

## PHYSICAL AND PERFORMANCE CHARACTERISTICS OF HEAVY VEHICLES

A wide variety of heavy vehicle types—including single-unit trucks, combination trucks with one, two, or three trailers, and buses—operate on U.S. highways. These heavy vehicle types each have unique physical and performance characteristics that interact with highway features. This chapter summarizes the physical and performance characteristics of heavy vehicles. The issues addressed in this chapter are as follows:

- Vehicle weights and dimensions
- Turning radius
- Offtracking and swept path width
- Trailer swingout
- Braking distance
- Driver eye height
- Acceleration characteristics
- Rearward amplification
- Suspension characteristics
- Load transfer ratio
- Rollover threshold

The relationship of these vehicle characteristics to the safety of highway/heavy vehicle interactions is discussed in later chapters.

### VEHICLE TYPES AND CONFIGURATIONS

Table 1 identifies common truck and bus configurations that operate on U.S. highways. Table 2 identifies the primary truck and bus configurations that constitute the U.S. heavy vehicle fleet. The configurations identified in the table are those used as design vehicles in the American Association of State Highway and Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets (1)*, commonly known as the *Green Book*. The table also includes some additional vehicles recommended in *NCHRP Report 505 (2)* for future use in geometric design, but not currently included in AASHTO policy.

### VEHICLE WEIGHTS AND DIMENSIONS

Current federal law sets the following limits on heavy vehicle weights and dimensions:

- States may not set maximum weight limits on the Interstate System less than:
  - 36,400 kg (80,000 lb) gross vehicle weight
  - 9,100 kg (20,000 lb) for a single axle
  - 15,500 kg (34,000 lb) for a tandem axle
- States must permit weights for other axle groups so long as the weight on the axle group does not violate the bridge formula established in federal law and the gross vehicle weight does not exceed 36,400 kg (80,000 lb).
- States must permit tractor-trailer combination trucks with trailer lengths up to 14.6 m (48 ft) in length to operate on the National Network (NN).
- States must permit combination trucks consisting of two trailers with lengths up to 8.7 m (28.5 ft) per trailer to operate on the NN.
- States must permit trucks within the length limits given above with widths up to 2.6 m (8.5 ft) to operate on the NN.

The NN is a network of routes designated by Secretary of Transportation in consultation with the states. The NN includes the Interstate System plus other selected routes. The extent of the NN on noninterstate routes varies by region of the country. Typically, the noninterstate routes in the NN are fairly limited in the Eastern states and more extensive in the Western states.

States set the truck size and weight limits on their facilities within the framework set by the federal limits discussed above. Many states have

**Table 1. Characteristics of typical vehicles and their current uses**

Configuration type	Number of axles	Common maximum weight (lb)	Current use
Single-Unit Truck	2	under 40,000	Two-axle single-unit (SU) trucks. General hauling primarily in urban areas.
	3	50,000 to 65,000	SUs are the most commonly used trucks. They are used extensively in all urban areas for short hauls. Three-axle SUs are used to carry heavy loads of materials and goods in lieu of the far more common two-axle SU.
	4 or more	62,000 to 70,000	SUs with four or more axles are used to carry the heaviest of the construction and building materials in urban areas. They are also used for waste removal.
Intercity Bus	3	50,000	Used to transport passengers and their luggage on scheduled routes and on tours and charter trips.
Tractor-Semitrailer	5	80,000 to 99,000	Most used combination vehicle. It is used extensively for long and short hauls in all urban and rural areas to carry and distribute all types of materials, commodities, and goods.
	6 or more	80,000 to 100,000	Used to haul heavier materials, commodities, and goods for hauls longer than those of the four-axle SU.
STAA Double	5, 6	80,000	Most common multitrailer combination. Used for less-than-truckload (LTL) freight mostly on rural freeways between LTL freight terminals.
B-Train Double	8, 9	105,500 to 137,800	Some use in the northern plains States and the Northwest. Mostly used in flatbed trailer operations and for bulk hauls.
Rocky Mountain Double	7	105,500 to 129,000	Used on turnpike in Florida, the Northeast, and Midwest and in the Northern Plains and Northwest in all types of motor carrier operations, but most often it is used for bulk hauls.
Turnpike Double	9	105,500 to 147,000	Used on turnpikes in Florida, the Northeast, and Midwest and on freeways in the Northern Plains and Northwest for mostly truckload operations.
Triple	7	105,500 to 131,000	Used to haul LTL freight on the Indiana and Ohio Turnpikes and in many of the most Western states, used on rural freeways between LTL freight terminals.

Source: adapted from CTSW (3)

**Table 2. Design vehicle dimensions, adapted from the 2001 *Green Book (1)* and *NCHRP Report 505 (2)***

Design vehicle type	Symbol	Dimensions (ft)											Typical kingpin to center of rear tandem axle <sup>6</sup>
		Overall			Overhang								
		Height	Width	Length	Front	Rear	WB <sub>1</sub>	WB <sub>2</sub>	S	T	WB <sub>3</sub>	WB <sub>4</sub>	
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck (two-axle)	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Single Unit Truck (three-axle) <sup>6</sup>	SU-25	11-13.5	8.0	39.5	4	10.5	25	–	–	–	–	–	–
<b>Buses</b>													
Intercity Bus (Motor Coach)	BUS-40	12.0	8.5	40	6	6.3 <sup>5</sup>	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5 <sup>5</sup>	26.5	4.0	–	–	–	–	–
City Transit Bus	CITY-BUS	10.5	8.5	40	7	8	25	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12	21.3	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40	7	13	20	–	–	–	–	–	–
Articulated Bus	A-BUS	11.0	8.5	60	8.6	10	22.0	19.4	6.2 <sup>1</sup>	13.2 <sup>1</sup>	–	–	–
<b>Combination Trucks</b>													
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5 <sup>5</sup>	12.5	27.5	–	–	–	–	25.5
Intermediate Semitrailer	WB-50	13.5	8.5	55	3	2 <sup>5</sup>	14.6	35.4	–	–	–	–	35.5
Interstate Semitrailer <sup>6</sup>	WB-62*	13.5	8.5	68.5	4	2.5 <sup>5</sup>	21.6	41.0	–	–	–	–	41.0
Interstate Semitrailer	WB-67	13.5	8.5	73.5	4	2.5 <sup>5</sup>	21.6	45.5	–	–	–	–	45.5
"Double-Bottom"-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0 <sup>2</sup>	7.0 <sup>2</sup>	23.0	–	21.0
Rocky Mountain Double-Semitrailer/Trailer <sup>6</sup>	WB-92D	13.5	8.5	98.3	2.33	3	17.5	40.5	3.0 <sup>2</sup>	7.0 <sup>1</sup>	23.0	–	42.5
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0 <sup>3</sup>	7.0 <sup>3</sup>	23.0	23.0	21.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5 <sup>5</sup>	14.3	39.9	2.5 <sup>4</sup>	10.0 <sup>4</sup>	44.5	–	40.5

\* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

\*\* = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

<sup>1</sup> = Combined dimension is 19.4 ft and articulating section is 4 ft wide.

<sup>2</sup> = Combined dimension is typically 10.0 ft.

<sup>3</sup> = Combined dimension is typically 10.0 ft.

<sup>4</sup> = Combined dimension is typically 12.5 ft.

<sup>5</sup> = This is overhang from the back axle of the tandem axle assembly.

<sup>6</sup> = Modified from 2001 *Green Book* as recommended in Reference 2.

- WB<sub>1</sub>, WB<sub>2</sub>, and WB<sub>4</sub> are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

established truck size and weight limits that exceed those mandated by the federal government. For example, many states permit tractor-semitrailers with 16.2-m (53-ft) trailers to operate on the NN, even though federal law requires only that 14.6-m (48-ft) trailers be permitted. The maximum trailer length currently permitted by any state for single semitrailer trucks is 18.3 m (60 ft).

A number of states also permit multiple trailer trucks with greater weights and trailer lengths than allowed under federal law, to operate on specific highways either under permit and/or under specified conditions. Such trucks are generally known as Longer Combination Vehicles (LCVs). The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) instituted a freeze on increases in state size and weight limits for LCVs. State limits in effect were allowed to remain in place (“grandfathered”), but no further increases in those limits are permitted. ISTEA defined an LCV as:

...any combination of a truck tractor with two or more trailers or semitrailers which operates on the Interstate System at a gross vehicle weight greater than 80,000 lb.

Table 3 summarizes which states permit LCVs to operate with weights over 36,400 kg (80,000 lb).

Table 2 includes the dimensions of the AASHTO design vehicles. Appendix A presents drawings of these design vehicles to illustrate the most common types of trucks and buses that make up the U.S. heavy vehicle fleet. While the trucks in Appendix A are shown with van-type cargo areas, other cargo-area types in common use include flatbeds, bulk carriers (dump trucks), tankers, automobile carriers, and other special-purpose vehicles. The vehicle dimensions shown in Table 2 and Appendix A, and particularly the spacing between axles and hitch points and the front and rear overhang distances, are the primary determinants of the turning radius, offtracking, and swept path width of heavy vehicles, which are discussed below. These performance characteristics, in turn, are key factors in the design of intersections and horizontal curves to safely accommodate heavy vehicles.

The weight of a truck is not, by itself, a factor in its safe operation. However, heavier trucks need more powerful engines to accelerate from a stop at intersections and to maintain speed on upgrades. Furthermore, a truck’s cargo should be loaded evenly, side to side and fore to aft of the cargo area, to maintain a low center of gravity for the vehicle as a whole. The center-of-gravity height is a key determinant of a vehicle’s rollover threshold, as discussed later in this chapter.

