Faculty of Engineering
Department of Civil Engineering

Highway and airport engineering

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2. Design Controls and Criteria

DESIGN VEHICLES

- A design vehicle is selected to represent all vehicles on the highway. Its weight, dimensions, and operating characteristics are used to establish the design standards of the highway.

- The selected design vehicle is used to determine critical design features such as radius at intersections and turning roadways as well as highway grades.

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VEHICLES
Kinematic (Dynamic) Characteristics

- Acceleration (Constant or variable):
  - Passing maneuvers
  - Gap acceptance
  - Dimensions of freeway ramps and passing lanes
  - Motion elements (Distance and Velocity)

DESIGN VEHICLES
The following guidelines apply when selecting a design vehicle:

1. When a parking lot or a series of parking lots are the main traffic generators, the passenger car may be used.

2. For the design of intersections at local streets and park roads, a single-unit truck may be used.

3. At intersections of state highways and city streets that serve buses with relatively few large trucks, a city transit bus may be used.

DESIGN VEHICLES

The following guidelines apply when selecting a design vehicle:

4. At intersections of highways and low-volume county highways or township/local roads with less than 400 ADT, either an 84-passenger large school bus 40 ft. long or a 65-passenger conventional bus 36 ft. long may be used.
5. At intersections of freeway ramp terminals and arterial crossroads, and at intersections of state highways and industrialized streets that carry high volumes of traffic, the minimum size of the design vehicle should be WB-20.

DESIGN VEHICLES

Table 2-1a. Design Vehicle Dimensions (SI Units)

Design Vehicle Type	Symbol	Overall Height	Overall Width	Overall Length
Passenger Car	P	1.30	2.13	5. 79
Single-Unit Truck	SU-9	3.35–4.11	2.44	9. 14
Single-Unit Truck (three-axle)	SU-12	3.35–4.11	2.44	12.04
Intercity Bus (Motor Coaches)	BUS-12	3.66	2.59	12.36
	BUS-14	3.66	2.59	13.86
City Transit Bus	CITY-BUS	3.20	2.59	12.19
Conventional School Bus (65 pass.)	S-BUS 11	3.20	2.44	10.91
Large School Bus (84 pass.)	S-BUS 12	3.20	2.44	12.19
Articulated Bus	A-BUS	3.35	2.59	18.29
				Combi
Intermediate Semitrailer	WB-12	4.11	2.44	13.87
Interstate Semitrailer	WB-19*	4.11	2.59	21.03
Interstate Semitrailer	WB-20**	4.11	2.59	22.40

VEHICLES TYPES

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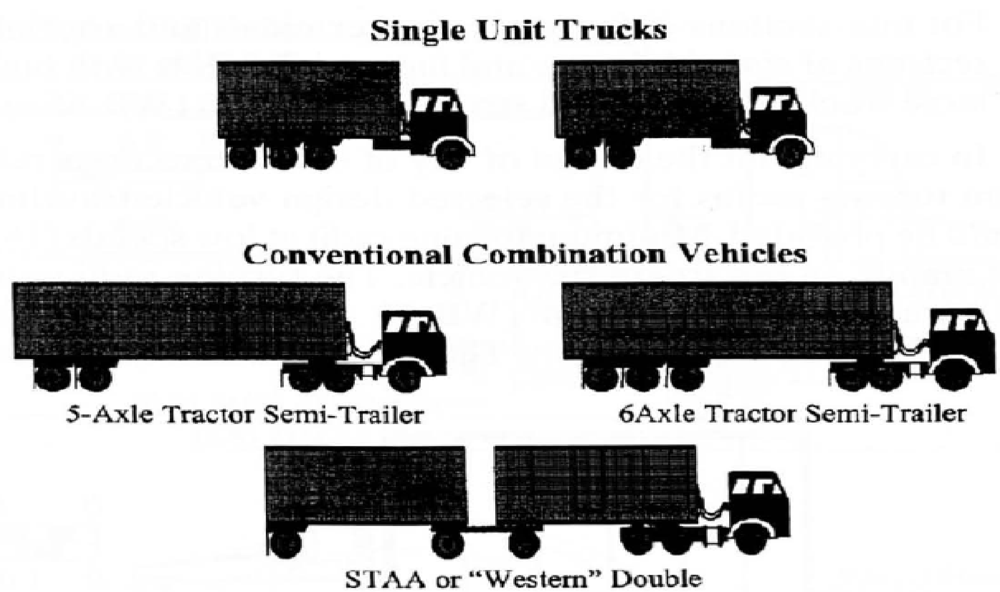
Truck Types



