Safety of Large Trucks and the Geometric Design of Two-Lane, Two-Way Roads

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ABSTRACT

Recent federal and state designations of primary highways for use by longer, wider, and heavier tractor-trailer trucks, pursuant to the Surface Transportation Assistance Act of 1982, contain a high percentage of arterials with deficient geometric and cross-sectional design features. Recent studies indicate the severe accident overinvolvement potential of larger, especially tandem-trailer, trucks on both rural undivided and urban divided highways. Research in the past few years demonstrates both the proclivity of larger trucks for certain kinds of accidents because of their design characteristics and their incompatibility with the substandard operating conditions found especially on older two-lane, two-way rural arterials. The safety-deficient design characteristics of larger trucks are reviewed and the incompatibility of their operation with horizontal curvature, superelevation, skid resistance, and, in particular, passing sight distance deficiencies is surveyed. Recent investigations of passing sight distance and marked passing zone deficiencies on roads designated for use by longer, wider trucks are explored. The results of these investigations are buttressed by a number of papers and research studies produced during the past 5 years. Preliminary comments are made on the new AASHTO geometric design guide, which appears to condone substandard design features on highways open to use by larger trucks. Last, the current paucity of accident data collection on large trucks, the need for better on-site investigation of large-truck accident causation, and the necessity of more sustained research on the behavior of large trucks on each functional class of roadway are indicated.

It is rapidly becoming clear that certain geometric design elements play a pivotal role in the safe operation of large commercial vehicles on our nation's roads. When these elements, some of which are considered in the body of this paper, are deficient, they provide the context for vehicle and driver responses that lead to truck accidents. Moreover, the operation of long, wide trucks, especially on two-lane, two-way (TLTW) roads with substantial geometric deficiencies, markedly compromises the safety of automobile motorists who must share the roadway with big trucks.

A discontinuity has emerged during the last few years between the results of research and public policy on the compatibility of large trucks with older arterial and collector roadways. The aims of increased productivity for American trucking interests and the perceived need for uniformity of truck size and configuration and of access privileges to these older roads have produced mandates and arguments in statute and regulation that attempt to establish the safety parity of larger trucks with automobiles.

This author thinks that the investigations of the past several years into such topics as passing, stopping, and decision sight distance on TLTW roads; superelevation; the behavior of large trucks at high speeds on roads with moderate to severe curvature; and other related subject areas should convince us all that there is a considerable divergence between the appearance and the reality of safety of big trucks on roads with impoverished design.

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It is unfortunate that the issue of highway design adequacy and big truck safety should have been propelled into the arenas of high politics and of court advocacy. Neither of these forums is the place to establish the acceptability of older, non-Interstate roads for use by longer and wider trucks. However, as has been the case innumerable times in the past, the actions of the legislatures and the courts in response to the pressures of important public interests have precipitated the intense scrutiny of a critical area of public health and safety. The results of impartial research nevertheless have the unenviable task of bringing up the rear and responsible practitioners have the Herculean job of attempting the reform of policies already in place.

As indicated at the outset, this author is strongly persuaded that a small number of geometric design features are of pivotal importance to the operating safety of large trucks on TLTW roads. The investigative efforts of a number of researchers during the past few years have shown that sight distance for passing and horizontal curvature are central design parameters for determining the operating safety margins of large trucks on TLTW roads. This is certainly not to say that other design and cross-sectional features do not also have a role to play in the safety of large trucks on these roads. The interdependence of these features (e.g., lane width, superelevation, vertical curvature, and stopping sight distance) along with pavement surface characteristics (coefficient of friction) is heavily determinative of the margins of safe vehicle operation. Furthermore, the traffic engineering applied to these roads, especially with regard to the marking of passing and no-passing zones, is of decisive importance in fostering safe operations. Also, passing zone warrants, standards, and practices are woefully inadequate and will be discussed later in this paper.

The recent research of Lieberman (1) demonstrates the thorough inadequacy of the American Association of State Highway and Transportation Officials (AASHTO) sight distance formulas for the successful execution of the passing maneuver at higher speeds on TLTW roads. Lieberman has shown that significantly longer sight distances are needed when the impeding vehicle is a truck not an automobile. He also points out correctly that the inadequacy of the AASHTO passing sight distance formulas results from the postulation of automobiles passing only automobiles, an approach still used in the latest AASHTO geometric design guide (the "green book") (2). It should be noted that Lieberman's assumptions of acceleration capabilities for the passing maneuver and the speed differential between the impeding truck and the passing automobile are AASHTO's and these assumptions are unrealistically sanguine for many actual vehicles and on-the-road conditions. His analysis does stress that the issue of inadequate safety is particularly acute where vehicles with low height-of-eye, such as many subcompact automobiles, attempt to pass large trucks at 85th percentile traveling speeds in excess of 44 mph. However, it should be pointed out here that the acceleration capabilities of many legal vehicles in the United States in the 45 to 65 mph range are substantially below the figures assumed in the AASHTO formulas and calculations. Just to mention one or two examples, the Mercedes-Benz 240D (3) and the Peugeot 504 (4) diesels having passing-speed abilities far below the rates premised in the AASHTO criteria. There are many other examples of recent automobiles, light vans, and multipurpose vehicles with very poor passing abilities.