## **TURNING RADIUS**

The minimum turning radius of a truck is defined as the path of the outer front wheel, following a circular arc at a very low speed, and is limited by the vehicle steering mechanism. Parameters such as weight, weight distribution, and suspension characteristics, have a negligible role in turns at very low speeds [e.g., less than 16 km/h (10 mi/h)]. The turning radii of representative trucks are presented in Table 4. The turning radius of a truck influences highway geometric design through consideration of offtracking and swept path width, which are discussed below.

## **OFFTRACKING AND SWEEPED PATH WIDTH**

A train travels on tracks and, thus, its rear wheels precisely follow the paths of the front wheels. With vehicles that are not on tracks, such as bicycles, automobiles, and trucks, the rear wheels do not follow the front ones. This phenomenon, in which the rear wheels of a vehicle do not follow the same path as the front wheels as the vehicle makes a turn, is known as offtracking. There are two types of offtracking, referred to as low-speed and high-speed offtracking. Low-speed offtracking occurs as vehicles traveling at very low speed make a turn; in low-speed offtracking, the weight, weight distribution, suspension characteristics, and other vehicle-dynamic parameters are negligible factors in the amount of offtracking that occurs. High-speed offtracking, as its name implies, incorporates dynamic effects, and becomes more

**Table 3. Longer combination vehicle weight limits by state (3)**

Gross vehicle weight limit (lb)	Truck tractor and two trailing units	Truck tractor and three trailing units
86,400	NM	
90,000	OK	OK
95,000	NE	
105,500	ID, ND, OR, WA	ID, ND, OR
110,000	CO	CO
111,000	AZ	
115,000		OH
117,000	WY	
120,000	KS, MO <sup>1</sup>	
123,500		AZ
127,400	IN, MA, OH	IN
129,000	NV, SD, UT	NV, SD, UT
131,060		MT
137,800	MT	
143,000	NY	
164,000	MI	

<sup>1</sup> From Kansas, within 20 miles of border.

Source: Final Rule on LCVs published in the *Federal Register* at 59 FR 30392 on June 13, 1994.

**Table 4. Minimum turning radius for selected heavy vehicles (1, 2)**

Design vehicle type	Symbol	Minimum design turning radius (ft)	Centerline turning radius (ft)	Minimum inside radius (ft)
Single-unit truck	SU	42.0	38.0	28.3
Single-unit truck (three-axle)	SU25	51.5	47.5	36.4
Intercity bus	BUS-40	45.0	40.8	27.6
Intercity bus	BUS-45	45.0	40.8	25.5
City transit bus	CITY-BUS	42.0	37.8	24.5
Conventional school bus (65 pass.)	S-BUS-36	38.9	34.9	23.8
Large school bus (84 pass.)	S-BUS-40	39.4	35.4	25.4
Articulated bus	A-BUS	39.8	35.5	21.3
Intermediate semitrailer	WB-40	40.0	36.0	19.3
Intermediate semitrailer	WB-50	45.0	41.0	17.0
Interstate semitrailer <sup>1</sup>	WB-62	45.0	41.0	7.9
Interstate semitrailer	WB-67	45.0	41.0	4.4
Long interstate semitrailer	WB-71	21.5	17.0	13.8
"Double-bottom" semitrailer/trailer	WB-67D	45.0	41.0	19.3
Rocky mountain double semitrailer/ trailer	WB-92D	82.0	78.0	82.4
Turnpike double-semitrailer/trailer	WB-109D	60.0	56.0	14.9
Triple-semitrailer/trailer/trailer	WB-100T	45.0	41.0	9.9

<sup>1</sup> Revised WB-62 design vehicle proposed in Reference 2.

pronounced as the vehicle speed increases. Each type of offtracking is discussed below.

### Low-Speed Offtracking

During turning at low speeds, the front wheels try to drag the rear ones toward them and across the inside of the curve. The magnitude of this phenomenon is small for bicycles and automobiles, and is usually ignored. For heavy vehicles, however, it can be substantial and is an important factor in the design of intersections, ramps, and other highway elements.

There are two commonly used descriptors of offtracking: one is the *offtracking amount*, defined as the radial offset between the path of the centerline of the front axle and the path of the centerline of a following axle shown in Figure 1; the other, and more important descriptor for use in highway design is the *swept path width*, shown for a tractor-semitrailer in Figure 2 as the difference in paths between the outside front tractor tire and the inside rear trailer tire.

Offtracking increases gradually as a vehicle proceeds through a turning maneuver. This increasing offtracking is termed partially developed offtracking (sometimes referred to in the literature as nonsteady-state offtracking or transient offtracking). As the vehicle continues to move in a constant radius curve, the offtracking eventually reaches what is termed its fully developed offtracking value (sometimes referred to in the literature as steady-state offtracking or, misleadingly, as maximum offtracking). Each type of offtracking is discussed more fully below.

#### Fully Developed Offtracking

On longer-radius turns, such as typical horizontal curves on highways or ramps, fully developed offtracking is usually reached; once this value is attained, offtracking does not increase further as the vehicle continues around the curve. Fully developed offtracking is considered in the geometric design of horizontal curves, especially on two-lane roads, in determining whether the roadway needs to be wider on the curve than on the normal tangent cross

section. Similarly, it is considered in the design of freeway ramps. Even though such facilities are designed primarily for highway speeds (or near-highway speeds), where low-speed offtracking should not be a factor, consideration is also given to situations such as congestion, where vehicles are forced to travel at low speeds.

In performing offtracking calculations, certain equations are applied consecutively to the distances between adjacent pairs of axles or hinge points. The contribution to offtracking of each inter-axle distance is roughly proportional to the square of that distance. Thus, the dominant term for the offtracking of most tractor-semitrailers is the so-called kingpin-to-rear-axle dimension, the largest distance.

The offtracking of a vehicle with two axles, for example, may be approximated, using the Pythagorean Theorem (see Woodrooffe et al. (4), for example) as:

$$OT = -R + \sqrt{R^2 - \ell^2} \quad (1)$$

where  $\ell$  is the distance between the two axles,  $R$  is the radius of the curve, and negative offtracking implies tracking inward toward the center of the arc. If  $\ell \ll R$ , then this may be reduced to the simpler form  $-0.5(\ell^2/R)$ , which is the often used Western Highway Institute formula (5). Eq. (1) is sufficiently accurate for most purposes, but additional effects of multiple axles (e.g., tandems, tridem, etc.), roadway superelevation, and body roll may also be included (see Glauz and Harwood (6)). (This formulation also assumes  $\ell \ll R$ .)

As noted above, Eq. (1) or its equivalent is applied consecutively to each pair of axles or hinge points of the truck; each application gives the offtracking of the center of the following axle or hinge point relative to the center of its leader. These computed offtracking amounts are additive, except that the sign of the contribution from the center of the drive axles to the kingpin is reversed if the kingpin is moved forward (the usual case), as

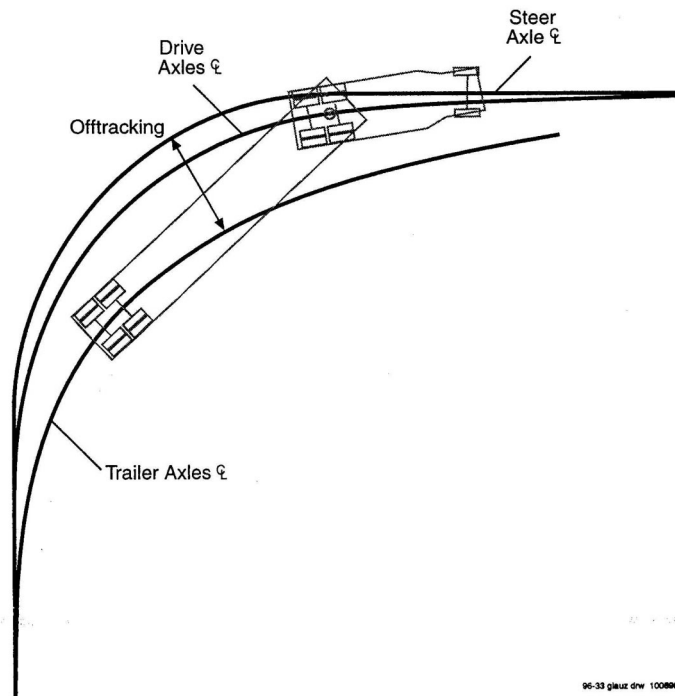


Figure 1. Illustration of truck offtracking.

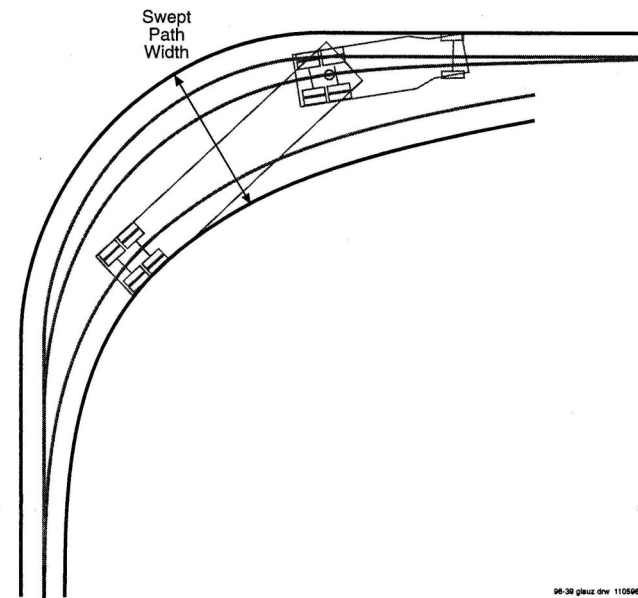


Figure 2. Illustration of swept path width.

is the contribution from the drive axles to the pintle hook of the first trailer in a doubles combination (which swings outward rather than tracking inward). The largest component of the offtracking for a long semitrailer is the distance from the kingpin to the center of the rear tandem axle, known as the KCRT distance.

