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Improving Truck Safety at Interchanges

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report is part of a four-part series summarizing recent research findings in the area of selected truck geometric features. One of the critical large truck research areas is safety impacts of trucks--including geometric and operational issues, vehicle stability and handling, and accident rates. A number of research studies have been completed in the following areas: truck climbing lanes, grade severity rating systems for trucks, interchange ramp geometry design, and the operation of larger trucks on roads with restrictive geometry. This report summarizes the findings of the research on interchange ramp geometry design. For specific details on the research, the reader should consult the research reports referenced in the summary report.

Sufficient copies of this report are being distributed to provide one copy to each Regional office, Division office, and State highway agency. Direct distribution is being made to the Division offices. Additional copies are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Stanley Byington

Stanley R. Byington
Director, Office of Implementation

NOTICE

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Janet A. Coleman (HRT-20), Contracting Officer's Technical Representative. This summary report was based on the following study: "Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges: FHWA/RD-86/057."

16. Abstract

This report offers highway engineers guidance in designing interchanges so as to reduce the likelihood of truck accidents on highway interchanges. This report summarizes research showing that the interaction between truck dynamics and interchange geometry can contribute to rollovers, jackknifes, and other loss-of-control accidents. The research was conducted by the University of Michigan Transportation Research Institute (UMTRI) and supported by the Federal Highway Administration (FHWA).

Engineers can apply corrective actions to six specific ramp design features that were found to contribute to truck accidents: poor transitions to superelevation, abrupt changes in compound curves, short deceleration lanes preceding tight-radius exits, curbs placed on the outside of ramp curves, lowered friction levels on high speed ramps, and substantial downgrades leading to tight ramp curves.

Countermeasures for these design problems include incorporating a greater safety margin into formulations for side friction factors, reviewing and modifying posted speed limits, improving curve condition and downgrade signs at interchanges, increasing deceleration lane length, overlaying curbs with wedges of pavement or eliminating curbs altogether, resurfacing ramps with high-friction overlays, and redesigning sites where accidents are common.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

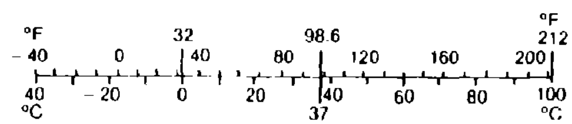
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE. Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER I
INTRODUCTION

Interchanges on freeways and expressways can be particularly hazardous for large trucks. Research shows that truck accidents on limited access facilities cluster at interchanges. As much as 20 percent of truck accidents occur at interchanges, and more truck accidents occur at off-ramps than on-ramps. Interchanges with inadequate design elements such as tight radius ramps, multiple curve ramps, and short deceleration and acceleration lanes can test and even exceed the limits of truck and driver performance capabilities.

Truck accidents on interchanges are primarily single-vehicle accidents involving rollovers and jackknifes that result from the interaction of truck performance characteristics with ramp geometry. These loss-of-control accidents are frequently associated with loop-type ramps.

This report is intended to help design engineers improve highway safety.[1] It is based on a study supported by the Federal Highway Administration (FHWA) and conducted by the University of Michigan Transportation Research Institute (UMTRI). Researchers at UMTRI identified six major problems in ramp design and recommended some specific countermeasures:

- **Poor transition to superelevation** at interchanges creates high levels of side friction demand that increase the threat of rollover. One countermeasure is to incorporate a greater safety margin into formulations for side friction factors. Reviewing the adequacy of posted speed limits and advisory speeds and improving signs at interchanges are also realistic solutions.

- **Abrupt changes in compound curves**, especially where successive portions bring sudden changes of radii, is another problem. This geometry places excessive demands on truck drivers while pushing the side friction factor to the point of rollover. The most effective solution may be to add more adequate signs to alert drivers to changing curve conditions.

- **Short deceleration lanes preceding a tight-radius exit** have also created problems. Short lanes make it less likely that truck drivers will decelerate enough to negotiate short-radius curves, thereby increasing the potential for rollovers. Excessive braking, on the other hand, increases the possibility of jackknife. Increasing deceleration lane length may accommodate truck drivers and reduce the hazard.

- **Curbs placed on the outside of a ramp curve** may be tripping mechanisms in rollover accidents. Curb contact results from trucks' tendency toward high-speed offtracking. Engineers can plot the path radii and eliminate the problem by removing the curb.

- **Substantial downgrade leading to a tight ramp curve** can cause trucks to rollover. Trucks can speed up substantially on downgrades simply by coasting. This increase in speed, involuntary and often sudden, leads to a corresponding increase in lateral acceleration that contributes to accidents. Engineers might simply reevaluate and recalculate dynamic parameters to aid in redesign at sites where accidents are common. Placement of special signs at these sites also may be recommended.

- **Friction levels on a high speed ramp** may be dangerously lowered in certain conditions. Hydroplaning may occur in wet weather at sites with poor pavement texture conditions. One proven countermeasure is to resurface ramps with high-friction overlays.

In general, tight-radius curves, short acceleration and deceleration lanes, and unrealistic posted advisory speeds on loop-type connections create problems for heavy trucks. Particularly troublesome ramps may warrant immediate corrective action and driver warnings. Other ramps are candidates for redesign. All ramp users may benefit from better signs and more realistic advisory speeds.

CHAPTER II
STUDY DESIGN AND FOCUS

UMTRI researchers selected 15 ramps at 11 interchanges in 5 States for study. To select ramps for the study, they individually evaluated over 800 accident reports, examining the relationship between ramp geometry and vehicle dynamics. To determine specific problems and causes of accidents, the researchers used a computer model that simulated truck performance on the actual ramps.

The computer simulation model developed by UMTRI was used to represent the dynamic response of tractor-semitrailers along the ramps with a history of accidents. The model operates in a path-following mode through the use of a driver steering model. The model "looks ahead" and steers the vehicle along the specified curve much as an actual driver does.

Several response characteristics and mechanisms relate to loss-of-control accidents involving tractor-semitrailers. They figure prominently in the problems identified with the ramps in the study and throughout this report.

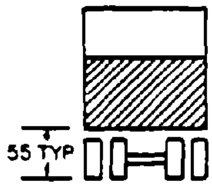
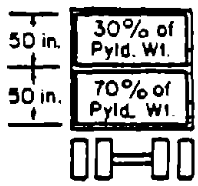
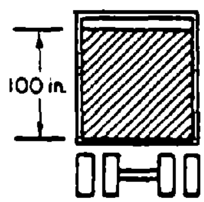
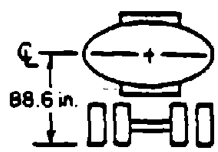
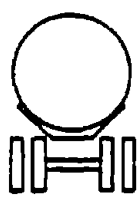
Low roll stability of the vehicle is the key response characteristic leading to loss of control. Peak values of lateral acceleration on the vehicle define a threshold beyond which the truck will rollover in a steady turn. The threshold varies depending on truck configuration, loading, and speed, as well as ramp geometry. The study showed at some sites vehicles passed that rollover threshold when drivers just slightly exceeded the posted speeds.

Rollovers generally result from lateral acceleration forces acting on a vehicle in a steady turn. This is a particular threat to drivers of heavily loaded trucks, for even in a steady turn, a severe steering maneuver or speeding will cause rollover. Commercial loading practice places the center of gravity high in absolute terms and also high relative to the width of the tire track; the ratio of the two dimensions is a measure of the basic roll stability. Figure 1 shows rollover threshold values in terms of peak lateral acceleration for the five different tractor-semitrailer configurations studied. By contrast, cars do not roll over until they experience 1.2 g's. This lack of stability causes heavy trucks to reach rollover in the vicinity 0.3 g's (figure 1) while cars do not roll over until they experience nearly 1.2 g's. Often in a steady turn, a severe steering maneuver or speeding will cause heavy trucks to roll over.

Loss of control accidents also include **jackknifes**. These accidents generally occur in conditions where tire/pavement friction is reduced, frequently with unloaded or lightly loaded trailers. Typically, jackknifes result from a simple traction deficiency at the drive wheels or light braking, which can cause the drive wheels to lock up. Differing tire/road friction levels on the steering and drive axles can cause a truck to jackknife simply from cornering on a slippery curve.

