### Table 6.10 Distribution of Distraction Activities (Listed next to the percentages are the 95% confidence intervals)

| Activity                             | Percentage (%) | Confidence Interval
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside person, object, or event (%)</td>
<td>29.4 ± 4.7</td>
<td></td>
</tr>
<tr>
<td>Adjusting radio/camera/DVD (%)</td>
<td>11.4 ± 7.2</td>
<td></td>
</tr>
<tr>
<td>Other occupant (%)</td>
<td>10.9 ± 3.5</td>
<td></td>
</tr>
<tr>
<td>Moving object in vehicle (%)</td>
<td>4.3 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>Other device/object (%)</td>
<td>2.9 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>Adjusting vehicleclimate controls (%)</td>
<td>2.8 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>Eating and/or drinking (%)</td>
<td>1.7 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>Texting and/or using cell phone (%)</td>
<td>1.5 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>Smoking related (%)</td>
<td>0.9 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Other distractions (%)</td>
<td>25.6 ± 6.0</td>
<td></td>
</tr>
<tr>
<td>Unknown distraction (%)</td>
<td>8.6 ± 5.3</td>
<td></td>
</tr>
</tbody>
</table>

Source: Smith et al., 2001.

---

**FIGURE 6.19**

---

fatalities.” Among the countermeasures proposed to counter drowsiness (NCSDR 2001), only rumble strips have a demonstrated effect on crashes. They reduce drive-off-the-road crashes by 30 to 50 percent.

**Driver Habits.** With the advent of cell phones, many drivers are acquiring a habit that, just a few years ago, was non-existent. If the use of cell phones by the operator of a motor vehicle is restricted or prohibited, some drivers will find it difficult to comply. Other habits and preferences have been the focus of traffic safety advocates in recent years. Driver behavior regarding the use of seat belts and motorcycle helmets has been the subject of debate between the advocates of private rights and public safety. Fricke and Larson (1989) looked at the relationship between a driver’s use of seat belts and his/her use of turn signals. Both seatbelt use and turn signal use were required by law but were seldom enforced. Their use was largely a matter of voluntary compliance by the driver. The researchers found a positive correlation between seatbelts use and turn signal use. Apparently, driver behavior is made up of conscious decisions and accumulated habits. The traffic engineer must account for this when designing a roadway and its traffic control features.

**Traffic Control at Workzones.** In 1999, 868 workers and motorists were killed in work zone-related crashes (Walls, 2001). Although the problems with the I-25 workzone described at the start of this section are not unusual, they still need to be addressed. When the county engineer had a friend drive him through the work zone, he noted 12 signs over the 4-mile approach to the work zone, warning drivers of the potential hazard ahead. Still, as Figure 6.9 shows, some drivers do not merge until the last few yards.

A traffic engineer who wants to warn motorists of a work zone ahead faces several challenges. Temporary signs such as the 12 signs used along I-25 can be placed on the approach to the work zone. If the message is, for example, "Merge Right," most motorists will comply. The time between when the message becomes visible to a driver and when the desired action is taken will probably be widely distributed. Some drivers may not ever comply. Was the lack of compliance by these drivers a result of not having seen the sign or because of something related to driver attitude? Depending on the answer to this question, lack of compliance becomes a matter of better sign design and placement or a matter for law enforcement.

### 6.3 Vehicle Attributes That Affect Safety

In roadway situations that involve other cars, large trucks, motorcycles, bicycles, and pedestrians, the driver’s ability to cause an automobile to stop, accelerate, or maneuver quickly may determine if a crash will occur. A key factor is the automobile’s braking capability. The road surface and the tire tread also affect stopping distance. The capability to steer the vehicle is the other major attribute that affects safety. However, with power steering, that limitation is less of a factor.

#### 6.3.1 Forces Acting on Automobile

Consider the automobile travelling up an incline as shown in Figure 6.20.

The force that gives motion is derived from the engine acting through the wheels along the direction of travel:

\[
F = F_i + F_L = ma = \frac{W}{g} \frac{dv}{dt} \quad \text{and} \quad v = \frac{dx}{dt}
\]  

(6.12)
where $F_t$ and $F_r$ = the engine force applied at the front and rear wheels, respectively.
$W$ = weight of the vehicle in pounds.
$g$ = force of gravity.

Summing the forces acting on a car in motion, we get Equation 6.13:

$$ F + R_t + R_{grad} + R_{aero} = \frac{W}{g} \alpha + W_f \cos \Theta_k + W \sin \Theta_k + R_{aero} = 0 \quad (6.13) $$

where $R_t$ = the sum of rolling resistance from each of the tires $R_t = R_{fr} + R_{ft} + R_{bk} + R_{bk}$
$W_f$ = the coefficient of rolling resistance, usually $f_r = 0.01[1 + (V/14)]$, $V$ in fps (Taberck, 1957).
$R_{grad}$ is the component of gravity acting normal to the road.

In this text, we will ignore the aerodynamic force: $R_{aero} = 0.5 \rho C_{D} V^2$.