### *Partially Developed Offtracking*

Partially developed offtracking is of concern where trucks traverse shorter curves or, more importantly, curves of smaller radius. Partially developed offtracking is of particular interest as it is a key factor in the design of intersections and other locations where vehicles are required to turn rather sharply.

In contrast to fully developed offtracking, partially developed offtracking cannot be determined from solving a simple equation, even for the case where the tractor travels on a simple circular path. Commercially available software packages are now commonly used by highway agencies to determine partially developed offtracking. All such computer programs operate by moving the front axle of a specified vehicle forward in small steps or increments along a specified path and then computing the resulting location of the rear axle(s).

Table 5 presents the maximum low-speed offtracking and swept path width in 90° turns of varying radii for typical truck types.

### **High-Speed Offtracking**

When a vehicle moves through a curve at higher speed, there is a tendency for the rear axles of the vehicle to move outward. This tendency to move outward is called high-speed offtracking. It acts in the opposite direction to low-speed offtracking, so the two phenomena tend to counteract each other. At lower speeds, low-speed offtracking predominates; as the speed increases, the net offtracking is reduced. At sufficiently high speeds, the two phenomena exactly cancel, resulting in no net offtracking, and at still higher speeds the net result

is that the rear of the vehicle tracks outside of the front.

The quantification of fully developed high-speed offtracking was initially modeled by Bernard and Vanderploeg (7), and their model was later expanded by Glauz and Harwood (6). The model includes the fully developed low-speed offtracking terms, discussed above, plus a speed dependent portion that is the high-speed contribution. It is proportional to the axle spacing,  $\ell$ , not to its square as is the case with low-speed offtracking. It is, however, proportional to the square of the truck speed, and increases with decreasing path radius. In practice, net outward offtracking, due to the high-speed term becoming dominant, does not occur until speeds reach the neighborhood of 89 km/h (55 mi/h), for example, on highway entrance or exit ramps. Net outward offtracking rarely exceeds 0.6 m (2.0 ft).

Net high-speed offtracking is a less important factor in highway design than low-speed offtracking, because high-speed offtracking generally offsets low-speed offtracking. At very high speeds, however, drivers of heavy vehicles need to be aware that the rear of their vehicle may track to the outside, rather than the inside, of a turn and position their vehicle accordingly.

Because net high-speed offtracking is usually not a significant factor in roadway design, compared to low-speed offtracking, its transient or partially developed form has not been studied.

### **TRAILER SWINGOUT**

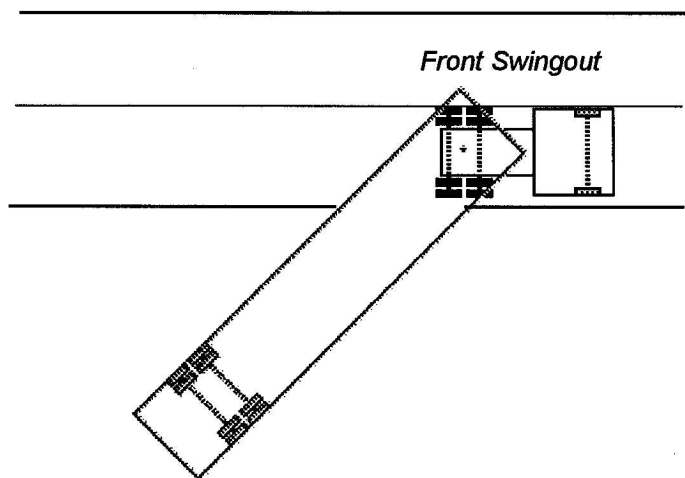
The front of a trailer is generally ahead of the front axles that support the trailer. Likewise, the rear of a trailer generally overhangs the rear axles. As a result, during a turn the front of the trailer swings to the outside of the front trailer axles (front swingout) and the rear of the trailer swings to the outside of the rear axles (rear swingout). Front and rear swingout are illustrated in Figure 3.



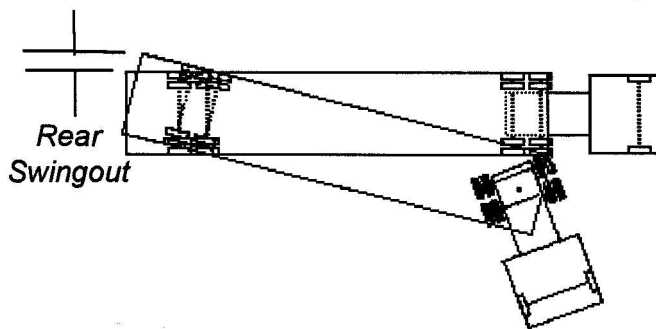
**Table 5. Maximum low-speed offtracking and swept path width for selected trucks in 90° turns (2)**

Design vehicle type	Symbol	Maximum offtracking (ft) for specified turn radius				Maximum swept path width (ft) for specified turn radius			
		50 ft	75 ft	100 ft	150 ft	50 ft	75 ft	100 ft	150 ft
Single-unit truck (two-axle)	SU	3.8	2.7	1.8	1.1	11.8	10.7	9.8	9.1
Single-unit truck (three-axle)	SU25	6.1	4.3	3.2	2.1	14.1	12.3	11.2	10.1
Interstate semitrailer <sup>1</sup>	WB-62	17.0	13.1	10.3	7.0	25.3	21.3	18.6	15.3
Interstate semitrailer	WB-67	19.4	15.0	12.1	8.3	27.6	23.4	20.3	16.6
Long interstate semitrailer	WB-71	21.5	17.0	13.8	9.6	29.8	25.3	22.0	17.9
“Double-bottom”-semitrailer/trailer	WB-67D	11.5	8.3	6.3	4.2	19.7	16.6	14.6	12.5
Rocky Mountain double-semitrailer/trailer	WB-92D	–	–	12.7	8.7	–	–	21.0	17.0
Turnpike double-semitrailer/trailer	WB-109D	–	–	17.1	12.0	–	–	25.3	19.2

<sup>1</sup> Revised WB-62 design vehicle proposed in *NCHRP Report 505 (2)*.



**Front Swingout**



**Rear Swingout**

*Figure 3. Illustration of front and rear swingout for a tractor-trailer combination making a turn (8).*

Swingout is a function of the trailer wheelbases and other dimensions, and the radius of the turn, and can be quantified using a modification of the low-speed offtracking programs discussed above.

On some trailers, the consequences of front swingout are reduced by beveling or rounding the front of the trailer. Nevertheless, in practical trailer configurations, the front overhang of a trailer is only of the order of 1 m (3 ft), and front swingout persists for only a few seconds during a turn. Moreover, it is clearly visible to, and thus under the control of, the driver.

On the other hand, rear overhang can be substantial. For example, with a 16.2-m (53-ft)

semitrailer with the rear axles moved forward to satisfy a 12.5-m (41-ft) king-pin-to-rear-axle limitation, the rear overhang is typically 2.7 m (9 ft). Although rear swingout is not as pronounced as front swingout due to the geometrics involved, it can persist for much longer periods of time during a turn, and is out of view of the driver. Table 6 shows the maximum rear swingout in 90° turns for a varying radii for selected trucks.

It is important to recognize that rear swingout, like low-speed offtracking, increases as the truck proceeds through a turn. Although the outside rear corner of the trailer follows a path outside of the rear trailer wheels, it is inside of the swept path. The outside of the swept path is determined by the

**Table 6. Maximum rear swingout for selected design vehicles in 90° turns (2)**

Design vehicle type	Symbol	Maximum rear swingout (ft) for specified turn radius			
		50 ft	75 ft	100 ft	150 ft
Single-unit truck	SU	0.35	0.24	0.18	0.12
Single-unit truck (three-axle)	SU25	1.07	0.73	0.53	0.35
Interstate semitrailer	WB-62	0.18	0.14	0.09	0.06
Interstate semitrailer (revised) <sup>1</sup>	WB-62	0.17	0.13	0.09	0.06
Interstate semitrailer	WB-67	0.17	0.14	0.10	0.07
Interstate semitrailer <sup>2</sup>	WB-67 (41-ft KCRT)	0.69	0.51	0.41	0.27
Long interstate semitrailer	WB-71	0.17	0.13	0.10	0.07
Long interstate semitrailer <sup>3</sup>	WB-71 (41-ft KCRT)	1.45	1.08	0.84	0.61
“Double-bottom”-semitrailer/trailer	WB-67D	0.08	0.05	0.05	0.03
Longer “double-bottom”-semitrailer/trailer	WB-77D	0.13	0.11	0.08	0.06
B-train double-semitrailer/semitrailer	WB-77BD	0.17	0.12	0.10	0.07
Rocky mountain double-semitrailer/trailer	WB-92D	–	–	0.05	0.04
Turnpike double-semitrailer/trailer	WB-109D	–	–	0.09	0.06
Long turnpike double-semitrailer/trailer	WB-120D	–	–	0.37	0.27

<sup>1</sup> Proposed revision to WB-62 design vehicle; KCRT distance increased from 40.5 to 41.0 ft.

<sup>2</sup> WB-67 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.

<sup>3</sup> WB-71 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.

outside front wheel of the tractor and not by the trailer wheels. This finding suggests that rear swingout is rarely a concern to other vehicles, unless they are making a parallel turn (2).

