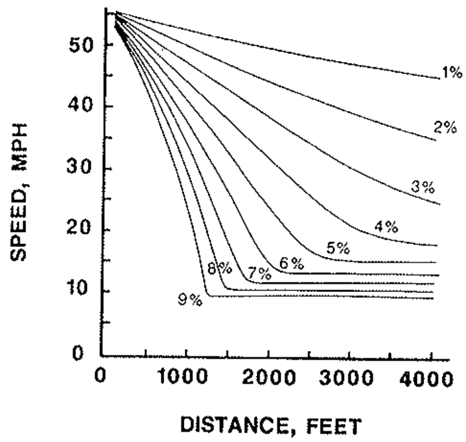

FIGURE A-7 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.00044, C_4 = 0.04, and GVW/NHP = 400.

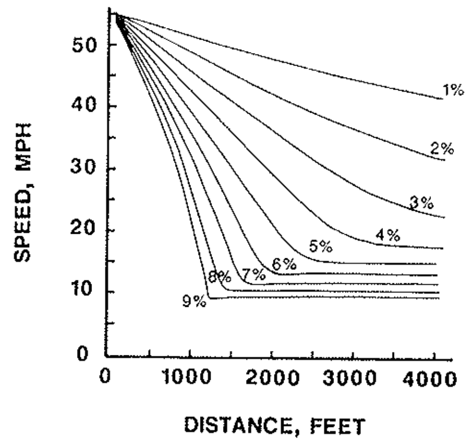

FIGURE A-8 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.003, C_4 = 0.0228, and GVW/NHP = 400.

Influence of the Geometric Design of Highway Ramps on the Stability and Control of Heavy-Duty Trucks

ROBERT D. ERVIN, CHARLES C. MacADAM, and MICHELLE BARNES

ABSTRACT

A research study is described in which accidents experienced by tractor-semitrailers on expressway ramps were found to depend largely on the interaction between highway geometrics and vehicle dynamic behavior. The accident rates of tractor-semitrailers on expressway ramps in five states were scanned to select 14 individual ramps that exhibited an unusual incidence of serious accidents involving these vehicles. The geometrics of each ramp were fully defined in a computer simulation in such a way that the dynamic behavior of example tractor-semitrailers could be examined. The results of combined study of accident data, simulated vehicle response, and geometric details of ramp design are presented. The findings of the study indicate that the maneuvering limits of certain trucks are quite low relative to those of automobiles so current practice in ramp design leaves an extremely small margin for control of heavy vehicles. The primary design issues are embodied in the nominal side friction factor achieved at each curve, the transition geometry, and the layout and signing of curve segments in order to assure that truck speeds are suitably reduced for negotiating small-radius curves.

The geometric design of highway ramps is guided by the design policy of AASHTO (1). These policies provide specific guidance on the relationships among curve radius, superelevation, transition sections, vehicle speeds, and other details that control ramp design. For a given anticipated ramp layout, there exists a range of variations, which are allowed within the design policy, in each design parameter. In the real world, ramps that are in service around

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the country exhibit even further variations in parameters because they were built before the tighter prescriptions of modern design or because certain physical or economic obstacles made strict adherence to the AASHTO policy unachievable. Accordingly, it is clear that highway ramp design varies widely around the country.

When considering the margins of safety that existing ramps provide for the operation of heavy-duty trucks, it is immediately apparent that the considerations that underlie ramp design recommendations in the AASHTO design manual (1) make little or no allowance for the special requirements of trucks. Indeed, it is clear that the geometric design of ramps is almost exclusively rationalized on the basis of automobile usage. This situation is in distinct contrast with the specific attention that is given to truck requirements in other areas of road design, such as climbing lanes, the width of turning roadways, corner radii at intersections, and certain sight distance considerations. The particular truck requirements of interest here are those that govern the limits of vehicle stability and control. Thus, both because of the variations in design that exist from one ramp to the next and because even the recommended design policies take no particular note of truck stability and control limits, it appears to be reasonable to explore the possible conflicts that trucks may encounter in negotiating highway ramps.

Particular impetus for such exploration is given by the accident record for trucks in general, recognizing for example that the accident file of the Bureau of Motor Carrier Safety (BMCS) for 1980 shows that 9 percent of all jackknife accidents and 16.8 percent of all truck rollovers occur on ramps. Clearly, such percentages are much higher than the fraction of total highway miles represented by ramp sections. The influence of certain of the geometric design variables of ramps on accidents or operational aspects, or both, has been examined by many investigators in the past (2-15), although no one has focused a ramp-accident study specifically on trucks. Nevertheless, some studies (2) have found trucks to be underinvolved in the population of all aggregated ramp accidents relative to their presence in the traffic stream. Such findings, together with the indication in the BMCS data that trucks are overinvolved in loss-of-control accidents on ramps, may suggest that the main problem that trucks experience on ramps is that of controllability, although the potential for collision accidents involving trucks on ramps may be no worse, or even better, than that of other vehicles.

To examine truck controllability problems on ramps, and to relate them to geometric design, a project was conducted by the University of Michigan Transportation Research Institute (UMTRI) under sponsorship of the FHWA. This paper is a report on the prominent findings of that study that serve to identify the special types of conflict that occur.

METHODOLOGY

The study first sought to identify specific examples of highway ramps on which had occurred an inordinate number of loss-of-control types of truck accidents. Because it was determined that national-level accident files do not contain sufficient detail to enable identification of individual ramps, it was necessary to draw from the accident files of selected states in order to identify ramps for study. Because it was not possible to clearly determine accident rates because of a lack of exposure information, a "first cut" in selecting ramps was done on the basis of absolute numbers of truck accidents at individual sites. With the aid of automated data-processing capabilities, a number of states were able both to identify individual, heavily involved ramps and to supply hard-copy reports for each truck accident on the selected ramps. During examination of each of the individual accident reports for each candidate ramp, a total set of 15 ramps was selected. The participating states were California, Illinois, Maryland, Michigan, and Ohio.

Engineering drawings were obtained documenting the geometric design, posted speeds, and traffic control devices at each of the selected ramp sites. The individual accident reports from each ramp were then examined closely to locate the approximate point on the ramp at which the loss-of-control events appeared to be occurring. In general, it was possible to focus attention on a specific curve or transition area on each ramp. The geometric data needed to completely define the curvature, superelevation, and grade of each ramp section of interest were then provided as input to a comprehensive simulation of the dynamic behavior of heavy-duty trucks (16). The simulation model provides a 32-degree-of-freedom representation of a tractor-semitrailer, allowing the full range of steering and braking maneuvers over the three-dimensional roadway. The model is configured such that an active "driver" system steers the vehicle, following the lane centerline with response characteristics that are demonstrably like those of a real driver up to the control limit conditions (17). The validity of the simulation model has been demonstrated in various exercises that compared computed results with experimental measurements from full-scale tests (18-20).

Each of the selected ramps was examined by means of the simulated operation of tractor-semitrailers that were represented in two loading conditions, namely (a) a baseline loading placing the payload center of gravity (CG) at 83 in. above the ground--a value that is thought to characterize a large fraction of typical truck traffic and (b) a loading case with the payload CG at a height of 105 in., which is representative of various specialized tank vehicles as well as van trailers carrying a full cube load of homogeneous freight. The tractor-semitrailers were simulated at various speeds--some cases at the posted advisory speed value and some above--over each ramp. The gross motion response of the vehicle was then interpreted in terms of a likely loss-of-control outcome.