The research of Gericke and Walton (5) demonstrates that the AASHTO sight distance formulas for geometric design are inadequate for any vehicle attempting to pass any other vehicle on TLTW highways, and especially inadequate for automobiles passing trucks. Gericke and Walton stress that prospective increases in the length of trucks will correspondingly increase aborted passing maneuvers of automobiles and will thereby increase safety hazards. They emphasize that additional passing sight distance will be needed if safety is not to be compromised. Unfortunately, they do not fully address the issue of successful versus unsuccessful aborts. No existing analysis treats completely the nature, variety, and frequency of the maneuvers and consequences of the inability of vehicles to safely conclude an abort, although some inquiries do show conclusively the high percentage of aborts that are necessary in automobile-passing-truck attempts on TLTW roads. Moreover, at the present time there are no data on the consequences of unsuccessful aborts; that is, whether and to what extent the vehicle that cannot successfully abort runs off onto the roadside of the opposing lane, has a head-on collision with an opposing vehicle, has an accident with the impeding vehicle during the attempted drop-back, or has an accident with a trailing vehicle when the aborting vehicle attempts to reenter the queue. These data and research are badly needed. In contrast to the complexity and subtlety of the aborted passing maneuver problem and its impact on highway safety, the AASHTO Policy on Geometric Design of Highways and Streets (2,p.148) states:

> When required, a driver can return to the right lane without passing if he sees opposing traffic is too close when the maneuver is only partially completed.

And (2,p.156)

> Even on low-volume roadways a driver desiring to pass may, on reaching the passing section, find vehicles in the opposing lane and thus be unable to use the section. . . .

The research of Saito (6) shows the correlative inadequacy of the passing zone sight distance and pavement marking criteria and practices of the national Manual on Uniform Traffic Control Devices (MUTCD). Although a previous article in the ITE Journal by Weber (7) showed quite conclusively that the use of AASHTO sight distance and MUTCD passing zone standards results in the marking of thoroughly inadequate passing zones, particularly on vertical and horizontal curves, the only change to these formulas and resulting markings has been the marginal one brought about through the lowering of the height-of-eye criterion from 3.75 to 3.5 ft [48 Fed. Reg. 54336 (1983)]. As Weber (7,p.16) points out:

> Passing zones of lesser standards . . . are lethal to the inexperienced driver who has undue trust in the markings. Such marginal zones neither fulfill the expectations of safety experts nor do they increase the economic benefit of the road. . . .

Yet, in the last year and a half, many thousands of miles of roads marked consistently with excessively short, inadequate passing zones have been opened to use by longer trucks.

Saito (6) confirms Weber's analysis and adds to the small number of research considerations of aborts. He shows that successful aborts are impossible under most high-speed conditions on the basis of current MUTCD passing zone sight distance and striping standards. He argues that there is a high probability of collision potential due to the inability of the aborting vehicle to reenter the lane behind the impeding vehicle when the 85th percentile speed is greater than 40 mph. Through the use of kinematic modeling, Saito demonstrates algebraically that the impossibility of successful passing on the basis of MUTCD passing criteria can also be used to demonstrate that successful aborts of the passing maneuver cannot be performed after a certain point has been reached by the overtaking vehicle.

The importance of Saito's demonstration cannot be overestimated. However, one shortcoming of this approach is the postulation of only automobiles attempting to pass other automobiles. If the kinematic model is extrapolated, it shows substantial increases in the lengths of times and distances for successful aborts of automobiles attempting to pass long trucks and, moreover, shows that an increase in the percentage of unsuccessful aborts occurs as the impeding vehicle's length is increased. At one point Saito (6,p.21) does briefly consider an automobile passing a truck 55 ft long. His computations and graphic representation clearly imply that a significant increase in what he terms the "collision zone" is effected by the attempt of automobiles to abort the attempted passing of trucks, but his own consideration of this derivative conclusion is too brief. It appears that, on the basis of his model, a consistent arithmetic increment of additional length in the impeding vehicle, ceteris paribus, causes a corresponding logarithmic increase in the percentage of aborts.

