Geometric Design of Exclusive Truck Facilities

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ABSTRACT

Past truck research is studied to determine the applicability of AASHTO geometric design policies to exclusive truck facilities. The policies addressed include those with respect to vehicle characteristics, sight distance, horizontal alignment, vertical alignment, and cross-section elements. Each existing AASHTO design policy is described, the applicability of the policy to exclusive truck facilities is discussed, and alternative design criteria are recommended where past research warrants possible changes.

Rapid traffic growth has prompted the Texas State Department of Highways and Public Transportation (SDHPT) to examine various techniques to handle the corresponding increase in truck traffic demands. The SDHPT sponsored a study to evaluate the needs of a special truck lane along the I-35 corridor between Dallas and San Antonio. The objectives were to identify areas with a high volume of trucks, establish operational and design procedures to deal with truck traffic, and evaluate the effects of the proposed recommendations.

One specific alternative of interest was the feasibility of using existing median areas to accommodate exclusive truck facilities (ETFs). These lanes would be located on intercity corridors where high volumes of truck traffic existed or were projected. The I-35 corridor was selected as the initial segment for evaluation. Findings of this initial study will be used to establish procedures for evaluating other high-volume truck corridors in the state.

The analysis procedure involved two distinct phases. The first documented the physical problems associated with placing ETFs in the existing right-of-way. The second phase consisted of the review of current geometric design policy to determine its applicability to ETFs. Major elements of the study included geometrics, right-of-way availability, operations, safety, pavement requirements, and costs of the potential improvements.

Roadway geometry was a primary consideration in the analysis. Geometric design was addressed initially because it affects right-of-way limits, operational efficiency, safety, and construction costs. Current roadway design policies largely reflect those outlined in AASHTO's Green Book (1). However, these policies are based on the assumption that the majority of the design traffic will be automobiles, with a relatively small percentage of large trucks.

No publication exists that provides specific guidelines for the geometric design of ETFs. A detailed literature review of truck-related information was conducted to determine the feasibility of applying the findings to the design of ETFs. This paper summarizes the review of the pertinent design elements and identifies areas where additional design criteria are necessary. The following elements were examined: vehicle characteristics, sight distance, horizontal alignment, vertical alignment, and cross-section elements. Further research is needed to satisfactorily address the design requirements of ETFs.

VEHICLE CHARACTERISTICS

There are numerous publications dealing with vehicle characteristics and their effect on roadway design. The literature generally provides guidance on geometric requirements for several specific vehicle characteristics.

AASHTO (1) policy addresses two distinct classes of vehicles--passenger cars and trucks. Passenger car characteristics should be excluded in the design of ETFs. The AASHTO truck class is categorized by single-unit trucks, buses, truck tractor-semitrailer combinations, and trucks or truck-tractors with semitrailers in combination with full trailers. Current vehicle dimensions are shown in Table 1. Truck characteristics can be further divided into two categories--size and performance. The size category includes vehicle height, width, and length and driver eye height. The performance category includes weight-to-horsepower ratios, braking ability, acceleration, and deceleration. A summary of truck characteristics and the geometric features that they affect is shown in Table 2 (2).

TABLE 1 AASHTO Design Vehicle Dimensions *(1)*

Design Vehicle Type	Vehicle Dimensions (ft) Height	Width	Length
Single-unit truck (SU)	13.5	8.5	30
Intermediate semitrailer (WB-40)	13.5	8.5	50
Large semitrailer (WB-50)	13.5	8.5	55
Double-bottom semitrailer with full trailer (WB-60)	13.5	8.5	65

Vehicle height is generally 13.5 ft because of clearance restrictions on U.S. highways. Truck operators and manufacturers have expressed little interest in raising limits of vehicle height because of existing loading-dock dimensions, stacking limitations of most commodities, and vehicle instability on sharp curves in high wind situations (3). No change in AASHTO policy for design vehicle height appears necessary for the design of truck facilities.

AASHTO recommends a design vehicle width of 102 in. The Surface Transportation Assistance Act of 1982 requires states to allow the operation of 102-in.-wide trucks on the Interstate system regardless of the maximum-vehicle-width laws in the individual states. The 102-in. width should represent a minimum design vehicle width. Larger widths could be used, depending on the amount of oversize permits issued along the particular corridor. Increased vehicle widths directly affect pavement costs because of lane-width requirements. Therefore increasing design vehicle width may require cost/benefit analyses on an individual-corridor basis.