The simulation results, supported by various other research findings that generalize on the dynamic behavior of heavy vehicles, serve to identify certain aspects of ramp geometric design that tend to restrict the margins of safety available for truck operation. Five cases that serve to illustrate the more potentially significant of these aspects of ramp design will be discussed.

ILLUSTRATIVE CASES

Heavy-duty trucks and truck combinations suffer constraints on their maneuvering capability in negotiating ramps as a result of certain size parameters and also because of certain limitations in the mechanical performance of the vehicles and their components. In addition, it may be inferred from reading the hard-copy accident reports that a substantial number of truck drivers tend to take ramps too fast, perhaps because of the desire to keep up speed in anticipation of merging or simply because of a lack of appreciation for the small tolerance that some ramp designs afford for trucks exceeding the advisory speeds.

In the illustrative cases that follow, the cited "problems" fall either into the category of inherent limitations in truck stability and control qualities or into the category in which truck driver behavior appears to frequently involve peculiar misjudgments. Each case is first characterized by the particular aspect of ramp design that appears to be connected with the truck control problem of interest.

Case 1 (side friction factor is excessive given the roll stability limits of many trucks)

The first case involves the exit ramp that is sketched in Figure 1. As shown, Curve 3 is preceded and followed by spiral transitions and is posted with an advisory speed of 35 mph. The R and J designations indicate the approximate points at which vehicles involved in rollover and jackknife accidents came to rest. At 35 mph, the 342-ft radius of this ramp curve yields a centripetal acceleration of 0.24 *g*. Although the lead-in spiral is 150 ft long (ample for full attainment of the 0.28 ft/ft superelevation of the curve), the full superelevation is not developed until almost completely through the curve. Thus, at the point of entry of the steady curve, the superelevation level (e) is only 0.03 ft/ft, and the side friction factor (f) at that point is 0.21. Although it is unusual and perplexing to find a spiral transition that provides such an incomplete development of superelevation at the point of curvature, it is general practice on nonspiraled transitions to have achieved only one-half to two-thirds of the full superelevation level at the initial point of curvature.

Shown in Figures 2 and 3 are simulation results that illustrate the dynamic response at 35 and 40 mph, respectively, of a tractor-semitrailer that is loaded with freight in the high CG configuration (payload mass center at 105 in.) and that is operated over the cited curve. The results show that the vehicle at 35 mph experiences a near rollover, with a large amount of load being transferred from the right to the left tires. The transient character of the maneuver is such, however, that the roll response has not fully developed during the brief duration of the peak lateral acceleration level. Thus the vehicle "just squeaks by" at the posted speed by virtue of the relatively short-lived peak demand condition. In the 40 mph case (Figure 3) it can be seen that the tire loads on the right have reached zero at approximately 5.5 sec into the run--at which time the vehicle is approximately 50 ft beyond the leading end of the constant-radius curve. Although the zero-load condition on the tractor's inside wheels signals an imminent rollover, the body of the vehicle would not actually strike the ground for another 100 ft or so.

Although, at first note, it appears surprising that a common commercial vehicle will nearly roll over at the posted ramp speed on a primary U.S. highway, it is instructive to examine the margin of safety that is reflected in the side friction factor that pertains to the cited curve. Shown in Figure 4 is a diagram of the components that make up the instantaneous side friction factor at the advisory speed of 35 mph, plotted as a function of the longitudinal position along the ramp section. The figure presents the centripetal acceleration (e + f), the side friction factor (f), and a suggested "likely" side friction demand curve that is 15 percent above the f curve, reflecting the level of steering fluctuations that has been measured in tests of the normal driving of a tractor-semitrailer through expressway ramps (21). Because superelevation is not fully developed along the spiral transition, the peak side friction factor of 0.21, at the point of

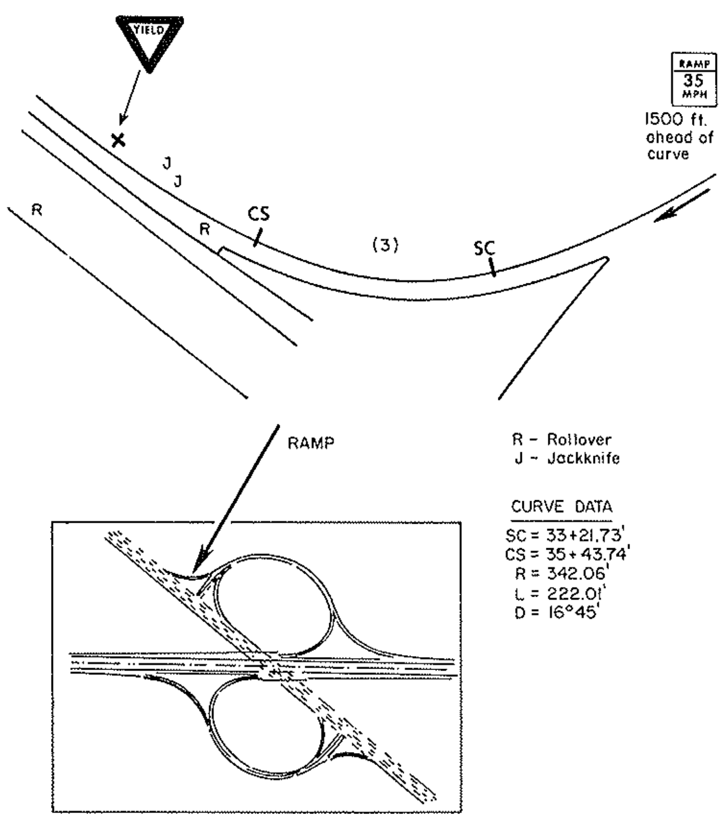


FIGURE 1 Layout of site that poses a challenge to truck roll stability level.

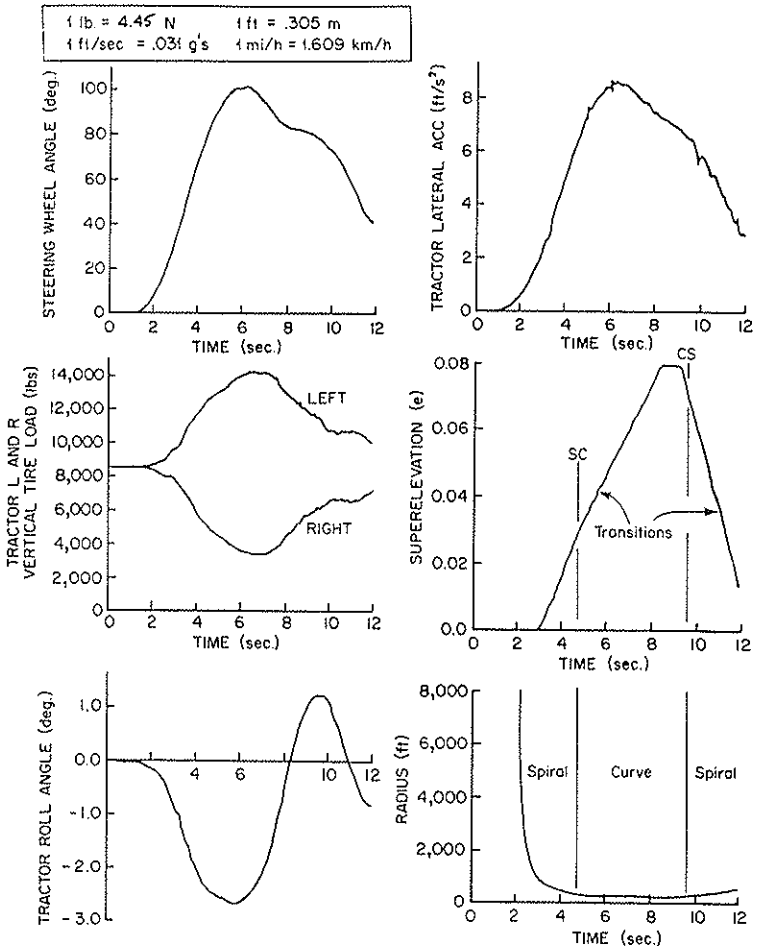


FIGURE 2 Vehicle response variables for travel through the ramp of Figure 1 at 35 mph.