"High-speed offtracking" is another factor leading to loss of control on curves. At low speeds, truck trailers tend to track inboard, but at high speeds, under the influence of lateral acceleration, the rear trailer wheels of articulated truck combinations drift outboard dramatically. This dynamic process is disorienting. Confused by the opposing responses at different speeds, drivers can lose control. Where curbs line the outside of a curve, moreover, high-speed offtracking can cause tires to hit the curb, producing rollover.

Truck braking performance varies widely depending on load. A truck's rear-axle brakes can literally experience a 500 percent load change with normal but changing configurations. Without a load, vehicles may overbrake in the rear. With a light load at the rear axle, overbraking can be compounded by premature lockup leading to loss of control and jackknife. At the other

CASE	CONFIGURATION		WEIGHT (lbs) GVW	PAYLOAD CG HEIGHT (in)	ROLLOVER THRESHOLD (g's)
A.		Full Gross, Medium-Density Freight (34 lb/ft³)	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/ft³)	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

1 lb. = .454 kg
1 in. = .0254 m
1 lb/ft³ = 16.01 kg/m³

Figure 1. Rollover threshold values for various example vehicles.[1]

extreme, limited braking can result in insufficient deceleration, also leading to loss of control.

Drivers' difficulty in controlling speed is another characteristic of loss of control accidents. Drivers must make conscious decisions to keep speed in check on downgrades, especially when negotiating a ramp. Control of loaded truck combinations requires the development of retardation forces. Use of engine drag and service brakes, along with supplemental retarder devices on some trucks, demands drivers' complete attention and good judgment.

Limited acceleration capability of trucks, especially on ramps, also strongly influences driver strategy. Drivers' attempts to reach highway speed in preparation for a merge can result in overdriving. Drivers sometimes increase throttle midway through a ramp or even reduce necessary retardation braking on a ramp downgrade, risking loss of control. Under these conditions, an unexpectedly sharp curve can produce jackknife or rollover.

While drivers can control some of these variables, engineers should also consider factors that affect trucks--geometric features such as curves and grades, lateral acceleration forces, and weather. Designers should be mindful that criteria for ramp design that facilitate automobile driver comfort and control sometimes do not accommodate drivers of heavy vehicles. Recognition of this fact is important to responsible design and safety.

CHAPTER III
PROBLEMS AND SOLUTIONS

The UMTRI study identified six ramp design features that contributed to the accidents analyzed. Figure 2 illustrates each of these problem features.

1. Poor transition to superelevation.
2. Abrupt changes in compound curves.
3. Short deceleration lane preceding tight radius exits.
4. Curbs placed on the outside of ramp curves.
5. Substantial downgrades leading to tight ramp curves.
6. Reduced friction levels on high speed ramps.

Curved ramps are prominent geometric features of interchanges and can cause problems for heavy trucks. The basic relationship of

$$R = \frac{V^2}{15(e+f)} \qquad (1)$$

is used to define the minimum safe radius, R, for a given design speed, V, the maximum allowable rate of superelevation, e, and the maximum allowable side friction factor, f. Both simple and spiral curves are used in curved ramp design. Figure 3 shows the terminology used to describe both simple and spiral curves and their transitions and employed in the discussion of problems that follows.

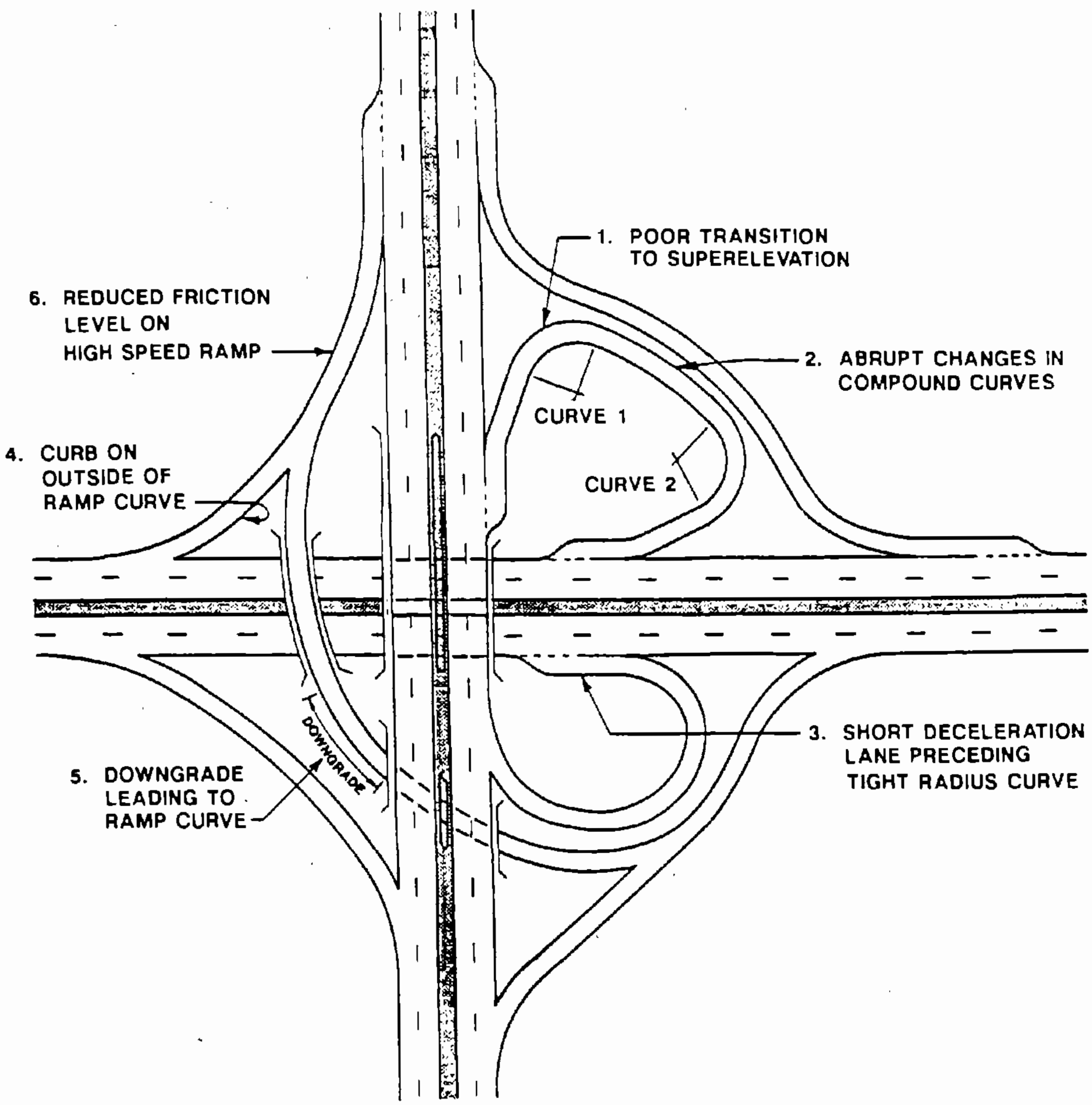
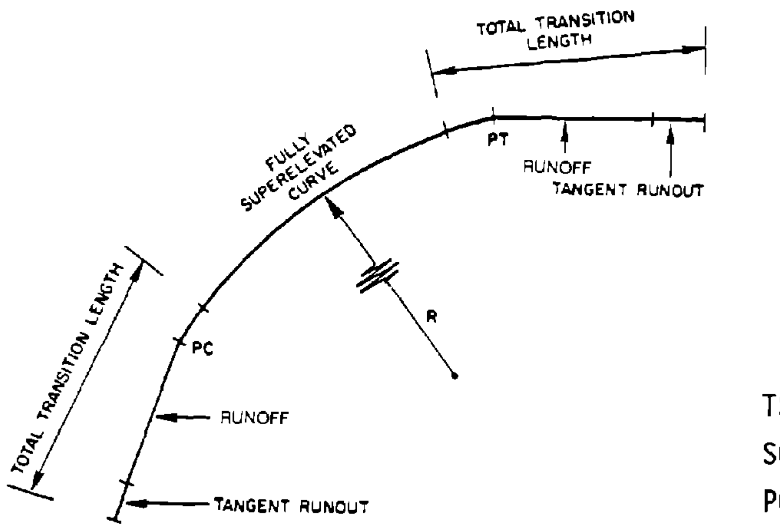
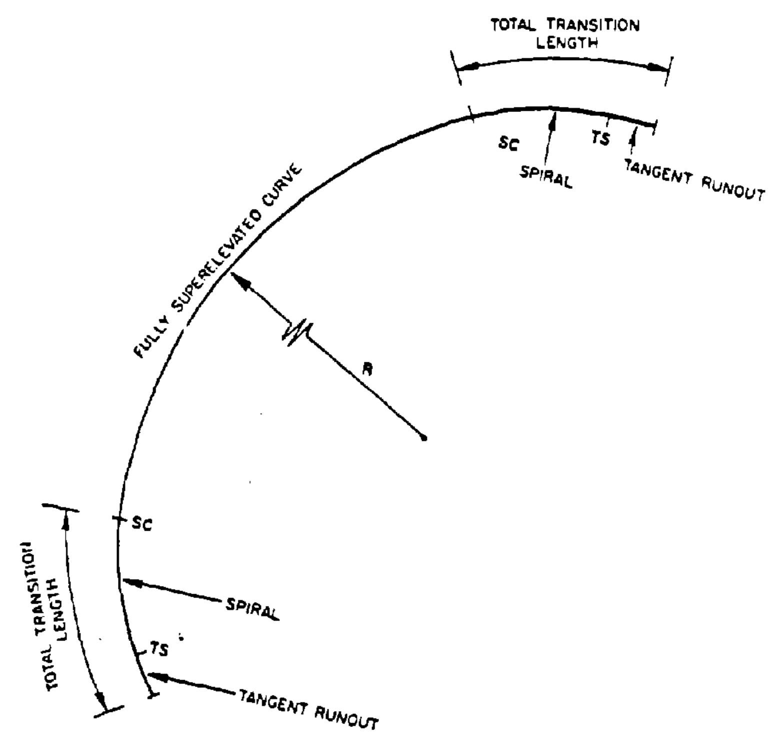