TABLE 2 Geometric Features and Related Vehicle Characteristics *(2)*

Geometric Feature	Related Vehicle Characteristic
Sight distance	
Stopping sight distance	Braking distance, eye height
Passing sight distance	Vehicle length, acceleration
Horizontal alignment	
Superelevation	Vehicle height (C.G.)
Degree of curve	Vehicle height (C.G.)
Widths of turning roadways	Vehicle length, width
Pavement widening on curves	Vehicle length, width
Vertical alignment	
Maximum grade	Weight-to-horsepower ratio
Critical length of grade	Weight-to-horsepower ratio
Climbing lanes	Weight-to-horsepower ratio
Vertical curves	Eye and headlight heights
Vertical clearance	Vehicle height
Cross-section elements	
Lane widths	Vehicle width
Shoulder widths	Vehicle width
Traffic barriers	Vehicle mass and C.G.
Side slopes	Vehicle height (C.G.)

Note: C.G. = center of gravity.

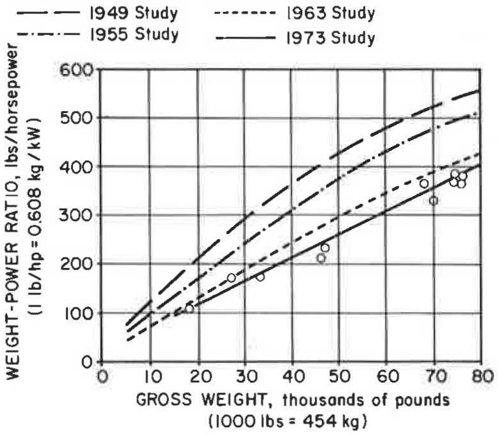

FIGURE 1 Trend in weight-to-horsepower ratios from 1949 to 1973 *(1)*.

AASHTO design vehicle length varies according to the vehicle type. The longest design vehicle is a WB-60, which is 65 ft. Since the 1982 Surface Transportation Assistance Act, vehicles up to 65 ft long are permitted access to the Interstate system. Several states have allowed combinations of greater than 65 ft to operate on their roadways for a number of years (4). Walton and Burke (5) have assembled a series of configurations for various truck types of differing size and weight that represent feasible maximum vehicle lengths. The longest vehicle configuration presented is a triple combination that is 105 ft long. This configuration is legal in some states at this time. Because this vehicle type is already in service, it is recommended as the minimum design vehicle configuration for ETFs.

A study of truck driver eye height yielded values of 94 in. for cab-over and 101 in. for cab-behind-engine truck configurations (6). These heights were determined for an individual of average height seated in each type of truck. Six trucks from three manufacturers were used in this study. However, Middleton et al. (7) reported a different relationship for truck driver eye height: 107 in. for a cab-over truck, 93 in. for a cab-behind configuration, and 91 in. for a low-cab-over configuration. This study was based on an average of eye heights provided by five different truck manufacturers. The difference in these findings demonstrates the need to determine the range of truck driver eye height. Once an appropriate range has been established, a sensitivity analysis should be performed to determine the significance of the variations.

Current AASHTO policy (1) uses a weight-to-horsepower ratio of 300 lb/hp to represent the characteristics of heavy vehicles operating on grades. Previous versions of the policy (8,9) used a 400:1 ratio. Figure 1 shows the changes in the average weight-to-horsepower ratio for vehicles operating on U.S. highways between 1949 and 1973. Walton and Gericke (10) state that today's trucks perform better than national representative trucks of the past because of superior engines and transmissions.

AASHTO policy argues that 300-lb/hp trucks have operating characteristics that are acceptable to the highway user, that carrier operators are voluntarily using this value in the determination of maximum truck loading, and that the manufacturers of trucks find this value acceptable for the design of the vehicle. However, a 1984 study (11) found a larger portion of multiple combination trucks operating in the range of 0 to 100 lb/hp (see Figure 2). The 300-lb/hp value, nonetheless, appears appropriate for the design of ETFs.

Heavy-vehicle braking performance depends primarily on tire type and condition, weight of the vehicle, road surface characteristics, number of axles, and number of tires per axle. Several researchers have measured heavy-vehicle braking distance. However, because pavement friction, driver selection, vehicle condition, and test procedures varied among researchers, caution must be exercised in interpreting the results of previous vehicle braking studies.