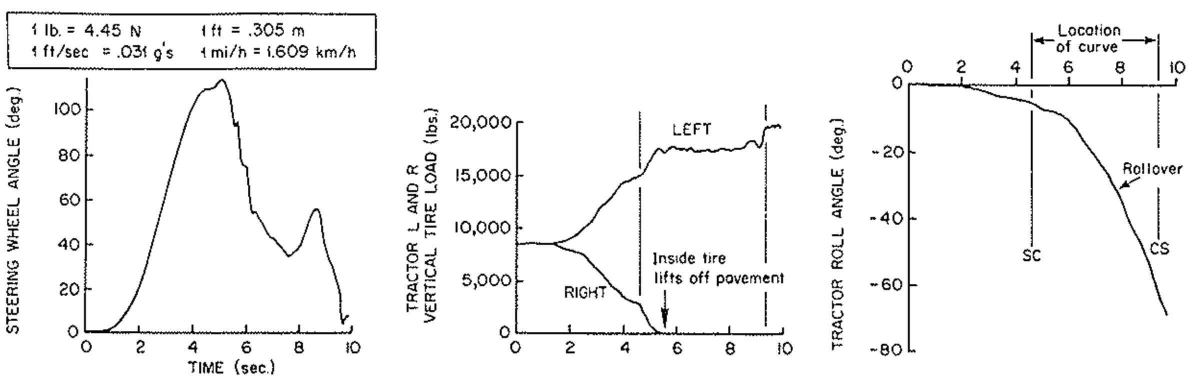


FIGURE 3 Response variables showing rollover at 40 mph.

curvature (SC), corresponds to a demand level of 0.24, allowing for steering fluctuations. This demand level is essentially equal to the steady-state rollover threshold limit of fully loaded tractor-semitrailers that lie at the low end of the stability range of vehicles in common service (22).

To reconcile the clear hazard that such a curve will pose for many heavy-duty vehicles, it is useful to note, first, that at the final superelevation value of 0.08 ft/ft, the curve would be characterized by a nominal friction factor of 0.16. This value is in virtual compliance with the AASHTO recommendation of a maximum of 0.155 for the side friction value in curves posted at 35 mph. The first issue, then, concerns the basic matter of the suitability of a design policy that allows friction factor levels of 0.155 (or 0.16), recognizing that loaded heavy vehicles exhibit static rollover threshold levels as low as 0.24. A full discussion of this matter would require review of (a) the essential basis for the AASHTO policy on side friction factors and (b) the mechanics and operational realities that determine the roll stability levels of heavy commercial vehicles. Although no comprehensive treatise can be attempted here, a minor elaboration on each point is warranted.

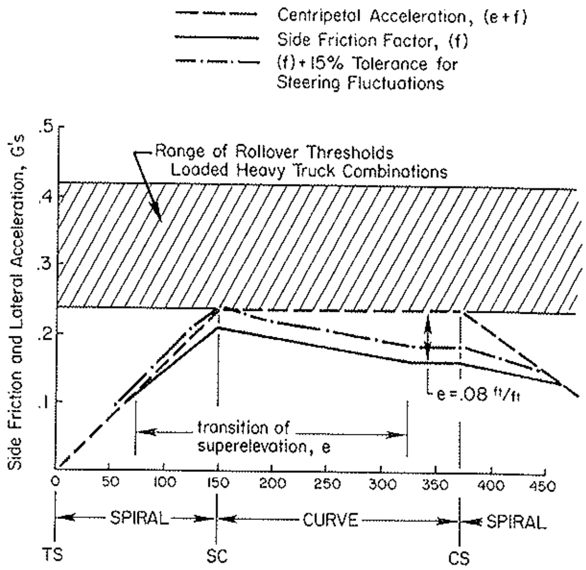


FIGURE 4 Elements of side friction demand compared with range of truck rollover tolerance for ramp curve layout of Figure 1.

The AASHTO policy (1) on side friction factor allowance is clearly based on consideration of (a) the proximity of the friction demand level to the lateral traction limits of automobiles, beyond which "side skidding" may occur and (b) the point of discomfort noted by automobile drivers. It is clear that the maximum recommended values for side friction factor have been set by AASHTO primarily to avoid driver discomfort. It is apparent that this policy intends a substantially larger margin than is achieved with heavy trucks that are at the lower (but by no means rare) end of the stability spectrum. For example, the discussion of the AASHTO policy in the green book (1) indicates that the effective limit condition is established by the maximum side friction capacity of automobile tires (as low as 0.35 at 45 mph) that can be sustained without skidding on wet pavements with smooth treads. Accordingly, the guidelines that limit the design value of side friction factor (to a maximum of 0.17 at 20 mph) appear to reflect a substantial degree of conservatism in behalf of automobiles. Indeed, the design policy for side friction factors has been derived to accommodate the limits of driver discomfort--at which levels the conservatism relative to side skidding is quite generous.

Considering the margin of safety for trucks, however, it is apparent that there also exists a fundamental difference between the respective probabilities that trucks and automobiles will "bump against" their respective maneuvering limits when traversing a demanding ramp. Although, on one hand, an automobile may be constrained by a 0.35 traction coefficient only when (a) smooth tires and (b) a poor pavement texture condition are combined with (c) wet weather, an adversely loaded truck will be continually constrained by its low rollover threshold characteristic as it goes down the road. Accordingly, it can be seen not only that the truck margin of safety on AASHTO-recommended ramps can be exceedingly narrow, in absolute terms, compared with the margins provided for automobiles but also that the risk of loss of control for certain trucks is continual rather than temporally dependent on maintenance factors and weather.

The low stability level of trucks derives, of course, from the height (H) of the center of gravity of the combined payload and tare vehicle relative to the track width (T) and to a host of other sensitivities involving the compliances of tires, suspensions, fifth wheels, and frames (23). Perhaps part of the reason that truck stability limits may have been traditionally overestimated, and thus dismissed in considerations of highway design, is that the vehicle was considered to be effectively rigid in roll, such that the roll stability limit, in g's, would be simply T/2H. If it had been assumed that trucks were as stable as the T/2H figures suggest, with minimum values around 0.45 g's, it would have been reasonable to conclude that the skidding limit of approximately 0.35 for automobiles constituted the effective design condition. Because of the compliant elements in actual trucks, however, rollover occurs at approximately 60 percent of the T/2H values (22). Shown in Figure 5, for example, are five common vehicle loading arrangements with their accompanying roll stability limits. Clearly, a number of common freight loadings render vehicle rollover threshold levels that are quite near the levels of side friction factors that prevail in the Case 1 example.