In a paper offered last year, Garber and Saito (8) applied Saito's analysis to real-world sight distance and passing zone conditions on TLTW highways in mountainous areas. Passing-attempt data from Virginia roads were used in the analysis to demonstrate that MUTCD passing zone values are inadequate for passing zone marking of TLTW highways with significant vertical and horizontal curvature. They show the functional relationship of AASHTO passing sight distance values and MUTCD passing zone length values, and the inadequacy of both sets to accommodate safe passing maneuvers. The minimum values of the MUTCD for passing zone length are inadequate at lower speeds and increasingly inadequate at higher speeds. This inadequacy begins as low as the 85th percentile speed of 30 mph. A 90 percent increase in the minimum length of passing zones over the MUTCD minimum values is needed in order to ensure the safe completion of the passing maneuver at the 50 mph 85th percentile speed. Even at the 85th percentile speed of 30 mph, a 35 percent increase in length is necessary. These recommended additional lengths will also accommodate successful aborts.

These research results make it abundantly clear that passing sight distance and passing zone standards are critically important engineering features on TLTW roads with significant curvature. The automobile-truck relationship in the passing maneuver is highly dangerous on many thousands of miles of rural arterial and collector routes that are designed with inadequate sight distance and marked for permitted passing maneuvers, which cannot be accomplished, in some cases, even by a majority of the vehicles making the attempts. It might be indicated here that the South Carolina Department of Highways and Public Transportation (SCHPT) reviewed their TLTW highways for passing capabilities in light of the federal designation of many of their primary routes for use by longer, wider, and tandem-trailer trucks. SCHPT found many instances in which only 30 percent, and sometimes as low as 25 percent, of the marked passing zones on a given route would allow an automobile to pass another automobile, and these percentages were further reduced when the pass was of a standard tandem-trailer or equivalently long truck [i.e., in the case of a tandem-trailer rig, two 27-ft-long trailing units plus the length of the cab (FHWA Docket 83-4)].

A few more geometric design elements and their bearing on the safety of large trucks need to be considered. Recent research on stopping sight distance (SSD) by Olson et al. (9) has shown the inadequacy of the current green book formulas for SSD by revealing the improper assumptions lying behind AASHTO calculations. These include a locked-wheel premise for braking that, on close examination, proves to be unrealistic and hazardous because the result of locked-wheel braking is the inability of the driver to maintain proper control of the vehicle, particularly to avoid encroachment into an adjacent lane. On TLTW roads, avoidance of opposing lane encroachment is, of course, crucial and when inadequate SSD combines with locked-wheel braking on a horizontal curve, the consequences can be catastrophic: the locked-wheel vehicle will proceed off the road tangentially to the curve and the crown or superelevation of the road will cause the locked-wheel vehicle to slide toward the downhill side of the road in a manner that the driver cannot correct by steering (9,p.55).

Olson et al. argue that locked-wheel stopping is not desirable and that it should not be portrayed in design standards as an appropriate course of action (9,p.55). An additional consideration about the hazardousness of a locked-wheel standard is the relatively low value of pavement skid resistance available at high speeds, particularly on wet surfaces.

As important as the research of Olson et al. is for the general issue of reforming SSD requirements, many important insights were gained from this major investigative effort into other issues that affect the safety of trucks. In the course of the study, the capabilities, design, and efficiency of truck braking systems were called seriously into question in their relation to the design features of typical highways. With regard to SSD, the authors concluded that, given the substantially inferior frictional capabilities of truck tires (approximately 0.7 the frictional capability of automoble tires), current SSD available on many highways is thoroughly inadequate. For controlled (i.e., unlocked-wheel) stops in which the truck driver modulates his brakes to prevent spinning or jackknifing and maintain steering control, it was found that trucks require stopping distances that are approximately 1.4 times those required for automobiles. In tests conducted by Olson et al. involving repeated stops by heavy trucks from only 40 mph on a 12-ft-wide lane on a curve with a 1,000-ft radius, of 60 runs performed by professional drivers, 11 resulted in loss of directional control and departure of the vehicles from their lanes (9,p.90). Because Olson et al. argue for allowable stopping distances for automobiles of 85 ft for 50 mph, 190 ft for 60 mph, and 350 ft for 70 mph (9,pp.2-3), it is obvious that trucks are not accommodated in their stopping distance requirements in current design standards despite the supposed compensation for inferior braking lent by the operators' superior height of eye.

