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Longitudinal Barriers for Buses and Trucks

T. J. HIRSCH

ABSTRACT

In May 1976 two significant accidents occurred involving traffic bridge rails. An ammonia truck in Houston, Texas, struck a bridge rail leaving 11 dead, 73 hospitalized, and causing 100 other injuries for a total of 184 casualties. In Martinez, California, a school bus struck a bridge rail and left 29 dead and 23 injured. As a result of these accidents, an extensive effort has been made to develop longitudinal traffic barriers or rails capable of restraining and redirecting buses and large trucks. The results of 34 crash tests conducted using automobiles and mostly buses and trucks on 16 different traffic rails were obtained from the references. Vehicles represented are 4,500-lb passenger automobiles, a 4,000-lb van or light truck, 20,000-lb school buses, 32,000- to 40,000-lb intercity buses, and 40,000- to 80,000-lb tractor-trailer trucks. Results of these crash tests are summarized. Theory and crash test results are presented to demonstrate the magnitude of the impact forces these traffic rails must resist and how high they must be to prevent vehicle rollover. Typical designs of longitudinal barriers that have been successfully crash tested in accordance with recommended procedures are presented.

In May 1976 two significant accidents involving traffic rails occurred. An ammonia truck in Houston, Texas, struck a bridge rail and fell on traffic below leaving 11 dead and 73 hospitalized and causing 100 other injuries for a total of 184 casualties. In Martinez, California, a school bus struck a bridge rail and fell upside down leaving 29 dead and 23 injured. As a result of these accidents, an extensive effort has been made to develop longitudinal traffic barriers or rails capable of restraining and redirecting buses and large trucks.

Before 1956, when the Interstate Highway Act was passed by Congress, most highway bridges crossed rivers, streams, or other natural features. Few highways had traffic lanes divided or separated by median barriers. Longitudinal barriers such as bridge rails, median barriers, and guardrails were designed only to restrain and redirect passenger automobiles. It was the general attitude that buses and trucks were driven by trained, skilled, professional drivers, and sensational traffic barrier accidents with buses and trucks were rare.

Since 1956 tens of thousands of miles of divided traffic lane Interstate highways, urban expressways, and freeways have been built. Most of the bridges

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(1) on these systems are grade separation structures that cross other densely populated traffic lanes. In addition, with the demise of railroads and the increase in school busing, there has been a significant increase in the number of buses and trucks on the roadways. Consequently, the number of sensational bus and truck accidents involving longitudinal barriers has increased. Many highway engineers now believe that there are selected locations where barriers capable of restraining and redirecting buses and trucks are needed.

A search of the recent literature (1972 to 1985) yields 14 references to 34 crash tests into longitudinal traffic barriers that were conducted essentially in accordance with current recommended practice (2). These crash tests used automobiles, vans, buses, and trucks ranging in weight from approximately 4,000 to 80,000 lb. In general, the passenger automobile and van tests were conducted at 60 mph at a 25-degree angle into the longitudinal barriers. The school and intercity buses weighed from 20,000 to 40,000 lb, and tests with these vehicles were conducted at 60 mph at a 15-degree angle into the longitudinal barriers. The tractor-trailer trucks weighed from 40,000 to 80,000 lb and were crash tested at 50 mph at a 15-degree angle into the barriers. A summary of these vehicle crash test results is presented in Table 1.

These crash test results and some elementary theory (17-19) are presented to demonstrate the magnitude of the impact forces these longitudinal traffic barriers must resist and also how high these barriers must be to prevent vehicle rollover. In addition, typical designs are presented in Figures 1-3 of longitudinal barriers that have been successfully crash tested in accordance with current recommended procedures (2). The costs per foot of length shown on Figures 1-3 would be typical of Texas and are for comparison only.

BASIC MOTOR VEHICLE AND BARRIER PROPERTIES TO BE CONSIDERED

Most current longitudinal traffic barriers (guardrails, bridge rails, and median barriers) are designed only to restrain and redirect passenger automobiles ranging in weight from 1,700 to 4,500 lb. The recommended strength test (2) is for a 4,500-lb automobile to be redirected at 60 mph and a 25-degree angle impact. Figure 1 shows some basic properties of these automobiles and two common and effective longitudinal barriers that can restrain and redirect them. These automobiles have centers of gravity (CGs) ranging from 18 to 24 in. above the roadway. The 27-in.-high standard guardrail and 32-in.-high concrete safety shape are strong enough to redirect the automobiles and high enough to prevent rollover. These barriers exert a redirecting and stabilizing force on the fenders, tires, and door panels of the impacting car, as shown in the figure. The approximate cost per foot of these traffic barriers is shown for comparison purposes.