Although the transition of superelevation in this example is nonideal, and certainly disapproved of by AASHTO as a design practice, the fact that a zero margin of safety exists with some trucks should not be dismissed as attributable simply to the transition anomaly. For the more common cases in which superelevation is transitioned without spirals, the AASHTO-preferred method would have two-thirds of the superelevation achieved at the point of curvature. Even this policy would still allow a side friction factor as high as 0.20 in the transition portion of the curve, thus yielding 0.23 as the effective side friction demand level, allowing for steering fluctuations. Thus it appears that the problem that led to the identification of the Case 1 ramp as heavily involved in truck loss-of-control accidents is (a) understandable in terms of ramp geometry and (b) rather generally anticipated for ramp curves that are built to the limits of the recommended AASHTO practice.

It is also worthwhile to note that AASHTO design policy for low-speed urban streets allows side friction factors up to 0.30! Such a level will surely yield rollover in a large fraction of the population of loaded commercial vehicles.

Case 2 (truckers assume that the ramp advisory speed does not apply to all curves on the ramp)

One aggravating aspect of the truck loss-of-control problem on ramps is that many ramps involve multiple curved segments that have differing side friction factor demands, although only one ramp speed is generally posted. As a consequence, it appears that truckers occasionally assume, at some point along the ramp, that they have now passed the curve or curves that warranted the low value for the posted speed. Subsequently, they begin to speed up in preparation for the merging task, only to find that the remaining curve is at least as demanding of the low advisory speed condition as was the preceding portion of the ramp.

A clear case in point is the ramp shown in Figure 6--a loop with four curves within a partial cloverleaf, rural interchange. The ramp is posted at 25 mph and has two rather sharp curves at either end and two intermediate curves with more moderate

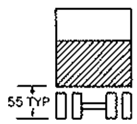
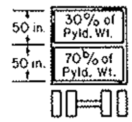
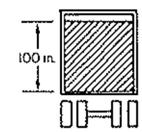
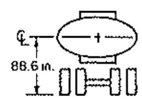
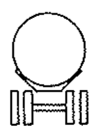
CASE		CONFIGURATION	WEIGHT (lbs) GVW	PAYLOAD CG HEIGHT (in)	ROLLOVER THRESHOLD (G's)
A.		Full Gross, Medium-Density Freight (34 lb/ft^3)	80,000	83.5	.34
B.		"Typical" LTL Freight Load	73,000	95.0	.28
C.		Full Gross, Full Cube, Homogeneous Freight (18.7 lb/ft^3)	80,000	105.0	.24
D.		Full Gross Gasoline Tanker	80,000	88.6	.32
E.		Cryogenic Tanker (He_2 and H_2)	80,000	100.	.26

FIGURE 5 Loading data and resulting rollover thresholds for example tractor-semitrailers at full load.

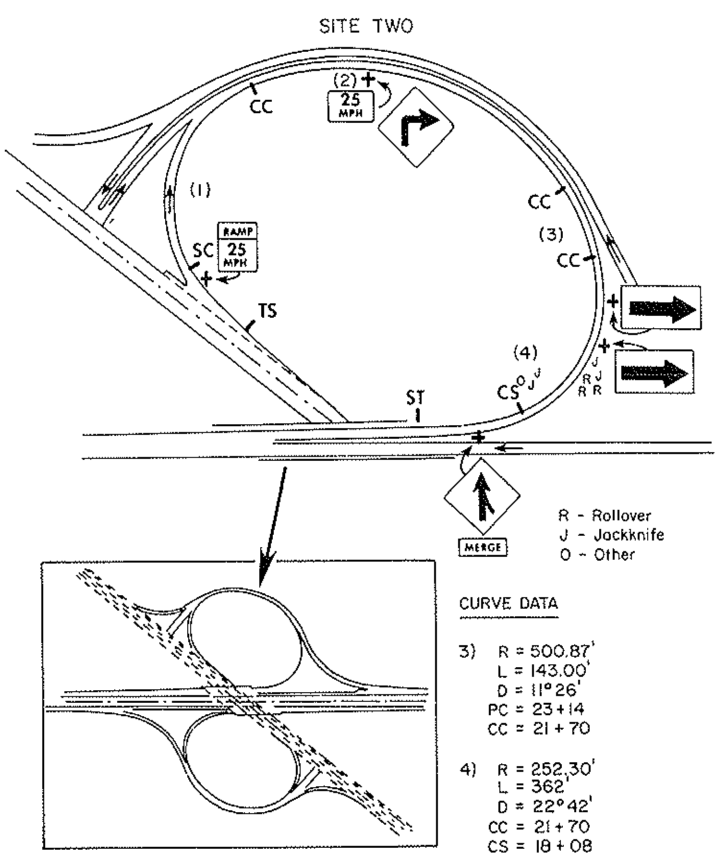


FIGURE 6 Layout of compound curve ramp.

radii. Listed in the following table are the essential data for each of the four curves.

Curve No.	Radius (ft)	Length (ft)	Side Friction Factor
1	250	435	0.09
2	520	993	0.00
3	500	144	0.003
4	252	362	0.09

Spiral transitions to the tangent legs at both ends of this ramp provide that both Curves 1 and 4 are superelevated at 0.08 ft/ft throughout their lengths. Thus the nominal values listed for side friction factor are also the maximum values.

The truck accidents that occur on this ramp are all clustered at the approximate midlength location of Curve 4. Because Curves 1 and 4 are both characterized by identical values of side friction factor, it can only be surmized that truck drivers (a) reasonably satisfy the speed requirements of Curve 1 but then (b) misjudge the continuing need for retaining the low advisory speed while traveling the 1,100 ft through the mild curves (Curves 2 and 3). The analysis shows that a high-CG tractor-semitrailer such as cited in Case 1 would roll over in Curve 4 if the driver permitted his speed to exceed 34 mph.

The number of jackknife accidents reported at this site equals the number of rollover incidents, which suggests that heavy braking is probably being applied when the driver perceives that general loss of control is imminent. Although this site was unusual because the posted speed was mandated by the designs of both the initial and the final curves on the ramp, a number of other problem sites were also identified where drivers apparently lost the conviction that the speed advisory still applied later in the ramp. Again, the trucker is peculiarly vulnerable in the event of such a misjudgment because of the small tolerance that the low-stability vehicle has for increased side friction factors.

Also, it appears reasonable to hypothesize that the very short lengths of acceleration lane available for bringing a fully loaded rig up to speed serve to encourage the driver to achieve as much speed as possible within the ramp before merging. For example, it was noted that a typical 80,000-lb tractor-semitrailer combination powered by a 250-hp engine will require in excess of 5,000 ft to accelerate from a ramp speed of 25 mph to 50 mph (24). Indeed, even the provision of an AASHTO-recommended acceleration lane, 1,100 ft in length (1), does virtually nothing to lessen the truck driver's concerns over merging with minimum disruption of through traffic. Thus, although the truck driver who exceeds the posted ramp speed can be criticized, it appears more realistic to observe that the sum of the highway geometric constraints imposed in this case has "boxed in" the driver and, perhaps, promoted the possibility of misjudgments.