The same equation also applies to braking, where the rolling resistance is supplemented by the force operating to stop the car through the friction applied to the highway. The braking acceleration (or deceleration) is usually assumed to be a constant, if the car does not go into a skid. If the coefficient of friction is $f_r$, the initial velocity is $v_i$, and the final velocity is $v_f$, the braking distance $D_B$ from the time the brake is applied is given in Equation 6.14.

$$ D_B = \frac{v_i^2 - v_f^2}{2a} = \frac{v_i^2 - v_f^2}{2fg} \quad (6.14) $$

On a level road, Equation 6.13 becomes

$$ F + R_t = W(f_r + f_f) = 0; a = fg $$

This explains the rightmost form of Equation 6.14.

The time needed to go from $V_i$ to $V_f$ is given in Equation 6.15.

$$ T_{v_i,v_f} = \sqrt{\frac{2D_B}{fg}} \quad (6.15) $$

where $f$ = the dimensionless coefficient of friction of the road
$g$ = the force of gravity: 32.2 ft/s² or 9.8 m/s². If braking takes place on a hill with a positive (uphill) grade $G$, the braking distance will be

$$ D_B = \frac{v_i^2 - v_f^2}{2g(f + \tan \Theta_k)} = \frac{v_i^2 - v_f^2}{2g(f + G)} \quad (6.16) $$

where $G$ is the grade in percent divided by 100.

**Example 6.10**

John is driving his 14-foot long automobile at 50 mph, when the traffic signal in front of him changes to yellow. He is 130 feet from the intersection when he applies the brakes after a 1-second reaction time.

A. If John's car can decelerate at a rate of 15 ft/s², at what velocity will he be moving when he reaches the intersection?

B. If the yellow light is 4 seconds long, where will John be when the light turns red?

C. Based on the answers to part A and part B, will John be able to clear the intersection (width = 50 feet) before the light turns red? If not, let us assume he will continue through at the speed found in part B when the light changes to red. How long will the light have been red when he clears the intersection?

**Solution to Example 6.10**

A. Use Equation 6.14 to find John’s speed upon reaching the intersection:

$$ v_i = \frac{(130 \times 1.47)^2 - v_f}{2 \times 15} \quad v_i = 38.76 \text{ fps} = 26.4 \text{ mph} $$

B. When the light turns red, his speed will be

$$ v_i = v_i - [(v_i - 45) \times 4] = (50 \times 1.47) - [(4 - 1) \times 15] $$

$$ = 73.5 \text{ fps} = 50.5 \text{ mph} $$

and the distance he will have traveled is

$$ D_B = \frac{(50 \times 1.47)^2 - (28.5)^2}{2 \times 15} = 153.0 \text{ feet} $$

which is 23.0 feet after entering the 50-foot intersection.
where \( W \) = weight of the vehicle in pounds.
\( g \) = force of gravity.

Summing the forces acting on a car in motion, we get Equation 6.13:

\[
F + R_e + R_{\text{drag}} + R_{\text{aero}} = \frac{W}{g} a + W f_s \cos \Theta + W \sin \Theta + R_{\text{aero}} = 0 \tag{6.13}
\]

where \( R_e \) = the sum of the rolling resistance from each of the tires \( R_e = R_{\text{frt}} + R_{\text{rtr}} + R_{\text{brk}} \),
\( f_s \) = the coefficient of rolling resistance, usually \( f_s = 0.01 \left(1 + \frac{V}{V_{\text{max}}} \right) \), \( V \) in fps (Taborek, 1957).

\( R_{\text{drag}} \) is the component of gravity acting normal to the road.

In this text, we will ignore the aerodynamic force: \( R_{\text{aero}} = 0.5 \rho C_D V^2 \).

The same equation also applies to braking, where the rolling resistance is supplemented by the force operating to stop the car through the friction applied to the highway. The braking acceleration (or deceleration) is usually assumed to be a constant, if the car does not go into a skid. If the coefficient of friction is \( f \), the initial velocity is \( v_i \), and the final velocity is \( v_f \), the braking distance \( D_b \) from the time the brake is applied is given in Equation 6.14.

\[
D_b = \frac{v_i^2 - v_f^2}{2a} = \frac{v_i^2 - v_f^2}{2fg} \tag{6.14}
\]

On a level road, Equation 6.13 becomes

\[
F + R_e = W f_s = 0; a = \frac{f_s W}{g}
\]

This explains the rightmost form of Equation 6.14.

6.3 Vehicle Attributes That Affect Safety

The time needed to go from \( v_i \) to \( v_f \) is given in Equation 6.15.

\[
T_{\text{brk}, \text{to} v_f} = \frac{D_b}{2fg} \tag{6.15}
\]

where \( f \) = the dimensionless coefficient of friction of the road
\( g \) = the force of gravity: 32.2 ft/s\(^2\) or 9.8 m/s\(^2\) If braking takes place on a hill with a positive (uphill) grade \( G \), the braking distance will be

\[
D_b = \frac{v_i^2 - v_f^2}{2g(f + \tan \Theta_g)} = \frac{v_i^2 - v_f^2}{2g(f + G)} \tag{6.16}
\]

where \( G \) is the grade in percent divided by 100.