Figure 2 shows some basic properties of buses (school and intercity) and two traffic rails that have restrained and redirected them. School buses (66 passenger) generally weigh from 20,000 to 26,000 lb loaded. Intercity buses (45 passenger) generally weigh from 32,000 to 40,000 lb loaded. The CG of these buses ranges from 46 to 58 in., with an average of about 52 in. The two minimum height rails that have prevented these buses from rolling over under 60 mph, 15-degree angle impact are the two shown with heights of 38 and 42 in. The approximate cost per foot of the barrier is shown for comparison purposes.

Traffic rails 32 in. and 34 in. high have consistently produced rollover with buses at this speed and angle of impact. The significant redirection force from these barriers is delivered to the bus through the front and rear tires and axles. The largest impact force reported in Table 1 occurs when the rear tires and axle strike the barrier.

Figure 3 shows some basic properties of van and tank-type trucks and some longitudinal barriers that have restrained and redirected them. These trucks weigh from 25,000 lb empty up to 80,000 lb when fully loaded (21). The CG of an empty truck can be about 45 in., and a fully loaded truck could have a CG of from 60 to 78 in. Figure 3 shows three distinct locations or heights where a longitudinal barrier can effectively push on a van or tank truck to redirect it. A 42-in.-high barrier can push on the 42-in.-high tires (and axle). For a van-type truck, the floor system from 48 to 54 in. high is capable of receiving a significant redirecting force. Above this height the van truck generally has a very thin weak sidewall that is not capable of receiving much redirecting force.

A tank truck can receive a redirecting force through the tires up to 42 in. high and then another redirecting force at about 84 in. high into the central area of the usually circular tank. A traffic rail element between approximately 42 and 78 in. usually has nothing to push against.

The 42-in.-high concrete parapet barrier shown redirected without rollover an 80,000-lb van truck with a 65-in.-high CG. A similar truck with a 78-in.-high CG rolled over the 42-in.-high barrier (5). All these tests are nominally at 50 mph and 15-degree angle impact.

The 50-in.-high combination barrier (concrete parapet with metal rail on top) restrained and redirected an 80,000-lb van truck with a 66-in.-high CG. The truck rolled over on its side. However, it did not go over the bridge rail, and the truck remained on the simulated bridge. This was considered a successful test for a truck. A rollover would not be acceptable for a passenger automobile or a bus.

The 54-in.-high combination bridge rail shown smoothly restrained and redirected an 80,000-lb van truck with a 64-in.-high CG (no rollover).

STRENGTH REQUIREMENTS OF LONGITUDINAL BARRIERS

A relatively simple method of predicting the impact forces on a longitudinal barrier is the equations presented in NCHRP Report 86 (22).

Figure 4 shows a vehicle striking a longitudinal traffic rail at an angle (θ). From this illustration of the impact event it can be shown that the average lateral vehicle deceleration (G_{lat}) is

$$\text{avg } G_{lat} = [V_I^2 \sin^2(\theta)]/(2g\{AL \sin(\theta) - B[1 - \cos(\theta)] + D\}) \qquad (1)$$

If the stiffness of the vehicle and rail could be idealized as a linear spring, the impact force-time curve would be in the shape of a sine curve; then the peak or maximum lateral vehicle deceleration (max G_{lat}) would be

$$\text{max } G_{lat} = (\pi/2)(\text{avg } G_{lat}) \qquad (2)$$

The lateral impact force (F_{lat}) on the traffic rail would then be equal to the lateral vehicle deceleration times the vehicle weight, thus