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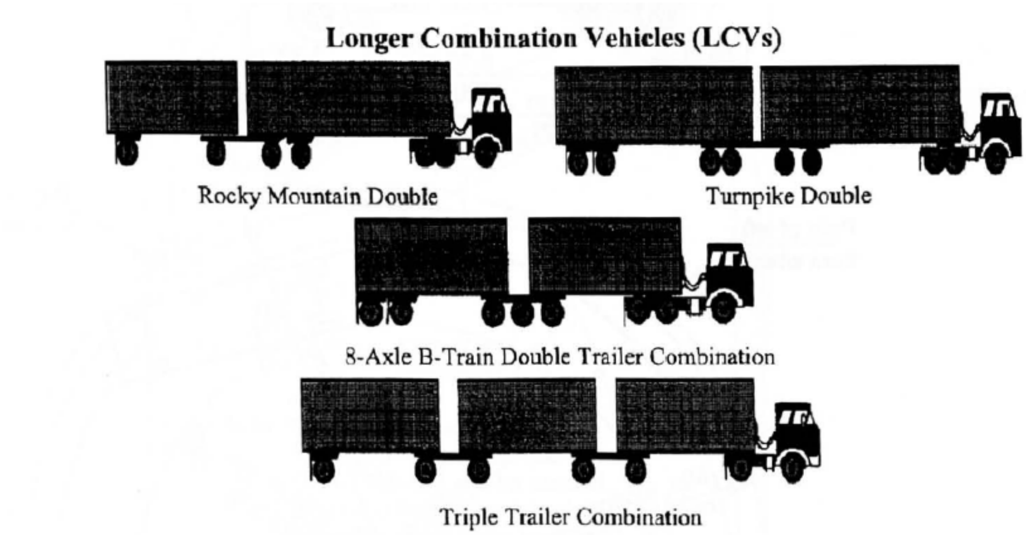
Truck Types



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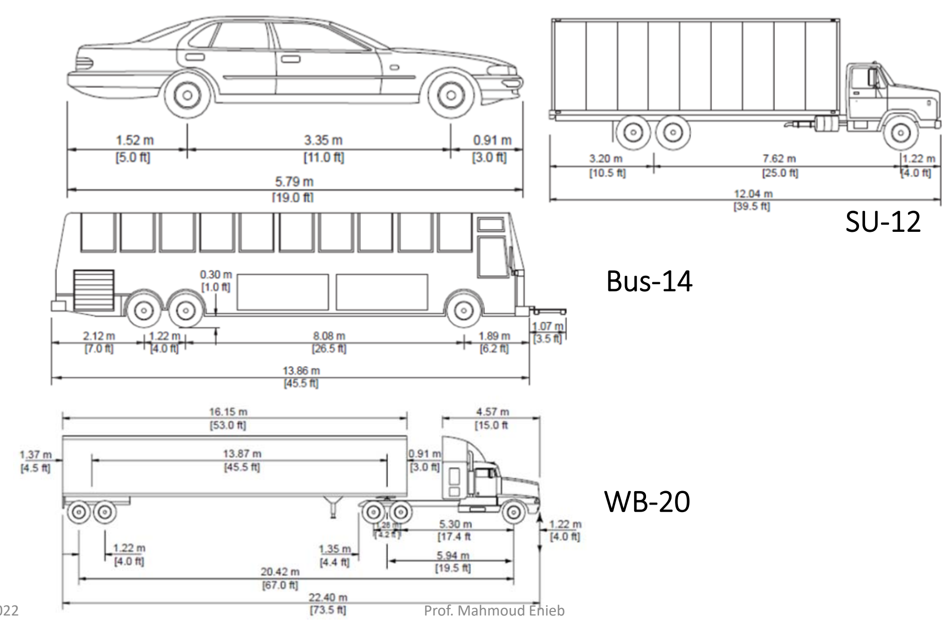
VEHICLES TYPES



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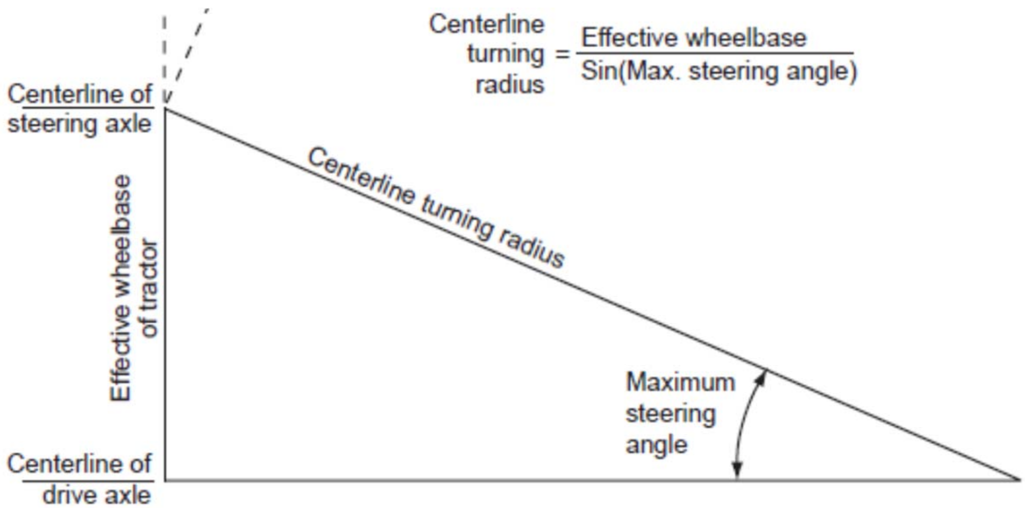
Calculation of Min. centerline turning radius