### BRAKING DISTANCE

Braking distance is the distance needed to stop a vehicle from the instant brake application begins (1). Braking distance is used in the determination of many highway design and operational criteria, including stopping sight distance, vehicle change intervals for traffic signals, and advance warning sign placement distances. The process of bringing a heavy vehicle to a stop requires a complex interaction between the driver, the brake system, the truck tires, the dimensions, and loading characteristics of the vehicle, and the pavement surface characteristics. Heavy vehicles use both air and hydraulic brake systems. Combination trucks typically have air brake systems; buses often have hydraulic brakes.

### Locked-Wheel Braking vs. Controlled Braking

Heavy vehicle braking maneuvers can be performed in two general modes: locked-wheel braking and controlled braking. Locked wheel braking occurs when the brakes grip the wheels tightly

enough to cause them to stop rotating, or “lock,” before the vehicle has come to a stop. Braking in this mode causes the vehicle to slide or skid over the pavement surface on its tires. Controlled braking is the application of the brakes in such a way that the wheels continue to roll without locking up while the vehicle is decelerating. Drivers of vehicles with conventional brakes generally achieve controlled braking by “modulating” the brake pedal to vary the braking force and to avoid locking the wheels.

Locked-wheel braking is commonly used by passenger car drivers during emergency situations. Passenger cars can often stop in a stable manner, even with the front wheels locked. In this situation, the driver loses steering control, and the vehicle generally slides straight ahead. On a tangent section of road this is perhaps acceptable behavior, although on a horizontal curve the vehicle may leave its lane, and possibly the roadway.

Combination trucks, by contrast, have much more difficulty stopping in the locked-wheel mode. Figure 4 illustrates the dynamics of a tractor-trailer truck if its wheels are locked during emergency braking (9). The behavior depends upon which axle locks first—they usually do not all lock up together. When the steering wheels (front axle) are locked, steering control is

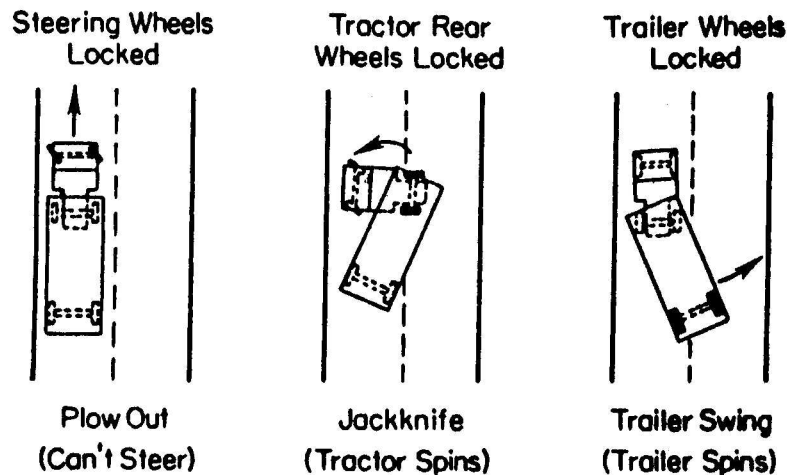


Figure 4. Tractor-trailer dynamics with locked wheels (9).

eliminated, but the truck maintains rotational stability and it will skid straight ahead. However, if the rear wheels of the tractor are locked, that axle(s) slides and the tractor rotates or spins, resulting in a “jackknife” loss of control. If the trailer wheels are locked, those axles will slide, and the trailer will rotate out from behind the tractor, which also leads to loss of control. Although a skilled driver can recover from the trailer swing through quick reaction, the jackknife situation is not correctable. None of these locked-wheel stopping scenarios for trucks are considered safe. Therefore, it is essential that combination trucks stop in a controlled braking mode and that highway geometric design criteria should recognize the distances required for trucks to make a controlled stop.

### **Antilock Brake Systems**

Antilock brake systems have been introduced in the heavy vehicle fleet to enable vehicles to make controlled stops without locking the wheels and losing vehicle control.

Antilock brake systems operate by monitoring each wheel for impending lock up. When wheel lock up is anticipated, the system reduces brake pressure on the wheel. When the wheel begins to roll freely again, the system reapplies braking pressure. The system constantly monitors each wheel and readjusts the brake pressure until the wheel torque is no longer sufficient to lock the wheel. The antilock brake system is controlled by an onboard microprocessor.

Antilock brake systems are now required for new trucks, tractors, and trailers in accordance with Federal Motor Vehicle Safety Standard (FMVSS) 121 (10). Antilock brake systems have been required for air-brake-equipped tractors manufactured on or after March 1, 1997; air-brake-equipped trailers and single-unit trucks manufactured on or after March 1, 1998, and hydraulic-brake-equipped single-unit trucks and buses manufactured after March 1, 1999. Antilock brake systems were also available as an option for some of these vehicles before those dates.

Because their useful life is relatively short, nearly all truck tractors in the current fleet currently

have antilock brakes or will soon be replaced by a tractor that does. A recent field study found that approximately 43 percent of trailers in combination trucks are currently equipped with antilock brake systems (2). Based on the service life of trailers, it can be expected that within 10 years nearly all trailers will be equipped with antilock brake systems.

The introduction of antilock brakes has improved the braking performance of the truck fleet. FMVSS 121 specifies a performance standard for truck braking distance. The required braking distances for heavy vehicles equipped with antilock brakes are summarized in Table 7. *NCHRP Synthesis of Highway Practice 241 (11)* has observed that truck braking distances remain longer than passenger car braking distances on dry pavements. By contrast, on wet pavements, which are most critical to safety, the braking distances of trucks and passenger cars are nearly equal.

### **DRIVER EYE HEIGHT**

The drivers of heavy vehicles generally sit higher than passenger car drivers and, thus, have greater eye heights. As a result, truck and bus drivers can see farther than passenger car drivers at vertical sight restrictions, such as hillcrests. This may permit truck and bus drivers to see traffic conditions or objects in the road sooner and, therefore, begin braking sooner. The *AASHTO Green Book (1)* specifies a value of 1,080 mm (3.5 ft) for driver eye height, based on consideration of a passenger car as the design vehicle. By contrast, a value of 2,400 mm (8.0 ft) is recommended by the *Green Book* for truck driver eye height. This value is based on relatively recent field studies reported in *NCHRP Report 400 (12)*. Driver eye height is considered directly in the design of vertical curves at hillcrests. However, there is no comparable advantage for truck and bus drivers at horizontal sight restrictions.

**Table 7. Truck braking distances specified as performance criteria for antilock brake systems in FMVSS 121 (18)**

Vehicle speed (mi/h)	Truck braking distance (ft) <sup>1</sup>		
	Loaded single-unit truck	Unloaded truck tractors and single-unit trucks	Loaded truck tractors with an unbraked control trailer
20	35	38	40
25	54	59	62
30	78	84	89
35	106	114	121
40	138	149	158
45	175	189	200
50	216	233	247
55	261	281	299
60	310	335	355

<sup>1</sup> Braking distance for truck service brakes; separate criteria apply to truck emergency brakes.

### TRUCK ACCELERATION CHARACTERISTICS

Two aspects of truck acceleration performance are important to highway/heavy vehicle interaction. The first aspect is the ability of a truck to accelerate from a full stop to clear a specified hazard zone such as an intersection or railroad-highway grade crossing. Typically, a hazard zone of this type is less than 66 m (200 ft) long; as a result, the speed attained by the truck is low. This first aspect of truck acceleration performance is, therefore, referred to as *low-speed acceleration*. The second aspect of truck acceleration is the ability of a truck to accelerate to a high speed either from a stop or from a lower speed. This type of acceleration, referred to here as *high-speed acceleration*, is needed by trucks in passing maneuvers and in entering a high-speed facility.

#### Low-Speed Acceleration

The low-speed (or start-up) acceleration ability of a truck determines the time required for it to clear a relatively short conflict zone such as an intersection or railroad-highway grade crossing. The primary factors that affect the clearance times of trucks are as follows:

- length of conflict zone
- length of truck
- truck weight-to-power ratio
- truck gear ratio
- roadway geometry (percent grade, curvature)

Because of their lower acceleration rates and greater lengths, heavy vehicles take longer than passenger cars to clear a specific hazard zone.

A simplified analytical model of the low-speed acceleration of trucks has been developed by Gillespie (13). The Gillespie model estimates the time required for a truck to clear a conflict zone, starting from a full stop, as:

$$t_c = \frac{0.682 (L_{HZ} + L_T)}{V_{mg}} + 3.0 \quad (2)$$

- where:  $t_c$  = time required to clear zone (s)  
 $L_{HZ}$  = length of conflict zone (ft)  
 $L_T$  = length of truck (ft)  
 $V_{mg}$  = maximum speed mi/h in the gear selected by the driver (= 60/gr on a level road)  
gr = gear ratio selected by driver

The Gillespie model was compared with the results of field observations of time versus distance for 77 tractor-trailer trucks crossing zero-grade intersections from a full stop (13). These data are shown in Figure 5. There is no information on the weights or weight-to-power ratios of these trucks although they probably vary widely. A line representing the clearance time predicted by Eq. (2) for a level grade is also presented in the figure.