Example 6.10

John is driving his 14-foot long automobile at 50 mph, when the traffic signal in front of him changes to yellow. He is 130 feet from the intersection when he applies the brakes after a 1-second reaction time.

A. If John’s car can decelerate at a rate of 15 ft/s\(^2\), at what velocity will he be moving when he reaches the intersection?

B. If the yellow light is 4 seconds long, when will John be when the light turns red?

C. Based on the answers to part A and part B, will John be able to clear the intersection (width = 50 feet) before the light turns red? If not, let us assume he will continue through at the speed found in part B when the light changes to red. How long will the light have been on when he clears the intersection?

Solution to Example 6.10

A. Use Equation 6.14 to find John’s speed upon reaching the intersection:

\[
130 = \frac{(50 \times 1.47)^2 - v_f^2}{2 \times 15} \quad v_f = 38.76 \text{ fps} = 26.4 \text{ mph}
\]

B. When the light turns red, his speed will be

\[
v_f = v_i - \frac{(v_i - v_f) \times a}{v_i} = (50 \times 1.47) - [(4 - 1) \times 15] = 73.5 \text{ fps} = 49.5 \text{ mph}
\]

and the distance he will have traveled is

\[
D_b = \frac{(50 \times 1.47)^2 - (28.5)^2}{2 \times 15} = 153.0 \text{ feet}
\]

which is 23.0 feet after entering the 50-foot intersection.
6.3 Vehicle Attributes That Affect Safety

A. The distance and time John would need to continue through the intersection at 28.5 fps (about 20 mph) will be:

\[
\frac{(50 - 23.0) + 14}{28.5} = \frac{41}{28.5} = 1.44 \text{ sec.}
\]

THINK ABOUT IT
Under the conditions described in the example, should John attempt to stop upon seeing the start of the yellow light, or should he proceed through the intersection?

6.3.2 Vehicle Braking

Vehicle dynamics play a crucial role in the design of the highway for safety. The design is based on the reaction time and the friction coefficient, which is related to the condition of the pavement on which the braking occurs. Although many individuals typically respond to stimuli in 1 second or less, the reaction time of 2.5 seconds is used in most design calculations.

Table 6.11 summarizes the results of using Equation 6.16 on level terrain (\(G = 0\)) with friction coefficient values that vary with speed. (See Figure 6.21.) The "computed stopping sight distance" (SSD) caption in the table means "the distance needed for a diver to detect an unexpected or otherwise difficult-to-perceive ... condition ... select an appropriate speed and path, and initiate and complete the maneuver safely and efficiently" [AASHTO, 2001, p. 115]. This distance is calculated from the following:

a. The distance covered during the natural delay or response time at the initial speed. That time may be as short as 0.5 seconds, if a person is very attentive.

b. The actual physical distance traveled while the car is being braked (decelerated) to a stop.

These two components combine to form Equation 6.17:

\[
SSD = (t_{response} + \frac{v_0}{2 \times g \times (f_{friction} \pm \text{Grade})})
\]

(6.17)

The friction coefficient between the road and the tires can cover a wide range of values, depending on the pavement surface materials, the tread on the tires, and whether the road is dry or wet. Ice roads exhibit a coefficient of friction closer to 0.1, but because the ice can be detected, drivers are expected to use extreme caution and drive slowly. The coefficient of friction used in Table 6.11 has been assumed to be constant for a given design speed. However, as Figure 6.21 shows, the friction coefficient varies with speed. Because the calculations use a lower and constant value of friction.
C. The distance and time John would need to continue through the intersection at 28.5 fps (about 20 mph) will be:

$$\frac{(50 - 23.0) + 14}{28.5} = \frac{41}{28.5} \text{ sec.} = 1.44 \text{ sec.}$$

THINK ABOUT IT

Under the conditions described in the example, should John attempt to stop upon seeing the start of the yellow light, or should he proceed through the intersection?

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a. The distance covered during the natural delay or response time at the initial speed. That time may be as short as 0.5 seconds, if a person is very attentive.

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Reaction Time (sec)</th>
<th>Reaction Distance (ft)</th>
<th>Coefficient of Friction</th>
<th>Braking Distance on Level Terrain (ft)</th>
<th>Compumed Stopping Sight Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.5</td>
<td>73</td>
<td>0.40</td>
<td>33.3</td>
<td>107</td>
</tr>
<tr>
<td>25</td>
<td>2.5</td>
<td>92</td>
<td>0.38</td>
<td>55.5</td>
<td>147</td>
</tr>
<tr>
<td>30</td>
<td>2.5</td>
<td>110</td>
<td>0.35</td>
<td>86</td>
<td>196</td>
</tr>
<tr>
<td>35</td>
<td>2.5</td>
<td>128</td>
<td>0.34</td>
<td>120</td>
<td>248</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
<td>147</td>
<td>0.32</td>
<td>167</td>
<td>303</td>
</tr>
<tr>
<td>45</td>
<td>2.5</td>
<td>165</td>
<td>0.31</td>
<td>218</td>
<td>363</td>
</tr>
<tr>
<td>50</td>
<td>2.5</td>
<td>183</td>
<td>0.30</td>
<td>278</td>
<td>461</td>
</tr>
<tr>
<td>55</td>
<td>2.5</td>
<td>202</td>
<td>0.29</td>
<td>336</td>
<td>586</td>
</tr>
<tr>
<td>60</td>
<td>2.5</td>
<td>220</td>
<td>0.29</td>
<td>414</td>
<td>644</td>
</tr>
<tr>
<td>65</td>
<td>2.5</td>
<td>238</td>
<td>0.29</td>
<td>486</td>
<td>744</td>
</tr>
<tr>
<td>70</td>
<td>2.5</td>
<td>257</td>
<td>0.28</td>
<td>553</td>
<td>840</td>
</tr>
</tbody>
</table>