Minimum Centerline Turning Radius Calculations

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Min. centerline turning radius

Vehicle	Max. steering angle (degree)	Effective wheel base (m)	Centerline turning radius (m)
Privet car	31.6	3.35	6.39
Single unit truck SU-9 (2axles)	31.8	6.1	11.58
Single unit truck SU-12 (3axles)	31.8	7.62	14.46
School Bus S-Bus-12	34.4	6.1	10.79
Bus-14 Intercity Bus	45.2	8.69	12.25
City Bus	41.4	7.62	11.52
WB-12 Semitrailer	20.3	3.81	10.97
WB-20 semitrailer	28.4	5.94	12.49

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Example1

- Calculate the centerline turning radius for private car, if Max. steering angle = 31.6^o and Effective wheelbase = 3.35m?

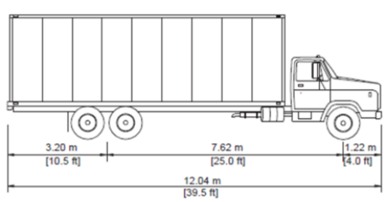
Solution

- Centerline turning radius = Effective wheelbase / (sin Max. steering angle)
- Centerline turning radius = 3.35/sin(31.6)

  = 6.39 m

Example2

- Calculate the centerline turning radius, if Max. steering angle = 31.8^o for the following single unit truck (SU-12)?

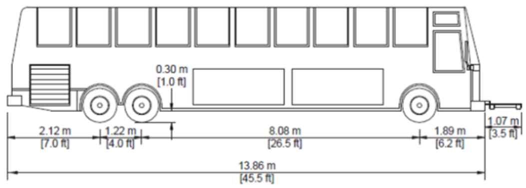


- Centerline turning radius = Effective wheelbase / (sin Max. steering angle)
- From figure Effective wheelbase = 7.62 m
- Centerline turning radius = 7.62/sin(31.8)

  = 14.46 m

Example3

- Calculate the centerline turning radius, if Max. steering angle = 45.2º for the following intercity Bus (Bus-14)?

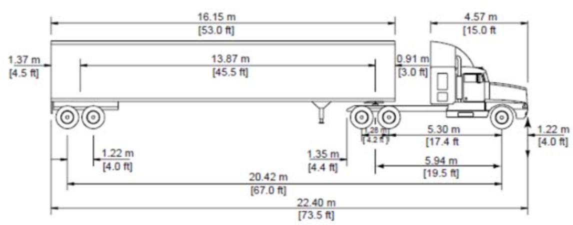


- Centerline turning radius = Effective wheel base / (sin Max. steering angle)
- From figure Effective wheel base = 8.08+1.22/2=8.69
- Centerline turning radius = 8.69/sin(45.2)

  = 12.25 m

Example4

- Calculate the centerline turning radius, if Max. steering angle = 28.4º for the following semitrailer (WB-20)?



- Centerline turning radius = Effective wheelbase / (sin Max. steering angle)
- From figure Effective wheelbase = 5.3+1.28/2=5.94
- Centerline turning radius = 5.94/sin(28.4)

  = 12.49 m

Dynamic Characteristics

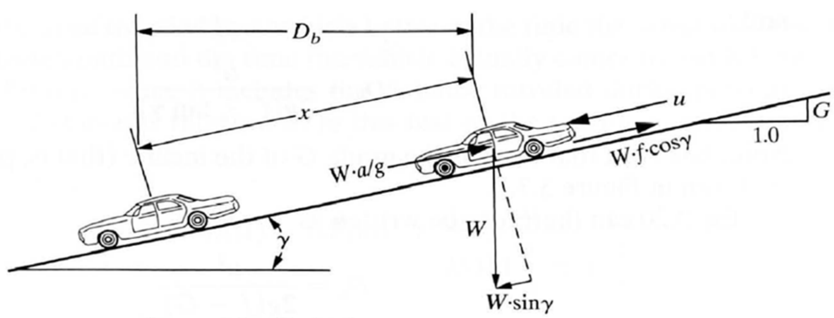
Braking distance

- The action of the forces (shown in Figure 3.6) on the moving vehicle and the effect of perception-reaction time are used to determine important parameters related to the dynamic characteristics of the vehicles.
- These include the braking distance of a vehicle and the minimum radius of a circular curve required for a vehicle traveling around a curve with speed u where u > 16 km/h

