A.1 Use of SI (Metric Units of Measure in SAE Technical Papers)

The long-term goal for SAE is international communication with minimal effort and confusion. Therefore, the use of SI units in all technical publications and presentations is preferred. The Society will strive toward universal usage of SI units and will encourage their use whenever appropriate.

However, the Society also recognizes that sectors of the mobility market do not yet use SI units because of tradition, regulatory language, or other reasons. Mandating the use of SI units in these cases will impede rather than facilitate technical communication. Therefore, it is the policy to allow non-SI units and dual dimensioning where communication will be enhanced. This shall not be viewed as an avenue to circumvent the long-term goal of 100 percent SI usage.

Instructions on SAE-approved techniques for conversion of units are contained in “SAE Recommended Practices, Rules for SAE Use of SI (METRIC) Units—TSB003.” Copies of TSB003 can be obtained from SAE Headquarters.

Although what follows represents a change to the current policy, it is not a change to the SAE Board of Directors’ Policy since it falls within the scope of the words, “where a conflicting industry practice exists.” Dual (metric/U.S. Customary) units for the following vehicle characteristics may be considered where communication will be enhanced.
A.2 Numbers, Significant Figures, and Rounding

A.2.1 Significant Figures

In all branches of science and technology, numbers are used to express values; i.e., levels or amounts of physical quantities. It is important to state numbers appropriately so that they properly convey the intended information. The number of significant figures contained in a stated number reflects the accuracy to which that quantity is known. For example, suppose the speed of a vehicle is reported as 21 m/s (69 ft/s). Is 21 m/s different from 21.0 m/s? According to the rules of significant figures, yes, but in practice, it may or may not. Could the number 21 m/s imply 20.9 m/s or less or could it imply 21.1 m/s or greater? It could, but such implications or interpretations must be determined from context, not the number 21 itself. Answers to some of these questions are related to the topic of uncertainty (covered in Chapter 1). To properly quantify and communicate a physical measurement or property, it should be stated as a reference value plus and minus an uncertainty. For example, a speed stated as \( v = 21.0 \pm 0.6 \) m/s clearly is meant to be between 20.4 and 21.6 m/s. This is one of the ways of estimating and revealing the uncertainty of results. But the basic rules of using significant figures and rounding must be understood before uncertainty can be expressed. Some of the rules for handling and interpreting the significance of numbers are covered in this Appendix. Note that the terms significant figures and significant digits are used synonymously.

### Table A.1

<table>
<thead>
<tr>
<th>Vehicle characteristic</th>
<th>Metric units</th>
<th>U.S. customary units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume, engine displacement</td>
<td>liters, L, or cubic cm, ( cm^3 )</td>
<td>cubic inches, ( in^3 )</td>
</tr>
<tr>
<td>Liquid volume</td>
<td>liters, L</td>
<td>pints/quarts/gallons</td>
</tr>
<tr>
<td>Engine power</td>
<td>kilowatts, ( kW )</td>
<td>brake horse power, ( bhp )</td>
</tr>
<tr>
<td>Engine torque</td>
<td>Newton-meters, ( N-m )</td>
<td>foot-pounds, ( lb-ft )</td>
</tr>
<tr>
<td>Mass</td>
<td>kilograms, ( kg )</td>
<td>slugs, ( lb-s^2/ft )</td>
</tr>
<tr>
<td>Pressure, stress</td>
<td>kiloPascals, ( kPa )</td>
<td>pounds per square inch, ( psi )</td>
</tr>
<tr>
<td>Temperature</td>
<td>degrees Celsius, ( ^\circ C )</td>
<td>degrees Fahrenheit, ( ^\circ F )</td>
</tr>
<tr>
<td>Area</td>
<td>square cm, ( cm^2 )</td>
<td>square inches, ( in^2 )</td>
</tr>
<tr>
<td>Linear dimensions</td>
<td>millimeters, ( mm ), meters, ( m ), or</td>
<td>inches, ( in., ft, ft, miles, ( mi )</td>
</tr>
<tr>
<td></td>
<td>kilometers, ( km )</td>
<td></td>
</tr>
<tr>
<td>Spring rates</td>
<td>Newtons per mm, ( N/mm )</td>
<td>pounds per inch, ( lb/in )</td>
</tr>
<tr>
<td>Speed</td>
<td>kilometers per hour, ( km/h ) or ( kph )</td>
<td>miles per hour, ( mph )</td>
</tr>
<tr>
<td>Fuel economy</td>
<td>kilometers per liter, ( km/L ) or ( kmpl )</td>
<td>miles per gallon, ( mpg )</td>
</tr>
<tr>
<td>Force</td>
<td>Newtons, ( N )</td>
<td>pounds, ( lb )</td>
</tr>
<tr>
<td>Acceleration</td>
<td>kilometers per second per second, ( km/s^2 ), g</td>
<td>feet per second per second, ( ft/s^2 ), g</td>
</tr>
</tbody>
</table>
The number of significant figures in a number is defined in the following way [A.1, A.2]:

1. The leftmost nonzero digit of a number is the most significant digit.
2. If there is no decimal point, the rightmost nonzero digit is the least significant digit.
3. If there is a decimal point, the rightmost digit is the least significant digit, even if it is a zero.
4. All digits, from the least to the most significant, are counted as significant.