and is capable of quick reactions, or it may extend to several seconds for elderly or drivers who are under the influence of alcohol or drugs, or are impaired or distracted.

b. The actual physical distance traveled while the car is being braked (decelerated) to a stop.

These two components combine to form Equation 6.17:

$$SSD = (t_{response} * \frac{v}{g}) + \frac{v^2}{2 * g * (\frac{v}{g} + \text{Grade})} \quad (6.17)$$

The friction coefficient between the road and the tires can cover a wide range of values, depending on the pavement surface materials, the tread on the tires, and whether the road is dry or wet. icy roads exhibit a coefficient of friction closer to 0.1, but because the ice can be detected, drivers are expected to use extreme caution and drive slowly. The coefficient of friction used in Table 6.11 has been assumed to be constant for a given design speed. However, as Figure 6.21 shows, the friction coefficient varies with speed. Because the calculations use a lower and constant value of friction...
coefficient for the table, the results should be conservative. The presumed road conditions chosen for design purposes are a wet concrete road.

It is assumed that the brakes are applied evenly and not "jammed-on," which would put the car into a skid. The friction coefficient is actually much less when skidding; hence, the stopping distance is greater. The table indicates stopping distance when on level terrain. If there is a hill, the stopping distance may be greater or smaller, depending on whether the car is traveling uphill (in which gravity will help the driver to stop) or downhill (where the effect is just the opposite). The computed distances in Table 6.11 can be used in highway alignment, traffic signal setting, passing (including road marking), and avoiding objects in the road when on a curve. The "design" values for stopping sight distance are given in Table 7.4.

Example 6.11

If \( f \) decreases according to the equation \( f = 0.4 - 0.002v \) as a vehicle's speed decreases during braking (see the heavy solid line on Figure 6.21), show that the stopping distance and time to stop for an initial speed of 60 mph are more conservative than using a constant value of \( f = 0.29 \) for 60 mph from Table 6.11.

Solution to Example 6.11

By combining equation \( f = 0.4 - 0.002v \) with gravity, the equation \( a = g^*f \) becomes \( a = g^*f = (0.4 - 0.002v) \times 32.2 \text{ ft/sec}^2 \). The deceleration due to the friction coefficient can be approximated as \( a = -12.9 + 0.044v \), where \( v \) is in feet per second and \( a \) is in feet per second squared. Because \( a \) represents deceleration here, the sign change.

The braking time is governed by the equation \( \frac{dv}{a} = (12.9 - 0.044v) \text{ ft/sec} \). Solving this equation accounts for the changing value of \( f \) as the speed of the braking vehicle decreases.

\[
\int_{v_0}^{v_f} \frac{dv}{12.9 - 0.044v} = \int_{t_0}^{t_f} dt
\]

If the initial speed \( v_0 = 88 \text{ fps} \), the time to brake from 88 fps is \( t_{brk} = 8.12 \text{ seconds} \), when \( f \) is allowed to vary as the vehicle slows down. When the constant value \( f = 0.29 \) for \( v = 60 \text{ mph} \) is used,

\[
t_{brk} = \frac{v_0}{32.2 + f} = \frac{88}{32.2 + 0.29} = 9.42 \text{ sec}
\]

Likewise, the stopping distance using Equation 6.14 is given by

\[
x_{st} = \frac{v_0^2}{2 \times (32.2 + 0.29)} = 414 \text{ ft}
\]

Using the constant friction factor yields a slightly more conservative result than the use of the more realistic friction factor that varies with speed. (See Table 6.12.) Using Table 6.11 in

6.3.3 Stopping Sight Distance

The SSD in Table 6.11 can be calculated for any given speed. For example, for \( V = 55 \text{ mph} \), the SSD includes the time to respond plus the time to brake. If 55 mph is the design speed, \( f = 0.30 \text{ in Table 6.11. Equation 6.17} \) gives us:

\[
SSD = (1.47 \times 55 \times 2.5) + \frac{(55 \times 1.47)^2}{2 \times 32.2 \times 0.30} = 202.1 + 338.3 = 540.5 \text{ ft}
\]

This is close to the entry of 538 feet in Table 6.11.