Dynamic Characteristics

Downhill

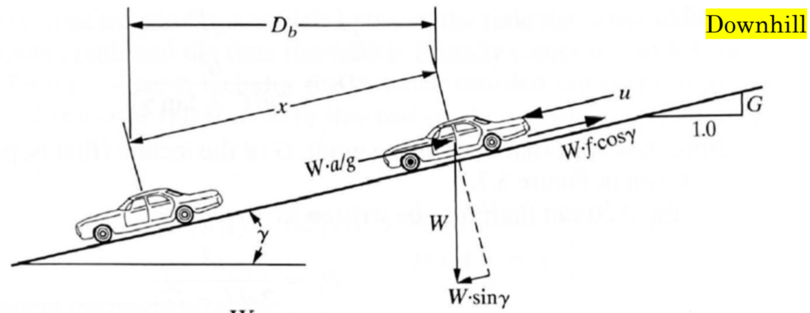
Braking distance



W = weight of vehicle
f = coefficient of friction
g = acceleration of gravity
a = vehicle acceleration
u = speed when brakes applied
D_b = braking distance
γ = angle of incline
$G = \tan\gamma$ (% grade/100)
x = distance traveled by the vehicle along the road during braking

Frictional force on the vehicle $= Wf\cos\gamma$

Downhill



$$W \sin\gamma - W f \cos\gamma = \frac{W a}{g}$$

$$a = -\frac{u^2}{2x}$$

$$W \sin\gamma - W f \cos\gamma = -\frac{W u^2}{2 g x}$$

$$D_b = x \cos\gamma$$

$$\frac{W u^2}{2 g D_b} \cos\gamma = W f \cos\gamma - W \sin\gamma$$

$$\frac{u^2}{2 g D_b} = f - \tan\gamma$$

$$D_b = \frac{u^2}{2g(f - \tan\gamma)}$$

$$D_b = \frac{u^2}{2g(f - G)}$$

If g is taken as 9.81 m/sec^2

u is expressed in km/h

$$D_b = \frac{u^2}{254(f - G)}$$

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- A similar equation could be developed for a vehicle traveling uphill , in which case the following equation is obtained.

$$D_b = \frac{u^2}{254(f + G)}$$

- A general equation for the braking distance can therefore be written as:

$$D\ (braking) = \frac{u^2}{254(f \pm G)}$$ **Metric units**

AASHTO recommends the coefficient of friction to be a/g and a to be 4.51 m/s^2 , then braking distance becomes:

$$D_b = \frac{u^2}{254\left(\frac{a}{g} \pm G\right)}$$

Or g = 32.2 ft/s^2

$$D\ (braking) = \frac{u^2}{30(f \pm G)}$$ **Britch units**

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Example 1

What is the distance required to stop an average passenger car when brakes are applied on a 2% downgrade if that vehicle was originally traveling at 40 mph?

Assume the friction factor 0.33

Solution

$$D\ (braking) = \frac{40^2}{30(0.33-0.02)} = 172 \text{ ft.}$$

The braking distance required to stop the vehicle is 172 feet

Example 2

A traveling car parked suddenly on a sharp horizontal curve (R = 150 m) and the driver hit a horse. The tracing distance of car on pavement was 60 m, perception reaction time = 2.5 s required:

The speed of car before braking?

Solution

Assume Friction Factor f = 0.30 and the road is level

$$D\ (braking) = \frac{V^2}{254(0.3+0)} = 60$$

V = 67.6 km/h

The speed of vehicle before hit a horse is equal 67.6 km/h

Example 3

A student trying to test the braking ability of his car, determined that the needed 32 ft more to stop his car downhill on a particular road than uphill when driving at 55 mph. Assuming that the coefficient of friction between the tires and the pavement is 0.3, determine:

the braking distance downhill and

the percent grade of the highway at that section of the road.