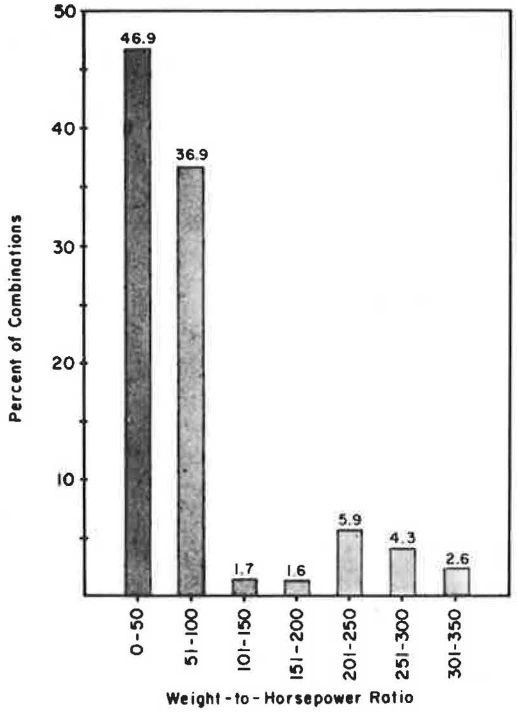

FIGURE 2 Distribution of weight-to-horsepower ratios for combinations operating in the United States *(11)*.

Peterson and Gull (12) conducted braking tests in Utah to determine the braking performance of single, double, and triple combination trucks. The tests were performed on both wet and dry pavement surfaces. The wet and dry coefficients of friction were 0.64 and 0.92, respectively. They noted that the FHWA Motor Carrier Safety Regulations specify deceleration rates of 21 $ft/(sec)^2$ for passenger cars and 14 $ft/(sec)^2$ for truck combinations on dry pavements. Federal regulations also require that a truck stop within a distance of 40 ft from an initial velocity of 20 mph. On the basis of the 40-ft stopping distance requirement and the 14-$ft/(sec)^2$ deceleration rate, the relationship of required braking distance versus initial speed is plotted in Figure 3. Also shown are the passenger car stopping distances predicted by using the AASHTO braking-distance equation. The FHWA truck stopping-distance curve illustrates the longer braking-distance requirements. For example, a truck traveling 30 mph on dry pavement requires approximately 50 ft more braking distance than does a passenger car traveling at the same speed on the same pavement. It will be necessary to develop braking-distance criteria for ETFs to reflect truck braking characteristics.

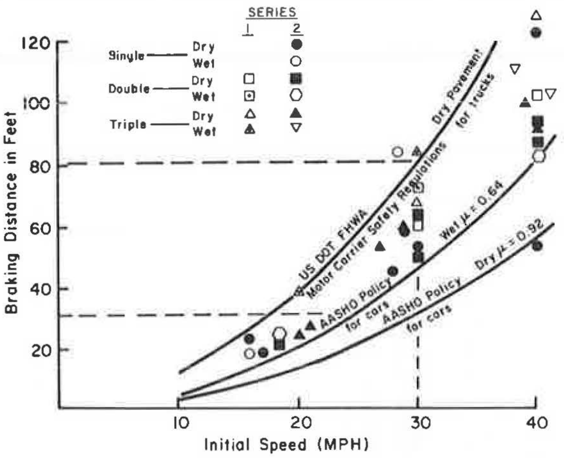

FIGURE 3 Braking distances of various combinations compared with AASHTO and FHWA stopping distance values *(12)*.

Truck performance on grades has been routinely investigated. Many studies have been conducted to describe truck deceleration on upgrades and acceleration on downgrades. This information is used to determine maximum permissible grades, critical lengths of grades, and climbing-lane design. Deceleration curves are shown from the 1965 AASHTO Blue Book (Figure 4 (9)], from the state of Texas in 1976 [Figure 5 (10)], from 1979 California studies [Figure 6 (13)], and from the AASHTO Green Book [Figure 7 (1)]. The improved performance indicated in these curves is attributable to decreasing weight-to-horsepower ratios. Increased performance of trucks on grades allows shorter, less frequent auxiliary truck lanes on uphill sections and greater permissible grades throughout the system. In short, a higher performance design vehicle results in lower construction costs because of minimized cut-and-fill operations and a reduced need for climbing lanes.

