Comprehensive Truck Size and Weight (TS&W) Study

Phase 1-Synthesis

Roadway Geometry

and

Truck Size and Weight Regulations

Working Paper 5

February 1995

Prepared for

Federal Highway Administration
U.S. Department of Transportation

By

Battelle Team
505 King Avenue
Columbus, Ohio 43201-2693

Comprehensive Truck Size and Weight (TS&W) Study

Phase 1—Synthesis

Working Paper 5—Roadway Geometry and TS&W Regulations

Geometry-related effects of changes in truck size and weight regulations include a diverse set of highway design elements related to virtually every aspect of vehicle design and operation. The turning, stopping, acceleration, hill-climbing, and other characteristics of trucks determine their ability to conform to the geometric design of existing highways. Changes in these characteristics may also affect the adoption of new geometric design standards used in the construction of highways and in the reconstruction of existing highways to provide better harmony between roadway and vehicle characteristics.

1.0 Technical Relationships of Policy Consequence Concerning Roadway Geometry

This section summarizes current knowledge of the roadway geometry aspects of truck size and weight, drawing upon the findings of recent reports on the subject:

Section 1.1 approaches the subject from the vehicle's perspective and discusses several of the most important vehicle performance characteristics influencing interaction with roadway geometry;

Section 1.2 views the issue from a roadway perspective, discussing roadway geometric features and how these features interact with specific vehicle performance characteristics;

Section 1.3 discusses the implications of various TS&W policy options.

1.1 Vehicle Performance Characteristics

This subsection discusses several important vehicle characteristics that influence vehicle interaction with roadway geometry and design, concentrating on low-speed offtracking, ability of a vehicle to decelerate and descend grades, ability to accelerate and climb grades, vehicle traction, and high-speed offtracking. Other working papers in this series discuss other aspects of vehicle design that may influence highway design. For example, the traffic operations working paper discusses the influence of vehicle length on freeway merging and lane-changing operations, while the vehicle handling working paper discusses hitching arrangements that influence a vehicle's stability. This paper briefly discusses how these same hitch arrangements might affect offtracking.

1.1.1 Low-Speed Offtracking

Whenever a vehicle with more than one axle turns, rear wheels fail to precisely follow the path of the front wheels. Offtracking simply measures the maximum distance between the paths of the steering axle and the axle of the most rearward wheels. Numerous steady-state, low-speed offtracking models exist, and the algorithms for calculating the path of the wheels are well documented in the literature (Sayers 1986, for example). From these algorithms, it is a simple matter to develop a path-plotting computer program that produces a trace of the complex steering paths likely to be found in actual operation of trucks (Billing et al 1986A). One of these models can be used to plot differences in offtracking for various types and arrangements of vehicles (Mingo 1993).

The prevalent algorithms use a "bicycle wheel" model, which does not incorporate the effects of tire friction on the paths of the rear axles. Consequently, these simple algorithms underestimate the amount of offtracking from vehicles with rear tandem axles or tridem axles (Mikulcik et al 1990).

The simple offtracking models show that a combination vehicle with a short wheelbase tractor and a semitrailer with a 41-foot distance from the kingpin to the rear axle requires use of the adjacent lane on both the approach and destination legs at virtually all 90-degree intersections (Mingo 1993). The models can show in great detail how much more space is required at intersections of various design as either the kingpin dimension or the number of trailers is increased. The models can also calculate and plot trajectories so that the total swept path of the vehicle can be compared to the available space at the intersection.

Field studies were conducted by the Wisconsin DOT in the process of selecting roadways to place on the "designated highway system" for operation of the longer semitrailers legalized by the Surface Transportation Assistance Act (STAA) of 1982. Geometrically-deficient urban intersections were singled out to ascertain the extent and type of encroachment that resulted from the right turn movements of the longer combination vehicles. Because of the typical low speed during such turning movements, the low-speed offtracking characteristic has not been considered a primary safety concern, but it has led to the loss of roadway elements such as guardrail, curbing, lighting fixtures and the like. Inconvenience to other motorists, as the turning vehicle occupies their lane as well as its own, has been the major consequence. The Wisconsin studies resulted in a report and a computer program that incorporated a procedure for differentiating between intersections that require only minor modification and those that must be rebuilt to provide acceptable levels of service. The procedure allows design engineers to select modifications to existing urban intersections which would allow STAA vehicles to operate while accommodating safety and convenience concerns at a minimum cost (DeCabooter and Solberg, 1988).

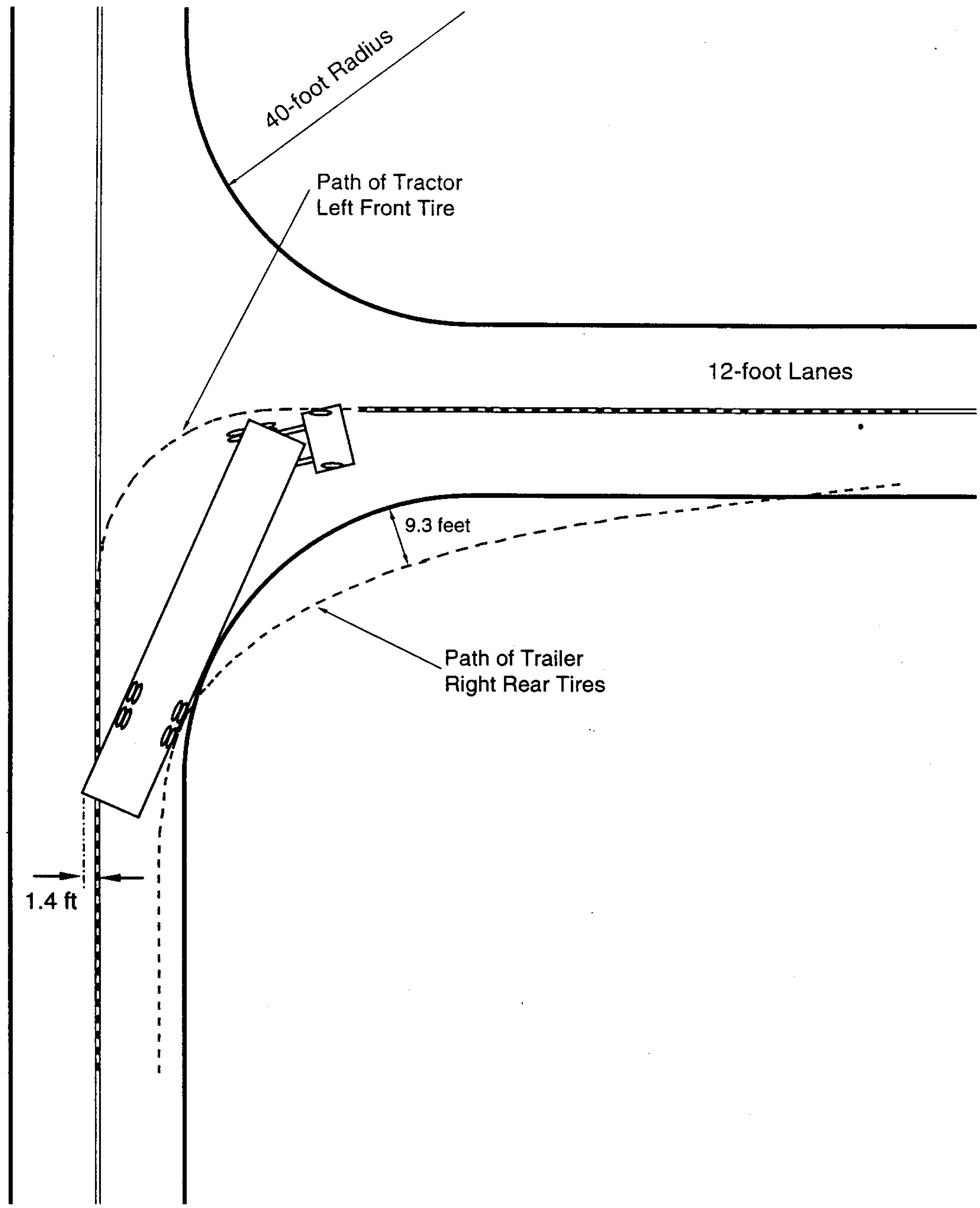
Low-Speed Offtracking as a Function of Vehicle Length

The low-speed offtracking characteristic of any commercial vehicle is a function of several length aspects of the vehicle, whether in combination or operating as a single unit. Length of wheelbase of the drive unit of a vehicle affects the minimum turning radius of a vehicle, and in a single-unit vehicle also determines its offtracking characteristics. Length of wheelbase and arrangement of each unit in a combination vehicle, and distance between units, affects the offtracking of the combination.