Figure 2. Composite illustration of ramp geometric features leading to truck accidents.



a) Straight Curve Transition

TS = Tangent to Spiral
SC = Spiral to Curve
PC = Point of Curve
PT = Point of Tangent
ST = Spiral to Tangent
R = Radius



b) Spiral Curve Transition

Figure 3. Terminology used in describing a straight and spiral section connecting transitions.[1]

Poor Transition to Superelevation

Design standards call for attaining a portion of the needed superelevation on a transition section. For simple curves, one-half to two-thirds of the superelevation should be developed prior to the PC. If a spiral transition is used, full superelevation is implemented over the length of the spiral.

Poor transition to superelevation contributed to accidents at two sites in particular where both rollovers and jackknifes occurred. Figure 4 depicts one of the sites that incorporated a spiral transition to the curve. In this situation, the full superelevation level of 0.08 was developed 77 ft (23 m) ahead of the point of curvature, continuing for another 179 ft (54.6 m) along the 222-ft (67.7 m) curve.

The simulation results confirmed by the incidence of accidents indicate that trucks having low levels of rollover threshold have little or no margin of safety on curves constructed to existing design criteria for side friction factor. The corrective action is to maintain side friction factors at low values, both through better transitioning and reducing maximum friction factor values and along steady curves. New constraints can be formulated to add a safety margin to lateral acceleration peaks. The UMTRI researchers suggest the following formula for establishing maximum side friction factor (f_{max}):

$$f_{max} = ((RT-SM)/\ 1.15) - (e-e_{at\ PC}) \qquad (2)$$

As formulated, the maximum f value is a function of the selected rollover threshold (RT) value, the margin of safety (SM) and the superelevation attained at the point of curvature (PC). The expression includes the factor (1.15) to account for steering fluctuations that have been measured in tests of normal driving of a tractor-semitrailer through expressway ramps.

Table 1 shows the derived maximum side friction factors for two values of rollover threshold and for three transition designs. A safety margin of 0.10 g's has been used to cover the contingency of a truck running at 40 mi/h (64 km/h), for example, on a ramp that is designed for 30 mi/h (48 km/h). Since the limiting condition for trucks is rollover, as opposed to driver comfort for passenger cars, the suggested limits on maximum f would apply for any design speed.

Ramp design using the suggested lower maximum values of side friction factor results in considerably less sharp curves if a low rollover threshold value is assumed. Because the cost implications can be substantial, designers should establish the volumes and types of trucks that might use the facility before using the lower f values.

Table 1. Suggested maximum side friction factors to accommodate trucks.

Rollover Threshold, RT	Superelevation, e	Maximum f for: 50% @ PC	66.7% @ PC	Spiral Transition
.28	.10	.11	.13	.16
	.08	.12	.13	.16
	.06	.13	.14	.16
	.04	.14	.15	.16
.24	.10	.07	.09	.12
	.08	.08	.09	.12
	.06	.09	.10	.12
	.04	.10	.11	.12

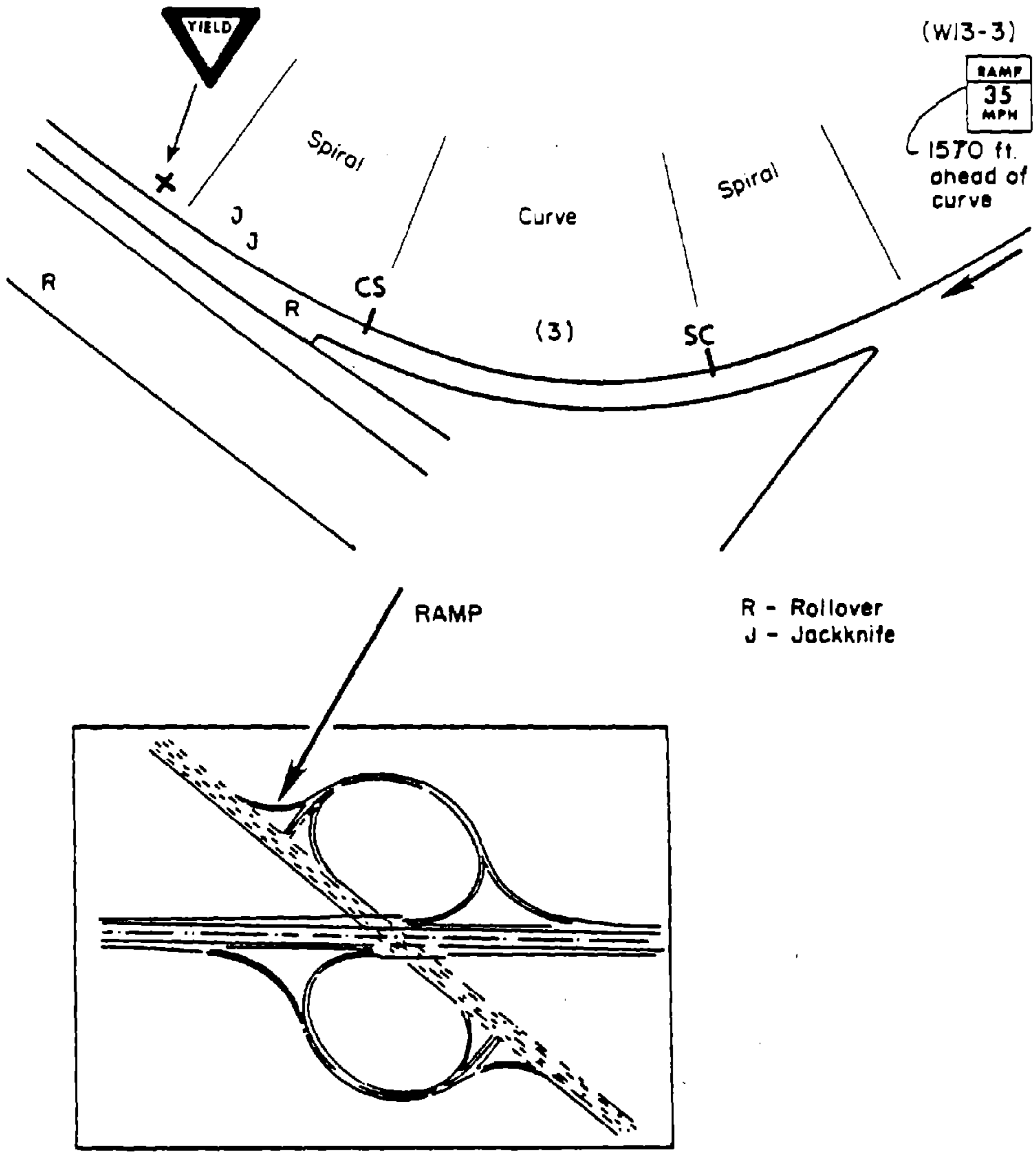


Figure 4. Illustration of a site with a transition problem.[1]