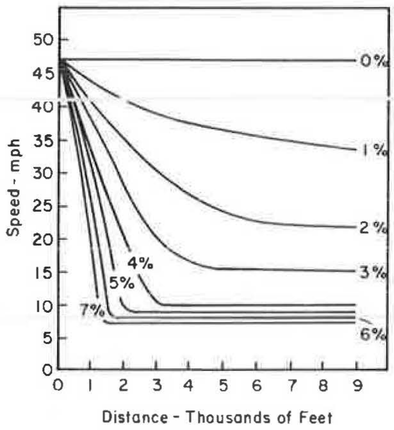

FIGURE 4 Deceleration curves from 1965 AASHTO Blue Book *(9)*.

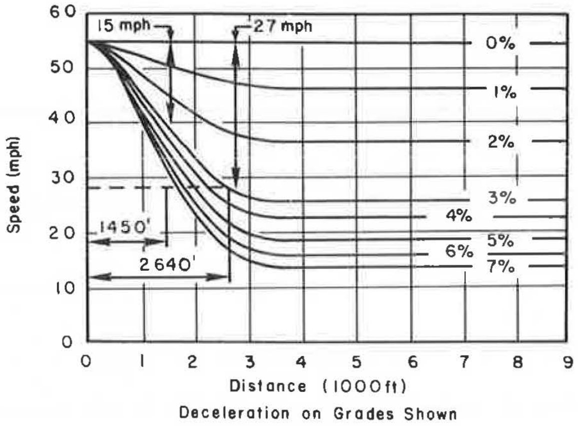

FIGURE 5 Deceleration curves from Texas in 1976 *(10)*.

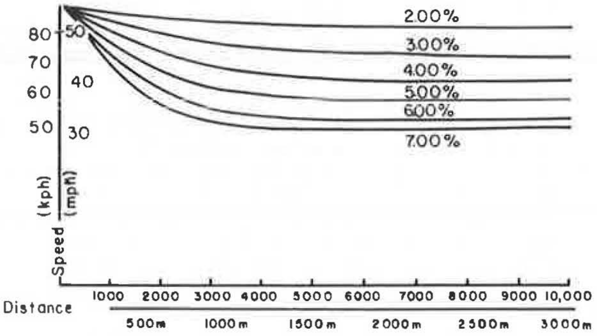

FIGURE 6 Deceleration curves from 1979 California studies *(13)*.

SIGHT DISTANCE

AASHTO (1) assumes that the increased stopping distances that trucks require are compensated for by the greater sight distance of the truck drivers because of higher eye heights. Studies indicate that this may not always be the case, especially where heavily loaded trucks are concerned (7,14).

A study of truck sight distance requirements (14), for example, concluded that heavily loaded trucks require stopping distances of such magnitude as to eliminate any sight distance advantages over current AASHTO criteria. Sight distance advantages of trucks on crest vertical curves were calculated relative to sight distances provided for passenger cars. Braking distances were then calculated by us-

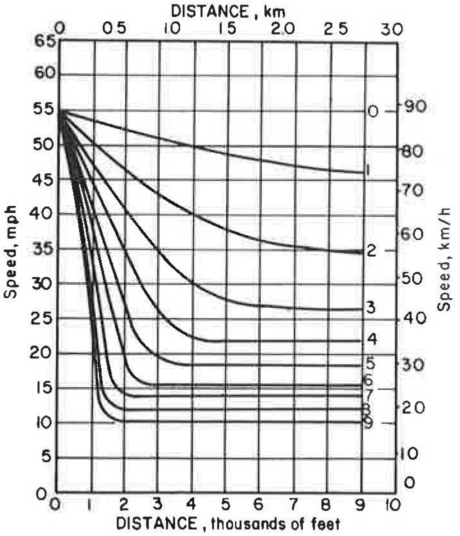

FIGURE 7 Deceleration curves from AASHTO Green Book *(1)*.

ing data from on-the-road vehicle braking tests conducted by the Bureau of Motor Carrier Safety. It was found that the upper range of truck braking distances obtained in the study was large enough to negate the advantages of the commanding view afforded truck drivers.

The foregoing study also addressed the sight distance requirements for truck passing zones. Trucks generally enjoy a 17 to 27 percent increase in sight distance relative to that of passenger cars on crest vertical curves. In current practice, passenger car operating characteristics are used in the determination of passing zones for cars passing cars on two-lane highways. However, passing-zone requirements for cars passing trucks are 1.25 to 2 times the distance required for cars passing cars. Trucks passing trucks unfortunately require even greater distances. It is therefore necessary to revise passing-zone design to reflect the truck-passing-truck situation.

