Existing Design Standards

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ABSTRACT

Truck operations have a pronounced effect on the design of highways. Various characteristics of trucks are reflected in the standards used today for planning, designing, and operating highways. In determining geometry, the type, size, weight, gradability, acceleration, deceleration, and turning features of trucks all play an important part. These are accounted for by a classification of design vehicles that are represented by the largest trucks and their most imposing characteristics of operation. In the design process, one class of vehicles is selected for a particular type of highway or set of conditions. The application of standards, which reflect design vehicle performance, generally produces appropriate results. There are a few areas in which operational aspects of trucks may be further considered. Also, the more recent introduction of "extra" large trucks not yet included in national geometric highway standards for certain conditions should be addressed. The features and adequacy of present standards are reviewed and areas in which reinforcement or inclusion of additional standards or concerns is needed are highlighted.

Truck operations have a pronounced effect on the design of highways. Various characteristics of trucks are reflected in the standards used today for planning, designing, and operating highways. In determining geometry, the type, size, weight, gradability, acceleration, deceleration, and turning features of trucks all play an important part.

The primary guide or policy on highway geometric design is the American Association of State Highway and Transportation Officials (AASHTO) "A Policy on Geometric Design of Highways and Streets, 1984" (1), better known as the green book. The green book, for geometric design purposes, replaces the 1965 blue book on rural highways (2), the 1973 red book on urban highways and arterial streets (3), and other AASHTO publications. The technical data for the policy in the green book were essentially completed before the enactment of the Surface Transportation Assistance Act (STAA) of 1982, which increased the allowable maximum dimensions for truck tractor-trailer combinations ("extra large" trucks). The AASHTO subcommittee on design is currently updating these criteria and addenda to the green book will be published reflecting the effects of the extra large trucks.

In 1981 Gericke and Walton (4) published the results of a study of the effects that an increase in legal truck limits would have on geometric design elements and the implications that it would have for segments of the Texas highway system.

The physical characteristics of vehicles and the proportions of variously sized vehicles using the highways are positive controls in geometric design. Design vehicles are selected motor vehicles with the weight, dimensions, and operating characteristics used to establish highway design controls for accommodating vehicles of designated classes. The green book describes two general classes of vehicles: automobiles and trucks. The truck class includes single-unit vehicles, recreational vehicles, buses, truck tractor-semitrailer combinations, and trucks or truck tractors with semitrailers in combination with full trailers (1,pp.19-36).

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TURNING RADIUS

Scale drawings showing the minimum turning paths of the 10 design vehicles are included in the green book. These turning paths are often reproduced at various scales on transparent material in sets of "turning radius templates." They are excellent design aids in determining the design of such critical features as radii at intersections, radii of turning roadways, channelization details, and pavement edges at curved sections.

Of the three truck tractor-semitrailer combinations, WB-40, WB-50, and WB-60, the WB-50 is critical for design purposes. Figure 1 (1, Figure II-6)

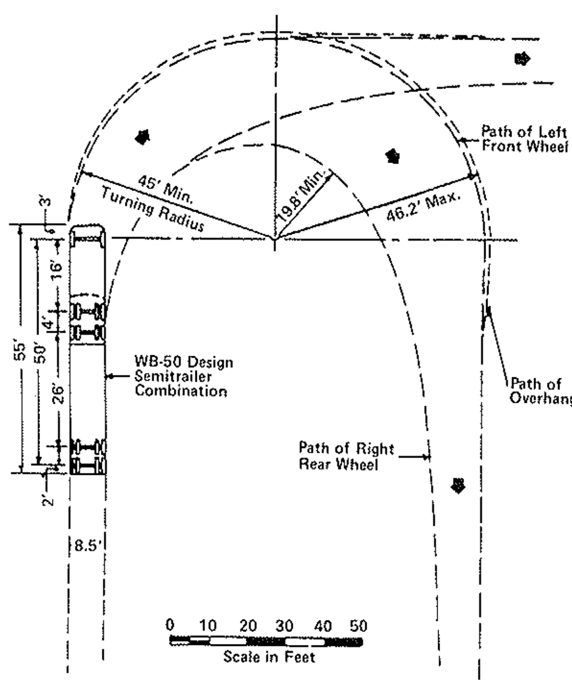

FIGURE 1 Minimum turning path for WB-50 design vehicle (reprinted with permission of AASHTO).

shows that an inside radius of 19.8 ft. and an outside radius of 46.2 ft. should be considered in design.