An alternative measure, especially for existing severely curved ramps, would be to rely on the standard warning signs, i.e., advisory speed, turn, large arrow, and chevron alignment signs, and even special warning signs. Figures 5, 6, and 7 illustrate signs being tested in California and in the Washington, DC, metropolitan area.

Abrupt Changes in Compound Curves

Abrupt changes in compound curves were serious problems at three ramp sites, two of which had a relatively flat radius curve between two tight-radius curves. Although this design is discouraged by current design standards, the more critical design flaw appears to be the misleading nature of the overall ramp layout. These ramps are difficult for drivers to assess.

The flatter curve section between two sharper curves invites misjudgments. After passing through the first curve marked with a low advisory speed, drivers may speed up to prepare for merging, unaware of a second curve ahead that is at least as demanding.

Simulation results for multiple curves at selected ramps indicate that abrupt jumps in lateral acceleration occur when heavy vehicles enter the curve. At one ramp, the nominal values for side friction factor are also the maximum values. At the same time, the very short lengths of acceleration lane available for bringing a fully loaded rig up to speed may encourage drivers to attain as much speed as possible within the ramp before merging. The geometric constraints created by multiple curves coupled with drivers' ignorance about the remaining curves can produce loss of control.

Figure 8 shows the compound curve simulated in the study. A driver satisfying the speed requirements on curve 1 might misjudge the continuing need for low speed through curves 2 and 3. Upon entering curve 4 at a relatively high speed, the driver could easily exceed the vehicle's controllability limits.

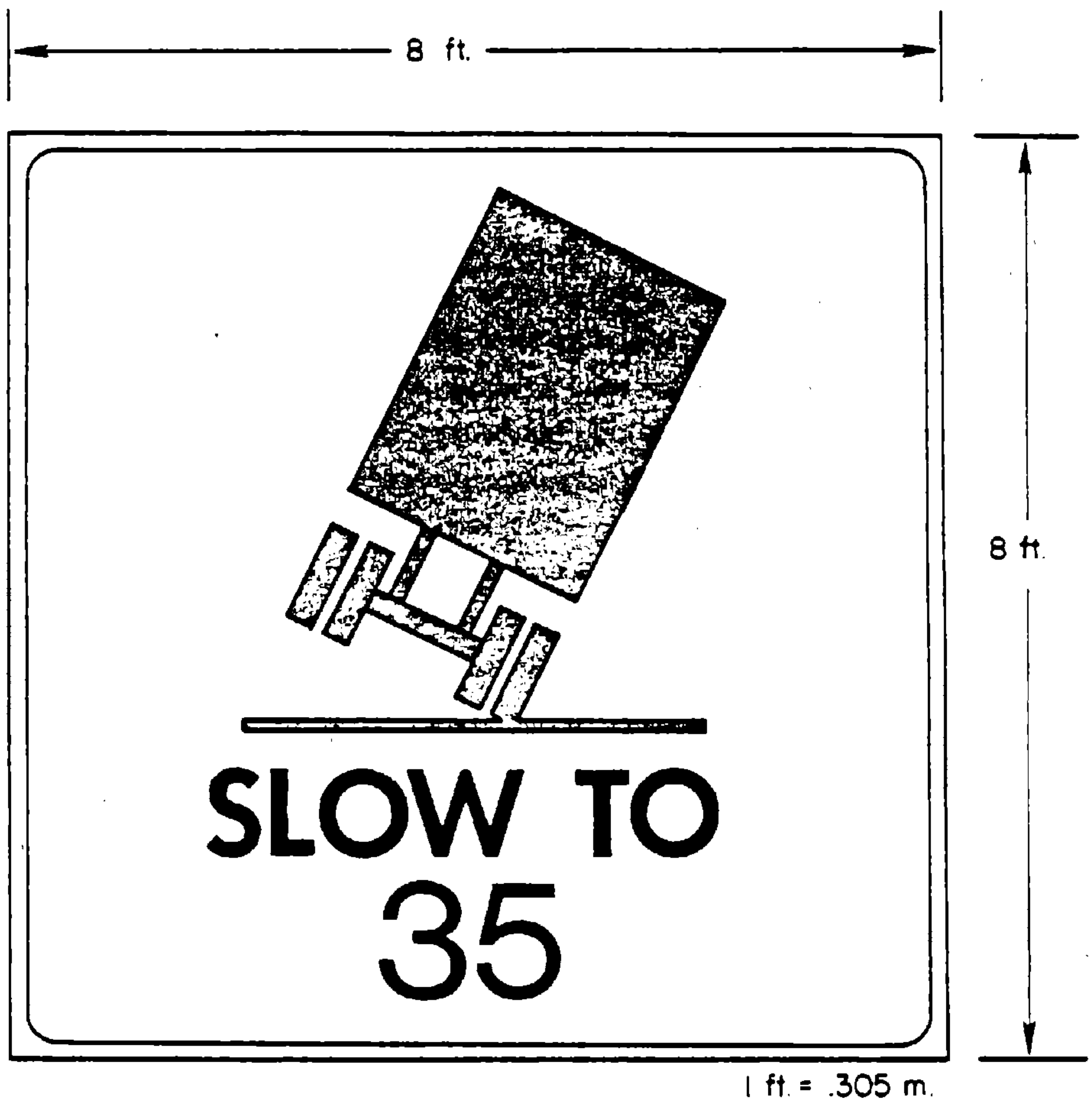


Figure 5. Warning sign used in California at ramps having history of truck rollovers.[1]

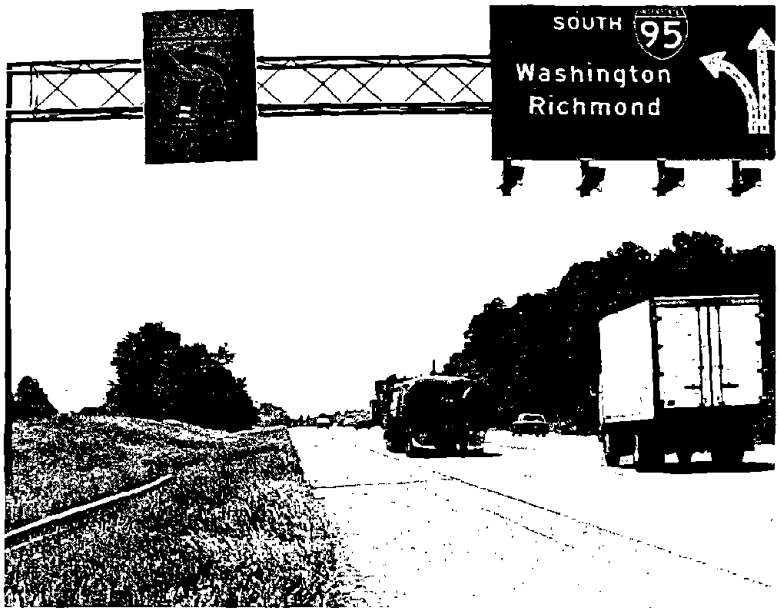


Figure 6. Sign being tested on the Washington, DC, beltway.