$$\text{avg } F_{lat} = (\text{avg } G_{lat})W \qquad (3)$$

and

TABLE 1 Summary of Vehicle Test Results

Author	Test No.	Test Condition Vehicle-CG (in.) and Vehicle Weight-Speed-Angle (lb-mph-degrees)	Max. Avg. 0.05-sec Force		Height of		Barrier and Remarks
			Load Cells (kips)	Accelerometer (kips)	Resultant (in.)	Barrier (in.)	
Noel *(3,4)*	3451-32	Plymouth-22 4,680-52.9-15	52.1	43.6	21.2	42	Concrete wall; smooth redirection
	3451-36	Plymouth-22 4,740-59.9-24	59.9	69.6	21.9	42	Concrete wall; smooth redirection
Buth *(5)*	4798-7	Dodge van-30 3,983-59.2-24		20.0		27	W-beam guardrail, 2.34-ft deflection; van rolled over 270 degrees
Buth *(4)*	3451-9	School bus-50-43[a] 19,940-55.2-15		83.7		27	Reinforced W-beam bridge rail; redirection, front axle stripped[a]
	3451-10	School bus-50-43[a] 20,010-52.0-13.3		70.1		27	Reinforced W-beam bridge rail; redirection, front axle stripped[a]
	3451-11	Intercity bus-46 31,880-58.4-16		63.8		27	Reinforced W-beam bridge rail; redirection, bus rolled over
	3451-4	School bus-50 19,760-59.8-14.3		102.8		30	6- x 8-in. steel tube on 9-in. concrete parapet; redirection, bus rolled over
	3451-23	School bus-50 19,920-57.3-14.8		97.6		32	4-in. aluminum rail on 18-in. concrete parapet; redirection, bus rolled over
Davis *(6)*	3080-1	School bus-51.5 20,270-61.6-15		120.0		32	CMB concrete; bus rolled over
	3115-1	School bus-51.5 19,990-60.9-16		120.0		32	CMB concrete; bus rolled over
Ivey *(7)*	3825-8	School bus-50 20,000-57.7-15		106.0		32	CMB concrete parapet; bus rolled over
Kimball *(8)*	RF-26	School bus-55 23,000-57.1-14.7		89.7		32	Thrie-beam bridge rail; bus rolled over
	RF-27	Scenicruiser bus-56 40,000-59.7-17.6		No data		32	Thrie-beam bridge rail; bus rolled over
Davis *(6)*	8307-1	Scenicruiser bus-50 40,020-54-16.2		150.0		32	CMB concrete; redirection
	8307-3	Scenicruiser bus-50 40,030-54-14		170.0		32	CMB concrete; redirection
Buth *(5)*	4798-12	Scenicruiser bus-56 39,970-59.6-14.5		179.9		34	Thrie-beam median barrier; bus rolled over
Kimball *(8)*	RF-28	Scenicruiser bus-56 40,000-56.3-14.5		164.0		38	Thrie-beam bridge rail; smooth redirection
Hirsch *(9)*	230-3	School bus-50 19,690-54.4-15		96.5		42	Concrete parapet and metal rail; smooth redirection
Noel *(3,4)*	3451-34	School bus-50 20,030-57.6-15	73.8	82.2[b]	32.7	42	Concrete wall; smooth redirection
	3451-35	Intercity bus-46 32,020-56.9-15.7	211.2	220[b]	28.4	42	Concrete wall; smooth redirection
Hirsch *(9)*	230-5	Intercity bus-46 32,080-61.1-15		105.9		42	Concrete parapet and metal rail; smooth redirection, 44-in. rail deflection
Kimball *(10)*	BR-8	School bus-53± 19,000-60.9-13.9		74.1		59	Collapsing ring bridge rail
	BR-11	Intercity bus-53± 40,000-54.2-15.1		88.0		59	Collapsing ring bridge rail, 35-in. permanent deflection
Bronstad *(11)*	TTR-2	School bus-53± 20,000-55.2-13.7		80.0		60	Thrie-beam bridge rail; bus rolled over, rail deflection
	TTR-3	School bus-53± 20,000-53.9-15.3		70.0		60	Thrie-beam bridge rail; good redirection
Ivey *(12)*	3825-17	Ford truck-58 18,240-60.1-15		153.0		32	CMB concrete; truck rolled over
Davis *(6)*	8307-2	Tractor-trailer van-60 40,030-53-15		110.0		32	CMB concrete; truck mounted and straddled CMB
Hirsch *(13)*	CMB-7	Tractor-trailer van-55 48,800-44.7-15		143.2		32	CMB concrete parapet; smooth redirection
Buth *(5)*	4348-2	Tractor-trailer van-78 80,180-52.8-15		194.0		42	Concrete parapet CMB type; truck rolled over
	4798-13	Tractor-trailer van-65 80,180-52.1-16.5		108.5		42	Concrete parapet CMB type; redirection
Hirsch *(14)*	416-1	Tractor-trailer van-66 80,080-48.4-15		188.0		50	Concrete parapet CMB type and metal rail; truck rolled over
Hirsch *(15)*	230-6	Tractor-trailer van-64 79,770-49.1-15		200.5		54	Concrete parapet and metal rail; smooth redirection
Kimball *(10)*	BR-14	Tractor-trailer van-50 40,000-57.3-15.6		117.0		59	Collapsing ring bridge rail, 10-ft deflection; truck rolled over, defective rail
Hirsch *(16)*	911-1	Tractor-trailer tank-72 80,120-51.4-15		188.6		90	Concrete parapet; smooth redirection

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[a] In Tests 3451-9 and 10 the school bus had a CG of 50 in. before impact. During impact with the 27-in.-high rail, the front axle was knocked out from under the bus and the front end of the bus dropped 24 in. The CG was almost instantly lowered 7 in. down to 43 in. before the rear axle impacted the rail. This unusual behavior had a significant stabilizing influence on the bus.