When the design speed is 65 mph, the coefficient of friction is \( f = 0.29 \) and the stopping distance is longer:

\[
SSD = (1.47 \times 65 \times 2.5) + \frac{(65 \times 1.47)^2}{2 \times 32.2 \times 0.29} = 238.9 + 488.9 = 727.8 \text{ ft}
\]

In Table 6.11, the computed value is given as 724 feet. The design standard values of SSD in the far right-hand column of Table 7.4 are to be used for geometric design problems. If the minimum design standard cannot be met under the specified conditions of speed, grade, and/or radius, then at least one of the conditions must be altered in the design.

Example 6.12

A car is traveling down a 3 percent grade at 50 mph. How much longer will the stopping distance be than when it is traveling at 50 mph on a level surface?

Solution to Example 6.12

If the AASHO Green Book’s 2.5-second suggested perception-react time (see Section 6.2) is used in Equation 6.17, the stopping distance on level terrain is

\[
D = 2.5 \times 1.47 \times 50 + \frac{(50 \times 1.47)^2}{2 \times 32.2 \times 0.3} = 184 + 280 \text{ ft} = 464 \text{ ft}
\]
coefficient for the table, the results should be conservative. The presumed road conditions chosen for design purposes are a wet concrete road.

It is assumed that the brakes are applied evenly and not “jammed-on,” which would put the car into a skid. The friction coefficient is actually much less when skidding; hence, the stopping distance is greater. The table indicates stopping distance when on level terrain. If there is a hill, the stopping distance may be greater or smaller, depending on whether the car is traveling uphill (in which gravity will help the driver to stop) or downhill (where the effect is just the opposite). The computed distances in Table 6.11 can be used in highway alignment, traffic signal setting, passing (including road marking), and avoiding objects in the road when on a curve. The “design” values for stopping sight distance are given in Table 7.4.

**Example 6.11**

If \( f \) decreases according to the equation \( f = 0.4 - 0.002 v \) as a vehicle’s speed decreases during braking (see the heavy solid line on Figure 6.21), show that the stopping distance and time to stop for an initial speed of 60 mph are more conservative than using a constant value of \( f = 0.29 \) for 60 mph from Table 6.11.

**Solution to Example 6.11**

By combining equation \( f = 0.4 - 0.002 v \) with gravity, the equation \( a = g \frac{f}{v} \) becomes \( a = g \left[ 0.4 - 0.002 (0.4 - 0.002/1.47) v \right] = 32.2 \left( 0.4 - 0.0036 v \right) \). The deceleration due to the friction coefficient can be approximated as \( a = -12.9 + 0.044 v \), where \( v \) is in feet per second and \( a \) is in feet per second squared. Because \( a \) represents deceleration here, the sign change.

The braking distance is governed by the equation \( \frac{v^2}{2} = \frac{a t^2}{2} = \frac{a t^2}{2} \left[ \ln(12.9 + 0.044 v) - \ln(0.044) \right] \). Solving this equation for the changing value of \( a \) in the speed of the braking vehicle decreases:

\[
\frac{v^2}{2} = \frac{12.9 + 0.044 v}{2} \left[ \ln(12.9 + 0.044 v) - \ln(0.044) \right]
\]

If the initial speed \( v_i = 88 \) fps, the time to brake from \( 88 \) fps is \( t_{brake} = 8.12 \) seconds, when \( f \) is allowed to vary as the vehicle slows down. When the constant value \( f = 0.29 \) for \( v = 60 \) mph is used,

\[
t_{brake} = \frac{V}{2} \frac{2}{2} = \frac{88}{32.2 \times 0.29} = 9.42 \text{ sec}
\]

Likewise, the stopping distance using Equation 6.14 is given by

\[
x_{brake} = \frac{88^2}{2 \times 32.2 \times 0.29} = 414 \text{ ft}
\]

Using the constant friction factor yields a slightly more conservative result than the use of the more realistic friction factor that varies with speed. (See Table 6.12.) Using Table 6.11 in

**6.3 Vehicle Attributes That Affect Safety**

<table>
<thead>
<tr>
<th>Time to stop (sec)</th>
<th>Variable f</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.42</td>
<td>7.89</td>
</tr>
<tr>
<td>Distance to stop (ft)</td>
<td>414</td>
</tr>
</tbody>
</table>

conservative because it assumes a vehicle moving at 60 mph will need 414 feet to stop. Accounting for the increase in \( f \) as speed decreases during braking leads to a lower stopping distance of 367 feet.

**6.3.3 Stopping Sight Distance**

The SSD in Table 6.11 can be calculated for any given speed. For example, for \( V = 55 \) mph, the SSD includes the time to respond plus the time to brake. If 55 mph is the design speed, \( f = 0.30 \) in Table 6.11. Equation 6.17 gives us

\[
SSD = \left( 1.47 \times 55 \times 2.5 \right) + \left( \frac{(55 \times 1.47)^2}{2 \times 32.2 \times 0.30} \right) = 202.1 + 338.3 = 540.5 \text{ ft}
\]

This is close to the entry of 538 feet in Table 6.11.