The horizontal sight distance criteria on curves used by AASHTO may also need to be reformulated (2). AASHTO assumes that on vertical curves, the increase in truck driver eye height relative to that in passenger cars compensates for the increased braking requirements of heavy trucks. However, the sight distance requirement on a horizontal curve is not a function of driver eye height alone. It is primarily a function of the distance of an obstruction from the center of the inside travel lane. Thus, the direct application of a safe stopping sight distance based on passenger car driver eye height cannot be used for ETFs.

Specific eye height criteria will have to be established for ETFs. The selected criteria will be reflected in the design of vertical curves, passing-zone markings, and horizontal curves.

HORIZONTAL ALIGNMENT

AASHTO uses the minimum-radius equation for the design of horizontal curves:

$$e + f = V^2/15R \qquad (1)$$

where

V = vehicle design speed (mph),
e = superelevation rate,
f = limiting side friction factor, and
R = radius of curvature (ft).

The side friction factor (f) was established based on comfort of the driver while negotiating a turn. One weakness of this method has been identified by Weinberg and Tharp (15), who state that f fails to take into account the tendency of the vehicle to overturn on a curve. A side friction factor that has not exceeded the driver comfort range may be of sufficient magnitude to cause a heavily loaded vehicle with a high center of gravity to overturn while it is negotiating a curve (3).

The determination of the distribution of the actual centers of gravity of commercial vehicles is necessary to properly evaluate the sensitivity of on-the-road variations. Certain computer programs that model heavy-vehicle responses to various inputs could possibly be used to redefine the f-value in terms of overturning moments of a variety of vehicle configurations.

The maximum values of superelevation used in practice are primarily limited by climatic conditions, terrain characteristics, and rural or urban design considerations rather than by vehicle characteristics. For ETFs, the rate of superelevation may need to be revised to reflect the limiting f-values associated with rollover thresholds (16). Preliminary review indicates that the critical value of f may be near 0.25 for low-speed turning maneuvers. Superelevation on turning roadways at intersections and interchanges may need to be increased relative to current practice so that excessive friction requirements associated with these maneuvers do not result in vehicle turnovers.

VERTICAL ALIGNMENT

In 1969, Glennon and Joyner (17) reevaluated the AASHTO design criteria that related truck operating characteristics on grades to the implementation of truck climbing lanes. They found that the 400-lb/hp ratio used for truck speed-distance curves represented a reasonable lower boundary for trucks operating on the roadway at that time. They recommended that the AASHTO 15-mph speed reduction criterion be reduced to 10 mph. In addition, they recommended that the downhill portion of the auxiliary truck lanes be extended to allow reentry speeds closer to average running speeds. The current AASHTO design policy (1) has adopted the 10-mph speed reduction and a 300-lb/hp ratio for critical length-of-grade determination. These criteria can be reasonably applied to ETF design.

Middleton et al. (7) studied the relationship between available stopping sight distance of heavy trucks and the required braking distance on crest vertical curves. They concluded that on such curves where there were large differences in tangent grades, drivers of heavy trucks would not always have the required sight distance needed to stop in time to avoid hitting a 6-in. obstacle on the road. The same was true for a 15-in. obstacle, which was chosen to represent the taillights of a passenger car. Vertical-curve design policy will need to consider critical combinations of tangent grades to avoid sight distance deficiencies on ETFs.

Gordon (14) found that because visibility on sag curves is a function of headlight heights and beam angles, trucks would experience no sight distance deficiencies on sag curves designed according to AASHTO policy.

CROSS-SECTION ELEMENTS

Lane Widths

Weinberg and Tharp (15) state that lane widths on tangent and comparatively flat curves have been determined by the summation of safe lateral clearance between opposing vehicles, the clearance between the vehicle and pavement edge, and the width of the vehicle. On turning roadways, offtracking and front and rear overhang characteristics are added to the foregoing variables to obtain needed lane widths. In short, adequate pavement widths are a function of body and edge clearances for meeting and passing vehicles.

The Red Book (8), Blue Book (9), and Green Book (1) state that lanes 12 ft wide are preferred for high-type multilane facilities and two-lane highways. For freeways, the assumption is made that traffic conditions that dictate the use of a multilane configuration also dictate the use of 12-ft lane widths. For two-lane highways, a 12-ft lane width is considered essential in maintaining adequate clearance between commercial vehicles. For ETFs a 13-ft lane width may be desirable, especially if large volumes of oversize vehicles are to use the facilities. Walton and Gericke (10) state that the need for adequate clearance between vehicles necessitates providing 12-ft lanes for the operating of 102-in.-wide trucks.