[b] Corrected for shifting load.

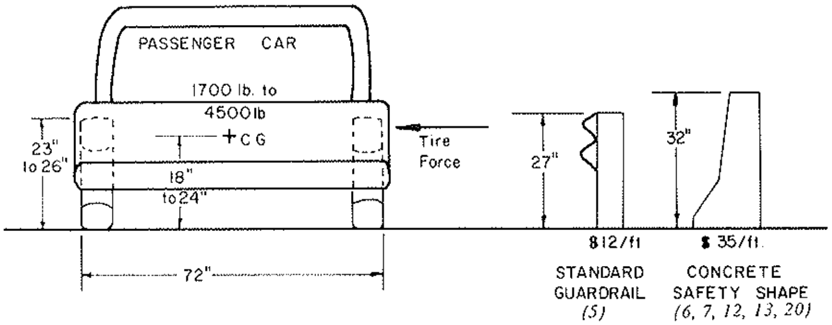


FIGURE 1 Basic properties of passenger automobile and effective longitudinal barriers.

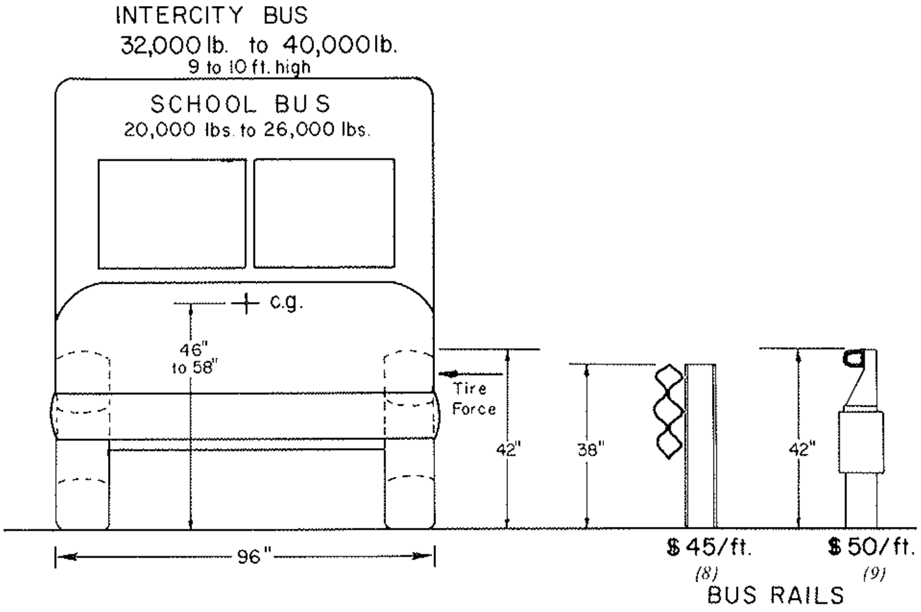


FIGURE 2 Basic properties of buses and two effective longitudinal barriers.