PAVEMENT WIDENING ON CURVES

Pavements on curves are sometimes widened to make operating conditions on curves comparable to those on tangents. Pavement widening is needed on certain curves because (a) trucks occupy a greater width because rear wheels generally track inside front wheels in rounding curves or (b) the drivers experience difficulty in steering their vehicles in the center of the lane. The need for widening is greater for curves that are unspiralized or unsuperelevated, or both. Two-lane highways with radii larger than 400 ft generally do not require widening as is shown in Table 1 (1, Table III-22). Minimum pavement inner edge curves for at-grade intersections and the effect of curb radii on turning paths are described in the green book (1,pp.727-751).

Figure 2 (1, Figure II-11) shows the swept path of vehicles similar to those of the STAA of 1982. It is noted (1,p.28) that "continuing research is being conducted into off-tracking of these vehicle configurations and the designer should verify the type and characteristics of the vehicle being used for design purposes."

SIGHT DISTANCES

The derived minimum stopping sight distances in the green book (1,p.138) are for automobile operation. Trucks generally require longer braking distances, but, because truck drivers are generally able to see the vertical features of obstructions substantially farther ahead because of the higher position of the seat in the vehicle, separate stopping sight distances for automobiles and trucks are not used in highway design standards. It is cautioned, however, that when horizontal sight restrictions occur on downgrades, particularly at the ends of long downgrades, the greater height of eye of the driver is of little value to him. It is recommended that designers use stopping sight distances that meet or exceed the values in Table 2 (1, Table III-1). The issue of lack of front wheel brakes and poor brake adjustment is discussed in a following section.

Necessary sight distances at intersections for stopped vehicles (automobiles or trucks) crossing a major highway, turning left onto a two-lane major highway, and turning right onto a two-lane major highway are presented in the green book (1,p.785).

Of particular concern is the required sight distance along the crossroad at terminals of ramps at interchanges. The data given in Table 3 (1, Table IX-9) indicate that the required sight distances for trucks are substantially greater than are those for automobiles (P vehicle). Figure 3 (1, Figure IX-29) shows how sight distances are measured at ramp terminals.

Passing sight distances are discussed in considerable detail in the green book (1,pp.148-162) but with almost no mention of trucks.

HORIZONTAL CURVES

Tables are presented in the green book for various values of rate of superelevation, design speed, degree or radius of curve, and recommended length of spiral or transition curve (1,pp.188-191). Spiral (transition) curves provide the only practical way in which superelevation can be attained in a theoretically correct manner. When the superelevation runoff is effected without a spiral curve, usually partly on curve and partly on tangent, the driver may have to steer opposite to the direction of the curve ahead when on the superelevated tangent portion in order to keep his vehicle on tangent (1, p.195). In most agencies that do not use spirals, the current design practice is to place approximately two-thirds of the runoff on the tangent approach and one-third on the curve. Without the use

TABLE 1 Calculated and Design Values for Pavement Widening on Open Highway Curves—Two-Lane Pavements, One or Two Way (reprinted with permission of AASHTO)