Olson et al. also address the behavior of vehicles on horizontal curves, a topic that is particularly important for trucks. Neuman (10) and Glennon et al. (11) have, along with Olson et al., demonstrated the critical importance of spiral transitions in the design of horizontal curves. Olson et al. showed that one of the salient effects of spiral transitions is to reduce the need for object clearance on the inside of the path of travel when the driver is in the tangent section (9,p.45). Neuman and Glennon et al. showed conclusively that, even if spiral transitions are not provided, drivers always will tend to guide their vehicles through a path that essentially duplicates the behavior of a vehicle in a spiraled transition. When spirals of sufficient length are provided, dramatic effects are achieved in reducing the most critical aspects of vehicle path behavior. Properly spiraled curves radically decrease the hazards of path overshoot. This in turn substantially lowers lateral tire acceleration, thereby ameliorating undue reliance on tire side friction demands.

However, there are many thousands of continuous curves on highways and in some states the policy is explicitly not to design and build spiraled curves of appropriate length. Although the new AASHTO design policy does imply throughout its treatment of spiral transitions the superior accommodation of actual driver and vehicle behavior achieved by designing spiraled curves (2,pp.195,198), in the end the endorsement by the green book is really only tepid and the overall analysis of the functional importance of spiraled transitions is insufficient and simplistic, particularly in the failure to correlate the differing natures of spiraled versus nonspiraled curves with regard to run-off-the-road encroachments and the functional interdependence of different curve geometries and roadside environment.

The question of spiral curve transitions is of special value in viewing the needs of large trucks and, in the interrelationship of spiral curves with lane width and superelevation, constitutes a pivotal design matrix that should be investigated carefully for trucks. In the data base used by Glennon et al. (11) in their study of safety on rural highway curves, it was found that the average accident rate for curves is three times the rate for tangents, that the average single-vehicle run-off-the-road accident rate for curves is four times that for tangents, and that accident severity on curves is greater than on tangents. In addition, Glennon et al. pointed out the high sensitivity of accident rates on curves to the nature of the roadside environment, including the severity of the slope and clear-zone width. They also show that drivers traveling at or near a curve's design speed will tend to exceed the tire side friction demands implied by AASHTO friction factors and that the actual margin of safety on wet pavement is only 50 percent of that currently set forth in the green book. Moreover, they stress that the current design manual should explicitly consider the tradeoff necessary between curvature and superelevation, which it does not.

In concluding with specific recommendations, Glennon et al. (11,p.9) suggest that

> [T]he avoidance of large central angles between successive tangents is recommended. AASHTO policy should state that central angles of no more than 45° are preferred. Larger central angles require either sharp curvature or long curves, both of which adversely affect safety.

It is interesting to note here another rebuttable presumption of the AASHTO green book in regard to curves. The text would have it that, "[f]or most curves the average driver can effect a suitable transition path within the limits of normal lane width" (2,p.195). The expression "normal lane width" is left undefined in this passage, but this author submits that, indeed, many curves, especially those that are unspiraled with lanes less than 12 ft wide on TLTW roads, cannot be properly and safely negotiated by a large truck even when traveling at the posted speed. Opposing lane encroachment on a TLTW road by the truck is guaranteed and this due partly to the excessive demands made on the vehicle and driver by the inadequate design of the curve and partly, with some rig configurations, to substantial inboard offtracking. [For a discussion of offtracking behavior see Millar and Walton (12) and Ervin et al. (13,p.156).] Any attempt to correct for this by the driver will result in encroachment onto the shoulder if, indeed, there is any shoulder.

The manifest hazardousness of both opposing lane and roadside encroachment should be apparent to all. Yet, although the green book nowhere has a unified, coherent treatment of the unique needs of design for very large vehicles, it nevertheless sees through a glass darkly that big rigs will encroach beyond the delineated travel lanes. At one point, in the consideration of turning roadways, the guide recommends that large vehicles pass each other on inadequately wide pavements by intentionally employing the shoulder or stabilized roadside area (2,p.234). But the green book recognizes neither that such encroachments at high speeds on many curves are compelled by the nature of curve geometry and the behavior of many big rigs nor the consequent harazardousness of this maneuver. The green book's exhortation (2,p.233) that

> [i]n negotiating pavements designed for smaller vehicles, larger vehicles will have less clearance and will require lower speed and more caution and skill by drivers. . . .

is naive and an admission that design cannot control traffic safety. [The issues of truck wheel lateral placement and typical ranges of lateral variation are relevant here. For some recent data, see Shankar and Lee (14,p.9).]