In 1945, Taragin (18) studied the relationship between lane widths and vehicle operation. He collected data on lateral placement of passenger cars and trucks on various types of two-lane highways. The roadway widths of these highways varied from 18 to 24 ft and shoulder width varied from 2 to 10 ft. Lateral placement data were collected for cars and trucks traveling freely, encountering opposing vehicles, and passing vehicles traveling in the same direction. Saag and Leisch (2) utilized these data to determine the desired left and right lateral clearance for cars and trucks on rural highways. They concluded that truck drivers desire 2.5 ft of clearance between the left side of the truck and the left edge of the traffic lane when they are meeting or passing other trucks. In addition, for the same maneuver, the driver desires a clearance of 2 ft from the right side of the truck to the right edge of the traffic lane. They further concluded that with a truck width of 8 ft or more, trucks on 12-ft-wide pavements did not have enough lateral pavement width to achieve these clearances. Saag and Leisch presented an equation to determine desirable pavement lane widths as a function of vehicle width:

$$L = 4.5 + W_v \tag{2}$$

where

W_v = vehicle width (ft),
L = lane width (ft), and
4.5 = sum of desired right and left clearances (ft).

Thus for an 8.5-ft-wide truck, the desired lane width is 8.5 + 4.5, or 13 ft.

Taragin assumed that drivers were satisfied with lane widths when the lateral position of the vehicle within the traveled way remained constant for free-moving, opposing, and passing maneuvers. In addition, he assumed that drivers positioned their vehicles near the center of the traveled lane when they were satisfied with the lane widths provided. On the basis of these assumptions, certain studies indicate that truck drivers are not satisfied with lanes 12 ft wide.

For example, a study was conducted by Canner and Hale (19) to determine vehicle encroachment on bituminous shoulders and lateral placement of vehicles within the right-hand lane of four-lane divided highways. The vehicles studied were trucks with dual tires on the back axle, tractor-trailer combinations, and buses. The highway sections were edge striped so that the effective lane width was 12 ft. However, the pavement extended 3 ft outside the right-edge stripe in some sections. At these sections, heavy vehicles moved toward or crossed over the right-edge stripe more often than on sections where the edge stripe was located at the edge of the pavement.

Lee (20) conducted studies of lateral placement of trucks on four-lane divided highways with 12-ft traffic lanes. His data indicate that the largest percentage of observations of wheel placement were within 2 ft or less from the right pavement edge. As the size of the truck increased, the percentage of observations within the 2-ft distance increased. Also, the frequency of placement within the 2-ft distance increased on curved sections of roadway.

The foregoing two studies support the statement by Saag and Leisch that truck drivers are not satisfied with 12-ft lane widths. Thus, as a consequence, lane widths of 13 ft or greater are recommended for exclusive truck operations.

Width of Shoulders

AASHTO (1) defines highway shoulders as a portion of the roadway for the accommodation of stopped vehicles, emergency use, and lateral support of surfaces and base courses of the roadway. Shoulders are recommended to be of sufficient width to provide 2 ft of clearance between the edge of the traffic lane and the stopped vehicle.

Right shoulders are commonly 10 ft wide on freeways and other high-type facilities; in areas with a high volume of truck traffic, 12-ft right shoulders are recommended. For sections with many through lanes, 10-ft-wide left shoulders are recommended. Shoulders should be continuous and full width across all structures.

AASHTO policy (1) distinguishes between graded and usable shoulders. The graded shoulder width is the distance from the edge of the travelled way to the intersection of the shoulder slope and the front slope of the roadside. The usable shoulder width is that which can be used when a driver makes an emergency or parking stop. A distance of 2 ft from the outer edge of the usable shoulder to roadside barriers, walls, or other vertical elements is recommended. Adequate shoulder widths reduce the potential for collisions with fixed obstacles, overturning of vehicles, running off the roadway, and pedestrian accidents.

Authorization of 102-in.-wide trucks on roadways should not affect AASHTO's current policy on shoulder widths because a 102-in. vehicle width is assumed in its design vehicle. For special-use truck facilities with high percentages of oversize trucks, it may be necessary to reevaluate shoulder width criteria.