Shorter wheelbases in relation to the length of a single unit truck, or of a tractor, semitrailer combination, are accompanied by longer rear overhangs and the potential for "negative offtracking"; that is, the intrusion of the rear of the vehicle into adjacent lanes opposite to the direction of the turn. For example, the left rear corner of a semitrailer will swing into the lane which is left of and adjacent to the lane from which a tractor, semitrailer combination unit began its right turn. This negative offtracking not only increases the size of the swept path, but also creates an unexpected event that could prove hazardous under certain roadway traffic and geometric conditions. Neither the operator of the combination vehicle nor the operators of nearby vehicles expects a part of the turning vehicle to intrude into the lane opposite to the direction of the turning movement.

In a tight right turn, such as a truck might encounter when turning from one two-lane roadway to another, the left rear end of a 57-foot semitrailer combination, with a 40-foot kingpin-to-axle dimension and a 14.5-foot rear overhang, will encroach into the adjacent lane by slightly over two feet, if the operator attempts to stay out of the opposing traffic lane as much as possible and is able to disregard the roadway edge to the right. In doing so, the vehicle's right rear wheel will travel more than nine feet beyond the right curbing at an urban intersection, or that same distance beyond the pavement edge/boundary of a typical rural intersection (see Figure 1). If the wheelbase is lengthened to more than 40 feet by sliding the rear tandem rearward, the encroachment would increase by about 0.6 feet for each foot of added wheelbase (Fancher et al 1989).

Figure 1: Path of Tractor Semitrailer Keeping Tires within Lanes (40-Foot Kingpin to Rear Axle, 14.5-foot Rear Axle to Rear of Trailer)

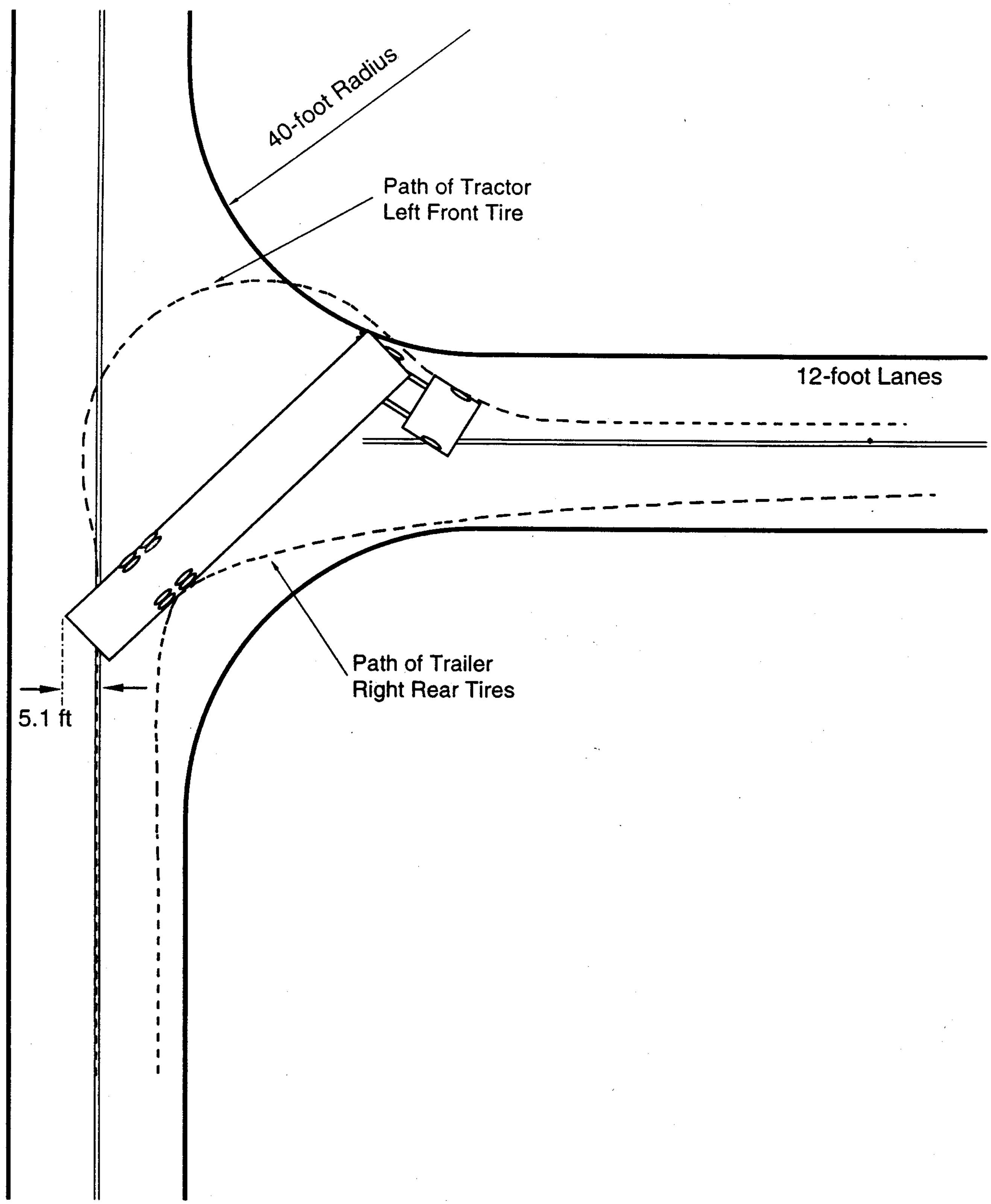


The same vehicle will encroach as much as five feet into the adjacent lane to the left if the operator tries to stay within the roadway edge to the right as much as possible (see Figure 2). Further, such encroachment occurs long after the driver has "left the scene"; that is, his seat in the tractor is already 60 feet around the corner, and he is facing 90 degrees away from the lane into which the semitrailer has encroached. Using acceleration rates developed in a pilot study as part of a research effort for FHWA (Harwood et al, 1990, page 150), the encroachment occurs 10 to 15 seconds after the truck driver has committed himself to the turn. Any oncoming vehicle's chance of braking in time to avoid colliding with the encroaching trailer rear is dependent upon the speed of that vehicle and on the stopping sight distance feature of the roadway at that intersection. On a road with a 30 mph design speed built according to AASHTO criteria, the stopping sight distance will be 200 feet (Harwood, et al, 1990, page 64). A 50 mph design will have incorporated a stopping sight distance of 475 feet. In either of these situations, the truck driver would not be able to see oncoming traffic that will be affected by his or her vehicle's swingout at the time the decision to turn is made.

In addition to the hazard posed to oncoming traffic on a two-lane roadway, negative offtracking of a right-turning vehicle poses a problem for traffic in adjacent lanes that are intent on passing the slow-moving, turning vehicle (a perfectly normal and legal maneuver). As the left rear of the semitrailer swings into their lane, it does so at a typical height of 55 inches off the ground, which, for most automobiles, coincides with the space between the bottom of the windshield and the roof.

Another negative consequence of long rear overhangs is that the overhang exceeds the horizontal distance from the bumper to the windshield in autos, so that the rear of the trailer enters the passenger compartment of the auto in the event of a rear-end collision, with the auto riding under the trailer. The trailer's rear axle or rear tires could prevent such an intrusion if they were closer to the rear of the trailer. Moving the rear axle set takes only seconds, and can be done by the operator without assistance. Observation of combination vehicles in the Eastern U.S. and a conversation with a veteran truck driver suggest that operators frequently place the rear axle group all the way back for highway driving, and all the way forward as they leave their origin and as they approach their destination. The longer wheelbase provides for a smoother ride and reduces jackknife tendency on the mainline portion, while the shorter wheelbase allows tighter turns. If such tactics are commonplace, then the vehicle operators have minimized the likelihood of the trailer entering the passenger compartment of a colliding auto, in the event of a rear-end collision on the main rural

Figure 2: Path of Tractor Semitrailer Keeping Tires within Traveled Way (40-Foot Kingpin to Rear Axle, 14.5-foot Rear Axle to Rear of Trailer)



highways, but have maximized the negative offtracking, or rear-end swingout, of the vehicle as they encounter right turn movements at geometrically-restrictive intersections.