	Widening (ft) for Two-Lane Pavements on Curves for Width of Pavement on Tangent of:													
	24 ft					22 ft					20 ft			
	Design Speed (mph)					Design Speed (mph)					Design Speed (mph)			
Degree of Curve	30	40	50	60	70	30	40	50	60	70	30	40	50	60
1	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	1.0	1.0	1.5	1.5	1.5	2.0
2	0.0	0.0	0.0	0.5	0.5	1.0	1.0	1.0	1.5	1.5	2.0	2.0	2.0	2.5
3	0.0	0.0	0.5	0.5	1.0	1.0	1.0	1.5	1.5	2.0	2.0	2.0	2.5	2.5
4	0.0	0.5	0.5	1.0	1.0	1.0	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0
5	0.5	0.5	1.0	1.0		1.5	1.5	2.0	2.0		2.5	2.5	3.0	3.0
6	0.5	1.0	1.0	1.5	–	1.5	2.0	2.0	2.5		2.5	3.0	3.0	3.5
7	0.6	1.0	1.5	–		1.5	2.0	2.5			2.5	3.0	3.5	
8	1.0	1.0	1.5			2.0	2.0	2.5			3.0	3.0	3.5	
9	1.0	1.5	2.0			2.0	2.5	3.0			3.0	3.5	4.0	
10-11	1.0	1.5				2.0	2.5				3.0	3.5		
12-14.5	1.5	2.0				2.5	3.0				3.5	4.0		
15-18	2.0					3.0					4.0			
19-21	2.5					3.5					4.5			
22-25	3.0					4.0					5.0			
26-26.5	3.5					4.5					5.5			

NOTES: Values less than 2.0 may be disregarded.

3-lane pavements: multiply above values by 1.5.

4-lane pavements: multiply above values by 2.

Where semitrailers are significant, increase tabular values of widening by 0.5 for curves of 10° to 16°, and by 1.0 for curves 17° and sharper.

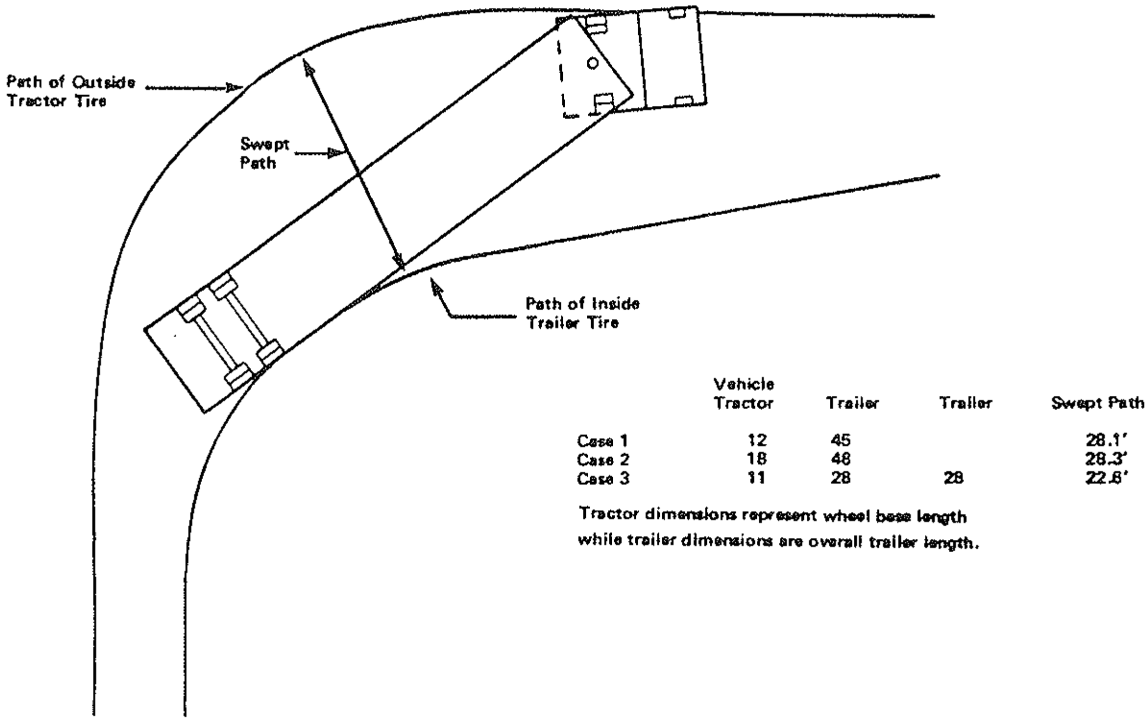

FIGURE 2 Swept path width for various truck vehicles low-speed offtracking in a 90-degree turn (reprinted with permission of AASHTO).