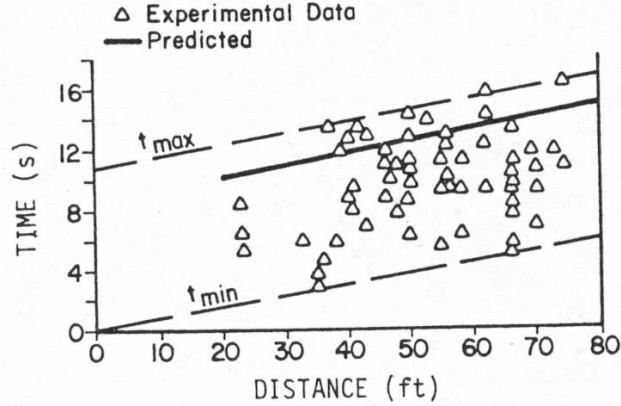


Figure 5. Field observations of times for 19.8-m (65-ft) tractor-trailer trucks to clear intersection distances after starting from a stop (13, 14).

Eq. (2) provides a relatively conservative estimate of clearance times, since the majority of the experimental points fall below the prediction. The experimental data in Figure 5 are bounded by two parallel lines representing the maximum and minimum observed clearance times.

### High-Speed Acceleration

The acceleration capability of a truck at higher speeds is primarily a function of the truck weight-to-power ratio, the truck's current speed, and the local highway grade. Aerodynamic drag forces have a secondary effect, which decreases at higher elevation. The performance of diesel engines is not affected by elevation, although the performance of gasoline engines decreases with increasing elevation (2, 15).

The maximum acceleration of a heavy vehicle on an upgrade can be estimated as the minimum of  $a_c$ ,  $a_p$ , and  $a_e$  determined as (2, 16):

$$a_c = -0.2445 - 0.0004 V' - \frac{0.021 C_{de} (V')^2}{(W/A)} - \frac{222.6 C_{pe}}{(W/NHP) V'} - gG \quad (3)$$

$$a_p = \frac{15368 C_{pe}}{(W/NHP) V'} \quad (4)$$

$$1 + \frac{14080}{(W/NHP) V'^2}$$

$$a_e = \frac{0.4 V' a_o}{0.4 V' + \frac{1.5 a_o}{|a_o|} (a_p - a_c)}, \quad V \geq 10 \text{ ft/s} \quad (5)$$

$$a_e = \frac{10 a_o}{10 + \frac{1.5 a_o}{|a_o|} (a_p - a_c)}, \quad V < 10 \text{ ft/s} \quad (6)$$

- where:
- $a_c$  = coasting acceleration (ft/s<sup>2</sup>) during gearshifts
  - $a_p$  = horsepower-limited acceleration (ft/s<sup>2</sup>)
  - $a_e$  = effective acceleration (ft/s<sup>2</sup>) including an allowance of 1.5 s for gearshift delays
  - $V'$  = larger of speed at beginning of interval ( $V$ ) and 10 ft/s
  - $C_{de}$  = correction factor for converting sea-level aerodynamic drag to local elevation =  $(1 - 0.000006887E)^{4.255}$
  - $C_{pe}$  = altitude correction factor for converting sea-level net horsepower to local elevation = 1 for diesel engines
  - $E$  = local elevation (ft)
  - $W/A$  = weight to projected frontal area ratio (lb/ft<sup>2</sup>)
  - $W/NHP$  = weight to net horsepower ratio (lb/hp)

- $g$  = acceleration of gravity (32.2 ft/s<sup>2</sup>)
- $G$  = local grade (expressed as a decimal proportion)

Eq. (3) represents the coasting acceleration of the truck. Eq. (4) represents the acceleration as limited by engine horsepower. Eqs. (5) and (6) combine the coasting and horsepower-limited accelerations into an effective acceleration that allows the truck to use maximum horsepower except during gearshift delays of 1.5 s, during which the truck is coasting (with no power supplied by the engine). This model of truck performance is based on SAE truck-performance equations that were adapted by St. John and Kobett to incorporate gearshift delays (15, 16). There are no driver restraints on using maximum acceleration or maximum speed on upgrades because, unlike passenger car engines, truck engines are designed to operate at full power for sustained periods. On level sections and on downgrades, driver restraints often limit heavy vehicle acceleration to levels less than the vehicle capability computed with Eqs. (3) through (6).

Eqs. (3) through (6) can be used to plot heavy vehicle speed profiles on grades and, therefore, estimate the speed-maintenance capabilities of heavy vehicles on upgrades as a function of the three key parameters: the vehicle weight-to-power ratio, the vehicle speed, and the vertical profile of the highway. Recent field data have shown that the truck population using freeways has an 85th percentile weight-to-power ratio in the range from 102 to 126 kg/kW (170 to 210 lb/hp), while on two-lane highways the truck population is in the range from 108 to 168 kg/kW (180 to 280 lb/hp) (2).

### REARWARD AMPLIFICATION

When a combination vehicle makes a sudden lateral movement, such as to avoid an obstacle in the road, its various units undergo different lateral accelerations. The front axles and the cab exhibit a certain acceleration, but the following trailer(s) have greater accelerations. This has been experimentally verified and quantified (17). The lateral acceleration of the first trailer may be twice that of the tractor,

and the lateral acceleration of a second trailer may be four times as much.

The factors that contribute to increased lateral accelerations of the trailing units, the phenomenon known as rearward amplification, include the following:

- number of trailing units
- shortness of trailers (longer ones experience less amplification)
- loose dolly connections
- greater loads in rearmost trailers
- increased vehicle speeds

Quantifying rearward amplification in terms of multiples of lateral acceleration is relevant to vehicle design, but is not generally relevant to highway geometric design. It has been recommended that a reasonable performance criterion would be that the physical overshoot that a following trailer exhibits during such a maneuver, relative to its final displaced lateral position, be limited to 0.8 m (2.7 ft) (17).

### SUSPENSION CHARACTERISTICS

The suspension of a heavy vehicle affects its dynamic responses in three major ways:

- determining dynamic loads on tires
- orienting the tires under dynamic loads
- controlling vehicle body motions with respect to the axles

Suspension characteristics can be categorized by eight basic mechanical properties:

- vertical stiffness
- damping
- static load equalization
- dynamic inter-axle load transfer
- height of roll center
- roll stiffness
- roll steer coefficient
- compliance steer coefficient



A detailed discussion of the effects of these suspension characteristics on truck performance is presented by Fancher et al. (18).

- overall weight
- longitudinal weight distribution
- lateral weight distribution

### LOAD TRANSFER RATIO

The extent to which vertical load is transferred from the tires on one side of a vehicle to those on the other side is called the *load transfer ratio*. Load is transferred when a vehicle is stationary on a lateral incline, when rounding a curve, and when making a steering maneuver such as to avoid an obstacle. It is calculated as follows:

$$\text{Load Transfer Ratio} = \text{Sum}(F_L - F_R) / \text{Sum}(F_L + F_R) \quad (7)$$

where  $F_L$  and  $F_R$  are the tire loads on the left and right sides, respectively.

The load transfer ratio has a value of 0.0 when the loads on the two sides are equal, and  $\pm 1.0$  when all the load is transferred to one side or the other. When the latter situation is just reached, the unloaded side is about to lift off from the pavement, and rollover is imminent. The load transfer ratio for an automobile or a single-unit truck is for most practical purposes a single number. For a combination vehicle, it can be computed separately for each unit; the unit with the greatest ratio is usually the most likely to come on the verge of rolling over. The truck properties affected by the load transfer ratio, other than impending rollover, include handling response time, roll steer, and rearward amplification.

### ROLLOVER THRESHOLD

A vehicle's resistance to rollover is measured by the maximum lateral acceleration that can be achieved without causing rollover. This maximum acceleration, measured in units of the acceleration of gravity ( $g$ ), is known as the rollover threshold.

The rollover threshold of a truck is largely a function of its loading configuration. The following parameters of a truck's loading configuration affect its rollover threshold:

- center of gravity (CG) height

Most research suggests that a reasonable value for a minimum rollover threshold for loaded trucks is in the range from 0.34 to 0.40  $g$  (17, 19, 20). Most trucks have rollover thresholds substantially higher than this range. In an appendix to the U.S. Comprehensive Truck Size and Weight Study (21), it is stated that fatal accident data show so few cases with rollover thresholds less than 0.35  $g$  that rates cannot be calculated.

Vehicle rollover thresholds are not explicitly considered in highway design because horizontal curves and other locations where vehicles turn are designed to generate lateral accelerations well below the rollover thresholds of the vehicles that use the facility. However, the rollover thresholds of vehicles can be used to judge the margin of safety before rollover would occur at any particular highway feature.

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## ROLE OF ROADWAY GEOMETRIC DESIGN IN SAFELY ACCOMMODATING HEAVY VEHICLES ON THE HIGHWAY

This chapter addresses the role of roadway geometric design in safely accommodating heavy vehicles on the highway. The geometric design elements and issues addressed in this chapter include:

- design vehicles
- sight distance
- upgrades
- downgrades
- acceleration lanes
- horizontal curves
- intersection design
- interchange ramps
- roadside features

The geometric design policies of most state and local highway agencies are based on or derived from the AASHTO *Green Book*; therefore, the *Green Book* criteria for geometric design are the focus of much of the following discussion. The discussion draws extensively from the analyses of *Green Book* design criteria conducted recently in *NCHRP Report 505 (2)*.

### DESIGN VEHICLES

The design vehicles presented in the AASHTO *Green Book* are a primary tool for incorporating heavy vehicle considerations in highway geometric design. The *Green Book* design vehicles are especially important in the design of intersections. The *Green Book* design vehicles and their specific dimensions are presented in Appendix A.

### SIGHT DISTANCE

Sight distance plays a key role in the safe operation of the highway system. Several types of sight distance are considered in highway geometric design including stopping sight distances, passing sight distance, intersection sight distance, and railroad-

highway grade crossing sight distance. The relationship of heavy vehicle to each of these types of sight distance is discussed below.