Some states limit the maximum legal overhang of the trailer. New Mexico, for example, requires that the front end of the trailer be no more than three feet in front of the kingpin, and the rear end no more than seven feet from the centroid of the rear axle set. This means that a 57-foot trailer will have a kingpin-to-rear-axle-centroid dimension of at least 47 feet.

Other states limit the kingpin-to-rear-axle-centroid dimension. Mississippi, for example, requires this dimension to be no more than 41 feet, in order to keep offtracking within reasonable limits. This results in rear overhangs of at least nine feet beyond the axle centroid on a 53-foot trailer, and 13 feet on a 57-foot trailer (which are legal in Mississippi).

Whether imposed by regulation or by practical mobility concerns, a kingpin-to-rear-axle dimension of 39 to 41 feet is likely to be a common measurement, at least for the foreseeable future. The University of Michigan Transportation Research Institute (UMTRI), for example, in a 1990 report to FHWA, recommended an offtracking standard that could only be met by trailers with wheelbases of 40.3 feet or less (Fancher, et al, 1990).

Figures 3 and 4 illustrate tridem-axle 57-foot trailer and tandem-axle 53-foot trailer configurations that just meet UMTRI's proposed offtracking standard. Actually, the centroid of the rear axle set would be in the same place on either trailer regardless of whether a tandem or tridem were used, if the sole criterion was offtracking. In practice, depending upon the cargo density and its uniformity, the axle locations and fifth-wheel position may have to be adjusted somewhat to keep axle loads within legal limits.

Discussion

There is agreement that existing models used for calculating the swept width or low-speed offtracking of any vehicle do a good job of portraying changes in those two characteristics when modifications are made to the wheelbase and/or the positioning of axles on a truck or a combination vehicle. The legalization of semitrailer lengths of 53 feet and longer has prompted calls for setting a maximum limit of 41 feet for the distance from the kingpin to the centroid of the rear axle group, in order to limit intrusion into other lanes while turning. The tradeoff has been an increase

Figure 3: Tridem- Axle 57-foot Trailer Meeting Offtracking Standard

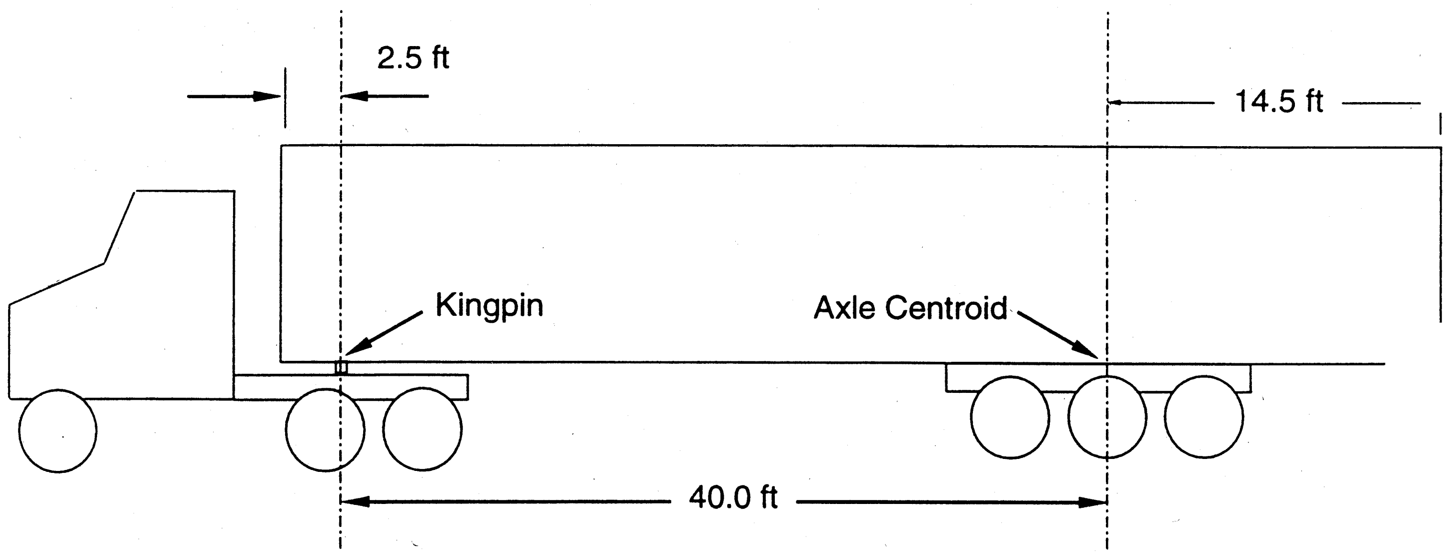
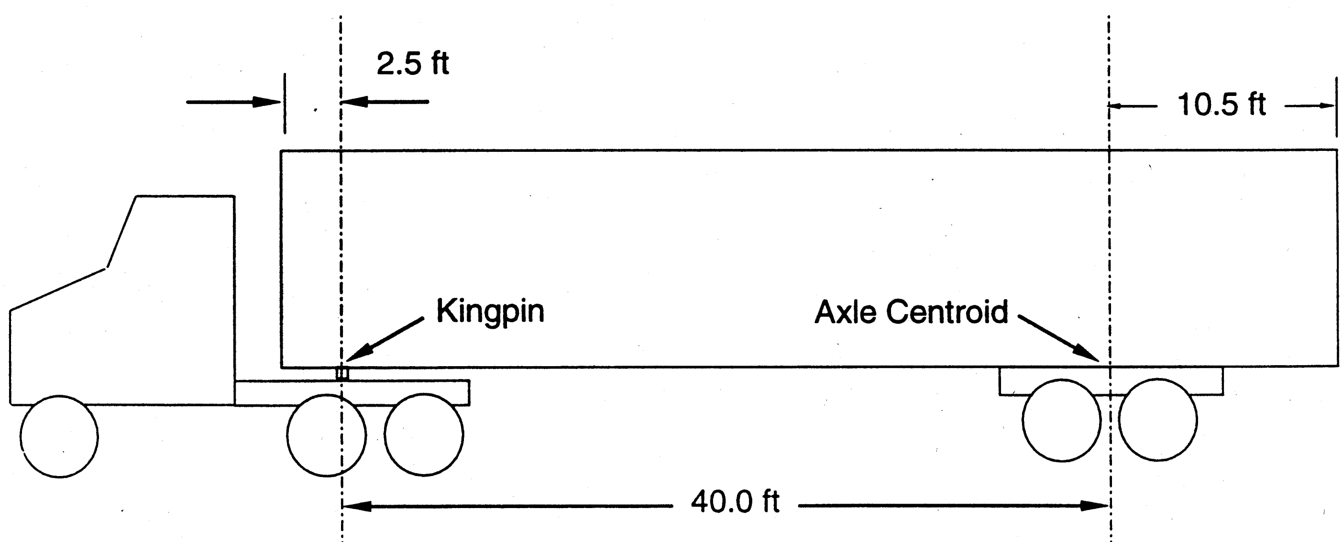


Figure 4: Standard 53-foot Trailer Meeting Offtracking Standard



in the "negative offtracking" of these vehicles, causing an intrusion into the opposing traffic lane when negotiating a right turn from a two-lane roadway onto another two-lane roadway. As a result, the available stopping sight distance of the roadway must be checked to ascertain the safety of allowing such a vehicle to perform such a maneuver. Additionally, the tradeoff creates a more serious potential for light vehicles to underride the trailer in the event of a rear-end collision into the combination vehicle, at any place on the roadway.