TABLE 2 Stopping Sight Distance on Wet Pavement (reprinted with permission of AASHTO)

Design Speed (mph)	Assumed Speed for Condition (mph)	Brake Reaction Time (sec)	Brake Reaction Distance (ft)	Coefficient of Friction (f)	Braking Distance on Level[a] (ft)	Stopping Sight Distance Computed[a] (ft)	Stopping Sight Distance Rounded for Design (ft)
20	20-20	2.5	73.3- 73.3	0.40	33.3- 33.3	106.7-106.7	125-125
25	24-25	2.5	88.0- 91.7	0.38	50.5- 54.8	138.5-146.5	150-150
30	28-30	2.5	102.7-110.0	0.35	74.7- 85.7	177.3-195.7	200-200
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0.31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650
65	55-65	2.5	201.7-238.3	0.29	347.7-485.6	549.4-724.0	550-725
70	58-70	2.5	212.7-256.7	0.28	400.5-583.3	613.1-840.0	625-850

[a]Different values for the same speed result from using unequal coefficients of friction.

TABLE 3 Required Sight Distance Along the Crossroad at Terminals of Ramps at Interchanges (reprinted with permission of AASHTO)

Assumed Design Speed on Crossroad Through the Interchange	Sight Distance Required to Permit Design Vehicle to Turn Left from Ramp to Crossroad (ft)[a] — Design Vehicle Assumed at Ramp Terminal: P	SU	WB-50	Sight Distance Available to Entering Vehicle When Vertical Curve on Crossroad Is Designed for Stopping Sight Distance[b]: P	SU or WB-50
70	740	1,060	1,430	920	1,040
60	630	910	1,230	730	820
50	530	760	1,030	540	600
40	420	610	820	420	480
30	320	460	620	310	350

[a]Sight distance measured from height of eye of 3.50 ft for P, SU, and WB-50 design vehicles to an object 4.25 ft high.

[b]Minimum available stopping sight distance based on the assumption that there is no horizontal sight obstruction and that S < L.

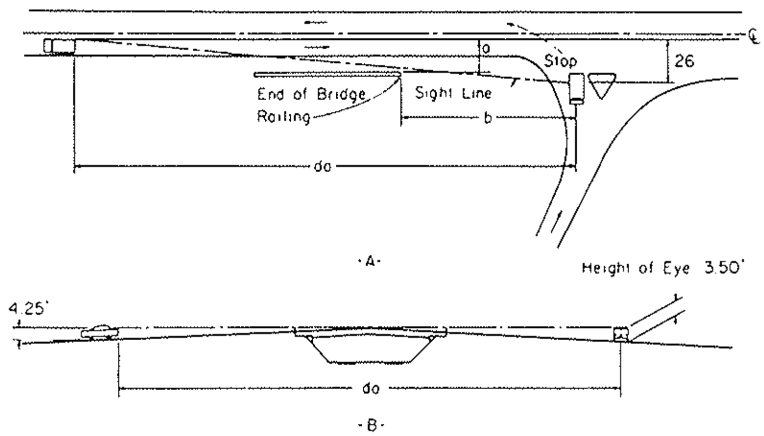

FIGURE 3 Measurement of sight distance at ramp terminals (reprinted with permission of AASHTO).

of spirals there is superelevation on the tangent where none is needed, and there is not enough superelevation on a substantial part of the circular curve (end sections). Vehicles traveling at the design speed thus develop side friction factors in excess of the allowable minimum on the end sections of the curve. Although the side friction factor developed on the tangent is undesirable, the development on curves of friction factors greatly in excess of the design basis results in hazardous conditions (1,p.203).