Figure 7. Sign being tested on the interstate in the Washington, DC, metropolitan area.

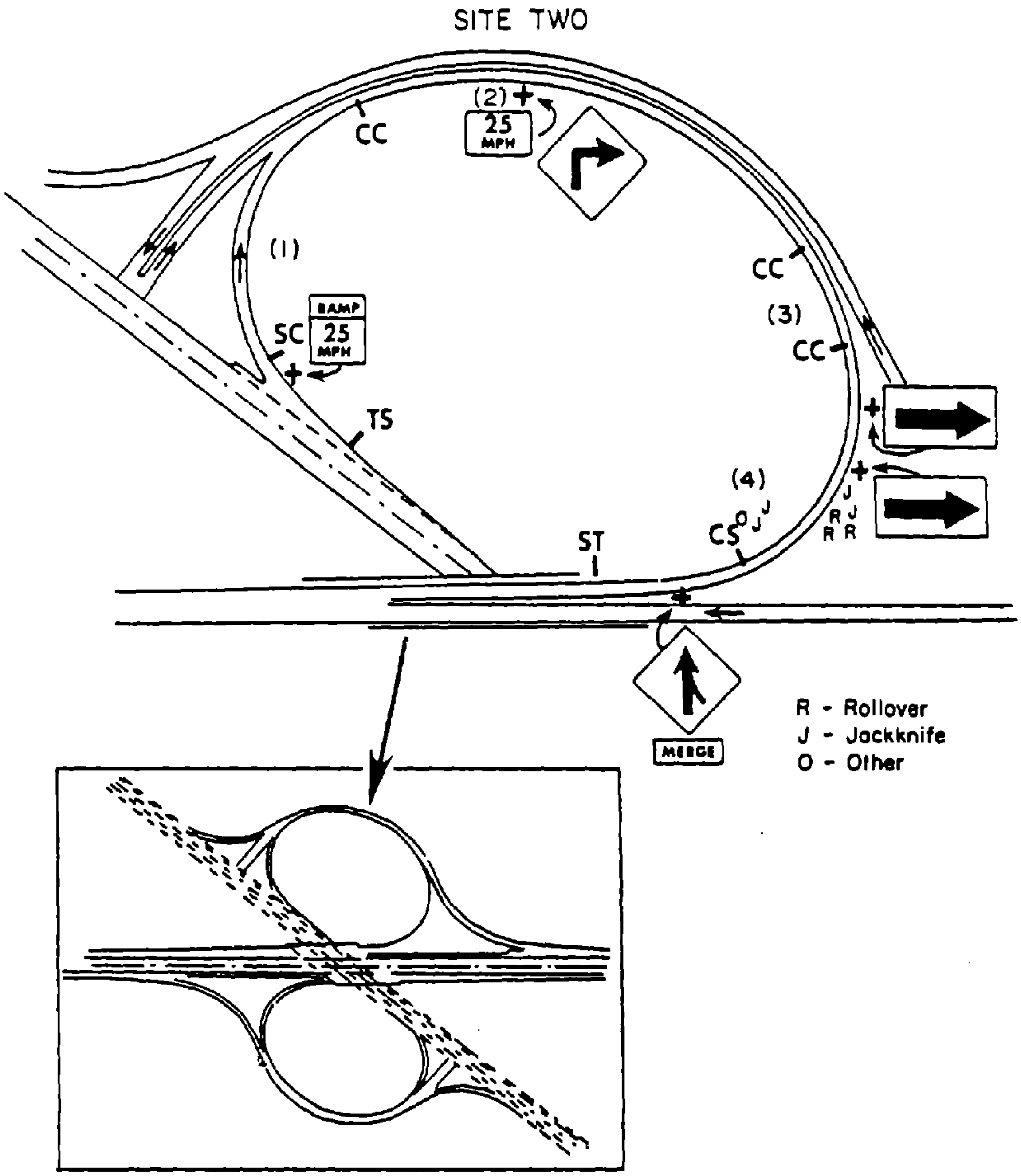


Figure 8. Site layout showing abrupt changes in a compound curve and side friction factor.[1]

It is helpful for engineers to determine the essential data for each of the curves at an interchange, including radius length and nominal side friction factor. Comparing successive curves in the series may reveal abrupt jumps in lateral acceleration between curves, as was the case for the site shown in figure 8.

A signing countermeasure for this problem is the use of the turn sign with appropriate advisory speed plate; the sign should be placed along the flat section in order to provide drivers with an updated warning that a sharp curve still remains ahead. The final curve can also be highlighted with the large arrow and/or chevron alignment signs. Whenever possible, engineers should also provide longer acceleration lengths for bringing fully loaded rigs up to speed. Drivers must be encouraged to achieve as much speed as possible within the ramp, rather than on the curve, before merging.

Short Deceleration Lane Preceding a Tight Radius Exit

A short deceleration lane preceding a tight radius exit created problems at 4 of the 15 ramp sites studied, only 1 of which had a deceleration lane shorter than current design guidelines recommend. Even recommended deceleration lanes lengths strained the braking capacity of heavy-duty truck combinations. In these circumstances, excessive braking or excessive speed led to accidents in both wet and dry conditions.

Although design guidelines call for care in design of deceleration lanes, especially for comfort, they underestimate current realities of truck speeds and braking capabilities. Average truck speeds on U.S. highways today at least equal those of cars. At equal speeds, however, trucks require longer distances than cars to decelerate to ramp speed. Yet, in many cases, truck drivers must decelerate to safe ramp speeds very quickly upon departure from the through roadway to avoid rollover. To achieve a speed low enough to avoid rollover, truck drivers may overbrake, causing jackknife accidents instead.

Measuring deceleration lanes length realistically is critical. As figure 9 illustrates, when a 375-ft (114 m) tapered deceleration lane leads directly to a 250-ft (76.2-m) curve, current design guidelines calculate the deceleration lane length inappropriately. Drivers are actually assumed to begin deceleration while traveling in the through lane and are allowed no distance for delay in applying brakes. In reality, only 100 ft (30.5 m) of roadway should be "counted" for deceleration, with the measurement beginning when the taper has progressed to a point where a full lane width--i.e., 12 ft--has been provided. Were the deceleration lane length measured accurately, the deceleration challenge facing the driver might be more apparent to the designer.

Simulation results also suggest that heavy-duty truck combinations on certain ramps cannot meet deceleration requirements imposed by current design standards. Designers should ensure that deceleration lane lengths on these ramps do not place excessive braking demands on drivers. Engineers should design ramps with the taper of the deceleration lanes beginning sooner to reduce braking demands on trucks to a more moderate level.

Table 2 provides minimum deceleration lengths for exit ramps that would be appropriate for deceleration requirements of heavy trucks. The values assume that trucks coast in gear for 3 s at 0.03 g's and then brake at 0.15 g's. The minimum lengths are 15 to 55 percent longer (depending upon highway design speed) than those required for passenger vehicles. As a result, these lengths are recommended for deceleration lanes where truck traffic volume is heavy and drivers encounter a tight curve early in the ramp. Where these values can not be used cost-effectively, or an excessively short deceleration lane already exists, then advance placement of appropriate warning signs, e.g., speed advisory and curve warnings, becomes critical.