Low-Speed Offtracking as a Function of Vehicle Configuration

Several aspects of a combination vehicle's configuration have an effect on that vehicle's low-speed offtracking characteristic; such as:

1. The number of articulation points (points at which one part of the vehicle can rotate with respect to another part), regardless of whether that articulation point is a pintle hook connection to a dolly's drawbar or the kingpin connection at the fifth wheel;

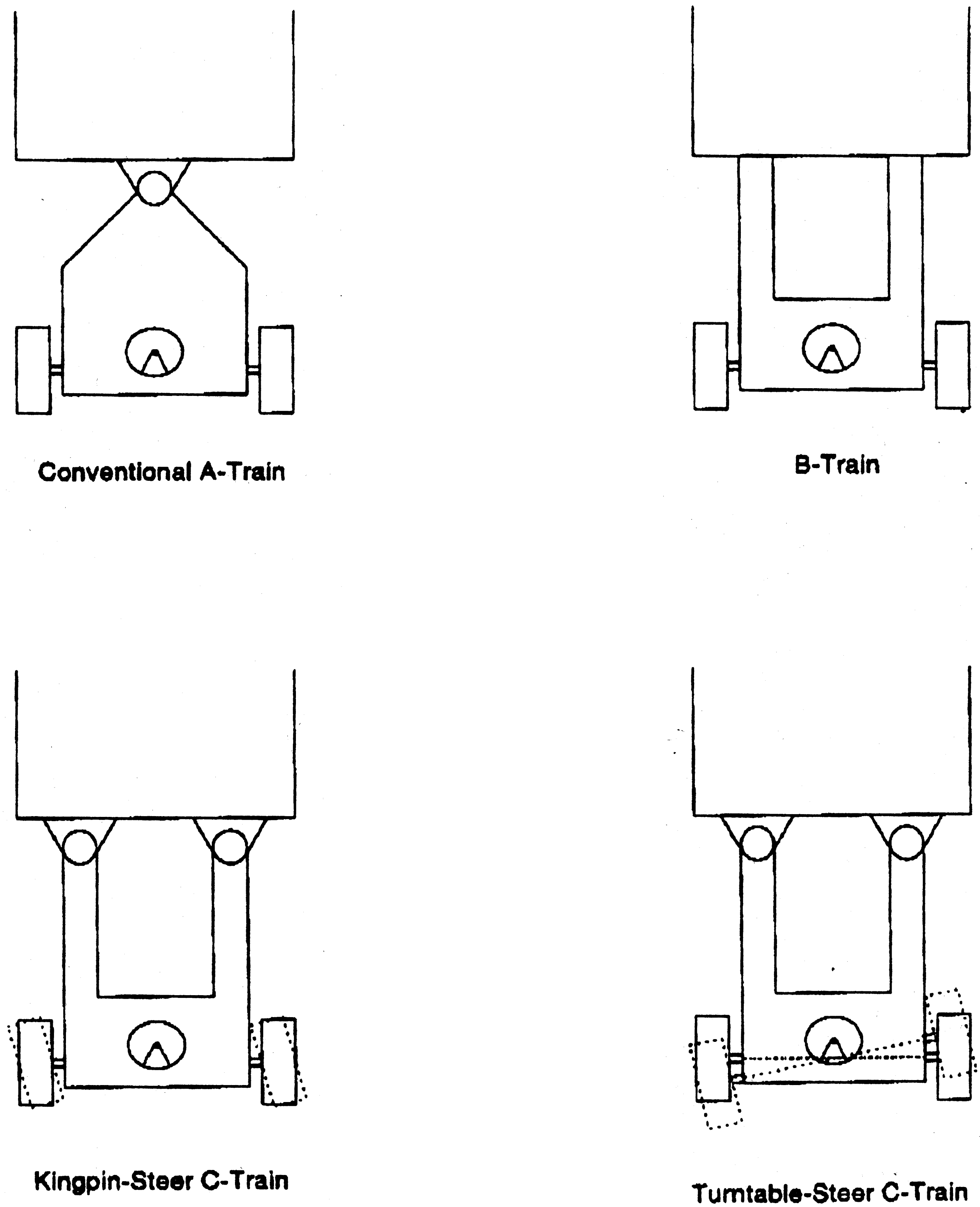
2. The type of hitch being used, whether single- or double-drawbar dolly (relevant to multiple trailer combination vehicles only).

For any given number of articulations, offtracking increases as the length between articulation points increases. Although the wheelbase of the tractor and the wheelbase of the trailing unit (the distance between the kingpin and the rear suspension of the trailing unit) both influence offtracking, the latter dimension is usually much larger and, therefore, has a far more profound effect on the offtracking of a typical semitrailer combination.

A vehicle with two short trailing units will likely experience less offtracking than a vehicle with a long semitrailer. On vehicles with multiple trailers, offtracking effects are essentially additive, so that vehicles with multiple trailers of the same wheelbase have much greater offtracking than vehicles with a single trailer of that same wheelbase.

Figure 5 illustrates several alternative hitching mechanisms used for multiple trailer combinations. The "B Train" and "C Train" devices are used widely in Canada, but not commonly in the U.S. To summarize the offtracking implications of these alternative hitching devices: B Train vehicles (all trailing units are hitched at fifth wheels that are extensions of the preceding trailer, and there are no pintle hook connections) offtrack more than A-Train vehicles (single drawbar dollies, with pintle hook connections to the rear of preceding trailers in addition to the fifth wheel

Figure 5: Comparison of Trailer Coupling Alternatives



hitches that follow). The offtracking performance of a C Train (trailing units behind the lead semitrailer are connected by dollies with a double drawbar) is better than that of an A-Train-equipped, multiple trailer combination when equipped with steerable axles (Woodrooffe and Billing, 1983, 27).

Generally, steps taken to increase stability of multiple trailer combinations worsen the offtracking character, whether the step taken is to tighten up the hitching devices by using B-dollies or B Train configurations, or is to replace a tandem axle group with a tridem axle.

Replacing standard tandem axles with permanent tridem axles on conventional combination vehicles has the effect of increasing vehicle offtracking and minimum turning radii.

Adding axles to an axle group (going from tandem axles to tridem axles, for example) has an even greater effect on tire scrub than it has on offtracking. Tire scrub occurs on all tandem, tridem, and other multiple-axle sets whenever a vehicle turns, unless the tires or axles are mounted in a way to allow rotation about a vertical axis; such as in a double drawbar dolly with a steerable axle.

Because of the difficulty of turning vehicles with three or more axles in an axle set, liftable third axles, or liftable third and fourth axles, are commonly employed when sufficient weight bonus incentives are offered (Billing et al 1990). When liftable axles carry their share of the load, "the truck cannot turn" (Billing et al 1990). On the other hand, if the liftable axles are unloaded (almost instantly via air pressure regulated by the driver) so that the truck can turn, "the truck's resistance to rollover is substantially reduced" (Billing et al 1990). In addition, pavement damage increases.

1.1.2 Decelerating

Stopping distance is a function of vehicle weight, combined effective braking power, brake system response time, and available tire-pavement friction under the conditions of interest. Truck brakes vary widely in effectiveness among seemingly identical vehicles, but a fully laden truck with well-adjusted brakes typically has sufficient brake torque available to provide decelerations of 0.4 to 0.5 g on a dry pavement and 0.20 to 0.25 on a wet pavement in good condition (Harwood et al 1990).

On a good road with dry pavement, the brakes themselves typically limit stopping performance, rather than tire/road friction. As long as a vehicle can apply braking force in proportion to the load on each axle, and as long as it can sustain that force, stopping distance should not depend upon configuration.

On a fully loaded vehicle, braking force proportions itself approximately correctly because all wheels have somewhat equal loads. Forward load transfer during braking hurts this efficiency, especially for higher centers of gravity and shorter trailers. The widespread practice of overloading forward trailer axles (to improve dynamic response characteristics) worsens this phenomenon. Partial loading of one or more trailers in a combination causes the worst braking performances (Clarke et al 1991). However, semitrailer combinations equipped with high-torque braking capacities will show improved stopping performance as the wheelbase of the vehicle is increased. Such longer wheelbase vehicles are capable of achieving higher levels of deceleration before encountering lockup of the rear trailer wheels (Ervin et al 1986, 124).

Downhill Braking—The braking systems of larger trucks receive their most stringent use in downhill braking. Sixteen percent of injury truck accidents involve runaway trucks on downgrades, with one mountainous state having a figure of 41 percent (Firestine 1989A). Aerodynamic resistance and rolling resistance can partially reduce the need for downhill braking, while braking power need goes up directly with weight. Lowering the load per axle can increase the available braking power if the same size wheels and braking components are used.