Compound circular curves are advantageous in effecting desirable shapes of turning roadways at atgrade intersections and at ramps at interchanges. On compound curves for open highways it is generally accepted that the ratio of the flatter radius to the sharper radius should not exceed 1.5 to 1. For compound curves at intersections where drivers accept more rapid changes in direction and speed, the radius of the curves can be as high as 100 percent greater than the radius of the sharper arc, a ratio of 2 to 1 (1,p.223). It is pointed out that spiral curves have an advantage in providing for natural travel paths and a correct transition from one superelevation rate to another (1,pp.222-223,249-250).

A reverse curve should have spiral transitions between the curves in order to properly handle the superelevation (1,p.250). As is shown later in this paper, circular curves, compound curves, and reverse curves, without proper spiral transitions, can present particularly dangerous situations for truck operations.

VERTICAL ALIGNMENT OF CURVES AND GRADES

The "critical length of grade" is used to indicate the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction of speed. To establish design values for critical lengths of grade for which gradability of trucks is the determining factor, the following data or assumptions are needed:

1. Size and power of a representative truck to be used as a design vehicle along with gradability data for this vehicle. A loaded truck, powered so that the weight-to-horsepower ratio is about 300 is representative of the size and type of vehicle normally used for design control on main highways.
2. Speed at entrance to critical length of grade.
3. Minimum speed on the grade below which interference to following vehicles is considered unreasonable. The common basis for determining critical length of grade is a reduction in speed of trucks below the average running speed. It is recommended that a 10-mph reduction criterion be used as the general design guide for determining critical lengths of grade. A design technique is suggested in the green book (1,pp.259-264).

For increased safety, climbing lanes are considered where the length of grade causes a reduction of 10 mph or more in the speed of loaded vehicles provided the volume of traffic and percentage of heavy trucks justify the added costs (1,pp.265-278).

Leisch et al. (5,6) and Rowan and Johnson (7) have suggested the use of a speed profile as a technique to achieve a consistent design speed, critical length of grade, and the design of creeper lanes for both existing highways and new designs.

The speed profile provides a continuous plot of the average speed of vehicles along the roadway in each direction of travel at a time when traffic is sufficiently light to represent a condition that may be termed "free flowing." Both automobile and representative loaded truck speeds are plotted along with the vertical and horizontal alignment. This allows a complete analysis, in an easy fashion, for a "new" highway and allows the designer to change design speeds, grades, and curves to achieve a consistent design.

On existing highways the technique can be used to determine the location of creeper lane beginnings and ends based on the 10-mph speed differential rule. Note in Figure 4 (5) that a climbing lane should begin at about Station 230 and extend to about Station 315. Note that the speed differential decreases to about 10 mph, an acceptable figure, at 305, but this would place the end of the creeper lane in a sharp horizontal curve.

The green book also describes a procedure for the design of emergency escape ramps for runaway trucks on steep downgrades (1,pp.293-303).

CROSSOVER CROWN (algebraic difference of cross slopes)

It is suggested that the use of cross slopes steeper than 2 percent on high-type, high-speed pavements with a central crown line is not desirable. In a passing maneuver, drivers must cross and recross the crown line and negotiate a total rollover (crossover crown) or cross-slope change of more than 4 percent. The reverse curve path of travel of the passing vehicle causes a reversal in the direction of the cen-