Solution

Let x ft = downhill braking distance

(x -32) = uphill braking distance

$$x = \frac{55^2}{30\,(0.3-G)}$$

$$x - 32 = \frac{55^2}{30\,(0.3+G)}$$

$$32 = \frac{55^2}{30\,(0.3-G)} - \frac{55^2}{30\,(0.3+G)}$$

$960(0.3-G)(0.3+G) = 55^2\,(0.3 + G) - 55^2\,(0.3 - G)$

$960\,(0.09 - G^2) = 55^2\,(2\,G)$

$86.4 - 960\,G^2 = 6050\,G$

$G^2 + 6.302\,G - 0.09 = 0$

$(G - 0.014)(G + 6.316) = 0$

G = 0.014 (that is, 1.4%)

$$x = \frac{55^2}{30\,(0.3-0.014)} = 352.6 \text{ ft}$$

Example 4

A motorist travelling at 55 mph on an expressway intend to exit from the expressway using an exit ramp with a maximum allowable speed of 30 mph. At what point on the expressway should the motorist step on her brakes in order to reduce her speed to the maximum allowable on the ramp just before entering the ramp. Assume that the coefficient of friction between the tires and the pavement is 0.3, and the alignment of this section of the road is horizontal?

Solution

$$D_b = \frac{55^2 - 30^2}{30\,(0.3 - 0)}$$

$= 236.1$ ft

The brakes should be applied at least 236 ft from the ramp

2.2 Levels of service

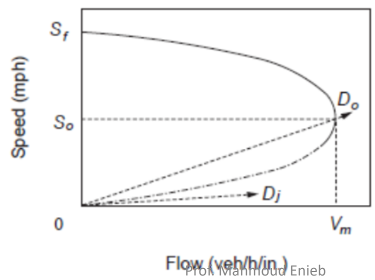
Level of Service	General Operating Conditions
A	Free flow
B	Reasonably free flow
C	Stable flow
D	Approaching unstable flow
E	Unstable flow
F	Forced or breakdown flow

Note: Specific definitions of levels of service A through F vary by facility type and are presented in the HCM (*37*).

2.2 Levels of service

Table 2-5. Guidelines for Selection of Design Levels of Service

Functional Class	Appropriate Level of Service for Specified Combinations of Area and Terrain Type			
	Rural Level	Rural Rolling	Rural Mountainous	Urban and Suburban
Freeway	B	B	C	C or D
Arterial	B	B	C	C or D
Collector	C	C	D	D
Local	D	D	D	D



3. Elements of Design

Sight Distance

- A driver's ability to see ahead is needed for safe and efficient operation of a vehicle on a highway.
- For example, on a railroad, trains are confined to a fixed path, yet a block signal system and trained operators are needed for safe operation.
- In contrast, the path and speed of motor vehicles on highways and streets are subject to the control of drivers whose ability, training, and experience are quite varied.

Four aspects of sight distance are discussed below:

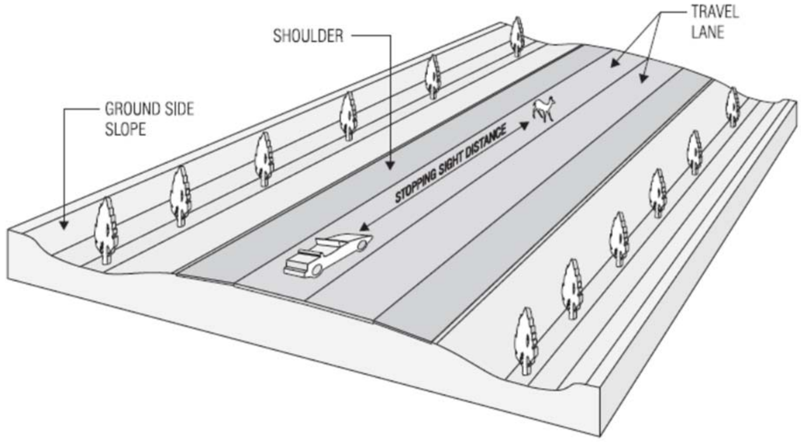
- (1) the sight distances needed for stopping, which are applicable on all highways;
- (2) the sight distances needed for the passing of overtaken vehicles, applicable only on two-lane highways;
- (3) the sight distances needed for decisions at complex locations; and
- (4) the criteria for measuring these sight distances for use in design

Sight distance

- SD is the length of the roadway a driver can see ahead at any time.
- The sight distance available at each point of the highway must be such that, when a driver is traveling at the highway's design speed, adequate time is given after an object is observed in the vehicle's path to make the necessary evasive maneuvers without colliding with the object.

The two types of sight distance are:

- Stopping sight distance (SSD).
- Passing sight distance PSD).



Stopping Sight Distance

- The stopping sight distance (SSD), for design purposes, is usually taken as the minimum sight distance required for a driver to stop a vehicle after seeing an object in the vehicle's path without hitting that object.
- This distance is the sum of the:

➢ Distance traveled during **perception-reaction time**.

➢and the **distance traveled during braking.**

Stopping Sight Distance

- Stopping Sight Distance =**Reaction Distance** + **Braking Distance**.
- **What is perception-reaction time**?
- The process through which a driver, cyclist, or pedestrian evaluates and reacts to a stimulus can be divided into four sub processes:

➢ 1. **Perception**: the driver sees a control device, warning sign, or object on the road.