Engine retarders, which provide stopping power to the drive axles via the engine and drive train and are widely used in mountainous areas, do not perform as well on heavier vehicles, especially doubles and triples, because of their lower ratios of drive axle load to total weight. A retarder with enough capacity to take much load off the wheel brakes for the heaviest combination vehicles could overbrake the tractor drive wheels enough to induce jackknifing even on only moderately slick surfaces. A smaller retarder would not provide as much braking, resulting in the heavier combination relying more upon the friction brakes. Heavier use of friction brakes creates the potential for rapid brake wear, brake overheating, and brake failure (Ervin et al 1984). In 1980, 40 to 70 percent of trucks in western states and 5 to 15 percent in eastern states used engine retarders (Clarke et al 1991).

1.1.3 Accelerating and Maintaining Speed

Grade climbing and acceleration capabilities are functions of a vehicle's ratio of weight to available power at the operating speed of interest, and to a lesser degree are functions of rolling and aerodynamic resistance. There has been a trend toward lower mean weight-to-power ratios during the past 20 to 30 years, implying better grade climbing ability and better acceleration characteristics among trucks (Harwood et al 1990, Vol. 2, 103).

Despite this trend, grade climbing ability and acceleration issues remain. One important aspect of vehicle acceleration is the length of time it takes for a vehicle to clear an intersection from a stop. While trucks have gotten more powerful, they have also grown in length, which counteracts the advantage gained by their increased power.

The extent to which a trucks's grade climbing and acceleration characteristics match those same characteristics in other vehicles using a road largely determines the degree of interference a truck causes in any particular stream of traffic. The continuing increase in truck traffic and the wide range of weight-to-power ratios in trucks (which implies a wide variation in the speed achievable on grades and on the time it takes to accelerate from a stop), may have resulted in increased interference in the free flow of mixed traffic. [These traffic interference issues are discussed more fully in Working Paper #6.]

1.1.4 Traction

Traction availability is a function of the ratio of drive axle weight to gross vehicle weight, as well as pavement-tire friction. In general, adding axles to a vehicle decreases the load on the drive axles and increases the severity of potential traction problems. Multi-trailer vehicles have uniquely low ratios of drive-axle load to vehicle weight. A low load ratio on the drive axles increases the likelihood of jackknifing.

Single unit trucks typically have from 50 to 80 percent of their weight on the drive axle(s). Single trailer combinations typically have from 45 to 55 percent of their weight on the drive axle(s). Western or turnpike doubles have from 20 percent to 25 percent, and triples have only about 15 percent. The laws of physics limit the amount of force that can be directed through the drive axle(s) to the tire-pavement point of friction. When the operator tries to apply more than the limit, the wheels spin and loss of control is possible.

1.1.5 High-Speed Offtracking

In low-speed offtracking, the rear wheels of a vehicle track inboard of the front wheels of the vehicle. In combination vehicles, another type of offtrack occurs at high speeds that involves the outward drift of the rear of the trailer with respect to the track of the tractor's axles. The extent of the offset, or offtrack, is a function of the trailer wheelbase and the speed of the vehicle. Concern with the consequences of high-speed offtracking increases as the number of trailing units increases, and is expressed predominantly when speaking of the operation of multi-trailer vehicles, especially triples. Simulation models produced net offsets of 0.5-0.8 feet for various-wheelbase semitrailer combinations, compared to 1.0-1.7 feet for various doubles and triples combinations negotiating a 600-foot radius curve at 55 mph (Ervin et al 1986A, 161).

The high-speed offtracking phenomenon requires that a substantial lateral acceleration level be present before a net outboard path is achieved at the trailer tires. Therefore, this characteristic is of significance only for a limited set of turning conditions; such as, when a vehicle negotiates a freeway ramp and a tight horizontal curve on the mainline at speeds in excess of the design speeds.

Moving to B-Trains or C-Trains would have only a negligible effect on high-speed offtracking (Fancher et al 1986). High-speed offtracking can result in hitting curbs on interchange ramps, creating a rollover hazard, or failing to stay in a lane on curves, but drivers can compensate entirely for high-speed offtracking characteristics of any given vehicle simply by slowing down and keeping their steering axles at least two feet from any ramp curbs (Fancher et al 1990).

High-speed offtracking also translates into a need to start an emergency steering maneuver sooner in order to be effective. This has a similar effect in terms of highway design to the poorer braking response of larger trucks. That is, more stopping sight distance is required to compensate.

1.2 Roadway Geometric Features

This section of the report views the interaction between roadway geometry and large trucks from a roadway perspective, discussing roadway geometric features and how these features interact with specific vehicle performance characteristics. The geometric features discussed here include interchange ramps, intersections, roadway horizontal and vertical alignment, highway cross section, and other geometric features.

The FHWA abstract of an August 1990 report by the Midwest Research Institute (MRI) states that "many of the current highway design and operational criteria are based on passenger car characteristics, even though truck characteristics may be more critical" (Harwood et al 1990).

1.2.1 Interchange Ramps

AASHTO policy on the design of interchange ramps is based on the operating characteristics of passenger cars, not trucks. Consequently, the significantly different offtracking, rollover, traction and braking characteristics of some trucks leads to a very small margin of safety against rollover for certain types of combination vehicles. Better speed advisory signs are needed to provide advance warning to those vehicles with the greatest rollover propensity. A 1992 report has identified those features that designers need to consider in order to provide adequate accommodations for trucks on interchange ramps (ITE 1992, 47). These features include:

- Deceleration lane lengths,
- Curbs on the outside of ramp curves,
- Ramp downgrades, and
- Horizontal curvature and superelevation.

<u>Deceleration Lane Lengths</u>

Length of deceleration lanes designed according to AASHTO policy do not provide adequate time for truck combinations to reduce their mainline speed to one that will allow the vehicle to safely enter the sharp curve of the exit ramp at the end of the deceleration lane without comprising its rollover stability. Research suggests that adequate accommodation of trucks would result in deceleration lane lengths considerably longer than are recommended by the AASHTO guidelines (Ervin et al, 1986B, 107). Trucks with rollover thresholds of 0.30 g (very low), can roll over on some freeway ramps when travelling as little as five mph over the design speed. "For example, on a minimum radius curve (107 feet) with a design speed of 20 mph and a superelevation rate of 0.08 ft/ft, the calculated speed at which the truck will roll over is 24.7 mph" (ITE 1992, 27). Also, many freeway ramp design speeds are much lower than the design speed of the through traffic lanes, calling for a significant speed reduction before trucks can safely negotiate the entrance curve of the ramp. The deceleration lane often does not provide the distance that trucks require to bring about adequate speed reduction, because the deceleration characteristics of autos rather than trucks is typically used to determine the length of the deceleration lane prior to the ramp entrance. Ervin's 1986 report to the FHWA concluded that the AASHTO policy for the length of deceleration lanes also does not allow truck drivers the benefit of a three-second coasting time in gear upon entering the deceleration lane before applying the brakes - an assumption about driving behavior that is implicit in the AASHTO procedure. Ervin estimated that deceleration lane length would have to be increased 30 to 50 percent longer than the AASHTO guidelines to realistically reflect the braking constraint of trucks (Ervin 1986, 119). The Institution of Transportation Engineers (ITE) Technical Council Committee took Ervin's finding and produced a table of deceleration lane lengths for trucks (ITE 1992, 48). When that table is compared to the AASHTO Table X-6, the extra length required to accommodate trucks, according to the ITE (for a deceleration lane from a highway with a design speed of 65 mph) ranges from 53 to 57 percent higher than the length recommended in the AASHTO guide - even greater than the estimates derived by Ervin. The absolute differences range from 180 feet on the approach to an exit ramp where traffic is assumed to be running at 50 mph, to 295 feet when ramp traffic is running at 25 mph.

1.2.2 Intersections

Many vehicle characteristics influence intersection design. Radius of curb returns or other pavement edge delineators follows directly from the types of vehicles that the designers wish to accommodate, balanced against considerations of available right-of-way, cost, and pedestrian safety. Typically, rural intersections use a greater radius of curvature than urban intersections, but neither is adequate to fully accommodate long semi-trailer combinations, rocky mountain doubles, or turnpike doubles. Instead, some degree of encroachment by turning trucks outside the roadway or into adjacent lanes is tolerated as a normal course of business at most intersections.