### Stopping Sight Distance

Sight distance is the length of roadway ahead that is visible to the driver. The minimum sight distance available on the roadway should be sufficiently long to enable a vehicle traveling at the design speed to stop before reaching a stationary object in its path. This minimum sight distance, known as stopping sight distance, is the basis for design criteria for crest vertical curve length and minimum offsets to horizontal sight obstructions. Stopping sight distance is needed at every point on the roadway. In the survey reported in Appendix B, only 23 percent of highway agencies identified stopping sight distance as related to safety problems encountered by heavy vehicles.

Stopping sight distance is determined as the summation of two terms: brake reaction distance and braking distance. The brake reaction distance is the distance traveled by the vehicle from when the driver first sights an object necessitating a stop to the instant the brakes are applied. The braking distance is the distance required to bring the vehicle to a stop once the brakes are applied.

Stopping sight distance criteria in the *Green Book* have undergone a thorough recent review and have been revised in the 2001 edition based on research in *NCHRP Report 400 (37)*. Design values for stopping sight distance are based on the following model:

$$SSD = 1.47Vt + 1.075 \frac{V^2}{a} \quad (8)$$

where: SSD = stopping sight distance, ft  
 t = brake reaction time, s  
 V = design speed, mph  
 a = deceleration rate, ft/s<sup>2</sup>

The first term in Eq. (8) represents the brake reaction distance and the second term represents the braking distance. The stopping sight distance design criteria applicable for all highway types are presented in Table 8. Figure 6 illustrates the application of stopping sight distance to crest vertical curves, while Figure 7 illustrates the application of stopping sight distance to horizontal curves.

The *Green Book* design criteria for stopping sight distance are based primarily on passenger car rather than heavy vehicle considerations. The key considerations that affect design criteria for stopping sight distance, vertical curve length, and offsets to sight obstructions on horizontal curves are as follows:

- assumed speed for design
- brake reaction time
- deceleration rate (or coefficient of tire-pavement friction)
- driver eye height
- object height

Stopping sight distance design for passenger cars and heavy vehicles does not differ with respect to assumed speed, brake reaction time, and object height. In fact, the brake reaction time of professional drivers may be better than the general driving population.

At crest vertical curves, truck and bus drivers have an advantage over passenger car drivers because they sit higher above the pavement and, thus, can see objects ahead that a passenger car driver cannot. The driver eye height for trucks used in geometric design is 2,400 mm (8.0 ft), as indicated in Chapter Two. Thus, heavy vehicle drivers actually need shorter vertical curves than passenger car drivers to attain adequate stopping sight distance. There is, however, no comparable advantage for heavy vehicle drivers on horizontal curves.

The design situation for stopping sight distance involves a vehicle braking to a stop on a wet pavement with relatively poor friction characteristics. Historically, the braking distances of

heavy vehicles have been longer than those for passenger cars. However, recent data show that, on wet pavements, the braking distances of trucks and passenger cars are nearly equal (11). Thus, the stopping sight distance needs for passenger cars and trucks are now comparable (2).

In summary, it appears that the current highway design criteria for stopping sight distance can safely accommodate heavy vehicles.

### Passing Sight Distance

Greater sight distance is required for one vehicle to pass another in the lane normally reserved for opposing traffic on a two-lane highway than is required simply to bring a vehicle to a stop before reaching an object in the road. Table 9 presents the passing sight distance criteria used in geometric design and the criteria used in marking of passing and no-passing zones on two-lane highways (1, 22). The geometric design criteria are more conservative than the marking criteria, but neither is based on a completely consistent set of assumptions.

The current passing distance criteria shown in Table 9 were derived on the basis of passenger car behavior and do not explicitly consider heavy vehicles. Using a new sight distance model with more consistent assumptions, Harwood et al. (14) derived sight distance requirements for various passing scenarios involving passenger cars and trucks, as shown in Figure 8. The figure indicates that all passing scenarios are accommodated within the current geometric design criteria. Furthermore, Harwood et al. also found that a truck can safely pass a passenger car on any crest vertical curve on which a passenger car can safely pass a truck. The current marking criteria for passing and no-passing zones do not necessarily accommodate all passing maneuvers that truck drivers might wish to make. However, there is currently no indication that the passing and no-passing zone markings lead truck

**Table 8. Design criteria for stopping sight distance (1)**

Design speed (mi/h)	Minimum stopping sight distance used in design (ft)
15	80
20	115
25	155
30	200
35	250
40	305
45	360
50	425
55	495
60	570
65	645
70	730
75	820
80	910

Note: Brake reaction distance predicated on a time of 2.5 s; deceleration rate of 11.2 ft/s<sup>2</sup> used to determine calculated sight distance.

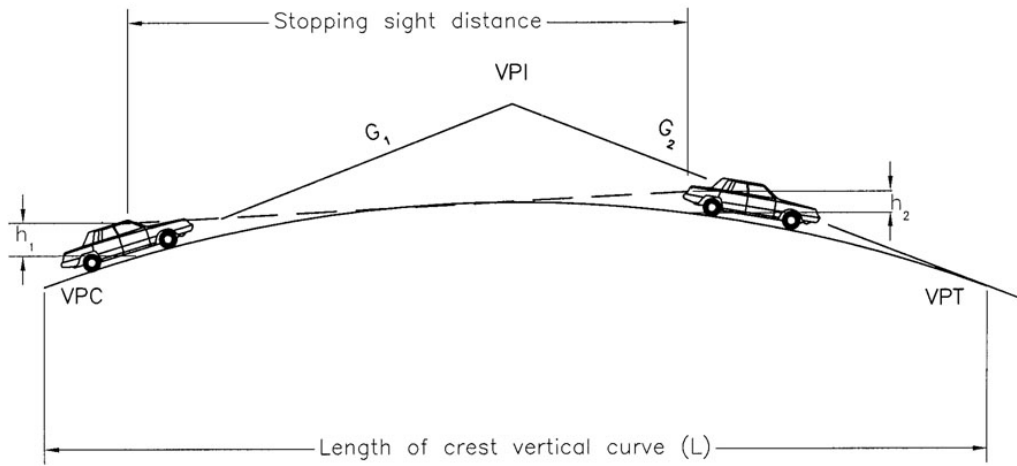


Figure 6. Application of stopping sight distance to crest vertical curves (1).

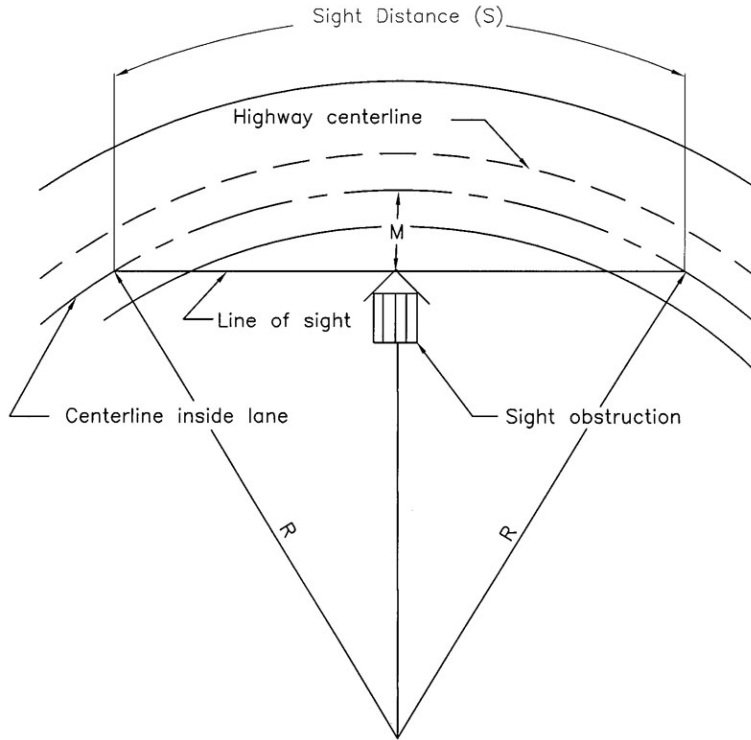


Figure 7. Application of stopping sight distance to horizontal curves (1).

**Table 9. Design and marking criteria for passing sight distance (1, 22)**

Design or prevailing speed (mi/h)	Passing sight distance (ft)	
	Highway design <sup>a</sup>	Marking of passing and no-passing zones <sup>b</sup>
25	900	450
30	1,090	500
35	1,280	550
40	1,470	600
45	1,625	700
50	1,835	800
55	1,985	900
60	1,985	900
65	2,285	1,100
70	2,480	1,200

<sup>a</sup> Based on AASHTO Green Book (1).

<sup>b</sup> Based on MUTCD (22).