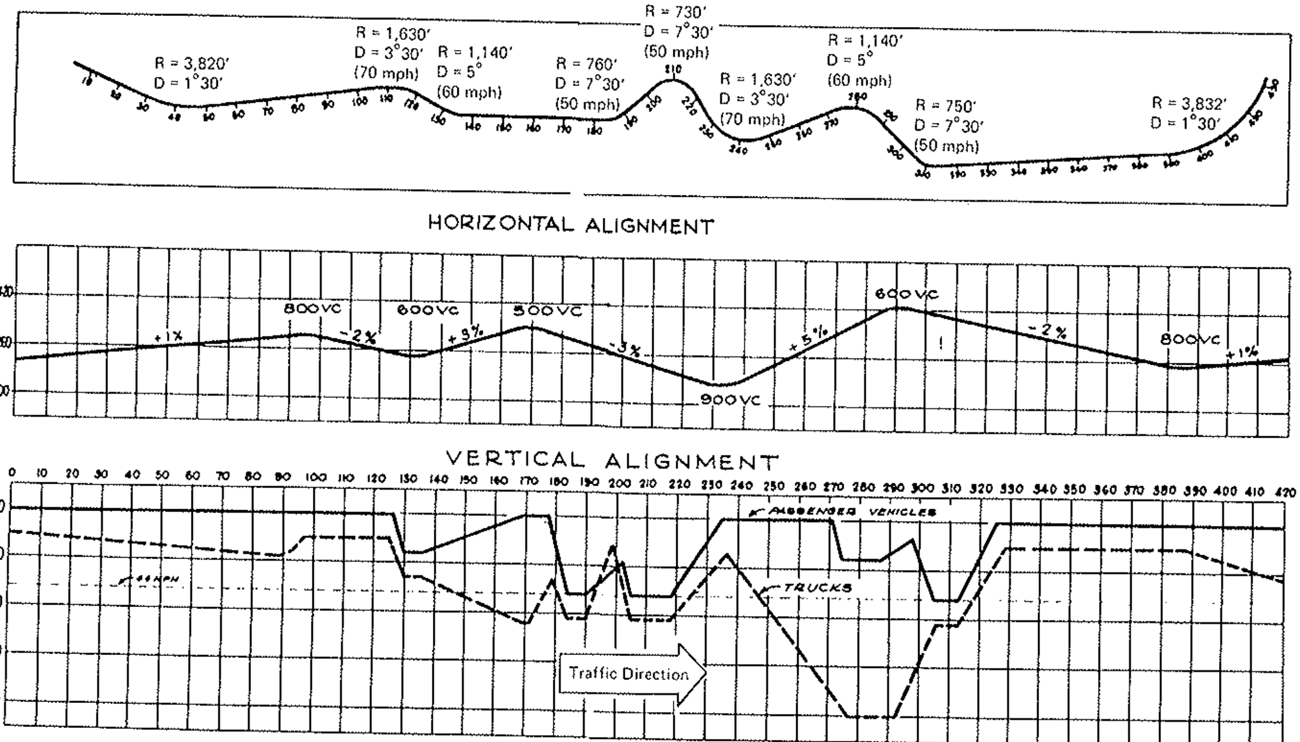

FIGURE 4 Speed profiles *(5)*.

trifugal force, which is further exaggerated by the effect of the reversing cross slopes. Trucks with high body loads crossing the crown line are caused to sway from side to side when traveling at high speed, at which time control is difficult (1,p.357).

For turning roadway and ramp terminals a desirable maximum algebraic difference at a crossover crown line is 4 or 5 percent but it may be as high as 6 percent at low speeds and where there are few trucks (1,pp.814,1018). The maximum crossover crown values have severe safety implications for trucks. This is, of course, a problem similar to that of designing proper transitions for superelevated sections on compound, reverse, and simple curves.

MEDIAN OPENINGS

An important factor in designing median openings is the path of each design vehicle making a minimum left turn at 10 to 15 mph (1,p.847). The paths of design vehicles making right turns were discussed earlier (Figure 1). Any differences between the minimum turning radii for left turns and those for right turns are small and are insignificant in highway design. In using turning radius templates, simply "turn the template over" to go from right turn to left turn. Note that the objective is to have the turning vehicles stay entirely in their own lanes (no encroachment on adjacent lanes) as is shown in Figure 5 (1, Figure IX-55).

SUBTLETIES OF DESIGNING FOR TRUCKS

Rollover

Hutchinson and Shapley (8) present some sobering implications regarding the potential for truck rollover.

In assessing the rollover potential of tractor-trailers, the conclusion arrived at will depend on the extent to which the various flexibilities and other properties of the trucks are considered.