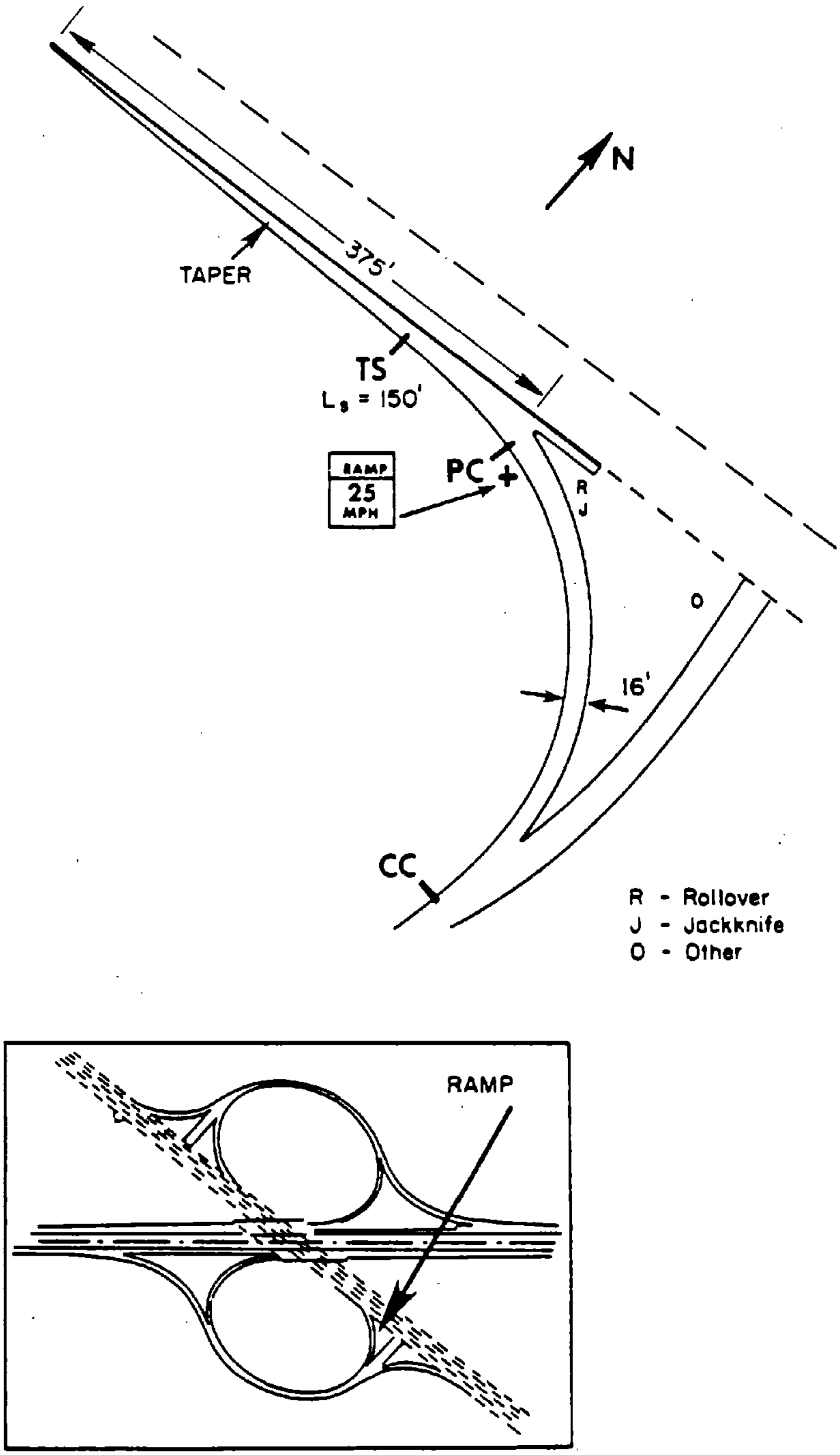


Figure 9. Illustration of a site with a short deceleration lane preceding a tight radius exit.[1]

Table 2. Minimum deceleration lengths for exit terminals with heavy truck volume and tight curves.

Highway Design Speed, V (mph)	Average Running Speed, Va (mph)	Deceleration Length L(ft) For Design Speed of Exit Curve, V′ (mph)								
		Stop Condition	15	20	25	30	35	40	45	50
		For Average Running Speed on Exit Curve, V′a (mph)								
		0	14	18	22	26	30	36	40	44
30	28	271	227	198	162					
40	36	413	370	341	305	262	212			
50	44	585	541	512	477	434	384	295	227	
60	52	785	741	712	677	634	584	495	427	352
65	55	867	823	795	759	716	666	577	509	434
70	58	954	910	881	845	802	752	664	596	521

V = Design of highway
Va = Average running speed on highway
V′ = Design speed of exit curve
V′a = Average running speed on exit curve

Curbs Placed on the Outside of a Ramp Curve

Curbs placed on the outside of a ramp curve, illustrated in figure 10, are generally not recommended in design practice. These curbs are particularly dangerous to trucks because trailers tend to "fling out" in a turn. The offtracking response of trailers on high speed curves can be hazardous if the rear wheels strike a curb. Lateral forces producing an additional roll moment may also contribute to rollover. Accident data from three sites implicate outer curbs as tripping mechanisms. At one site, elimination of the outer curb greatly reduced the incidence of truck rollovers.

Some drivers' ignorance of "high-speed offtracking" may be a factor in curb-related incidents. Drivers' natural tendency to steer close to the outer curb further compounds this potential problem.

Since the potential for outboard offtracking is related to the curve radius, an algorithmic solution for the total offtracking value is possible.[2] Engineers then can set the path radius to accommodate offtracking.

Elimination of the outer curb on ramps has also proven successful in reducing the incidence of truck rollovers. One method suitable for low height, mountable curbs is installing a wedged overlay of pavement, thus providing one continuous surface. A latex concrete overlay also adds superelevation thereby reducing the side friction factor as well. (Note: Curbs on the high side of superelevated curves do not generally enhance drainage.)

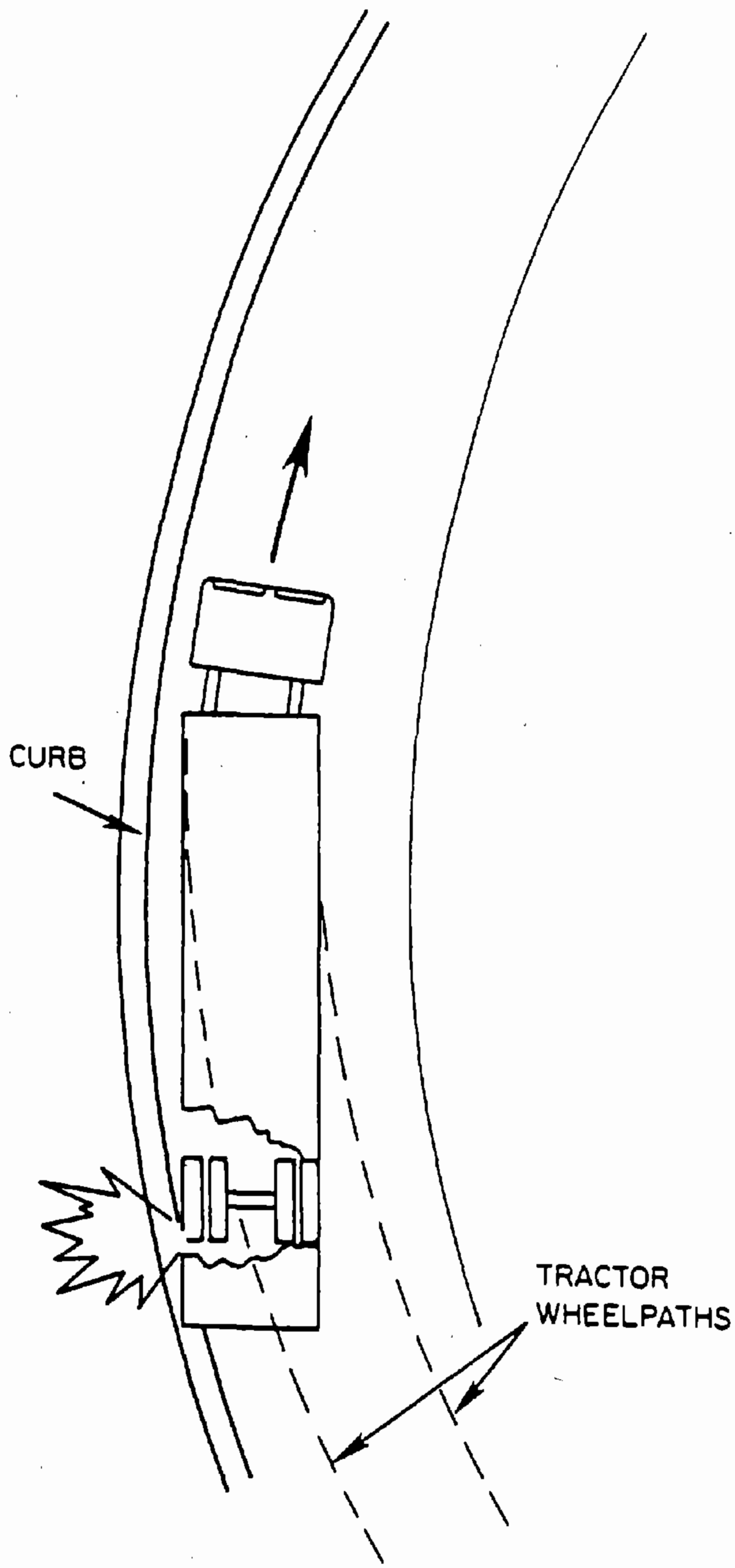


Figure 10. Site layout showing curb on outside of ramp exit.[1]