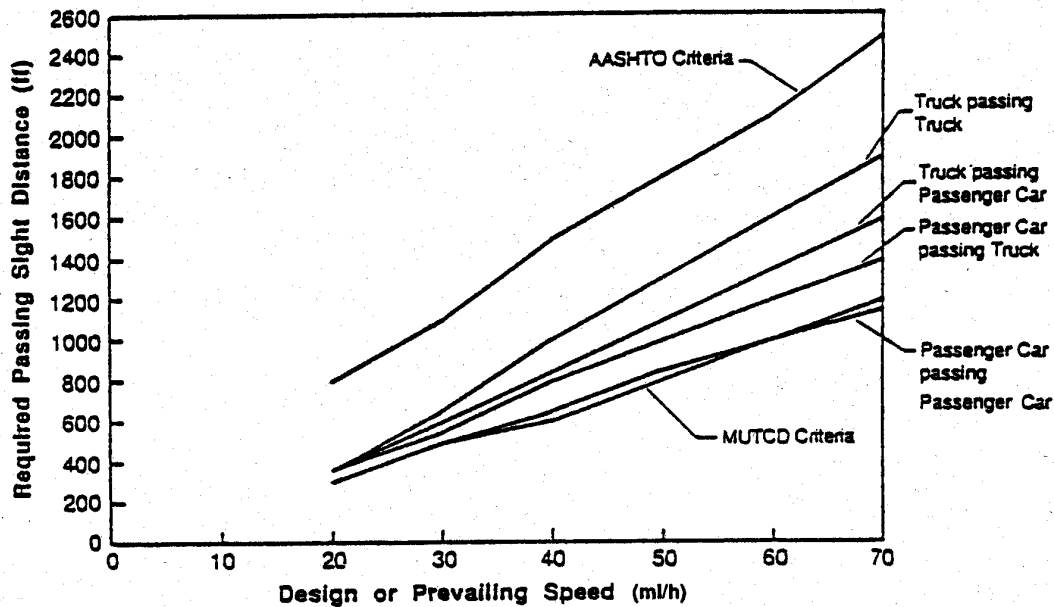


Figure 8. Required passing sight distance for passenger cars and trucks in comparison to current criteria (14).

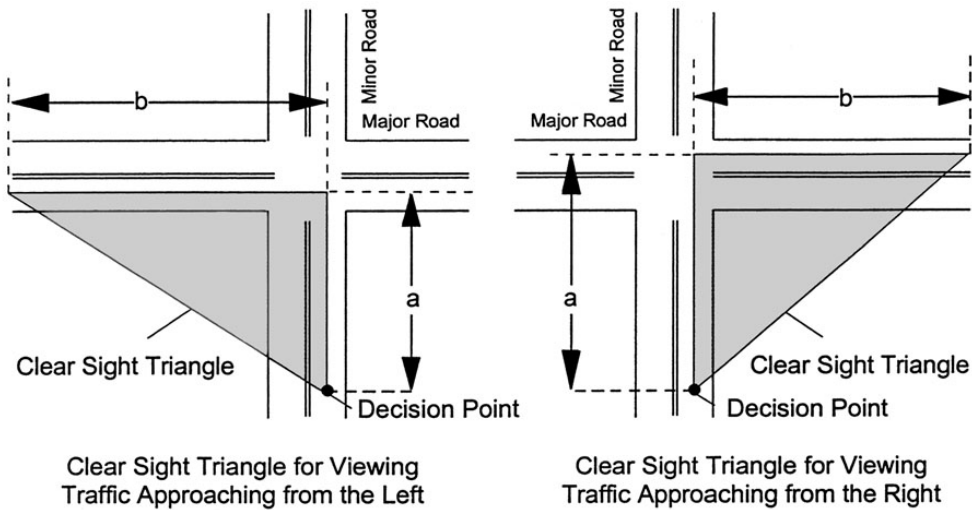
drivers to make poor passing decisions or that trucks are overinvolved in passing-related accidents. Thus, there is no indication that a change in the marking criteria to better accommodate trucks would have safety benefits (2). There is concern that such a change could eliminate some passing zones that are currently used effectively by passenger cars. Further research on this issue is needed.

### Intersection Sight Distance

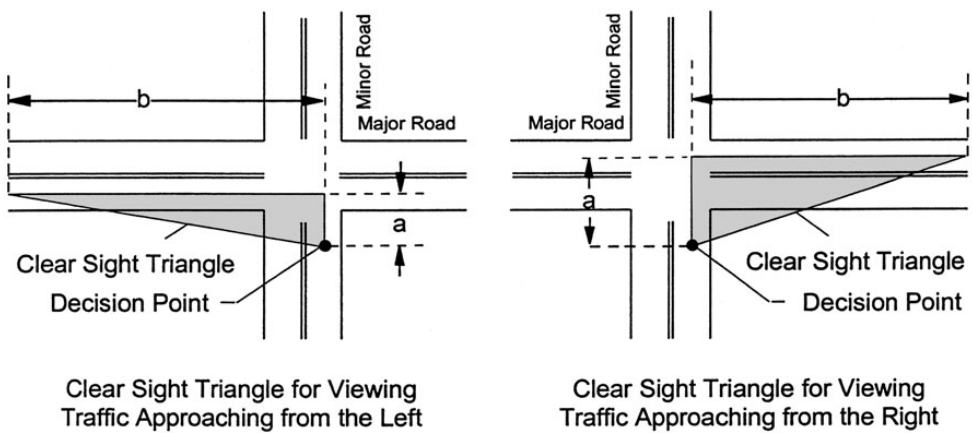
Sight distance is needed at intersections not only for drivers to see objects or other vehicles ahead on the roadway, but also to see potentially conflicting vehicles on other roadways. Sight distance at intersections is assured by maintaining triangular areas clear of sight obstructions in each quadrant of each intersection. Figure 9 illustrates the types of clear sight triangles that should be maintained at intersections: approach and departure sight triangles both to the left and to the right of each intersection approach.

Design criteria for intersection sight distance are established in the *Green Book* for a series of cases that apply to specific types of intersection traffic control and specific vehicle turning or crossing maneuvers. These design criteria were recently revised based on research in *NCHRP Report 383* (23). With one exception, the intersection sight distance criteria include explicit adjustment factors for heavy vehicles based on the research in *NCHRP Report 383*. The only case that does not explicitly address heavy vehicles is the design of intersections with no traffic control on any of the approaches. Such uncontrolled intersections typically have very low traffic volumes and even lower volumes of heavy vehicles.

Only 23 percent of highway agencies in the survey reported in Appendix B identified intersection sight distance as related to safety problems encountered by heavy vehicles.



**A -- Approach Sight Triangles**



**B -- Departure Sight Triangles**

Figure 9. Clear sight triangles for intersections (1).

### Railroad–Highway Grade Crossing Sight Distance

Sight distance is provided at railroad-highway grade crossings to ensure that approaching motor vehicles can see any train that is also approaching the crossing (1). Sight distance is provided at railroad-highway grade crossings with clear sight triangles similar to those illustrated for intersections in Figure 9. *NCHRP Report 505* (2) reviewed the current *Green Book* criteria for sight distance at railroad-highway grade crossings and found them adequate to accommodate heavy vehicles.

Recent experience has drawn attention to a safety issue unrelated to sight distance—the spacing between railroad-highway grade crossings and adjacent intersections—as an important factor for design and traffic control. Locations with short spacings between intersections and railroad tracks should be designed so that longer vehicles stopped at the intersection are not forced to stop in a position where the rear of the vehicle extends onto the railroad tracks.

Approximately 40 percent of highway agencies responding to the survey described in Appendix B



indicated the railroad-highway grade crossings are a safety concern related to heavy vehicles.

## UPGRADES

Heavy vehicles do not usually have engines sufficiently powerful to maintain normal highway speeds on long, steep upgrades. Slower vehicles have the potential to create both traffic operational and safety concerns at such sites. The speed maintenance capabilities of heavy vehicles on grades are primarily a function of the weight-to-power ratio of the vehicle, as documented in Chapter Two. As a heavy vehicle proceeds up a grade, it gradually loses speed until it reaches a crawl speed that is a function of the grade and truck characteristics. When traveling at its crawl speed, the heavy vehicle cannot accelerate but can travel at constant speed, without further speed loss.

To mitigate the potential traffic operational and safety effects of heavy vehicles, highway agencies often provide truck climbing lanes. An added lane on the upgrade allows heavy vehicles to avoid impeding passenger cars and other faster vehicles. The AASHTO *Green Book (1)* considers the provision of a climbing lane warranted when truck speeds are reduced by 16 km/h (10 mi/h) and certain minimum traffic volume or level of service criteria are met. A spreadsheet program has been developed for use by highway agencies to estimate speed profiles for specific trucks on specific upgrades (2).

There are no formal safety effectiveness measures for truck climbing lanes, although Harwood and St. John (24) have estimated a 25 percent accident reduction effectiveness for passing lanes on two-lane highways, in general.

In response to the survey presented in Appendix B, 66 percent of highway agencies indicated that they have formal warrants for truck climbing lanes. In response to the survey presented in Appendix C, 23 percent of industry respondents indicated that they consider long, steep upgrades to be a high-priority safety concern, while 61 percent of respondents indicated that they consider long, steep upgrades to be a low-priority issue that represent a safety concern at a few locations.

Approximately 66 percent of industry respondents indicated that they consider truck climbing lanes to be highly desirable improvements that should be used widely.

## DOWNGRADES

Long, steep downgrades also represent a safety concern for heavy vehicles. In the industry survey reported in Appendix C, 40 percent of respondents indicated that they consider long, steep downgrades to be a major safety concern at many locations, while another 53 percent of respondents consider downgrades to be a safety concern at a few specific locations.

Heavy vehicle drivers must travel slowly down long, steep grades to minimize braking. If the vehicle service brakes are used too frequently, they may overheat and the vehicle may run out of control due to loss of braking ability. To avoid such incidents, highway agencies are signing at the top of long downgrades to advise heavy vehicle drivers of the appropriate choice of speed or gear ratio. Conventional signing has been used for this purpose (see Chapter Four), but automated systems to advise drivers on safe downgrade speeds have come into use as well (see Chapter Five). In the industry survey reported in Appendix C, 97 percent of respondents indicated that downgrade signing is desirable or highly desirable and 78 percent indicated that automated signing for downgrades is desirable or highly desirable. Criteria for such signing have been developed in research by Allen et al. (25).