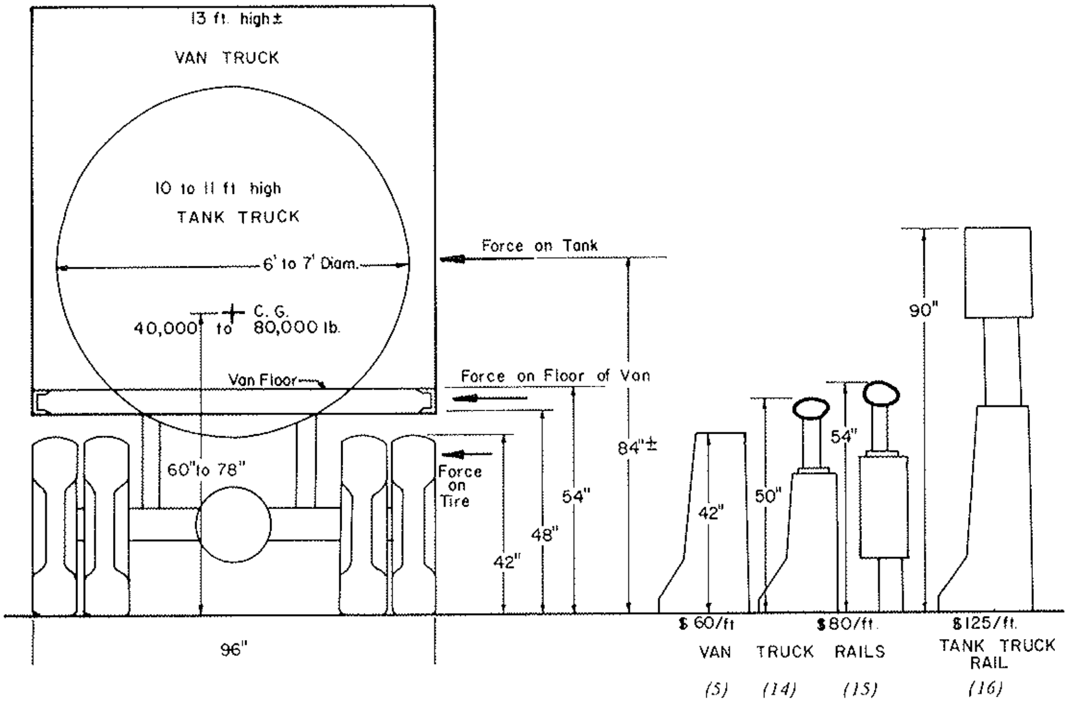


FIGURE 3 Basic properties of tractor-trailer trucks (van and tank types) and some longitudinal barriers that have restrained and redirected them.

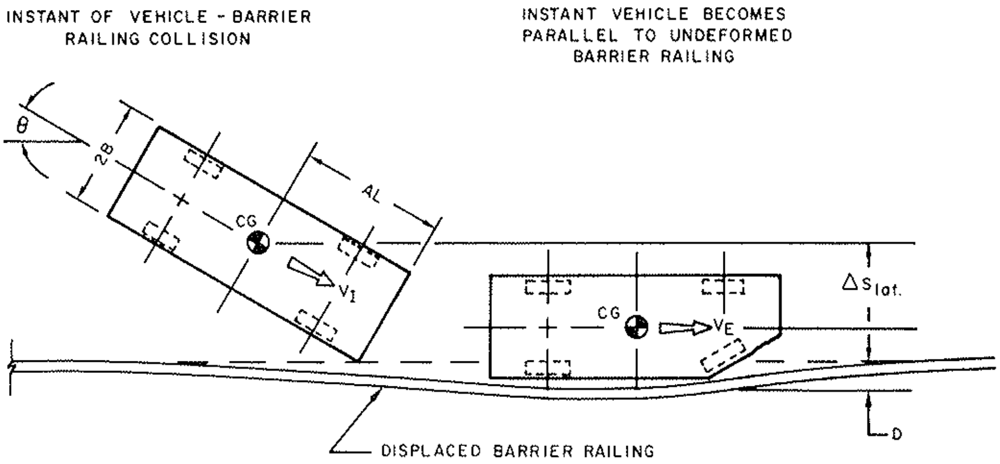


FIGURE 4 Mathematical model of vehicle-barrier railing collision *(22)*.

$$\max F_{lat} = (\pi/2)(\text{avg } F_{lat}) \qquad (4)$$

The longitudinal forces on the rail could be determined by multiplying the lateral forces times the coefficient of friction (μ) between the vehicle and the rail. The symbols used are defined as follows:

L = vehicle length (ft),
$2B$ = vehicle width (ft),
D = lateral displacement of barrier railing (ft) assumed to be zero for rigid rail,
AL = distance from vehicle's front end to center of mass (ft),
V_I = vehicle impact velocity (fps),
V = vehicle exit velocity (fps),
θ = vehicle impact angle (degrees),
μ = coefficient of friction between vehicle body and barrier railing,
a = vehicle deceleration (ft/sec²),
$\underline{g}$ = acceleration due to gravity (ft/sec²),
m = vehicle mass (lb-sec²/ft), and
W = vehicle weight (lb).