Case 3 (deceleration lane lengths are deficient for trucks, resulting in excessive speeds at the entrance of sharply curved ramps)

The 1965 AASHO blue book (25) gives a definitive background rationale behind the recommended lengths of deceleration lanes. Notwithstanding the careful basis that is developed for designing such lanes to meet the needs and comfort threshold of automobile drivers, both the blue and green book specifications for deceleration lanes place a substantial burden on the stopping capability of many heavy-duty truck combinations. The background figures in the blue book reveal that the "comfortable" level of deceleration for automobile drivers slowing from 55 mph is 0.24 *g*'s. The recommended lengths for deceleration lanes are calculated to allow approximately 3 sec of deceleration of the vehicle in gear, followed by braking at the "comfortable" automobile rate. The blue book does note that trucks require longer stopping distances than do automobiles to decelerate for the same difference in speed but finds longer allowances for deceleration lanes unwarranted because "average speeds of trucks are generally lower than those of passenger cars." Although the green book does not restate the observation concerning truck speeds, the newer recommendations for length of deceleration lane are virtually identical to those in the 1965 policy. Further, it appears reasonable to observe that average truck speeds on U.S. highways today are at least equal to, and perhaps exceed, those of automobiles.

The study of truck accidents on ramps has indicated cases in which the deceleration lengths available for trucks appear to be patently inadequate. The cases in which the problem becomes pronounced are those in which the ramp incorporates a rather sharp curve right at the end of the deceleration lane such that the low value of advisory ramp speed must be achieved very quickly after departure from the through roadway. Shown in Figure 7 is an example of such an exit ramp with a 249-ft radius and a max-

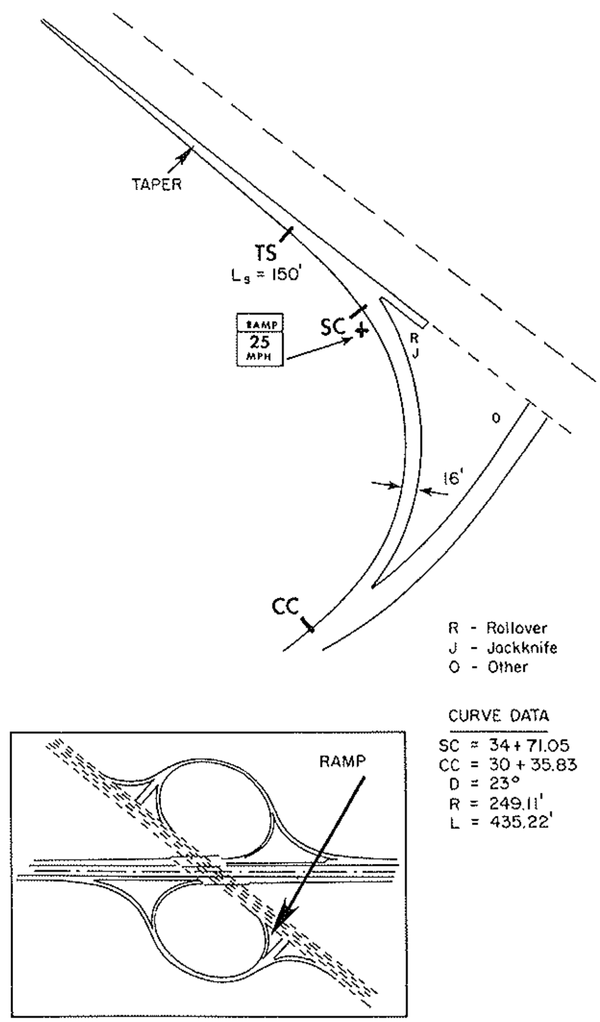


FIGURE 7 Layout of ramp with tapered deceleration lane.

imum superelevation value of 0.08 ft/ft. The side friction factor has a peak value of 0.13 at the advisory speed, given a transition that achieves approximately 50 percent of the full development of superelevation at the point of curvature. The tapered exit begins 375 ft ahead of the point of curvature and thus requires a nominal deceleration of 0.21 *g*'s even if braking begins immediately on entry to the curve. The 0.21-*g* requirement allows no distance for delay in brake application beyond the leading edge of the taper and assumes that the vehicle will begin decelerating while still placed fully in the through lane. According to the AASHTO recommendations, this deceleration lane is extremely short and provides only approximately 100 ft of roadway that should be "counted" for deceleration in recognition that the acknowledged deceleration lane begins only at the point at which the taper has progressed 12 ft from the right edge of the through lane.

The penalty paid by truckers who fail to achieve the required speed on entering this curve is, of course, most likely to be rollover. The accident data show both rollover and jackknife accidents occurring right at the beginning of the example curve. Of course, the jackknife accidents are seen as simply resulting from the overbraking behavior of truck drivers who are endeavoring to achieve a speed that is low enough to avoid rollover. Simulation results shown in Figure 8 illustrate that a tractor-semitrailer carrying freight at a more or less typical level of CG (payload mass center at 83 in.) passes through the curve easily at 25 mph but barely escapes rollover at 35 mph. Other calculations for the same vehicle with a high CG (payload at 105 in.) show that the rig rolls over quickly if it enters the ramp at 35 mph. Thus there is no question that the deceleration task must be accomplished by most loaded truck combinations if they are to safely negotiate curves that have this degree of demand.

The key issue, then, is the extent to which deceleration requirements of the level represented in this case, and more generally of the level implicit in AASHTO policy, can be reasonably accomplished by heavy-duty truck combinations. There is a great deal of evidence establishing that the braking capability of heavy-truck combinations is quite low (26,27). Even on a dry pavement, a stop at approximately 0.4 *g*'s would be considered a severe braking condition for a heavy truck. The Federal Motor Vehicle Safety Standard 121 that requires a deceleration capability of 0.41 *g*'s for air-braked trucks stopping from 60 mph was seen as imposing a serious challenge to the state of truck braking technology. This standard, applied to stopping on dry pavement, implied a braking efficiency of approximately 50 percent. Further, because trucks suffer from large variability in the effectiveness of the basic brake itself, poor main-