At particularly long or steep grades, highway agencies may provide roadside parking places at the top of the grade for heavy vehicle drivers to stop and check the temperature of their brakes and, if appropriate, to let the brakes cool. Such brake check areas may assist in reducing the frequency of out-of-control trucks on downgrades. Brake check areas are currently used by 49 percent of highway agencies and another 3 percent of agencies are considering their use (see Appendix B). Brake check areas are considered desirable or highly desirable by 90 percent of the industry survey respondents in Appendix C.

To assist heavy vehicle drivers who do lose control due to overheating of their brakes, many highway agencies provide emergency escape ramps in the middle or lower portion of long downgrades. Rather than continuing down a grade out of control, the driver can choose to enter the escape ramp where an arrester bed can bring the vehicle to a safe stop. Sixty-three percent of highway agencies have installed emergency escape ramps and such ramps are considered desirable or highly desirable by 100 percent of the respondents to the industry survey.

Allen et al. (26) have proposed a simulation model that could help highway agencies evaluate the need for emergency escape ramps. This issue has also been addressed by Abdelwahab and Morrall (27).

#### **ACCELERATION LANES**

Acceleration lanes are provided at entrance ramps to major highways to provide a location for vehicles to increase their speed before entering the highway. Design criteria for the length of acceleration lanes, including adjustment factors for heavy vehicles, are presented in the AASHTO *Green Book (1)*. Recent research in *NCHRP Report 505 (2)* concluded that the current design criteria for acceleration lanes accommodate average trucks but may not be long enough to accommodate the lowest performance trucks. Seventy-five percent of the respondents to the industry survey in Appendix C indicated that acceleration lanes were a major safety concern at many locations. Further research on this issue is needed.

#### **HORIZONTAL CURVES**

The design criteria for horizontal curves in the AASHTO *Green Book (1)* are based on keeping the lateral acceleration of the vehicle within limits that are comfortable to the driver. A vehicle can exceed these tolerable limits without approaching the point of skidding or rolling over, but heavy vehicles have lower margins of safety against skidding or rollover than passenger cars (2).

The lateral acceleration experienced by a vehicle traversing a horizontal curve is influenced by both

the radius and superelevation of the curve. Skidding or rollover by a heavy vehicle on a horizontal curve designed in accordance with *Green Book* criteria is likely only if the vehicle is traveling at a speed higher than the design speed of the curve. A truck will roll over before it skids at curves with design speeds of 70 to 80 km/h (40 to 50 mi/h) and below; for curves above that design speed, a truck will skid before it rolls over (2).

In the highway agency survey reported in Appendix B, 51 percent of highway agencies identified horizontal curve radius and 31 percent identified horizontal curve superelevation as a source of safety problems for heavy vehicles. In the industry survey reported in Appendix C, 67 percent of respondents identified sharp curves as a high-priority safety issue for heavy vehicles. Two respondents to the industry survey commented that inappropriate superelevation (and, particularly, the presence of reverse superelevation on some curves) creates a safety concern for heavy vehicles.

#### **INTERSECTION DESIGN**

Heavy vehicles are a key consideration in the design of at-grade intersections. Key intersection concerns for heavy vehicles include curb return radii for right turns, available storage length in left-turn lanes, median width, and visibility restrictions due to vehicles in opposing left-turn lanes.

The curb return radii for right turns are determined through a process that balances the needs of all highway transportation modes. The curb return radius should be sufficiently large to accommodate the offtracking and swept path of specific design vehicles that use the intersection without the vehicle encroaching on the curb or on an adjacent or opposing lane. At the same time, particularly in urban areas, it is desirable to keep the curb return radius small to minimize pedestrian crossing distances and avoid disturbing existing roadside development. Most designs involve some compromise between these objectives. In the survey reported in Appendix B, 51 percent of highway agencies identified curb return radii for right turns

as a source of safety concerns for heavy vehicles. Tight radii for right turns were identified as a high-priority safety concern by 94 percent of the respondents to the industry survey presented in Appendix C.

Left-turn lanes are designed to include sufficient length for deceleration, storage, and a transition taper. The storage length for turn lanes is strongly influenced by the volume of heavy vehicles using the lane. In particular, if more vehicles than anticipated use the left-turn lane, the queue may overflow into the through vehicle lanes, creating safety problems. In the industry survey reported in Appendix C, 69 percent of respondents indicated that insufficient storage length for left turns was a high-priority safety concern.

On divided highways, the median width at intersections should be selected to steer a design vehicle of appropriate length. *NCHRP Report 375 (28)* evaluated the design of divided highway intersections and recommended that medians at rural intersections should be as wide as practical and should accommodate the length of design vehicles that are present in sufficient numbers to serve as a basis for design. In urban areas, narrower medians operate more safely and the selected median width should generally be just wide enough to accommodate current, and anticipated future, left-turn treatments.

At some intersections, the view along the opposing roadway for the driver of a vehicle in a left-turn lane may be blocked by presence of a vehicle in the opposing left-turn lane. This is a particular concern when the vehicle in the opposing left-turn lane is large. Figure 10 illustrates the application of parallel and diagonal offset left-turn lanes to mitigate this problem. Both of these left-turn lane designs offset the opposing left-turn lanes by moving them out of the sight line of the left-turning driver.

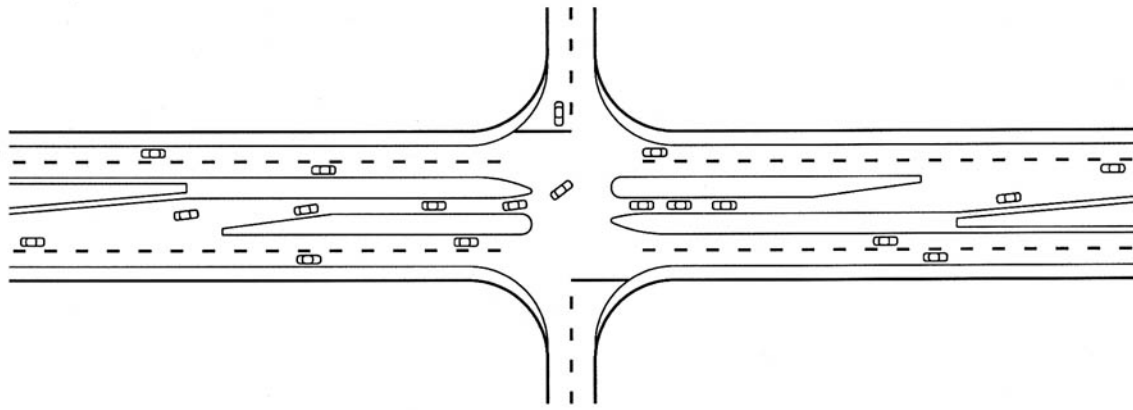
## **INTERCHANGE RAMP DESIGN**

Interchange ramps are designed to have sufficient width to allow vehicles to pass a stalled heavy vehicle. The design of horizontal curves on interchange ramps, particularly exit ramps, is challenging because vehicles leaving a major road may often exceed the design speed of the ramp. The design speeds for such ramp curves should be selected appropriately and, at some locations, conventional or automated signing may be needed to warn heavy vehicle drivers of the desired travel speed (see Chapters Four and Five).

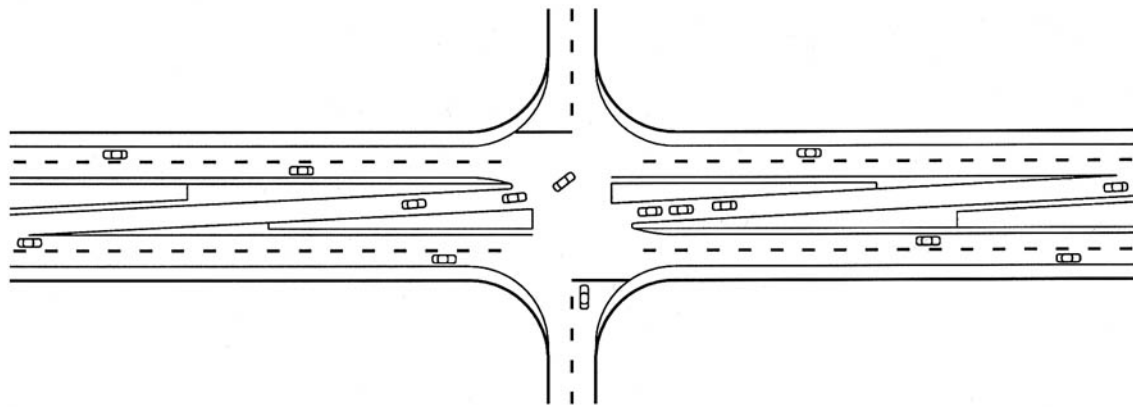
Interchange ramps were identified as a safety concern by 51 percent of the highway agencies responding to the Appendix B survey and as a major safety concern by 68 percent of the industry representatives responding to the Appendix C survey.

## **ROADSIDE DESIGN**

Roadside design includes the consideration of roadside slopes, roadside clear zones, and traffic barriers. These issues are addressed in the *AASHTO Roadside Design Guide (29)*. Roadside slopes and clear zone widths are designed for all vehicle types and do not explicitly consider heavy vehicles. Traffic barriers, such as guardrails, bridge rails, and median barriers, are intended to contain and redirect specific vehicle types that may run off the road. At some locations, highway agencies have used traffic barriers specifically intended to contain heavy vehicles including tall concrete median barriers and super heavy-duty guardrails at the bottom of long downgrades. The level 4 and 5 testing procedures in *NCHRP Report 350 (30)* are appropriate for barriers intended to contain heavy vehicles.



-A- PARALLEL



-B- TAPERED

Figure 10. Parallel and tapered offset left-turn lanes (1).