➢ 2. **Identification**: the driver identifies the object or control device and thus understands the stimulus.

➢ 3. **Emotion**: the driver decides what action to take in response to the stimulus; for example, to step on the brake pedal, to pass, , or to change lanes .

➢ 4. **Reaction** : the driver actually executes the action decided on during the emotion sub-process**.**

Stopping Sight Distance

- Total time required for perception, identification, emotion, and volition, sometimes referred to as (more commonly) as perception-reaction time
- The reaction time selected for design purposes should, however, be large enough to include reaction times for most drivers using the highways.
- **Recommendations made by the American Association of State Highway and Transportation Officials (AASHTO) stipulate 2.5 seconds for stopping-sight distances** :

➢ **perception-reaction distance = 0.278 Vt (Metric)**

➢ **perception-reaction distance = 1.47 Vt (US unit)**

Stopping Sight Distance

Effect of Grade on Stopping

When a highway is on a grade braking distance is modified as follows:

Metric	U.S. Customary	
$d_B = \dfrac{V^2}{254\left[\left(\dfrac{a}{9.81}\right) \pm G\right]}$	$d_B = \dfrac{V^2}{30\left[\left(\dfrac{a}{32.2}\right) \pm G\right]}$	(3-3)
where: d_B = braking distance on grade, m V = design speed, km/h a = deceleration, m/s^2 G = grade, rise/run, m/m	where: d_B = braking distance on grade, ft V = design speed, mph a = deceleration, ft/s^2 G = grade, rise/run, ft/ft	

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Stopping Sight Distance (SSD)

Effect of Grade on Stopping

$$SSD = 1.47ut + \frac{u^2}{30(\frac{a}{g} \pm G)};$$

where u = design speed (mi/h)
t = perception-reaction time (sec)
a = rate of deceleration (taken as 11.2 ft/sec^2)
g = gravitational acceleration (taken as 32.2 ft/sec^2)
G = grade

Note: the term $\frac{a}{g}$ is typically rounded to 0.35 in calculations.

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Stopping Sight Distance

Effect of Grade on Stopping

$$SSD = 0.278\,Vt + \frac{V^2}{254(f \pm G)}\ (Metric)$$

$$SSD = 1.47Vt + \frac{V^2}{30(f \pm G)}\ (U.S.Customary)$$

Where G is the percent of grade divided by 100

Friction Factor f

The American Association of Stat Highway Officials (AASHTO) recommend friction values as follow:

Speed (km/h) **Speed (mi/h)**	**48** **30**	**64** **40**	**80** **50**	**96.5** **60**	**112** **70**	
Friction f	0.36	0.33	0.31	0.3	0.29	

Example 1

The design speed of a multilane highway is 100 km/h. What is the minimum stopping sight distance (SSD) that should be provided on the road if:

(a) the road is level and

(b) the road has a maximum grade of $\pm$ 4%?

Assume the perception-reaction time 2.5 sec and the friction factor 0.3

Level

$SSD = 0.278\,x100x2.5 + \frac{100^2}{254(0.3+0)}$ = 69.5+131.7=200.7 m

Upgrade

$SSD = 0.278\,x100x2.5 + \frac{100^2}{254(0.3+0.04)}$ = 69.5+115.8= 185.3 m

Downgrade

$SSD = 0.278\,x100x2.5 + \frac{100^2}{254(0.3-0.04)}$= 69.5+151.4= 220.9 m

Example 2

A motorist traveling at 55 mph down a grade of 5 percent on a highway observes an accident ahead of him involving an overturned truck that is completely blocking the road. If the motorist was able to stop his vehicle 30 ft from the overturned truck, what distance away from the truck was when he first observed the accident. Assume perception-reaction time = 2.5 sec and *f* = 0.3.

Solution

SSD= 1.47 Vt + $\frac{V^2}{30\ (f \pm G)}$ = (1.47 x 55 x 2.5) + $\frac{55^2}{30\ (0.3-0.05)}$

= 202.13 + 403.33

= 605.5 ft

The distance of the motorist when he first observed the accident

= SSD + 30

= 605.5 + 30 = 635.5 ft.

Example 3

Two passenger cars are travelling at 65 mph on a highway moving in the same direction in the same lane. The cars are separated by 25 ft. for every 10 mph of their speed. The coefficient of friction (skidding resistance) between the tires and the roadway is 0.6. The perception reaction time is assumed to be 1 second. Determine the following:

c) If the lead car hits a parked tracker-trailer, what is the speed of the second car when it hits the first stationary car?