When the design speed is 65 mph, the coefficient of friction is \( f = 0.29 \) and the stopping distance is longer:

\[
SSD = \left( 1.47 \times 65 \times 2.5 \right) + \left( \frac{(65 \times 1.47)^2}{2 \times 32.2 \times 0.29} \right) = 238.9 + 488.9 = 727.8 \text{ ft}
\]

In Table 6.11, the computed value is given as 724 feet. The design standard values of SSD in the far right-hand column of Table 7.4 are to be used for geometric design problems. If the minimum design standard cannot be met under the specified conditions of speed, grade, and/or radius, then at least one of the conditions must be altered in the design.

**Example 6.12**

A car is traveling down a 3 percent grade at 50 mph. How much longer will the stopping distance be than when it is traveling at 50 mph on a level surface?

**Solution to Example 6.12**

If the AASHSTO Green Book’s 2.5-second suggested perception-reaction time (see Section 6.2) is used in Equation 6.17, the stopping distance on level terrain is

\[
D = 2.5 \times 1.47 \times 50 + \left( \frac{(50 \times 1.47)^2}{2 \times 32.2 \times 0.3} \right) = 184 + 280 = 464 \text{ ft}
\]

For a slope of 3 percent, the stopping distance is

\[
D = 2.5 \times 1.47 \times 50 + \left( \frac{(50 \times 1.47)^2}{2 \times 32.2 \times 0.03} \right) = 184 + 414 = 598 \text{ ft}
\]
On a downhill, however, gravity acts to increase the speed. Equation 6.17 is used.

\[ D = 2.5 \times 1.47 \times 50 + \frac{(50 \times 1.47)^2}{2 \times 32.2 \times (0.30 - 0.03)} = 184 + 311 = 495 \text{ ft} \]

The difference when gravity is acting with you means that it takes 495 feet - 464 feet = 31 feet longer to stop. Table 6.13 shows how downhill grades up to 5 percent affect stopping distances.

<table>
<thead>
<tr>
<th>TABLE 6.13</th>
<th>Braking Distance for Downhill Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (mph)</td>
<td>f</td>
</tr>
<tr>
<td>-------------</td>
<td>---</td>
</tr>
<tr>
<td>40</td>
<td>0.32</td>
</tr>
<tr>
<td>45</td>
<td>0.31</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
</tr>
<tr>
<td>55</td>
<td>0.30</td>
</tr>
<tr>
<td>60</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Example 6.13

The driving manual for the Department of Motor Vehicles in the State of Alaska states the braking distance for several speeds as indicated in Table 6.14. For the numbers given, what values have been assumed for driver response time and the coefficient of friction?

**Solution to Example 6.13**

The answers are given in the shaded portion of Table 6.4. For example, the calculations for \( v = 50 \text{ mph} \) are:

\[ t_r = \frac{\text{dist}}{\text{speed}} = \frac{55}{74} = 0.74 \text{ sec} \]

\[ f = \frac{v^2}{2 g \times \text{dist}} = \frac{74^2}{2 \times 32.2 \times 160} = 0.53 \]

<table>
<thead>
<tr>
<th>TABLE 6.14</th>
<th>Braking Distances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (mph)</td>
<td>Speed (fps)</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td>44</td>
</tr>
<tr>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>60</td>
<td>88</td>
</tr>
<tr>
<td>70</td>
<td>103</td>
</tr>
</tbody>
</table>

Source: Alaska DMV Manual, p. 44

Example 6.14

You are asked to investigate a crash in which a teenage driver hit a barricade traveling at about 25 mph. Your observations at the scene indicate that the road is posted with a 55 mph speed limit. The road is straight and level. The first sign warning of the barricade was located 1000 feet before the barricade, and the second sign was 600 feet before the barricade. The skid marks from the car begin 300 feet before the barricade. You are asked to testify to a jury about your findings. What will you tell them about braking and response time? According to the Weather Service, the road was wet but visibility was good.

**Solution to Example 6.14**

The car traveled 700 feet from the first warning sign to the initiation of the skid marks. If the teenager was traveling at the speed limit, her response time would have been 700 ft/(55 \times 1.47)/fps = 8.66 sec.

If the velocity at impact was 25 mph, the initial velocity \( v_i \) before 300 feet of skidding was

\[ v_i = \sqrt{v_i^2 + 2g \Delta d} = \sqrt{(25 \times 1.47)^2 + 2 \times 32.2 \times (300)} = 84.5 \text{ fps} = 57.5 \text{ mph.} \]

From the data, it would appear that the young driver did not respond to the first sign and reacted slowly to the second sign, with a response time of about \( t_r = \frac{d}{v_i} = \frac{300}{57.5 \times 1.47} = 3.55 \text{ seconds.} \) Moreover, she was driving above the speed limit.

