract No. DTNH22-83-C-07187, Transp. Res. Inst., Univ. of Mich., Rept. No. UMTRI-86-37, May 1987.

19. Safety Implications of Various Truck Configurations. Fancher, P.S. and Mathew, A. UMTRI Research Review, Ann Arbor Michigan: The University of Michigan Transportation Research Institute, Vol. 19, No. 4, Jan-Feb 1989.

20. Analysis of Accident Rates of Heavy-Duty Vehicles. Campbell, Kenneth L., Blower, Daniel, Gattis, R. Guy, and Wolfe, Arthur C. Ann Arbor Michigan: The University of Michigan Transportation Research Institute, Report No. UMTRI-88-17. April 1988. Sponsored by the National Highway Traffic Safety Administration, Contract No. DTNH22-83-C-07188.

21. The Influence of Size and Weight Variables on the Roll Stability of Heavy Duty Trucks. Ervin, Robert D. SAE Paper No. 831163. West Coast International Meeting, Vancouver, B.C., August 8-11, 1983.

22. Parametric Analysis of Heavy-Duty Truck Dynamic Stability. Winkler, C.B., Fancher, P.S., and MacAdam, C.C. Final Report, Contract No. DTNH22-80-C-07344, Transportation Res. Inst., Univ. of Michigan, Rept. No. UMTRI-83-13, March 1983.

23. Using a Vehicle Dynamics Handbook as a Tool for Improving the Steering and Braking Performances of Heavy Trucks Fancher, P.S. and Mathew, A. SAE Special Publication No. SP-699, Paper No. 870494, 1987.

24. Specialized Procedures for Predicting the Accident-Avoidance Potential of Heavy Trucks. Fancher, P.S. and Mathew, A. Presented at 11th International Conference on Experimental Safety Vehicles, Washington, D.C., May 1987.

25. Road Tank Design: Its Influence on the Risk and Economic Aspects of Transporting Gasoline in Michigan. Mallikarjunarao, C. Ph.D. Dissertation, University of Michigan, 1982.

26. Roll Response of Articulated Motor Trucks During Steady-Turning Maneuvers. Mallikarjunarao, C., Ervin, R.D., and Segel, L. Proceedings, 103rd Winter Annual Meeting of Amer. Society of Mech. Engrs., Phoenix, November 1982.

27. Braking Performance of Heavy U.S. Vehicles. Radlinski, R.W. SAE Paper No. 870492., International Congress and Exposition, Detroit, MI, February 1987.

28. Reducing the Risk of Spillage in the Transportation of Chemical Wastes by Truck. Ervin, Robert D., and Mathew, A. Ann Arbor: University of Michigan Transportation Research Institute. Report No. UMTRI-88-28, July 1988.

29. Estimation of the Probability of Wheel Lockup. R.D. Ervin and C. Winkler. International Journal of Vehicle Design. Vol. 9, No. 4/5. 1988.

30. Accident Rates for Heavy Truck Tractors in Michigan. D. Blower, K. Campbell and P. Green. Accident Analysis and Prevention. Vol 25, No. 3. pp 307-322. 1993.

31. Axioms Relating Size and Weight Constraints to the Response of Trailers in Combination Trucks. R.D. Ervin and Y. Guy. International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, British Columbia. 1986.

32. Statistical Analysis of the National Crash Severity Study Data, Final Report P.A. Gimotty, K.L. Campbell, T. Chirachavala,O. Carsten,and J. O'Day. Report No. UMTRI-80-38. Ann Arbor: Transportation Research Institute, The University of Michigan, June 1980.