Solution

Dp-r = 1.47 Vt = 1.47 x 65 x 1 = 95.55 ft

D_b= braking distance between car 1 and car 2 = [(65 x 25) /10] – 95.55 = 66.95 ft

$D_b = \frac{Vi^2 - Vf^2}{30\ (f+G)}$

$66.95 = \frac{65^2 - Vf^2}{30\ X\ 0.6}$

V_f^2 = 3019.9

V_f = 54.95 mph

Example 4

Two passenger cars are travelling at 65 mph on a highway moving in the same direction in the same lane. The cars are separated by 25 ft. for every 10 mph of their speed. The coefficient of friction (skidding resistance) between the tires and the roadway is 0.6. The perception reaction time is assumed to be 1 second. Determine the following:

b) At what speed the rule of 25 feet separation for every 10 mph between two cars is safe?

Solution

When the distance between the two cars is equal or greater than the SSD.

$\frac{V\ x\ 25}{10}$ = (1.47 Vt)+ $\frac{V^2}{30\ x\ 0.6}$

2.5 V = 1.47 V + (1/18) V^2

(1/18)V^2 -1.03 V = 0

V = 18.54 mph

* The rule of 25 ft separation is safe if the speed of the cars are 18.5 mph or less under the same conditions (f= 0.6, tp-r = 1 sec, G=0)

Example 5

Two passenger cars are travelling at 65 mph on a highway moving in the same direction in the same lane. The cars are separated by 25 ft. for every 10 mph of their speed. The coefficient of friction (skidding resistance) between the tires and the roadway is 0.6. The perception reaction time is assumed to be 1 second. Determine the following:

c) What should actually the separation distance between these two cars be at 65 mph?

Solution

Separation Distance = 1.47 Vt + $\frac{V^2}{30\ (f+G)}$ = (1.47 x 65 x 1) + $\frac{65^2}{30\ x\ 0.6}$

= 330.3 ft

Example 6

A driver with a perception-reaction time of 2.5 sec is driving at 55 mph when he observes that an accident has blocked the road ahead. Determine the distance the vehicle would move before the driver could activate the brakes. The vehicles will continue to move at 55 mph during the perception-reaction time of 2.5 sec.

Solution

Distance traveled = 1.47 Vt = 1.47 x 55 x 2.5
= 202.1 ft

Passing Sight Distance (PSD)

- The passing sight distance is the minimum sight distance required on a two-lane, two–way highway that will permit a driver to complete a passing maneuver without colliding with an opposing vehicle.

- These assumptions have been used by AASHTO to develop a minimum passing sight distance requirement for two-lane, two-way highways. The minimum passing sight distance is the total of four components as shown in following Figure

Passing Sight Distance (PSD)

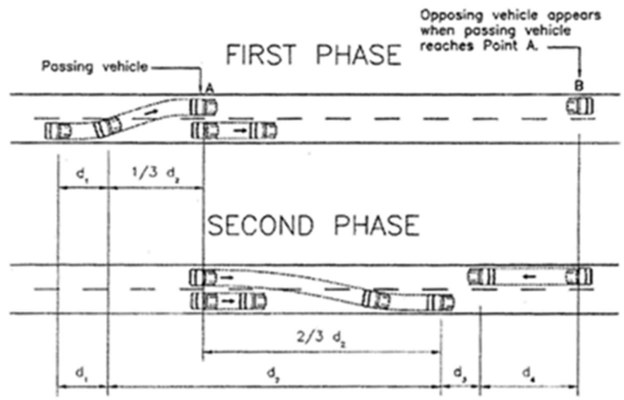

Exhibit 3-4. Elements of Passing Sight Distance for Two-Lane Highways

Passing Sight Distance

- **Where:**
- ***d*1** :distance traversed during perception-reaction time and during initial acceleration to the point where the passing vehicle just enters the left lane.
- ***d*2**: distance traveled during the time the passing vehicle is traveling in the left lane.
- ***d*3** :distance between the passing vehicle and the opposing vehicle at the end of the passing maneuver.
- ***d*4** :distance moved by the opposing vehicle during two thirds of the time the passing vehicle is in the left lane (usually taken to be 2/3 *d*2)**.**

Passing Sight Distance

The distance d_1 is obtained from the expression

$$d_1 = 1.47t_1\left(u - m + \frac{at_1}{2}\right) \quad (3.36)$$

where

t_1 = time for initial maneuver (sec)
a = average acceleration rate (mi/h/sec)
u = average speed of passing vehicle (mi/h)
m = difference in speeds of passing and impeder vehicles

The distance d_2 is obtained from

$$d_2 = 1.47ut_2$$

where

t_2 = time passing vehicle is traveling in left lane (sec)
u = average speed of passing vehicle (mi/h)

The clearance distance d_3 between the passing vehicle and the opposing vehicle at the completion of the passing maneuver has been found to vary between 100 ft and 300 ft.