For example, a perfectly rigid simple vehicle with a height of center of gravity above the ground (h) and an overall width of assembly (t) would roll over at a steady lateral acceleration of

$$A_{max} = tg/2h$$

where g is the acceleration due to gravity (ft/sec^2).

Note that t/2h is often called the "tripping coefficient" of friction. However, none of the components can really be considered rigid, especially the tires. Flexible tires further reduce effective truck width. Note also that the forces attempting to overturn the vehicle will also tend to deflect the tires and wheels.

Roll and lateral movement can also be generated by such things as looseness in the spring mounts and clearance in the fifth wheel. Both of these effects serve to reduce the lateral acceleration required for overturning.

Road surface irregularities, entering a curve, superelevation templet warp, and roughness as well as transient roll inputs induced in response to steering can directly disturb a vehicle in roll. When certain dynamic effects are present these vehicles may be caused to overturn at levels of lateral acceleration approaching half of their steady-state limit even without any special outside tripping force inputs.

Hutchinson and Shapley (8) give an example in which it is shown that the cornering ability of a loaded 18-wheeler does not compare at all favorably with that of the average well-designed automobile. In the example curve, the automobile would slide out at about 84 mph whereas the flexible truck would overturn at 46 mph using a tripping coefficient of friction of only about 0.17.

Surely then, simple curves without spirals, reverse curves, compound curves, and areas of high

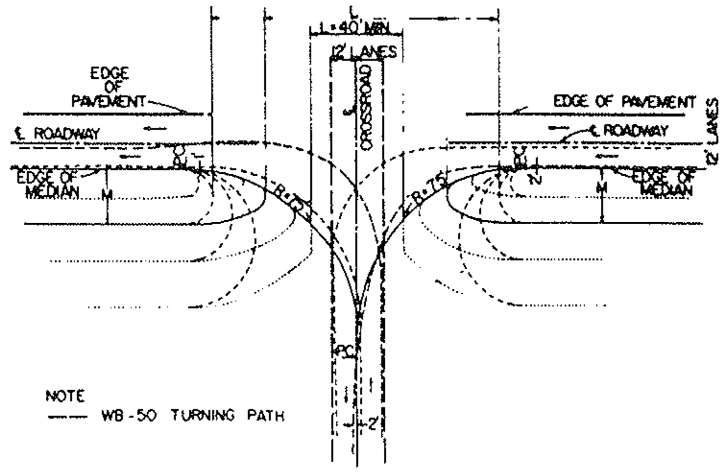

FIGURE 5 Minimum design of median opening for WB-40 design vehicle, control radius 75 ft (reprinted with permission of AASHTO).

crossover crown values are potential locations for truck rollovers at modest speeds.

The rollover of trucks can also be increased dramatically by a nudge (tripping force), in the direction of centripetal acceleration, by an automobile in the truck's fifth wheel or jackstand area. For example, suppose a truck on the inside lane of a curve and an automobile on the outside lane (side by side at the truck's fifth wheel area and traveling in the same direction) bump or nudge each other because one or both leave their respective lanes. This can easily increase the tripping action so the truck will quickly overturn onto the automobile.

Guardrails

One of the reasons a truck may strike a guardrail is a flat front tire. Some trucks are uncontrollable in the event of a flat front tire. This uncontrollability may reflect either the original design of the vehicle or poor maintenance. With a centerpoint front axle and a well-maintained rig, the alert driver of an 18-wheeler can often be expected to correct for flat front tire vehicle yaw within the lateral clear zone on modern highways. Unfortunately there is frequently a truck wreck anyhow. A flexible automobile-type single-beam W-section steel guardrail is often encountered parallel to the pavement about where the truck is brought under control. Portions of the guardrail often damage the brake and steering systems and have enough rail strength remaining to guide the truck into the obstructions the guardrail was "protecting" (8). Some guardrails, such as rigid concrete "New Jersey" barriers, are effective in guiding trucks yet minimizing vehicle damage and penetration (9).