**6.4 TRAFFIC CONTROL DEVICES**

Among his many duties, the Myhaca County Highway Engineer must ensure that roadway signs and markings in the County are properly installed and maintained (Figure 6.22). If a crash occurs where someone thinks that a sign should have been installed, the county may be sued. If the engineer installs signs wherever there is even the slightest justification for them, the County Highway Department will probably not have enough left in its annual budget to maintain them. If any sign is stolen, vandalized, or allowed to become unreadable, and a crash occurs, the county may be sued. In theory, the rules for installing traffic control devices (TCDs) is quite simple. In practice, placing and maintaining TCDs requires diligence and good management practices—or else the public safety may be compromised—and the county may get sued.
On a downhill, however, gravity acts to increase the speed. Equation 6.17 is used.

\[
D = 2.5 \times 1.47^*50 + \frac{(50 \times 1.47)^2}{2 \times 32.2 \times (0.30 - 0.03)} = 184 + 311 = 495 \text{ ft}
\]

The difference when gravity is acting with you means that it takes 495 feet - 464 feet = 31 feet longer to stop. Table 6.13 shows how downhill grades up to 5 percent affect stopping distance.

<p>| TABLE 6.13 Braking Distance for Downhill Grades |</p>
<table>
<thead>
<tr>
<th>V (mph)</th>
<th>f</th>
<th>No Grade</th>
<th>1%</th>
<th>2%</th>
<th>3%</th>
<th>4%</th>
<th>5%</th>
<th>Increase from 0% to 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.32</td>
<td>315</td>
<td>320</td>
<td>326</td>
<td>332</td>
<td>339</td>
<td>346</td>
<td>9.8%</td>
</tr>
<tr>
<td>45</td>
<td>0.31</td>
<td>385</td>
<td>392</td>
<td>400</td>
<td>408</td>
<td>417</td>
<td>427</td>
<td>10.9%</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
<td>464</td>
<td>473</td>
<td>483</td>
<td>495</td>
<td>506</td>
<td>519</td>
<td>12.0%</td>
</tr>
<tr>
<td>55</td>
<td>0.30</td>
<td>540</td>
<td>552</td>
<td>565</td>
<td>578</td>
<td>593</td>
<td>608</td>
<td>12.5%</td>
</tr>
<tr>
<td>60</td>
<td>0.29</td>
<td>637</td>
<td>652</td>
<td>668</td>
<td>685</td>
<td>704</td>
<td>724</td>
<td>13.6%</td>
</tr>
</tbody>
</table>

Example 6.13

The driving manual for the Department of Motor Vehicles in the State of Alaska states the braking distance for several speeds as indicated in Table 6.14. For the numbers given, what values have been assumed for driver response time and the coefficient of friction?

Solution to Example 6.13

The answers are given in the shaded portion of Table 6.14. For example, the calculations for \( v = 50 \) mph are

\[
\tau = \frac{\text{dist}}{\text{speed}} = \frac{55}{74} = 0.74 \text{ sec}
\]

\[
f = \frac{v^2}{2 \times g \times \text{dist}} = \frac{74^2}{2 \times 32.2 \times 160} = 0.53
\]

<p>| TABLE 6.14 Braking Distances |</p>
<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Speed (fps)</th>
<th>Thinking Distance</th>
<th>Braking Distance</th>
<th>Total Distance</th>
<th>Response Time</th>
<th>Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>29</td>
<td>22</td>
<td>25</td>
<td>47</td>
<td>0.76</td>
<td>0.32</td>
</tr>
<tr>
<td>30</td>
<td>44</td>
<td>33</td>
<td>57</td>
<td>90</td>
<td>0.79</td>
<td>0.33</td>
</tr>
<tr>
<td>40</td>
<td>59</td>
<td>44</td>
<td>102</td>
<td>146</td>
<td>0.75</td>
<td>0.38</td>
</tr>
<tr>
<td>50</td>
<td>74</td>
<td>55</td>
<td>160</td>
<td>213</td>
<td>0.74</td>
<td>0.53</td>
</tr>
<tr>
<td>60</td>
<td>88</td>
<td>66</td>
<td>227</td>
<td>194</td>
<td>0.75</td>
<td>0.53</td>
</tr>
<tr>
<td>70</td>
<td>103</td>
<td>77</td>
<td>310</td>
<td>387</td>
<td>0.75</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Source: Alaska DMV Manual, p. 44.

6.4 TRAFFIC CONTROL DEVICES

Among his many duties, the Mythaca County Highway Engineer must ensure that roadway signs and markings in the County are properly installed and maintained (Figure 6.22). If a crash occurs where someone thinks that a sign should have been installed, the county may be sued. If the engineer installs signs wherever there is even the slightest justification for them, the County Highway Department will probably not have enough left in its annual budget to maintain them. If any sign is stolen, vandalized, or allowed to become unreadable, and a crash occurs, the county may be sued. In theory, the rules for installing traffic control devices (TCDs) is quite simple. In practice, placing and maintaining TCDs requires diligence and good management practices—or else the public safety may be compromised—and the county may get sued.
6.8 Crash Rates. The number of crashes at the intersection of US 52 and SR 26 increased from 39 in 1989 to 43 in 1990. The 1990 approach ADTs are estimated to be the following: NB 3,545; SB 12,335; EB 7,200; and WB 9,760. What was the 1990 crash rate at this intersection?