The stopping sight distance available to drivers along the roadways at intersections is a critical intersection issue. MRI has found that:

- Vehicle length is an important determinant of sight distance at non-signalized intersections,

- Typical conventional combination vehicles (70 to 75 feet in length) require 14 to 17 percent more stopping sight distance to be able to safely cross intersections controlled by stop signs than the design vehicle used before 1990,

- A 300 lb/hp, 75-foot truck needs 58 to 135 percent more sight distance than a passenger car for turning right or left at a stop-sign-controlled intersection, and

- Trucks of all types typically need longer change intervals at signalized intersections than are commonly provided (Harwood et al 1990).

Sight distance at intersections has been cited as a great concern in the operation of the longer trucks authorized by the STAA of 1982 (TRB 1989, 150). The MRI study concludes that further investigation is needed to ascertain viable sight distance values for different types of vehicles.

1.2.3 Alignment

Highway alignment decisions typically trade off the costs of construction, right-of-way, and external social costs against vehicle operating cost and safety. In general, minimum standards are based on safety considerations, with recommended desirable higher standards that are based on operating cost considerations for various general traffic levels.

Horizontal Curves

Horizontal alignment features that incorporate vehicle characteristics include the radius of curvature and pavement width on curves. Both of these are based on vehicle offtracking characteristics. These features also relate to a vehicle's ability to withstand lateral forces, and this issue generally predominates in main line horizontal alignment decisions. Horizontal curve sight distance issues also control maximum safe speeds on many curves, translating into the need for lower truck speeds in many cases.

Factors to be selected in designing horizontal curves include a design speed, a rate of superelevation and a side friction factor. The side friction factors that are recommended were developed to maintain a certain amount of auto driver and passenger comfort. Application of the recommended procedures has resulted in the construction of horizontal curves which produce lateral accelerations in trucks that sometimes exceed the rollover limit of the trucks on dry pavements. At other times, on wet pavements, they produce lateral accelerations in trucks that exceed the tire/pavement friction force and lead to skidding. For semitrailer combinations with a rollover threshold of 0.35, the margin of safety against either skidding or rolling over appears to increase as the design speed of the curve increases. That is, on a curve with a design speed of 20 mph and a 0.04 superelevation, the truck will roll over at 27 mph; on a 30 mph design speed curve, same superelevation, the truck will skid out of control at 40 mph; at 40 mph design speed, the truck will skid at 54 mph; at 50 mph design speed, the truck will skid out at 67 mph (Harwood et al, 1990, 199). The design procedures seem to produce the most unsafe conditions for trucks on curves with low design speeds - such as are encountered on freeway ramps.

Vertical Curves

Crest vertical curves (curves that begin with an upgrade, a positive grade, and then transition to a downgrade, a negative grade) are typically designed to provide enough sight distance to allow a vehicle to brake to a stop before colliding with a hazard in the roadway. Factors used in the calculation of the length of vertical curve necessary to provide that safety include several whose values are quite different for automobiles and for trucks. The design guides use eye heights and deceleration rates that are typical for automobiles. The design eye height for autos has gradually reduced from 54 inches in 1954 to 42 inches today. Consequently, highways designed according to the earlier guidelines will have provided a shorter length of crest vertical curve than those designed and built according to more recent recommendations. Eye height for trucks is estimated to range between 75 and 93 inches. Therefore, the use of either eye height would have provided adequate sight distance for trucks, if deceleration rates were comparable. But deceleration rates for trucks and autos are not comparable; trucks need longer distances to stop, from any speed.

A study performed for the FHWA concluded that AASHTO criteria for stopping sight distance may be inadequate to accommodate trucks with conventional brake systems. The authors developed an alternative set of criteria based on their own estimates of truck driver braking performance, but cautioned that additional data is needed on the real-world distribution of driver braking performance. Further, the calculated stopping sight distance for trucks was not very sensitive to the difference between the 75- and the 93-inch eye height. (Harwood et al, 1990, 66).

Trucks cannot maintain speeds on some upgrades. Design guidelines call for the construction of truck climbing lanes alongside two-lane highways when the longer gradients cause truck speeds to be reduced by 10 mph. This "critical length of grade" is primarily dependent upon the ratio of the truck weight to its engine horsepower. That ratio has been reducing over time as truck engines become more powerful, even as the average gross weights increase.

1.2.4 Cross-Section

Simulation studies of the operation of semitrailer combinations on interchange area ramps suggest that the maximum break in grade allowed by the AASHTO design guide between pavement and shoulder is too high, and can induce rollover in some trucks (Ervin, 1986, 33). The evidence, however, is not strong enough to support any change in the recommended design procedure.

Similarly, AASHTO's 1989 "Roadside Design Guide" categorizes a 6:1 sideslope from edge of shoulder as a "mild" slope. Ervin questions whether some trucks can remain upright on such a slope after losing control and leaving the pavement. No hard evidence exists to support a change in the recommended practice.

1.2.5 Other Roadway Geometric Features

Overhead Clearance

Prevailing height limits have created a highway system that would require substantial investment to accommodate higher vehicles. A vehicle of maximum, legal height that both weighs out and cubes out under regulations possesses a rollover threshold low enough to provide a good argument against further increases in the height limit. Conversely, lowering height limits would increase stability of some vehicles in turns.

2.0 Implications of Policy Options

2.1 Limiting Vehicle or Trailer Lengths

Overall length of a vehicle and trailer length have been regulated to various degrees by states and the Federal Government during the history of truck size and weight regulation. Before the 1982 STAA, common state practice of regulating overall length resulted in cabs with minimum dimensions from the front bumper to the rear of the cab. Drivers and driver groups alleged a lack of safety and comfort in these resulting cabs, and those concerned with fuel efficiency argued that the blunt-nosed, cab-over-engine tractors had a very high drag coefficient, compared to what could be achieved with a long-nose, conventional cab. Fixing overall length limit for combination vehicles seemed to prevent those possible gains in driver safety and comfort, and fuel economy.

The 1982 STAA attempted to remedy this situation by requiring states to allow 48-foot semitrailers on a subset of the nation's highways, while disallowing their regulation of overall vehicle length. Early implementation of that statute showed that these vehicles did not fit within the bounds of many interchange ramps and intersections on the highway network. A grandfather clause in that legislation led to the operation of combination vehicles with semitrailer lengths ranging from 50 to 59.5 feet in 25 States (TRB 1989). The States knew that length of the semitrailer was not the precise feature that made some combinations unable to stay within their lanes. It is the wheelbase, the dimension from the kingpin to the center of the rear axle group, that is the primary determinant of the low-speed offtracking characteristic of a semitrailer combination. By 1989, nine States were also prescribing a maximum wheelbase for these vehicles.

2.2 Limiting the Distance From The Kingpin to The Rear Axle

This vehicle dimension is the primary contributor to the low-speed offtracking character of a truck. Therefore, it has a direct effect on the maneuverability of the vehicle on interchange ramps, at intersections, and on roadways with restrictive horizontal alignment. Past studies of the appropriateness of setting such a limit have examined the impact on the stability of the vehicle as well as on shipper productivity. A consensus value of 40-41 feet seems to minimize the effect on both (TRB 1989, 206).

2.3 Limiting Rollover Threshold or Set Rollover Standard

The static roll stability of a vehicle comes into play as the vehicle turns. Consequently, a rollover standard would improve the stability of vehicles on freeway ramps, on roadways with restrictive horizontal alignment and, to a lesser degree, during low-speed turning maneuvers at intersections.

Selection of an appropriate static roll threshold would be the first problem encountered. The Canadian Roads and Transportation Association of Canada (RTAC) study set a target of 0.40g; the TRB study of the Turner Truck set a target of 0.38g; and a target of 0.35g seemed more reasonable to the New Zealand government (Bass and White, 1989).

Studies conducted by UMTRI for FHWA found that the target level of 0.38g was "achievable with current hardware, especially if free plays in the springs and fifth wheel are kept to a minimum" (Fancher and Mathew, 1990, 29). This level was obtainable for a fully-laden, STAA-authorized semitrailer combination with the center of gravity of the payload at the center of the cargo container. However, the authors noted that some existing semitrailer combinations with high payloads, soft springs, 96-inch track widths, and considerable suspension lash may have rollover thresholds as low as 0.25g.