Substantial Downgrade Leading to a Tight Ramp Curve

At two ramp sites, substantial downgrades lead to tight ramp curves, making it critical for drivers to observe advisory speeds; figure 11 shows one example. Rollovers near the very end of the curve suggest that vehicles significantly increase speed along the preceding downgrade. The potential for heavy trucks to accelerate on downgrades explains rollovers documented in the study.

Simulation results indicate that excessive speed developed by the vehicle on the downgrade leads to a level of lateral acceleration producing rollover. On one ramp, a relatively long downgrade ramp coupled with a tight curve can produce rollovers simply due to the coasting deceleration. While inattentive drivers contribute to accidents, the critical interaction of several geometric factors is decisive: grade, grade length, side friction factor, and speed differential.

The potential for speed increases on a site can be calculated by determining the acceleration from an initial speed v_o to a final speed v_f due to coasting down the grade. Current guidelines allow for downgrade as high as 8 percent, although designers are cautioned to limit grades to 3 to 4 percent where truck and bus traffic is high. The UMTRI study suggests that a more conservative approach may be prudent. Design engineers should be aware of this question and avoid setting a grade percentage that will introduce a speed-increase problem. Standard curve warning and speed advisory signs may also be appropriate, but the combination of a steep downgrade and a curved ramp may require special signing for trucks.

Reduced Friction Levels on a High Speed Ramp

Reduced friction levels on a high speed ramp (figure 12) caused truck accidents on two ramps in wet weather. Resurfacing the ramp with a high friction overlay at one site eliminated the problem, a hydroplaning-like loss in tire/pavement friction resulting in loss of control. Interestingly,

SITE EIGHT

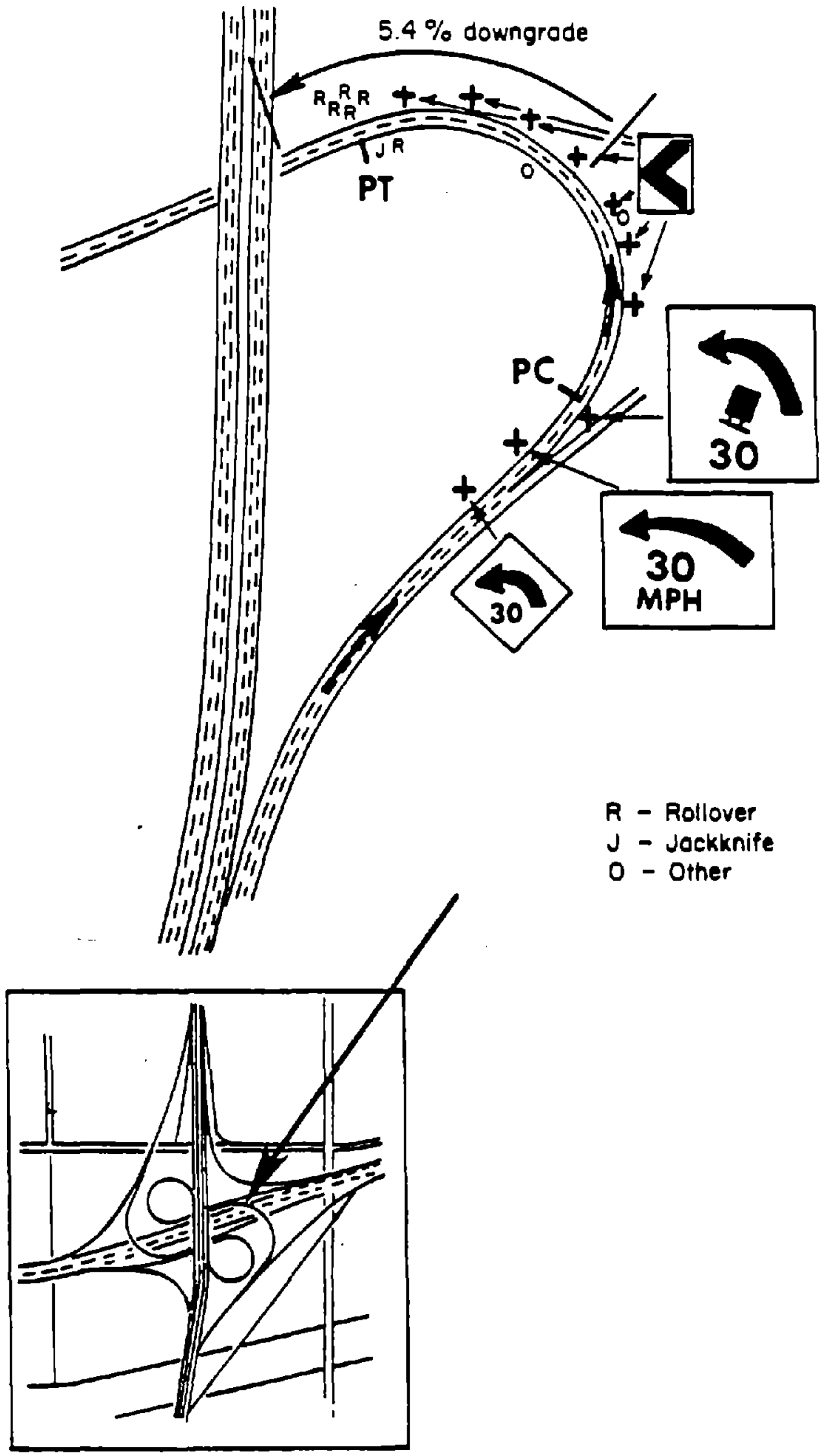


Figure 11. Site illustration showing a substantial downgrade leading to a tight ramp curve.[1]