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Passing Sight Distance

while d_4 equal to : $d_4 = (2/3)\ d_2$

Table 3.6 Components of Safe Passing Sight Distance on Two-Lane Highways

Component	Speed Range in mi/h (Average Passing Speed in mi/h) 30–40 (34.9)	40–50 (43.8)	50–60 (52.6)	60–70 (62.0)
Initial maneuver:				
a = average acceleration (mi/h/sec)[a]	1.40	1.43	1.47	1.50
t_1 = time (sec)[a]	3.6	4.0	4.3	4.5
d_1 = distance traveled (ft)	145	216	289	366
Occupation of left lane:				
t_2 = time (sec)[a]	9.3	10.0	10.7	11.3
d_2 = distance traveled (ft)	477	643	827	1030
Clearance length:				
d_3 = distance traveled (ft)[a]	100	180	250	300
Opposing vehicle:				
d_4 = distance traveled (ft)	318	429	552	687
Total distance, $d_1 + d_2 + d_3 + d_4$ (ft)	1040	1468	1918	2383

[a] For consistent speed relation, observed values are adjusted slightly.
SOURCE: Adapted from *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials, Washington, D.C., 2004. Used by permission.

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Example 1

Calculate the minimum passing sight distance required for a two-lane rural roadway that has a posted speed limit of 45 mi/h. The local traffic engineer conducted a speed study of the subject road and found the following: average speed of the passing vehicle was 47 mi/h with an average acceleration of 1.43 mi/h/sec, and the average speed of slow vehicle was 40 mi/h.

Obtain t_1 , t_2 , d_3 from table 3.6

Solution

Time to initiate maneuver, $t_1 = 4.0$ s
Determine the minimum passing sight distance for this roadway.
First, determine the distance traveled during the perception-reaction time.
$d_1 = 1.47\ t_1(u - m + (a\ t_1 / 2))$
u = average speed of the passing vehicle = 47 mi/h
m = 47 – 40 = 7
$d_1 = 1.47 \times 4 \times (47 - 7 + (1.43 \times 4 / 2))$ = 252 feet
Determine the distance traveled while passing the vehicle. Table 3.6, $t_2 = 10$ s.
$d_2 = 1.47\ u\ t_2$
$d_2 = 1.47 \times 47 \times 10$ = 690.9 feet
Now determine the distance between the passing vehicle and the opposing vehicle from table 3.6
d_3 = 180 feet

Solution

Now determine the distance moved by the opposing vehicle

$d_4 = (2/3)d_2$

$d_4 = (2/3) \times 690.9 = 460.6$ feet

The minimum passing distance can be found by adding all above distance together, $d_1 + d_2 + d_3 + d_4$ = minimum sight distance

PSD = 252 + 690.9 + 180 + 460.6 = 1583.5 feet

Therefore, the minimum passing sight distance required for this roadway is approximately 1600 feet
From Table 3.6. total passing sight distance = 1468 feet

Example 2

Vehicle moving at a speed of 50 mph is slowing traffic on a two-lane highway. What passing sight distance is necessary, in order for a passing maneuver to be carried out safely?
Calculate the passing sight distance by hand, and then compare it to the values recommended by AASHTO. In your calculations, assume that the following variables have the values given:

- Passing vehicle's acceleration rate = 1.47 mph/sec
- Passing speed of passing vehicle = 60 mph
- Speed of slow vehicle = 50 mph

Obtain t_1 , t_2 , d_3 from table 3.6

Solution

Time to initiate maneuver, t_1 = 4.3 s
Determine the minimum passing sight distance for this roadway.
First, determine the distance traveled during the perception-reaction time.
$d_1 = 1.47\ t_1(u - m + (a\ t_1 / 2))$
u = average speed of the passing vehicle = 60 mi/h
m = 60 – 50 = 10
d_1 = 1.47 x 4.3 x(60 – 10 + (1.47 x 4.3 / 2)) = 336 feet
Determine the distance traveled while passing the vehicle. Table 3.6, t_2 = 10.7 s.
$d_2 = 1.47\ u\ t_2$
d_2 = 1.47 x 60 x 10.7 = 943.7 feet
Now determine the distance between the passing vehicle and the opposing vehicle from table 3.6
d_3 = 250 feet

Solution

Now determine the distance moved by the opposing vehicle

$d_4 = (2/3)d_2$

d_4 = (2/3) x 943.7 = 629.2 feet

The minimum passing distance can be found by adding all above distance together, $d_1 + d_2 + d_3 + d_4$ = minimum sight distance

PSD = 336 + 943.7 + 250 + 629.2 = 2158.9 feet

Therefore, the minimum passing sight distance required for this roadway is approximately 2160 feet

From Table 3.6. total passing sight distance = 1918 feet