The work by Olson et al. (9) and Glennon et al. (11) appropriately complements a recent paper by Zador et al. (15) in furthering understanding of the relationship of horizontal curves and superelevation. These three studies make it apparent that present green book guidance is insufficient to provide adequate superelevation rates that guarantee a margin of safety for lateral acceleration of truck tires given the usual ranges of pavement surface friction coefficients found on older roads. Glennon et al. (11) concluded that, given the predictable curve overshoot behavior of the typical driver, more superelevation is required than is called for by AASHTO policy to produce AASHTO-specified lateral tire accelerations at design speed for nominally critical driver behavior. Olson et al. (9,pp.21,55) intimate the critical contribution of superelevation to safe, controlled braking in curves that will allow the driver to maintain his lane throughout his maneuver. Zador et al. (15) showed that after adjustments were made for both curvature and grade, fatal rollover crash sections were nevertheless still found to have less superelevation than comparison sections. The results of Zador et al. were based on comparisons of the linear regression estimates of superelevation rates as functions of curvature. Therefore the deficiencies in superelevation found in the study cannot be due to curvature differences between flat road sections and those with grades. Furthermore, if downhill grades were designed for realistic (i.e., higher) travel speeds, the rate of superelevation would be higher for curves with downhill grades than for comparable flat curves because of the higher average speeds of vehicles traveling downhill. The new manual only asserts that (2,p.194):

> On long or fairly steep grades, drivers tend to travel somewhat faster in the downgrade than in the upgrade direction. In a refined design this tendency should be recognized, and some adjustment in superelevation would follow.

How much adjustment to make is not mentioned; no sets of recommended values are provided in the green book to link the earlier discussion on curve design with the later consideration of the effects of grades (2, pp.252-265). The green book (2,p.264) does acknowledge that "[s]teep downhill grades can . . . have a detrimental effect on capacity and safety on facilities with high traffic volumes and numerous heavy trucks"; however, ". . . criteria are not established for these conditions. . . ."

It is evident that no such compensatory design has been provided on tens of thousands of miles of rural TLTW roads for downhill curve superelevation, a condition particularly serious for large truck safety given the usual modus operandi of big trucks of highballing downgrades to offset the gradual deceleration that accompanies the traversal of moderate to severe upgrades. When combined with the poor brakes and braking efficiency found in many big rigs (16), inadequately superelevated curves on downgrades are especially dangerous both for negotiation of the curve and for any necessary braking maneuvers. This is a point at which the SSD insights of Olson et al. (9) integrate with the superelevation discoveries of Zador et al. (15) and the curvature insights of Glennon et al. (11).

It is clear by now to any reader that older TLTW roads are riddled with substandard, hazardous design and operating features. Moreover, the latest design guide, the green book, gives inadequate direction for the substantial improvement of those geometric features that, in their interactive influence on driver and vehicle behavior, provide a context for predictably higher accident rates. And whatever the serious shortcomings of these badly designed, and oftentimes inadequately rehabilitated, roads may be for automobiles, their adverse effects on the safety of big trucks are magnified. The compatibility of big trucks with the operating environment produced by the interaction of narrow lanes, deficient superelevation, unspiraled and severe horizontal curves, and severe grades is largely fortuitous; and the attempt by some to rationalize away these systemic incompatibilities by appealing to the experienced compensating driving behavior of many truckers is sheer folly. An approach to geometric design on older roads that rationally accommodates the actual ranges of legally licensable drivers and vehicles is totally lacking. On TLTW roads with significant curvature and grades, there is no vehicle more disenfranchised from the protection that should be afforded any highway user than the big truck. Current efforts at a national level to argue the adequacy of these geometrically deficient facilities is nothing more than lame ex post facto constructions.

As Glennon and Harwood point out in their deservedly famous article of 1978 (17,p.80),

> The apex of the objective design process is the requirement that desired goals be defined and completely quantified. In addition, of course, these goals must be defined within the framework of a functional classification of highways. This points to a primary weakness of the AASHTO policies. Although they name the goals of safety, efficiency, economy, and comfort, they do not operationally define these goals.

And (17,pp.80,82)

> In the design process, a lack of understanding of basic design constraints and how they affect the solution contributes to piecemeal optimization. The current approach tends to ignore the consistency of various combinations of design elements and thus oversimplify the process and limit the reliability of relations for most design purposes.
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> [D]esign consistency means that combination of design elements (and their dimensional specification) . . . does not violate the abilities of the driver to guide and control the vehicle. Therefore, the concept of driver expectancy is wholly embodied in the general definition of design consistency.

And, finally (17,p.82),

> Although the concept of design consistency has been given substantial attention in the design policies, there is a general lack of explicit criteria for the contiguous combination of basic design elements or for the longitudinal variations of such features as horizontal alignment, vertical alignment, and cross section. Without these explicit criteria, highway designers will continue to build inconsistent geometric details into highways.

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