Equations 1-4 express average vehicle decelerations as a function of (a) type of barrier railing, rigid or flexible; (b) dimensions of the vehicle; (c) location of the center of mass of the vehicle; (d) impact speed of the vehicle; (e) impact angle of the vehicle; and (f) coefficient of friction between the vehicle body and the barrier railing. When computed deceleration values from these equations were compared with full-scale vehicle crash test data, it was found that these equations predict the behavior of standard-sized passenger automobiles to an accuracy of ±20 percent. Such a comparison is remarkable when the simplicity of the model and the difficulties involved in acquiring and reducing data obtained from full-scale dynamic tests are considered.

These equations were used to compute the lateral impact forces a vehicle would impose on a rigid traffic rail or bridge rail (Figure 5). For articulated vehicles like tractor-trailer trucks, only the tractor is considered to strike the traffic rail. The rear axles of the trailer and the load they are supporting are not considered. Numerous crash tests have shown that the big impact force is delivered by the rear tandem axles of the tractor.

Table 1 and Figure 5 present some actual measurements (from load cells) of impact forces during crash tests. Table 1 also gives some estimates of impact forces determined from accelerometers located on the vehicles. These estimates of impact forces from accelerometer readings were made in the following manner:

1. For the passenger automobiles, vans, school buses, and Ford trucks, the accelerometers were located near the CG of the vehicle. The impact forces were obtained by multiplying the maximum average 50-ms acceleration in $\underline{g}$'s by the total weight of the vehicle.
2. The impact forces for the intercity and scenicruiser buses were obtained as described in Step 1 except for the two tests (tests 8307-1 and 3) by Davis (6). For those two tests, the accelerometers were located over the rear axles and thus the maximum average 50-ms acceleration in $\underline{g}$'s was multiplied by the weight on the rear axles only.
3. Impact forces for all the articulated tractor-trailer rigs were obtained from accelerometers located on or near the rear tandem axles of the tractor. The maximum average 50-ms acceleration in $\underline{g}$'s was multiplied by the weight on the rear tandem axles only to obtain the recorded maximum forces.

When these maximum 50-ms forces from the crash tests with buses and trucks striking at nominally 60 mph and 15 degrees are compared with those predicted by Equation 4, they appear to be about 78 percent higher. Some reasons for this could be (a) buses and trucks have a greater wheelbase length, (b) the payload is a larger percentage of the total load and shifts during impact, (c) tractor-trailers are articulated, and (d) these test results are the maximum average 50-ms impact forces whereas the theory is an idealized sinusoidal maximum force that occurs during a time period of 200 ms or more.

HEIGHT REQUIREMENTS OF LONGITUDINAL BARRIERS

In the previous section data were presented on the magnitude of the lateral impact forces to which a longitudinal barrier would be subjected. Although a barrier must be strong enough to restrain and redirect a vehicle, it must also be high enough to prevent the vehicle from rolling over it.

Figure 6 shows a rear or front view of a vehicle striking a longitudinal rail. The force (F_{lat}) is the resisting force of the rail that would be located at the centroid of the rail member or top of a concrete parapet. The height (H) of this resisting force is defined as the effective height of the rail. For example, the top of a standard 12-in.-deep W-beam guardrail is mounted 27 in. high in Texas; however, its effective height (H) would only be 21 in.