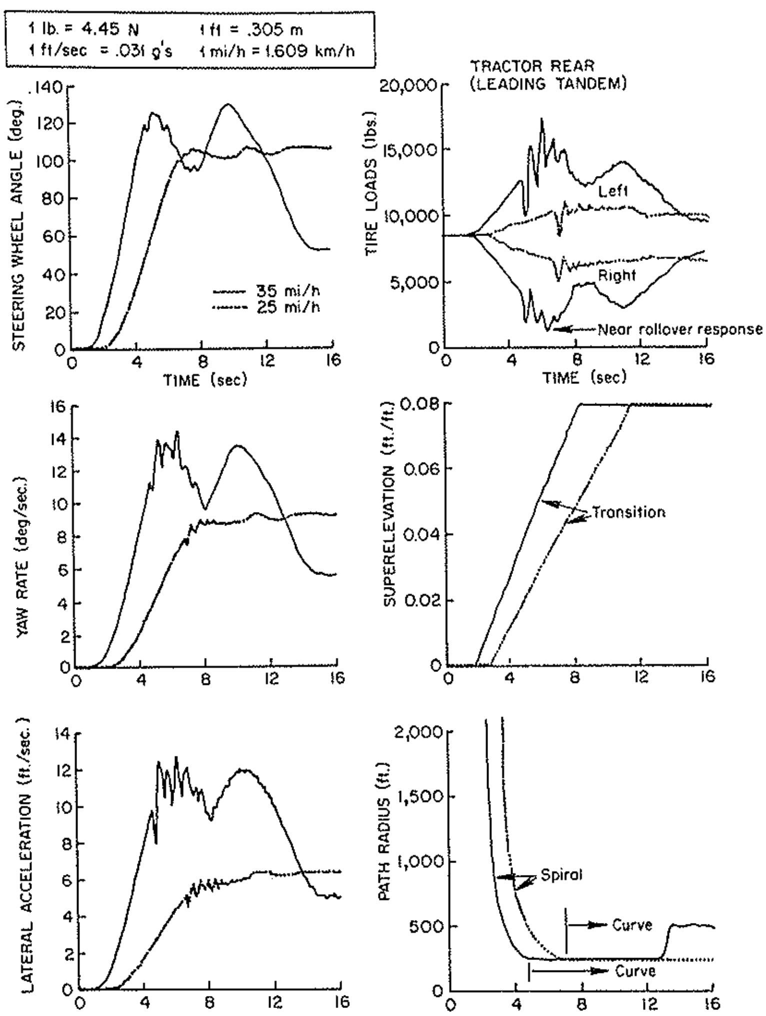


FIGURE 8 Vehicle response on entering the curved ramp of Figure 7 at 25 and 35 mph.

tenance of slack adjustment, and large variations in axle loading depending on the cartage application, levels of braking efficiency even lower than 50 percent are encountered in service.

Under partial loading conditions, a vehicle can exhibit both a low level of roll stability and an extremely poor level of braking capability. In such cases, the unfavorable distribution of axle loads makes it difficult for the truck to decelerate, even though the relatively high CG demands that speed be reduced as required by the curve in order to avoid rollover. Shown in Figure 9 is a plot of the maximum deceleration capability of a doubles combination with a partly loaded rear trailer and a loaded front trailer. To achieve a deceleration level equal to the 0.21-*g* condition required on the example ramp (with brakes applied right at the beginning of the taper) requires a rather substantial peak tire-road friction level of 0.55. The extremely poor stopping capability of this partly loaded vehicle is attributable to the light load prevailing at the rearmost axle. As braking is increased, the brake torque level applied at that axle quickly arrives at the point of saturating the shear force capability of the lightly loaded tires such that an unstable swinging motion of the second trailer is threatened. Similarly, a tractor-semitrailer with payload only in the front portion of the trailer, or a compartmented tanker with fluid emptied from its rear compartments, would exhibit very poor stopping performance (comparable with that of the example double), while also providing a low level of rollover resistance. Although completely empty truck combinations are also known to be conspicuously poor in braking efficiency, their higher roll stability levels tend to be somewhat compensating (assuming that the driver senses that full deceleration to the value of the posted ramp speed is not so crucial that he is prompted to overbrake).

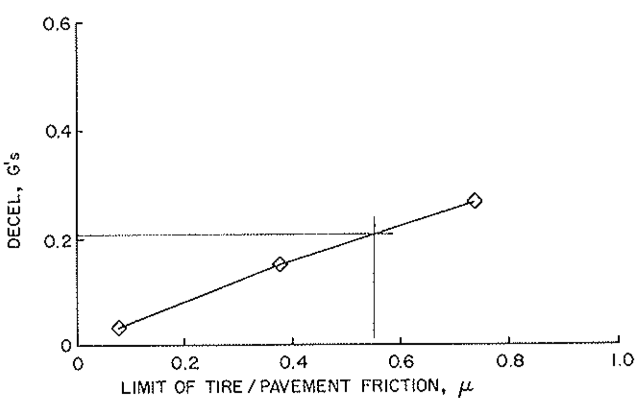


FIGURE 9 Maximum deceleration capability of partly loaded doubles combination as a function of the tire-pavement friction level.

The AASHTO policy for length of deceleration lanes clearly provides for more relaxed braking conditions than those required by the example ramp, although trucks must take liberties with the design relative to the expected usage by automobiles. In particular, the green book requires that deceleration length be measured on tapered exits beginning with the point at which 12 ft of taper is achieved. By this standard, the example ramp would have been constructed with the taper beginning approximately 390 ft sooner than it was. Trucks that begin braking right at the taper of such a deceleration lane would experience only a moderate braking demand. Taking the recommended lengths of deceleration lanes, generally, truck drivers could make a compromise usage of the suggested design by simply applying brakes throughout the available length of the lane thus forsaking the luxury of a 3-sec period for coasting in gear. By this approach, for example, the 490-ft value that the green book recommends for reducing speed from 55 to 25 mph would require a steady deceleration of 0.16 *g*'s--a level that should be reasonably achievable by almost all trucks under most wet and dry conditions.

The primary observation that has been made on the subject of deceleration lanes pertains to the very poor stopping capability of many truck combinations. Clearly, the problem in this regard is analogous to that encountered with regard to allowances for side friction factor. Namely, design specifications that are selected to assure comfortable operation of automobiles pose demands that may challenge the controllability limits of heavy-duty trucks.

Case 4 (lightly loaded truck tires are sensitive to pavement texture in avoiding hydroplaning on high-speed ramps)

Recent findings (28,29) that indicate the potential for hydroplaning with lightly loaded truck tires offer a likely explanation for loss-of-control problems that are seen at certain ramp sites in wet weather. These findings are based on the observation that at the light tire loads associated with empty truck combinations the footprint with which a truck tire contacts the pavement is unusually incapable of expelling water. Accordingly, very lightly loaded truck tires are vulnerable to a pronounced traction deficiency on pavements on which the water cover stands sufficiently above the textural asperities. Because the loss of tire traction on wet surfaces is clearly most pronounced when speed is high, potentially troublesome ramps are categorically those that have large-radius curves such as at interchanges between two high-speed highways. The applicable scenario leading to loss of control involves an unloaded truck combination; a high-speed turn that also poses a substantial side friction demand; and poor pavement texture or water drainage characteristics, or both.

An example ramp site that was found to provide a dramatic illustration of this phenomenon is sketched in Figure 10. The ramp constitutes a nearly steady curve, 2,600 ft in length, which is comprised of two curve segments of 1,400-ft radius with a 290-ft tangent section connecting the two. The entire curved portion of the ramp plus the 290-ft tangent section was superelevated at 0.05 ft/ft, yielding a side friction factor of 0.05 at the special truck advisory speed of 45 mph. The evidence suggests, however, that many truckers simply sustain the 55-mph speed that is posted for other vehicles and thus the trucks experience a side friction factor of 0.09.