SITE SIX

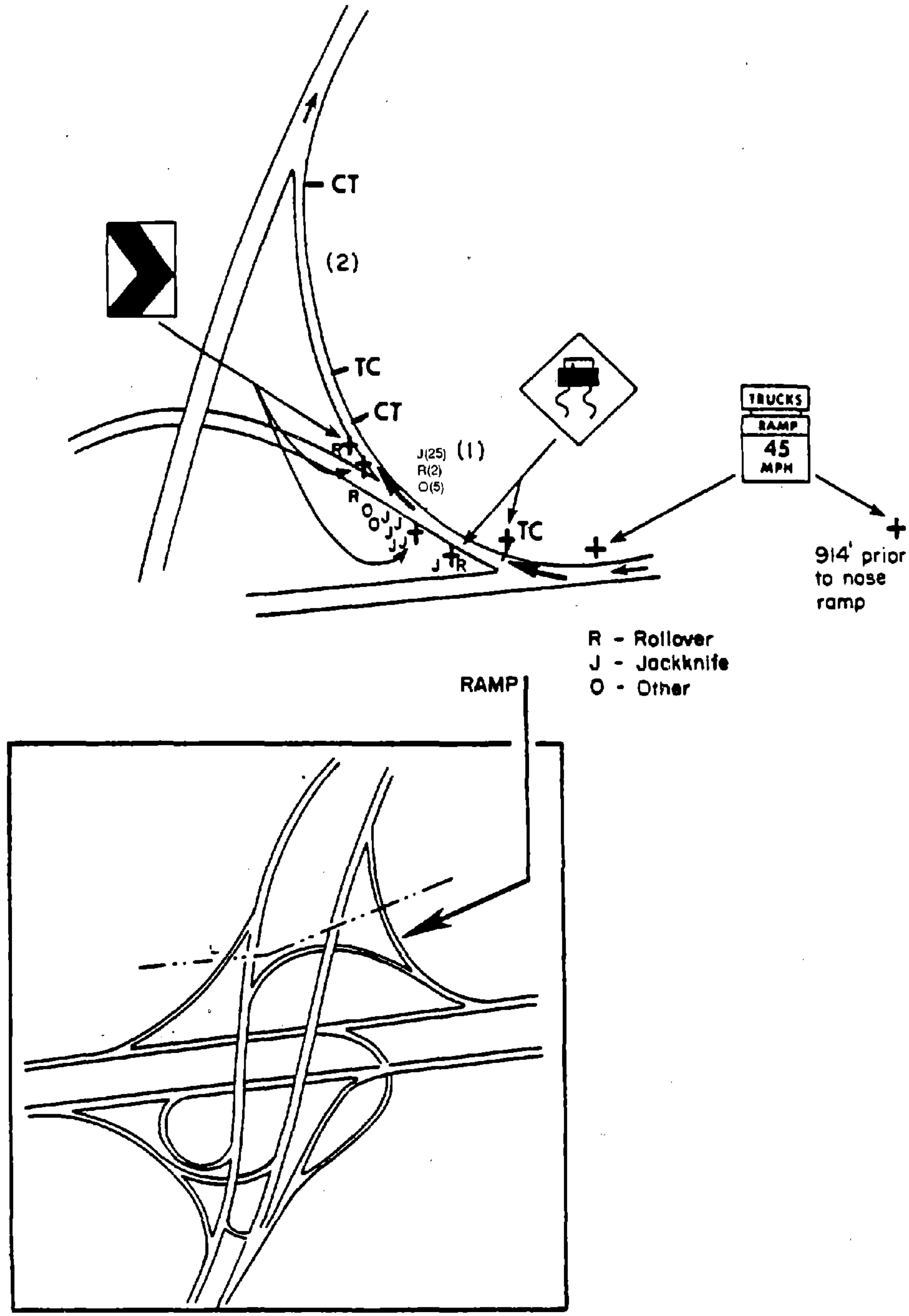


Figure 12. Illustration of a site where reduced friction on a high speed ramp is a problem.[1]

jackknifed vehicles tended to land inside of the curve while vehicles rolling over tended to land on the outside.

The potential for lightly loaded truck tires to hydroplane occurs because the footprint with which a truck tire contacts the pavement is usually incapable of expelling water. Trucks traveling at high speeds on large-radius curves--like those used in many "high design" interchanges between two freeways--are particularly susceptible to loss of control on wet pavements. Simulation showed that jackknifing occurs when tire/pavement friction levels at lightly loaded rear tires are substantially lower than those at the front tires.

Maintenance of ramp surfaces and measures to ensure adequate water drainage can accommodate lightly loaded truck combinations even when moderate to large demands for side friction occur.

Many loss-of-control incidents occur on curves when wet weather reduces pavement friction, but this situation does not necessarily implicate geometric design. Lightly loaded trucks can be expected to have control problems where pavement friction quality is deficient. The location of potential trouble spots requires a more focused surveillance by the highway engineering community. Use of an independent measure of pavement texture depth to estimate friction level on a ramp may be advisable. Adopting a method for characterizing ramp skid numbers, the subject of a 1983 FHWA study (FHWA/RD-82/150), also may promote highway safety.

CHAPTER IV
SUMMARY

The study results demonstrate that elements of geometric ramp design contribute to truck accidents. An understanding of these problems strongly suggests that appropriate design criteria can produce effective countermeasures. The highway engineering community can expect revised design practices to dramatically reduce truck hazards on ramps.

In general, tight radius curves on ramps and short acceleration and deceleration lanes cause problems with heavy trucks. Driver failure to heed posted advisory speeds is a contributing factor, but so are excessively high advisory speeds, too few signs, and poor placement of signs. The following paragraphs focus on specific study conclusions with practical solutions to potential problems.

Truck accidents on interchange ramps generally involve loss of control leading to rollover or jackknife. The cause is usually excessive lateral force acting on a vehicle. Developing appropriate superelevation levels along a curve can limit lateral forces that threaten driver control. Designers should specify spiral or straight curve transitions so as to reduce side friction demand along the entire ramp length. Recognizing differences in margins of safety between cars and trucks is also fundamental to safety.

Jackknife accidents occur in wet weather at sites with inadequate pavement friction levels. Loss of control may result from either a deficiency of lateral traction on curves due to near-hydroplaning or from light braking, which can cause lockup. Trucks may be particularly vulnerable on high speed ramps. Resurfacing ramps can increase tire pavement friction to beneficial levels. Water drainage can be improved. Using an independent measure of pavement texture to estimate friction levels may also be advisable.

Rollover accidents occur at sites with high levels of side friction demand. Simulation results confirm this perception. To limit lateral forces on the vehicle, highway engineers should ensure that superelevation is largely developed by the point of curvature. Outside curbs should be eliminated if implicated as tripping mechanisms in accidents. Other contributing conditions to be avoided are placement of a demanding curve at the bottom of a substantial downgrade, a curve early in a ramp preceded by a short deceleration lane, and a curve placed late in a compound curve creating a sharp-flat-sharp sequence of curve radii.

Current policy for geometric design of curves provides virtually no margin of safety against rollover for certain trucks. Heavy trucks can reach rollover in the vicinity of 0.3 g's, a very low threshold. Engineers can add a safety margin to calculated lateral acceleration peaks to produce designs that allow for centripetal forces and steering fluctuations.

Design guidelines on length of deceleration lanes treat trucks less realistically than cars. Even recommended lengths of deceleration lanes strain the braking capacity of heavy duty truck combinations. As a result, drivers' excessive speeding or excessive braking have led to accidents in both wet and dry conditions. Drivers are forced to speed for a merge ahead, yet must brake to avoid rollover, creating a challenge. To help drivers meet this challenge, engineers should be encouraged to design ramps with the taper beginning sooner.

Acceleration lanes that are too short to allow truck drivers to reach merge speed prompt drivers to speed on preceding ramps. Bringing a fully loaded rig up to a smooth merge speed is demanding on drivers and vehicles. Highway engineers should provide longer lanes to allow drivers to achieve as much speed as possible within the ramp, rather than on the curve, before merging.

Allowing ramp downgrades as high as 8 percent may be ill-advised at certain sites. Heavy trucks can naturally develop excessive speed leading to a lateral acceleration level producing rollover. Sites with sharp curves toward the bottom of grades create a critical demand for the advisory speed.

While inattentive drivers contribute to accidents, the critical sum of several geometric factors--grade, grade length, side friction factor, and speed differential--is decisive. In general, design engineers should avoid grades higher than 4 percent, the point at which speed increase becomes a problem.

Curve warning signs are improperly selected or placed on some ramps. Inadequate signs compound problems created by ramp geometry and limited truck capability. Engineers must examine the effectiveness of signs at individual sites. Imaginatively configured and easily recognizable signs can reduce accidents, as proven on California roads.

* * *

Accidents generally occur only when driver, vehicle, and roadway factors interact. That combination is difficult to predict. However, certain types of accidents involving heavy trucks at interchanges are related to ramp design features. Accident analysis and computer simulation modeling confirm this conclusion.

Engineers can apply countermeasures or corrective actions to certain problem features. They can exercise caution and good judgment in ramp design, allowing an adequate margin of safety. They need to be alert to shortcomings in design guidelines, where the realities of a modern transportation system may have outpaced traditional policies. They can evaluate ramp design early to spot potential trouble areas. Finally, they should consider that drivers must maintain control while operating under traffic pressures as well as dynamic constraints on their vehicles.

Highway safety is the paramount concern of the entire transportation community. Ramp geometry can play an important role in achieving this goal. Design practices that may compromise the safety of trucks on ramps deserve scrutiny. A concerted effort by all involved, from engineers to policymakers, can eliminate hazards and save lives.

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