Seguin et al. (21) mention shoulder characteristics as a source of potential truck problems on urban freeways. Right shoulder widths averaged 8 to 10 ft; more than 85 percent of right shoulders were 6 ft or wider. Left shoulders averaged 3 to 5 ft in width, and over 50 percent were narrower than 6 ft. In most cases, left shoulders were not adequate to handle trucks making emergency stops. The inadequate widths did not allow trucks to clear the through lanes without running into the median areas. Problems with narrow shoulder widths were often compounded by narrow median widths, which eliminated the possibility of shoulder widening. As more 102-in.-wide trucks use the urban Interstates, these problems will probably worsen. To avoid these types of problems, shoulders of adequate width should be provided on truck facilities. No change in AASHTO policy is considered necessary at this time; nevertheless, attention should be given to oversize-vehicle operation, which may warrant increases in shoulder width.

Guardrails

The Green Book (1) states that guardrails should be used where vehicles leaving the roadway would be subject to hazard, but only if the roadside hazard constitutes a greater threat to safety than striking the guardrail itself. Guardrails are designed to redirect the impacting vehicle, reduce its velocity, and guide it along the rail while it decelerates. Current design standards for guardrails assume a design vehicle of 4,500 lb traveling 60 mph and striking the rail at a 25-degree angle (22). No provisions for heavy vehicles are made in the design of most guardrails. As a consequence, most of the roadside hardware in existence today is proving to be inadequate for heavy vehicles such as trucks and buses (23). Facilities designed exclusively for heavy vehicles will require the redesign of roadside hardware.

Several types of guardrails and bridge rails are in use today that will successfully redirect heavy vehicles with minimal property damage. The most common is the concrete median barrier, or safety shape. Full-scale impact testing with heavy vehicles resulted in the successful restraining and redirection of a vehicle at speeds of up to 45 mph at a 15-degree impact angle (24). Concrete bridge rails have also been developed for redirection of errant trucks on elevated structures (25). However, because these rails are somewhat expensive ($41 per foot in 1980), research is needed to develop less costly barriers for heavy vehicles.

Drainage Channels and Side Slopes

Drainage channels, while performing the vital task of directing water away from the highway, should not pose a serious safety hazard to errant vehicles. Extensive studies have been performed to determine optimum ditch designs for highways using passenger cars as test vehicles (26). Because of obvious cost problems, few, if any, studies have been performed on the effects of ditches on the recovery of errant heavy vehicles.

Roadway side slopes are a similar matter. In most cases, vehicle testing on side slopes has been performed with passenger cars as test vehicles. Published data are lacking concerning the controllability of heavy vehicles on roadside slopes. Current criteria provide a starting point in the determination of safe roadside cross sections for heavy vehicles.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of a literature review of truck studies, the following additions to current highway design policy should be considered in the development of criteria for the design of ETFs:

1. Vehicle characteristics
    a. A 105-ft double or triple combination design vehicle should be incorporated into design policy.
    b. Ranges of truck driver eye heights for different truck classes are necessary.
    c. Standardized brake testing of vehicles is needed to produce accurate braking distance requirements for different truck classes.
2. Sight distance
    a. A design driver eye height representing a worst-case scenario should be considered in predicting sight distance requirements for cab-under-truck configurations.
    b. Sight distance requirements on horizontal curves should be calculated and increased stopping distance requirements of heavy vehicles should be accounted for.
3. Horizontal alignment
    a. The side friction factor (f) may warrant modification in consideration of truck overturning moments.
    b. Superelevation rates on turning roadways may need to be increased at low speeds to compensate for vehicle rollover.
4. Vertical alignment
    a. Provisions for auxiliary truck climbing lanes should reflect the 10-mph speed reduction criterion recommended in the revised AASHTO policy.
    b. Crest vertical curve length criteria should be examined for the stopping distance requirements of heavily loaded trucks.
    c. Passing-zone design on ETFs must consider truck performance limitations.
5. Cross-section elements
    a. A design vehicle representing a heavily loaded vehicle with a high center of gravity is needed for designing barriers for ETFs.
    b. Little information is available to predict behavior of errant heavy vehicles on varying roadside slopes. Research into this area is needed in order to develop criteria for a safe roadside environment on truck facilities.

These recommendations provide a starting point in developing geometric criteria for ETFs. They do not represent an opposing viewpoint to current AASHTO policy; rather, they identify areas of concern in the design and construction of unique truck roadways.

ACKNOWLEDGMENT

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