The final hurdle appears to be the ability to enforce such a standard. Variations in loading practice have a great effect on the center of gravity of a loaded cargo container, so that any payload with a higher center of gravity than at the center of the cargo container will degrade the rollover threshold of that vehicle.

In its concluding remarks in the Turner Study report, the TRB states, "The relationship between rollover threshold and accident experience has been clearly demonstrated and establishes the basis for regulation. Regulating rollover threshold would be complex, because it depends on both the design and the loading of the truck" (TRB 1990, 205).

2.4 Setting a Length Limit for Doubles Combinations

From the standpoint of highway geometry features, longer overall lengths of doubles combinations typically increase offtracking, especially at low speeds while turning corners, and also increase the potential for interfering with traffic flow because of the added difficulties in passing and merging.

Standard A-train configurations typify U.S. doubles operations, and trailer lengths range from 28 feet each on Western doubles to two 45-feet-long trailing units on Turnpike Doubles. Western doubles fit very well on the horizontal alignment of our highways, even better than the more ubiquitous STAA-authorized semitrailer combination. The Western double's maneuverability in tight situations is its greatest attribute; and with an overall length of about 70 feet, the Western double operates safely with respect to most other highway geometric features as well. Turnpike doubles present an insurmountable low-speed offtracking characteristic to the exit ramps on the roadways on which they are allowed to operate. Hence, special breakup areas are constructed adjacent to the turnpike's main roadway where the vehicles are separated into two semitrailer combinations before being allowed to exit from the turnpike. Studies conducted by the TRB concluded that twin 34-foot long doubles possessed offtracking characteristics similar to the STAA-authorized semitrailer combination, and were considerably more stable than the shorter Western doubles.

In contemplating setting a length limit for doubles operations, one first has to decide whether the "length" is the maximum length of any one unit, the maximum total length of the cargo-carrying units, or the maximum overall length of the combination. Operation of doubles with cargo units of different lengths is not widespread in this country. Such Rocky Mountain Doubles operate in only 11 Western States. But operations of doubles with the same length in each trailing unit have expanded considerably since passage of the STAA of 1982.

The consequences of past attempts to limit the overall length of semitrailer combinations suggest what would happen if the length of doubles were similarly restricted. That is, the length of the cargo units would be maximized at the expense of reduced driver comfort and safety, and fuel economy from a cab-over-engine, short-wheelbase tractor. Such a consequence would also maximize (worsen) the low-speed offtracking characteristic of a double that is limited in overall length, assuming a normal placement of axles.

Limiting the total length of the cargo-carrying units, to something like the Turner Truck studied by the TRB (32 to 34 feet), would likely result in the operation of doubles equipped mostly with tandem axles, to take advantage of the extra gross weight than allowed by application of Federal bridge formula. Such a vehicle would have reasonable offtracking characteristics, and would possess more stability and better dynamic braking performance than the five-axle Western doubles (28-foot units) they were designed to replace (TRB 1990).

3.0 Summary

- The low-speed offtracking characteristic of some STAA-authorized semitrailer combinations can cause damage to roadway appurtenances and inconvenience to other motorists; primarily at urban intersections with restrictive geometry.

- Attempts to minimize the consequences of this characteristic by limiting the semitrailer wheelbase lead to a longer trailer overhang. Such an event prompts closer attention to the available stopping sight distance at intersections before such turning movements can be safely accommodated.

- Drivers of semitrailer combinations who move their rear axle set all the way back for highway driving, to provide a smoother ride, have also reduced the tendency for jackknife by maximizing their stopping performance. They have also minimized the rearward amplification of the vehicle, but have worsened the low-speed offtracking character of the vehicle.

- Freeway deceleration lanes designed according to recommended procedures fail to provide enough braking distance for some trucks to reduce their speed to the design speed of the interchange exit ramp curve. Trucks with low rollover thresholds can roll over on some freeway ramps when travelling as little as 5 mph over the design speed of the ramp curve.

- Design of horizontal curves requires the selection of a rate of superelevation and the side friction factor. Use of the recommended side friction factors has resulted in the construction of horizontal curves that produce lateral accelerations that cause some trucks to roll over on dry pavements or skid out on wet pavements.

- Recommended design criteria for crest vertical curves may provide inadequate stopping sight distance for trucks with conventional brake systems. Highways designed according to older recommended procedures provide less sight distance than do highways built in accord with more recent procedures.

4.0 Knowledge Gaps and Research Needs

- Intersection stopping sight distances derived from application of AASHTO-recommended procedures have been shown to be inadequate in a pilot study conducted as part of a 1990 research effort for FHWA by the MRI. That study concluded that recommended sight distances needed to be increased by anywhere from 17.5 percent to 135 percent, depending upon the truck driver's braking performance, the length of the truck and the weight-to-power ratio of the truck. MRI called for a full-scale study of this issue.

- A specific aspect of the above study would be an investigation of the real-world distribution of truck driver braking performance.

- Highway departments need to know the cost and the effectiveness of measures taken to modify the roadway system to better accommodate the operating characteristics of trucks. AASHTO guides are continually being modified to reflect changes in truck size and configuration, but these guides apply primarily to new construction or to major reconstruction. Studies are needed to investigate what can be done at lower cost to improve the traffic safety environment. Freeway interchange areas appear to be a logical focus for study, as some States report up to 10 percent of truck accidents occurring on freeway ramps. Truck safety studies report that trucks often encounter trouble on exit ramps because of inadequate deceleration lane lengths. Lengthening the deceleration lane appears to be an effective way of allowing trucks to reduce their speed to a safe speeds on the exit ramp. This would be less costly than changing the geometry of the ramp curve itself. A nationwide survey of a sample of interchange areas could relate the design features in Section 1.2.1 to an historical accident record at each interchange, could provide estimates of the cost of modifying certain design features of the interchange area that seem "over-involved" in that accident record, and could provide estimates of accident savings by type of modification.

- We need to explore a possible need for more effective underride protection for trailers with large rear overhangs. The use of such trailers is expanding as states move toward allowing longer semitrailers without accommodating longer wheelbases. Such trailers may need both rear and side underride protection given their tendency to swingout into opposing traffic during tight turns.

5.0 References for Roadway Geometry Working Paper

1993

Lawrence, Mark A. Conversation with Roger Mingo Regarding Bread Trucks in Oklahoma. November 1993.

Mingo, Roger D. Notes on Implementation of Bicycle-Wheel Offtracking Model. May 1993. Unpublished programs and tables based on paper in TRR 1052 (Sayers 1986).

1992

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

1991

Clarke, Robert M.; Radlinski, Richard W.; and Knipling, R.R., "Improved Brake Systems for Commercial Motor Vehicles", Report to Congress as mandated by the Truck and Bus Safety and Regulatory Reform Act of 1988, NHTSA, April, 1991.

Harkey, D.L.; Zegeer, C.V.; Reinfurt, D.W.; Davis, S.E.; Stewart, J.R.; and Council, F.M., "Operational Impacts of Wider Trucks on Narrow Roadways", June 1991. The Scientex Corporation, Charlotte, Report No. FHWA/RD-90/103.

Jack Faucett Associates, "Evaluation of Out-of-Service Criteria"; April 1991, for FHWA.

MacAdam, C.C. "The Crosswind Sensitivity of Unladen Doubles and Triples Combinations and their Susceptibility to Wind-Induced Offtracking and Rollover." 1991. UMTRI. In 12th IAUSD Proceedings.

McNamara, Jim. "Why Do Brakes Go Out of Adjustment?" Transport Topics. June 10, 1991. ATA, Alexandria, Virginia.

Tracy, William. "Apply the Brakes to Irresponsible Braking." Transport Topics. August 5, 1991. ATA, Alexandria, Virginia.

1990

Billing, John R.; Nix, Fred P.; Boucher, Michael; Raney, Bill. "On the Use of Liftable Axles by Heavy Trucks", December 1990, Transportation and Technology Branch, Ministry of Transportation of Ontario. Report No. CV-90-06.