Dished Wheel Tracks

The abrasion of bare pavements by studded tires and the compression or lateral displacement of unstable flexible pavement often result in depressed wheel tracks. This causes a properly loaded set of dual tires to have one of the tires overloaded when it runs along the hump while the mate overhangs the dish or depression.

If the brakes are applied this can cause a yaw to the right on dry pavements and to the left under certain other circumstances (8). Hydroplaning is also a distinct possibility.

Washboard Pavement

Washboard pavements can cause the tires of a lightly loaded 18-wheeler to bounce up and down and skitter off the crown of a dry road into the ditch without braking at speeds as low as 30 mph (8).

Pavement Warp

For reasons already given in the foregoing discussion of truck rollover, compound curvature, excessive crown templet warp, and superelevation templet warp that "feels tricky" but "not too bad" in an automobile can be enough to cause load shift or rollover, or both, in large trucks traveling at the posted speed limit or advisory speed (8).

The causes of such templet warps may lie in original faulty design, but originally satisfactory design and construction (especially superelevation) may have been so altered during routine maintenance and overlays that no superelevation or even reversed superelevation may now exist! The use of a ball-bank indicator mounted on the dashboard of an automobile is recommended for quickly checking safe speeds versus superelevation. Is anybody checking superelevations after overlay projects?

Truck Brakes

Many trucks are running with no front tractor brakes. They have been disconnected to prevent "lockup" and lack of steering. No front brakes and lockup of driving wheel brakes are virtually certain to force the tractor to try to "reverse ends" resulting in a jackknife situation. Tractor and trailer brakes are often in poor adjustment. The resulting lack of brakes or adjustment increases the truck braking distance even more and can more than negate the positive effect of higher driver eye height in all braking situations.

Pavement Edge Dropoffs and Surface Discontinuities

In "The Influence of Roadway Discontinuities--A State-of-the-Art Report" (10,pp.42,37) the authors caution: "Large commercial vehicles, because of their size and design, may be more sensitive than passenger cars to some surface discontinuities. . . . From the knowledge of truck dynamic properties, it

may be expected that certain of these road features can create a greater vibration disturbance to trucks than to cars."

SUMMARY

The preceding overview of existing design standards, coupled with the stated concerns about the subtleties in designing for trucks, points to the need for a definitive highway design and maintenance guide to satisfy the unique safety-critical operational requirements of trucks.

It is hoped that this symposium will be of assistance to AASHTO's Subcommittee on Design in its efforts to update the green book to reflect the "large trucks" allowed under the STAA of 1982 (1,p.iv).

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Sight Distance Problems Related to Large Trucks

P. S. FANCHER

ABSTRACT

In this paper are discussed the influences of the properties of large trucks on (a) sight distances for accelerating across intersections, (b) passing sight distances on two-lane highways, and (c) stopping sight distances for crest vertical curves. The vehicle properties considered include power-to-weight ratios (acceleration capabilities), overall lengths, driver eye heights, and braking capabilities. The findings presented here indicate that (a) current policy of AASHTO may be used to obtain conservative estimates of the time required to accelerate across intersections, (b) longer periods of time in the left lane are needed for passing longer trucks, and (c) if controlled stops without jackknifing, trailer swinging, or vehicle spins are to be performed by truck drivers, the required stopping sight distances at high speeds are much longer than those recommended in the AASHTO policy.

The intent of this paper is to provide an understanding of how sight distance requirements are influenced by the properties of large trucks. Whether large trucks are involved in crossing intersections, passing situations on two-lane roads, or stopping to avoid objects on the highway, pertinent truck characteristics are enough different from those of automobiles that design policies based on automobile characteristics cannot be assumed to be appropriate. With regard to crossing intersections, there is a recommended AASHTO policy for heavy trucks (the WB-50 design vehicle) (1). However, AASHTO policy for passing sight distance is based on acceleration capabilities of automobiles. And, although trucks are mentioned, the policy for stopping sight distance on crest vertical curves is based on the

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