Forty-four loss-of-control accidents occurred at this site with tractor-semitrailers during a 2-year period following operating of the new roadway. All 44 accidents occurred when the pavement was wet. The rate of accidents was so great when wet conditions prevailed that a number of the accidents were witnessed by police officers who were on the scene to aid in the recovery of another truck that had lost control. Thirty-two of the accidents at this site involved tractor jackknife, five culminated in rollover, and seven involved other events such as simply running off the road or striking a guardrail. The ramp was resurfaced at the end of this 2-year period with a high-friction bituminous concrete overlay, after which the wet-weather accident problem essen-

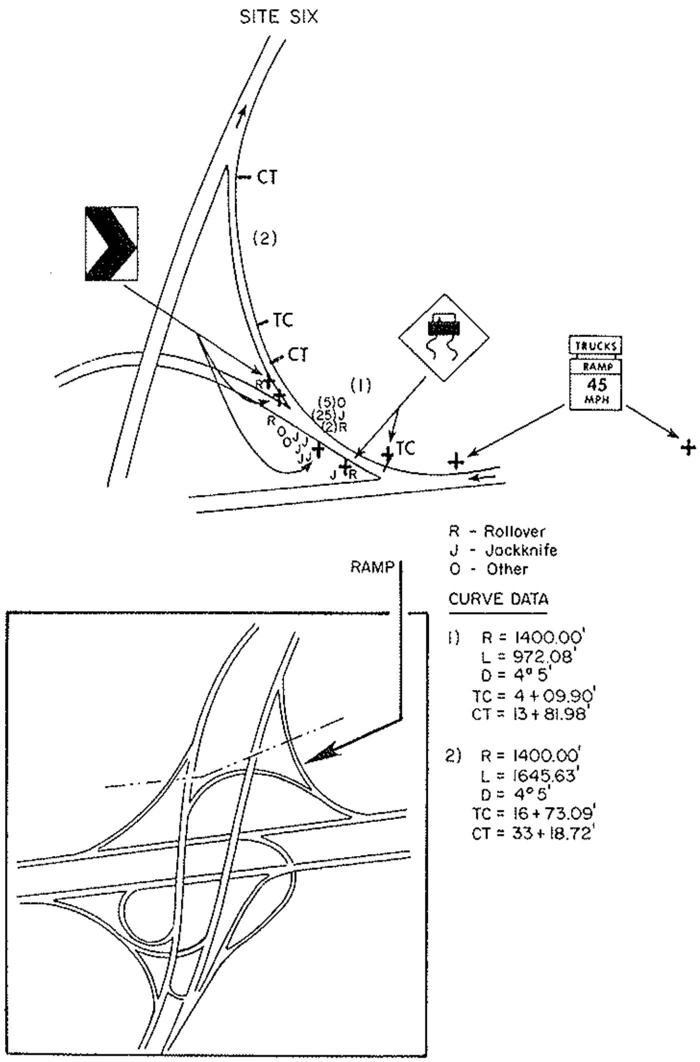


FIGURE 10 Layout of curved ramp site at which numerous loss-of-control accidents occurred with tractor-semitrailers in wet weather.

tially disappeared. Although the police-reported accident forms provided no note of vehicle loading, the large number of loss-of-control incidents that involved running off the road without rollover suggests that many of the semitrailers were lightly loaded or empty.

Shown in Figure 11 are simulation results illustrating the jackknife response of an unloaded tractor-semitrailer running on the example ramp at a constant speed of 55 mph. The conditions producing loss of control in this example involve the assumption of a near-hydroplaning level (mu = 0.12) at the tractor rear and trailer tires compared with a friction level at the front tires of 0.50. This peculiar distribution of tire-pavement friction levels was rationalized on the basis of large differences in tire load among the respective axles and the corresponding implications for friction, considering the potential for strong hydrodynamic influences (28). Static loads on front and rear tires were 4,700 and 1,300 lb, respectively. The simulation results indicate that if the friction levels attain the identified values, the vehicle becomes sufficiently disturbed in traveling over the superelevated tangent portion of the curve that a rapid jackknife divergency is precipitated (on saturating the lateral force output of the tractor rear tires).

Although this example simulation illustrates one possible set of conditions under which accidents such as those reported could occur, it should be recognized that braking and steering inputs could also disturb the vehicle to precipitate the actual jackknife sequence. That the great majority of the jackknifed tractor-semitrailers came to rest on the inside of the turn suggests that the jackknife typically began when tractor drive wheels were locked, following which brakes were released, causing the vehicle to go rapidly in the direction toward which the tractor had begun to rotate--toward the inside of the turn.

The item of general importance illustrated in this case is that heavy-duty vehicles are now known to be unusual in their potential for loss of control on wet pavements. Ramps that impose moderate to large demands for side friction factor while also permitting high-speed travel must be maintained with particular attention to pavement friction level and water drainage in order to safely accommodate lightly loaded truck combinations.

Case 5 (curbs placed on the outer side of curved ramps pose a peculiar obstacle that may trip and overturn articulated truck combinations)

Every truck driver knows that the rear axles on the trailing elements of an articulated truck combina-

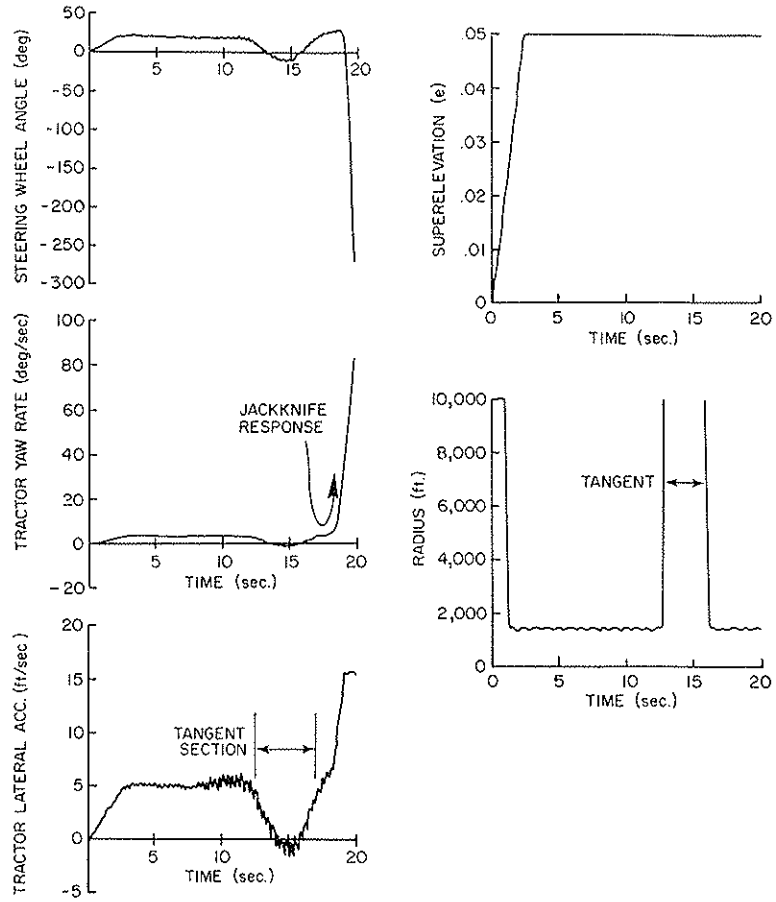


FIGURE 11 Response of tractor-semitrailer traveling at 55 mph without braking through the ramp shown in Figure 10.

tion will track inboard of the path of the tractor during low-speed, tight-radius turning maneuvers. This phenomenon has been called low-speed offtracking and has been recognized as a consideration in highway design for many years. It has been observed in recent years, however, that the trailers in tractor-semitrailer and doubles combinations tend to "fling out" in a turn as the lateral acceleration level increases, such that the rearmost axles may actually subtend paths that are outboard of those traced by tractor axles (30). The magnitude of the outboard offset in wheelpaths can be of the order of 2 to 3 ft in a steady turn (31). The particular safety concern that arises from this behavioral characteristic is that the rearmost axles may strike a curb that is situated, on certain ramps, along the outer side of the curve. Because it is thought that truck drivers are generally unaware of this so-called "high-speed offtracking" phenomenon, the safety problem may be exacerbated by the harmful natural instinct of drivers who may tend to steer close to the outer curb, believing that the trailer axles always tend to go inboard.