Fancher, Paul S.; and Mathew, Arvind, "Safety Implications of Various Truck Configurations", January 1990, UMTRI, Ann Arbor, FHWA Report No. FHWA/RD-89/085.

Harwood, D.W.; Mason, J.M.; Glauz, W.D.; Kulakowski, B.T.; and Fitzpatrick, K. "Truck Characteristics for Use in Highway Design and Operation", August 1990, Midwest Research Institute, Kansas City, FHWA Report No. FHWA/RD-89/226.

"Antilock Brakes on Trucks: They Deliver the Goods", in Status Report, Vol. 25, No. 5. May 19, 1990. Insurance Institute for Highway Safety (IIHS).

Mikulcik, E.C.; and Jensen, L.G. "Low Speed Off Tracking of Multiple-Axle Road Vehicles." Department of Mechanical Engineering, University of Calgary. Presented at SAE International Congress and Exposition, Detroit. March 1990.

Slagle, Wayne M. "Increased Stability of Twin Trailers." October 1990. In SAE Publication SP-843, Total Vehicle Ride, Handling and Advanced Suspensions. Talbott Associates for ATA.

SYDEC, Inc., with Jack Faucett Associates, "Productivity and Consumer Benefits of Longer Combination Vehicles", for Trucking Research Institute, January 1990.

Transportation Research and Marketing; Challis, Idaho; "A Study of the Operating Practices of Extra-Long Vehicles", December 1990, for AAA Foundation for Traffic Safety, Washington, D.C.

Transportation Research Board, "New Trucks for Greater Productivity and Less Road Wear", Special Report 227, Washington, D.C., 1990.

1989

Bass, Peter H. and White, David M.; "Safety Improvements for Increased Weights and Dimensions in New Zealand", in Proceedings of the Second International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, British Columbia, June 1989.

Council, Forest M. and Hall, William L., "Large Truck Safety in North Carolina: The Identification of Problem Locations in the Designated Route System", October 1989, University of North Carolina Highway Safety Research Center for Governor's Highway Safety Program.

Fancher, Paul; Mathew, Arvind; Campbell, Kenneth; Blower, Daniel; and Winkler, Christopher; "Turner Truck Handling and Stability Properties Affecting Safety", July 1989, UMTRI, Ann Arbor, for NCHRP, Washington, D.C.

Firestine, M.; McGee, H.; and Cunningham, D.; "Reducing Runaway Truck Accidents through Weight-Based Advisory Speeds", September 1989A, Walcoff and Associates, Inc., Alexandria, Virginia, FHWA Report No. FHWA/IP-89/023.

Firestine, M.; McGee, H.; and Toeg, P.; "Improving Truck Safety at Interchanges", September 1989B, Walcoff and Associates, Inc., Alexandria, Virginia, FHWA Report No. FHWA/IP-89/024.

LeBlanc, P.A.; El-Gindy, M.; and Woodrooffe, J.H.F. "Self-Steering Axles: Theory and Practice", August 1989, Vehicle Dynamics Laboratory, National Research Council of Canada. SAE Technical Paper Series 891633.

Transportation Research Board (TRB), "Providing Access for Large Trucks", TRB Special Report 223, Washington, D.C., 1989.

<u>1988</u>

Council, Forest M. and Hall, William L.; "Large Truck Safety in North Carolina", October 1988, University of North Carolina Highway Safety Research Center for Governor's Highway Safety Program.

DeCabooter, Philip H. and Solberg, Clinton E., "Designated Highway System Truck Operation Study", Paper presented at TRB, January 13, 1988.

Parker, D.J.; and Hutchinson, B.G.; "Large Truck Braking at Signalized Intersections", December 1988, Department of Civil Engineering, University of Waterloo, for Ministry of Transportation of Ontario.

<u>1987</u>

Clarke, R.M.; Leasure, W.A., Jr.; Radlinski, R.W.; and Smith, M.; "Heavy Truck Safety Study", March 1987, NHTSA, prepared in response to Sec. 216, Motor Carrier Safety Act of 1984.

Jones, Ian S. and Stein, Howard S.; "Defective Equipment and Tractor-Trailer Crash Involvement", September 1987, Insurance Institute for Highway Safety.

Robertson, H. Douglas; Harkey, David L.; Davis, Scott E.; August 1987, "Safety Criteria for Longer Combination Vehicles", Analysis Group, Inc., for FHWA Office of Research and Development.

Sparks, Gordon; Bielka, John; Smith, Anne; Marzolf, Donna; and Neudorf, Russ; "The Safety Experience of Large Trucks in Saskatchewan", (1987), University of Saskatchewan, Regina, for Saskatchewan Highways and Transportation and Transport Canada.

Winkler, C.B.; Fancher, P.S.; Carsten, O.; Mathew, A.; and Dill, P.; "Improving the Performance of Multitrailer Vehicles: A Study of Innovative Dollies", December 1987, UMTRI, Ann Arbor, for FHWA.

1986

Billing, J.R.; and Mercer, W.R.J. "Swept Paths of Large Trucks in Right Turns of Small Radius." In Symposium on Geometric Design for Large Trucks. Transportation Research Record 1052. 1986A.

Billing, J.R. and Mercer, W.; "Demonstration of Baseline Vehicle Performance: B-Train Double, C-Train Double, A-Train Triple, and C-Train Triple" (four reports), June 1986B, Ontario Ministry of Transportation and Communications, for CCMTA/RTAC Vehicle Weights and Dimensions Study.

Ervin, R.D.; Nisonger, R.L.; MacAdam, C.C.; Fancher, P.S. "Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks", July 1986A, UMTRI, Ann Arbor, FHWA Report No. FHWA/RD-83/029.

Ervin, R.; Barnes, M.; MacAdam, C.; Scott, R.; "Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges", August 1986B, UMTRI, Ann Arbor, for FHWA.

Fancher, P.S.; Ervin, R.D.; Winkler, C.B.; and Gillespie, T.D.; "A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks", December 1986, UMTRI, Ann Arbor, for NHTSA.

FHWA, "Longer Combination Vehicle Operations in Western States", October 1986 Report to Senate Appropriations Committee.

Safwat, K.N.A.; and Walton, C. Michael. "Expected Performance of Longer Combination Vehicles on Highway Grades." In Symposium on Geometric Design for Large Trucks, Transportation Research Record 1052, 1986.

Sayers, Michael W. "Vehicle Offtracking Models", In Symposium on Geometric Design for Large Trucks, Transportation Research Record 1052, 1986.

Transportation Research Board, "Twin Trailer Trucks", TRB Special Report 211, Washington, D.C., 1986.

1985

FHWA, "The Feasibility of a Nationwide Network for Longer Combination Vehicles", June 1985, Report to Congress pursuant to Sections 138 and 415 of the Surface Transportation Assistance Act of 1982.

1984

Ervin, R.D.; Fancher, P.S.; and Gillespie, T.D.; "An Overview of the Dynamic Performance Properties of Long Truck Combinations", University of Michigan Transportation Research Institute, Ann Arbor, July 1984.

1983

Billing, J.R.; Mercer, W.R.J.; Lam, C.P.; Wolkowicz, M.E.; and Stephenson, W.R.; "Tests of a B-Train Converter Dolly", May 1983, Ontario Ministry of Transportation and Communications.

Nisonger, R.L. and Ervin, R.D.; "Dynamic Behavior of the B-Type Converter Dolly", September 1983, UMTRI, for National Research Council of Canada.

Woodrooffe, J.H.F. and Billing, J.R., "Characteristics of Truck Combinations with the Double Drawbar Dolly", in the Roads and Transportation Association of Canada Research Series, Ottawa, 1983.

1982

Billing, A.M.; "Rollover Tests of Double Trailer Combinations", December 1982, Ontario Ministry of Transportation and Communications.

Hayhoe, G.F.; and Shapley, C.G.; "Factors Affecting the Skidding Performance of Trucks", Highway Truck Collision Analysis, Proceedings of the winter annual meeting of ASME, Phoenix, November 1982.

Seguin, Edmond L.; Crowley, Kenneth W.; Harrison, Paul C., Jr.; and Perchonok, Kenneth; "The Effects of Truck Size on Driver Behavior", March 1982, The Institute for Research, State College, Pennsylvania, for FHWA.