6.9 Crash Rates. The intersection of South Street and Earl Avenue had the highest number of accidents (41) in Tippecanoe County in 1991. Its accident rate was 3.730/MEV. What was the total ADT of all four approaches to South and Earl in 1991?

6.10 Roundabouts. The NB, SB, EB, and WB approach AADT at a roundabout in West Virginia are 5,242, 5,542, 3,877, and 944, respectively. The number of crashes at the roundabout for the years 1994, 1995, and 1996 were 9, 10, and 9, respectively. What is the crash rate at this roundabout?

Human Factors and Transportation Engineering

6.11 Human Factors in Daily Life. Make a list of items or environments that you have experienced that serve as examples of good or bad design from the perspective of human factors. They do not have to be related to transportation, although transportation examples are preferred.

6.12 Reaction Time Tests. With a good Internet search engine, use the words "reaction time test" to find two different reaction time tests on the Web. Try them. Describe the tests you tried, summarize your results, and comment on the validity of the tests.

6.13 Visual Acuity. The state DOT wants to erect a sign warning drivers of a merge in the road ahead. If the average driver must be able to see the sign from a distance of 400 feet, how tall must the letters be? Use the visual acuity data from Figure 6.18.

6.14 Visual Acuity Test. Print out some letters and numbers onto a sheet of paper, using Arial font, bold, point size 36. Attach the sheet to a wall. Ask someone else to start at the opposite side of the room and move forward until a character can be read. Note the character, its height, and the distance to the target. Have the subject continue moving forward until the subject has identified all characters on the target. Which character was misidentified? Which characters were easiest to see? Compute the subtended visual angle for each case. What guidance does this visual acuity experiment offer for the design of traffic signs?

6.15 Safety Device Design. What is the current status of the design and use of airbags in automobiles? Comment on air bags being one of the few safety devices that carry a warning label.

6.16 Human Factors. Based on your study of human factors in this course, respond "True" or "False" to each statement below.

- An individual's ability to perform a task may vary over time and depend on working conditions.
- Drivers tend to overestimate the speed of very large vehicles, such as locomotives.

6.17 Human Factors at Railroad Grade Crossings. What is it about trains at grade crossings that drivers often misjudge? Why is this a problem?

6.18 Stopping for a Train. You are traveling at 70 mph on a slushy road (friction coefficient = 0.20) when you hear a train whistle. You then see the warning sign that is placed 1000 feet before the gate-protected railroad grade crossing. You know you must try to stop.

(a) How close will you be to the gate when you come to a stop? Your reaction time is 1.5 seconds
(b) Where will the train be relative to the grade crossing when you come to a stop?

6.19 Racing the Train. A friend is driving along a local road at 55 mph. This friend hates to wait for anything, even the train that he sees heading for the grade crossing ahead. There is no gate at this grade crossing—only a cross buck sign and a bell. Your friend makes the decision to try to beat the train to the crossing. Although he can only guess at these values, the train is 1000 feet from the crossing and moving at 40 mph when your friend first sees it. At that time, your friend is 800 feet from the crossing.

(a) Assume your friend has a reaction time of 0.6 seconds. How far from the crossing will he be when he begins to accelerate?
(b) Your friend's car can accelerate at the rate of 28 ft/sec², but it has a maximum speed of 85 mph. How fast will it be going when it reaches the crossing?
(c) How much time did your friend take to reach the grade crossing? Did he beat the train?

6.20 Aging Society. What must a transportation planner or engineer take into consideration in a society where an increasing number of people are over 65 years of age?

Vehicle Attributes That Affect Safety

6.21 Stopping on a Downhill Grade. At one point on SR 835, there is a 4.9 percent downhill grade. How long will it take to bring a car traveling at 48 mph to a stop on that downhill segment if the driver's reaction time is 2.0 seconds and $f = 0.29$?

6.22 Traffic Accident. A transportation student is driving on a level road on a cold rainy night and sees a construction sign 520 feet ahead. The student strikes the sign at 35 mph. Further note, the student claims that he was not violating the 55 mph speed limit. You are investigating the accident and you will testify in court.

(a) What evidence will you seek?
(b) What will you tell the court? (Be specific about reaction times and possible initial speeds.)

Traffic Control Devices

6.23 Traffic Control Devices. Recently, the county highway engineer observed a two-person crew about to install a traffic control devices on the campus of Mythaca State University. At the base of the signpost were two signs, both with the message "Two Way Traffic Ahead." One sign had a rectangular shape with black letters on white background; the other was diamond-shaped with black on yellow. If the crew was making the correct change, which sign would be the correct one to put up?

(a) Diamond-shaped with black on yellow
(b) Rectangular shape with black letters on white background

Briefly explain your answer.

6.24 Traffic Control Devices. A driver on the northbound (NB) approach to a stop sign-controlled intersection sees the sign and supplemental plaque shown below. Drivers on which approaches to that intersection will have to stop? Circle the approach directions that comprise your answer.

(a) EB
(b) NB
(c) SB
(d) WB

STOP
2-WAY

STOP