As shown in Figure 12, the trailer attitude associated with the outboard offtracking motion is such that the outer trailer tire approaches the curb at a sideslip angle, with the tire pointed away from the curb rather than toward it. Accordingly, the tire tends to resist mounting at the curb face. Although no definitive experiments are known to have been conducted to examine tire force response under such curb contact conditions, it appears certain that large side force levels would be available so that rollover would be a likely outcome.

Shown in Figure 13 is a case in which truck rollover accidents appeared to have involved tripping at an outside curb. The ramp involves two 12-ft lanes that constitute an interchange leg between two urban expressways. The curve radius of 374 ft, together with a superelevation of 0.05 and an original ramp advisory speed of 35 mph, yielded a side friction factor of 0.17. The ramp incorporated a cross-sectional design, as shown in Figure 14, with curbs provided to assist in channeling water drainage. The right curb is a mountable type permitting access by disabled vehicles to a paved right shoulder.

This ramp provides, first, a relatively severe side friction demand together with the curb that is within approximately 20 in. of the lane edge along the outside of the curve. It would appear that truck combinations may have experienced sufficient outboard offtracking of the trailer axles, because of the substantial side friction factor, that the rearmost outer tire struck the mountable curb. Because the sideslipping tire, with its inward orientation, was unable to mount the curb, a lateral force response developed due to the curb contact and thus produced the additional roll moment needed to overturn the truck combination.

The practice of building curbs on the outside of a curved ramp was among the approved design approaches cited in the AASHO blue book (25). Even on loops or direct connection roadways with continuous-curve alignment in one direction, curbs along the outside edge were justified as providing "an effective delineator on the high side of the pavement." In the more recent green book (1), AASHTO policy has apparently changed such that the use of curbs on in-

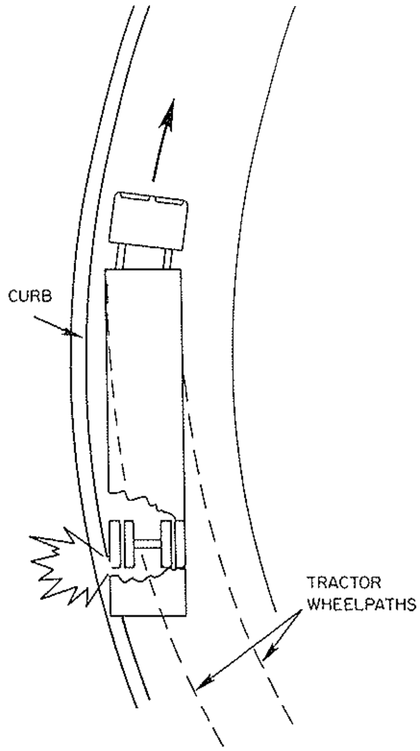


FIGURE 12 Outboard offtracking of semitrailer that leads to contact between trailer tires and an outside curb.

termediate and higher speed ramps is not recommended. Indeed, the green book suggests that curbs be considered only to facilitate particularly difficult drainage situations. It is clear that the use of a curb on the high side of a superelevated curve cannot be rationalized as an aid to drainage.

CONCLUDING REMARKS

The study that led to the findings presented herein examined individual ramps that had been found to have numerous truck loss-of-control accidents. Although, on one hand, a number of these ramps incorporated features that AASHTO policy discourages, it appears that even the current recommendations of AASHTO on geometric design will allow ramps that severely limit the safety margin available to many heavy-truck combinations. Indeed, the most useful aspect of this study, from the viewpoint of the highway design community, may be simply the illustration that truck stability and control levels are low relative to the vehicle control limits that are assumed in geometric design. Although it may be impractical in certain respects to truly design highways so that trucks can be operated as comfortably as automobiles, it does appear rational to suggest that highways be designed so that truckers obeying the posted speeds can be assured of nominally safe travel.

It would also appear beneficial for those maintaining the highway system to examine ramp sites that have frequent truck accidents to determine whether any of the peculiar problems identified here

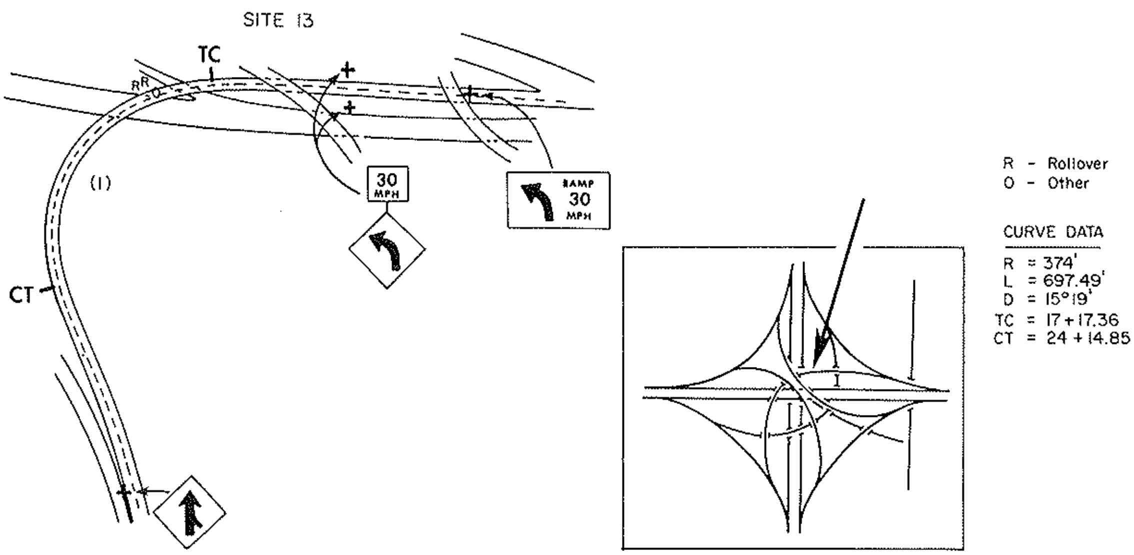


FIGURE 13 Layout of ramp on which curb-contact accidents occurred.

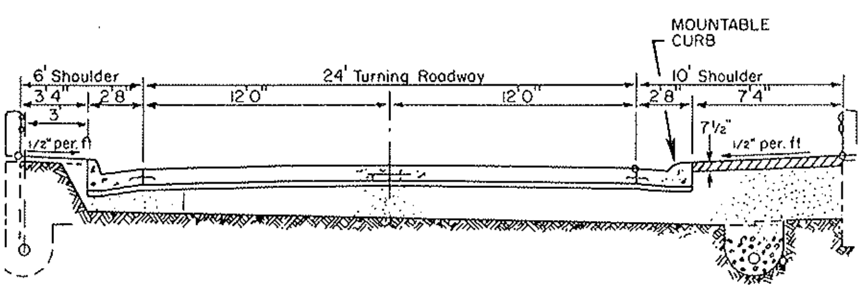


FIGURE 14 Cross section of roadway from ramp site shown in Figure 13.

might apply. Although many of the countermeasures implicit in the discussion here would involve major reconstruction of the ramp, improved speed advisories, resurfacing, and curb removal are also among the actions that can be taken in certain cases.

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