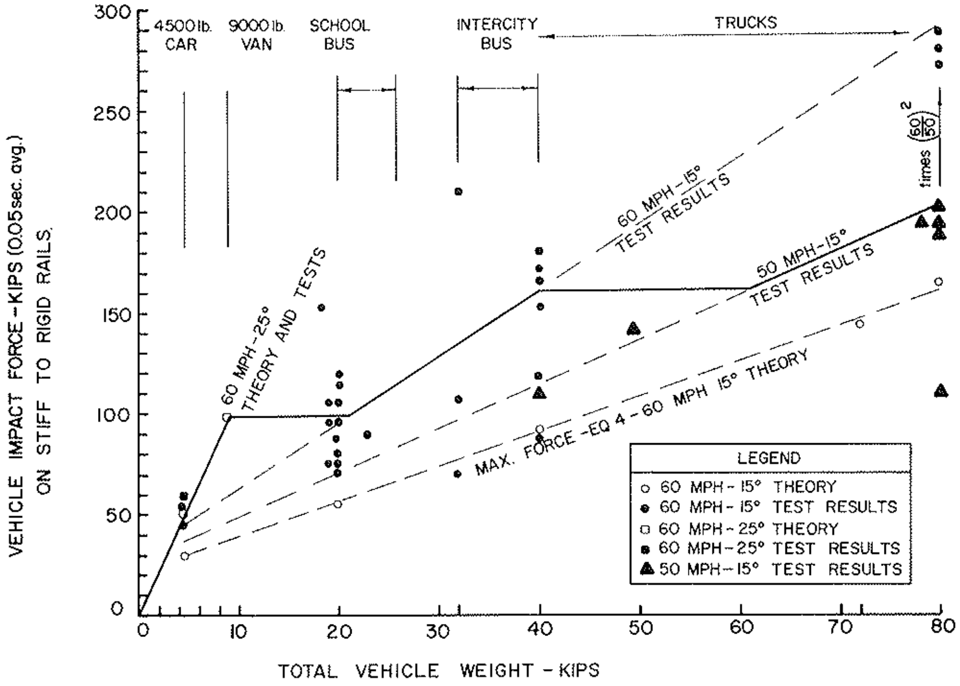
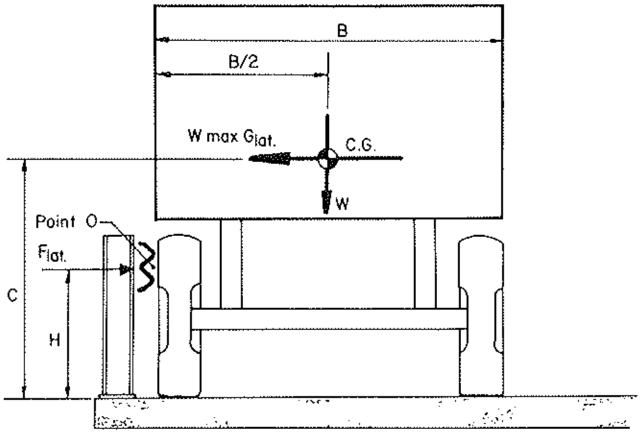


FIGURE 5 Comparison of vehicle impact forces and total vehicle weight, theory and test results for stiff rails.



W = weight of vehicle

max $G_{lat.}$ = max lateral deceleration of vehicle from Eq 2

C = height to vehicle c.g., in.

H = effective height of barrier rail, in.

O = center of overturning rotation located at centroid of rail or top of concrete parapet

B = width of vehicle, in.

$F_{lat.}$ = resisting railing force located at effective rail height

$$Mo = W \max G_{lat.} (C - H) - WB/2 = 0$$

$$H = \frac{\max G_{lat.} C - B/2}{\max G_{lat}} \qquad (\text{Eq. } 5)$$

FIGURE 6 Approximate analysis of bridge rail effective height required to prevent vehicle from rolling over rail.

In many cases the CG of an impacting vehicle may be much higher (C) than the effective height (H) of the rail. The vehicle does not necessarily roll over the rail in this case because a stabilizing moment equal to the weight of the vehicle (W) times one-half the width of the vehicle (B/2) is also acting on the vehicle. Equation 5, shown in Figure 6, indicates the approximate effective height required for a bridge rail to prevent a vehicle from rolling over it. This effective height is a function of the maximum lateral impact deceleration of the vehicle, the height of the CG of the vehicle, and the width and length of vehicle in this simplified mathematical model.

Figure 7 shows a comparison of the required effective height of a longitudinal rail to the CG height for five selected design vehicles. From Figure 7 it can be seen that to prevent a large passenger automobile with a CG of from 20 to 24 in. from rolling over the rail, an effective height of from 16 to 21 in. is required. As mentioned previously, the standard guardrail has an effective height of 21 in. To prevent a school bus with a CG of from 50 to 55 in. from rolling over, the rail would require an effective height of from 38 to 42 in. An intercity bus would require rails of similar effective heights. A large van tractor-trailer truck would require a rail with an effective height of from 50 to 54 in.

SUMMARY AND CONCLUSIONS

The information presented in this paper has shown that longitudinal barriers (guardrails, median barriers, and bridge rails) can be designed and constructed to restrain heavy vehicles such as buses and trucks. Figure 5 indicates the magnitude of the impact forces that these barriers must resist. These forces are for fairly stiff to rigid longitudinal barriers. To redirect a 20,000-lb school bus at 60 mph and a 15-degree angle, the barrier should resist

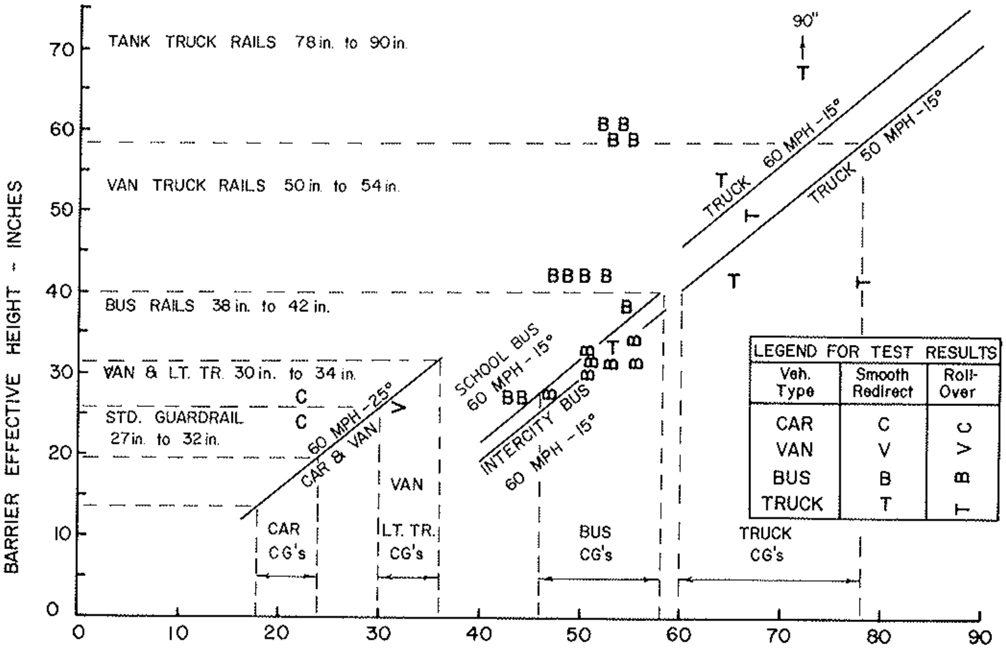


FIGURE 7 Comparison of required barrier height and vehicle CG, theory and test results.

about 100,000 lb of force. To redirect a 40,000-lb intercity bus at 60 mph and a 15-degree angle, the barrier should resist about 165,000 lb. To redirect an 80,000-lb tractor-trailer at 50 mph and a 15-degree angle, the barrier should be capable of resisting about 190,000 lb. Barriers similar to those shown in Figures 2 and 3 have demonstrated this. For precise design details of these barriers, the appropriate references should be consulted.

Figure 7 indicates that to redirect school and intercity buses without rollover, such barriers should be about 38 to 42 in. high. School buses are more vulnerable to rollover than are intercity buses. Figure 7 also indicates that van-type trucks need a barrier from 50 to 54 in. high to minimize rollover at 50 mph and 15-degree angle impact. Tank-type trucks need a barrier from 78 to 90 in. high to prevent rollover at the same speed and angle.

The tests conducted so far indicate that barriers with a vertical face on the traffic side are much better for resisting vehicle rollover. Barriers similar to the 54-in.-high combination rail shown in Figure 2 are an example. On the other hand, the sloping-faced concrete safety shape assists vehicles to roll over. For example, the 42-in.-high concrete safety shape in Figure 2 permitted the vehicle to roll 24 degrees before it contacted the top of the barrier. The 50-in.-high combination rail in Figure 2 permitted the impacting truck to roll 11 degrees before it contacted the upper steel rail.

ACKNOWLEDGMENTS

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Traffic Control Device Problems Associated with Large Trucks

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ABSTRACT

The changing pattern of traffic and increased truck volumes and sizes are resulting in blockage of road signs. The inability of drivers to see advisory and warning signs will result in an increasing number of accidents leading to a growing number of law suits with the states as defendants. There are some guidelines that engineers can use, but a general solution is not available at this time.

How often do you find that your view of the road ahead is suddenly obliterated by a truck pulling into the lane in front of you? Then you look in your rear view mirror to find yourself sandwiched between two units with a third passing to your left, and, in the congestion and confusion, you miss an important directional or advisory sign. How many people realize that when they pull out to pass a truck, they may also be cutting off their view of all signs for the next 1/4 mi? And who of us can read a sign more than 1/4 mi away?

There are potential accident situations developing as a result of the presence of more trucks on the road. Think of drivers misreading, misinterpreting, or missing a sign altogether because of total or partial blockage and then overreacting or overcompensating, or both, in an effort to recover from the situation in which they find themselves. They miss a ramp, pass the intersection at which they should have turned, are in the wrong lane for through traffic, do not see a stop sign, or are confronted with a sudden traffic pattern change. The legal ramifications for the political entity that is responsible for the roadway could be devastating.

Ours is a society that believes that if there is a problem, the solution is to sue. For a plaintiff

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