So, for example, 2.610 and 2,498 have four significant digits each, whereas 0.125 and 728,000 have three significant digits. The following numbers each has five significant digits: 1000.0, 1206.5, 12,065,000 and 0.00012065. Unless it is stated to be exact, the speed of 21 m/s has two significant figures. If it is exact, then 21 is equivalent to 21.0000 . . . , with an unlimited number of zeros. Each of the speeds 20.4 and 21.6 has three significant figures.

When numbers are very large or very small, it is convenient to express them in scientific notation. To use scientific notation, a decimal point is placed immediately after the leftmost significant digit and the number is given a suffix of 10 raised to a power \(n\). The value of \(n\) is positive or negative. If the magnitude (disregarding the sign) of the stated number is less than 1, then \(n < 0\). If the stated number is greater than 10, \(n > 0\). If the stated number is between 1 and 10, \(n = 0\). The value of \(n\) is the power of 10 that returns the number in scientific notation to its original value. For example, 0.0000687 becomes \(6.87 \times 10^{-5}\) and 12,360,000 becomes \(1.236 \times 10^7\). Note that the number of significant digits does not change when converting to or from scientific notation.

### A.2.2 Rounding of Numbers

After completing calculations or when listing the results of measurements, it usually is necessary to round numbers to a lesser number of significant figures by discarding digits. Three possibilities can arise; these are:

1. **The leftmost discarded digit is less than 5.** When rounding such numbers, the last digit retained should remain unchanged. For example, if 3.46325 is to be rounded to four digits, the digits 2 and 5 would be discarded and 3.463 remains.

2. **The leftmost discarded digit is greater than 5 or it is a 5 followed by at least one digit other than 0.** In such cases, the last figure retained should be increased by one. For example, if rounded to four digits, 8.37652 would become 8.377; if rounded to three digits, it would be 8.38.

3. **The leftmost discarded digit is a 5, followed only by zeros or no other numbers.** Here, the last digit retained should be rounded up if it is an odd number, but no adjustment made if it is an even number. For example, 21.165, when rounded to four significant digits, becomes 21.16. The number 21.155 would likewise round to the same value, 21.16.
A reason for this last rule [A.2] is to avoid systematic errors that otherwise would be introduced into the average of a group of such numbers. Not all computer software follows this rule, however\(^1\), and when rounding for purposes of reporting results of measurements and/or calculations, the even-odd rule is not critical.

### A.2.3 Consistency of Significant Figures When Adding and Subtracting

When adding and subtracting numbers, proper determination of the number of significant figures is stated as a rule [A.1]. The rule is, *the answer shall contain no significant digits farther to the right than occurs in the number with the least significant digits*. The simplest way of following this rule is first to add or subtract the numbers using all of the stated significant figures\(^2\) followed by rounding of the final answer. For example, consider the addition of the three numbers, 964,532 and 317,880 and 563,000. These have six, five, and three significant figures, respectively. The sum by direct addition is 1,845,412. The answer then is adjusted, or rounded, to conform to the number with the least significant figures (563,000 with three), giving the final result, 1,845,000. This number has no more zero digits to the right of the comma than does 563,000. Now consider the sum of the three numbers, 964,532, -317,880 and -563,000; the direct result is 83,652. As above, this must be made to conform with the significant figures of 563,000 by using the rounding rule and is 84,000.

In the last example, the concept being conveyed is that the number 563,000 is “indefinite” to the right of the “3” digit. It is not known if 563,000 could really mean 562,684 or 563,121 or other values, because 563,000, itself, may have been obtained by rounding. If it had been stated as 563,000.0, then everything would be different (since 563,000.0 would have seven significant figures and 317,880 would then have the least significant digits of the three numbers to be added in the above example).

### A.2.4 Consistency of Significant Figures When Multiplying and Dividing

ASTM SI-10 [A.1] states a rule for multiplying and dividing as *the product or quotient shall contain no more significant digits than are contained in the number with the fewest significant digits*. For example, consider the product, 125.64 × 829.4 × 1.25, of the three numbers with five, four, and three significant digits, respectively. The answer from straightforward multiplication is 130,257.27. After rounding to three significant figures, the proper end result of the multiplication is 130,000. Note that the answer, 130,000, by itself appears to have only two significant figures. This illustrates that ambiguities sometimes can arise when determining significant figures and that the amount of significant figures of a number may need to be found from context. A way of resolving

---

1. The reader may wish to try such an example in their favorite software.
2. ASTM SI-10 suggests first rounding each individual number to one significant figure greater than the least before adding or subtracting and then rounding the final answer. Though this may be better, it is not the way most computer software operates. Rounding after summing typically gives the same result.
such ambiguities is to express results of rounding in scientific notation. In this case the result would be $1.30 \times 10^5$.

### A.2.5 Other Forms of Number Manipulation

Not all calculations are done with addition, subtraction, multiplication, and division. There are the taking of roots, logarithms, trigonometric functions, etc. In addition, sometimes strict adherence of rounding rules can produce paradoxical or impractical results (see the following example). So more general rules are needed. In summary, two very general, but some practical rules are recommended:

1. In rounding of numbers and conversion of units, retain a number of significant digits such that accuracy and precision are neither sacrificed nor exaggerated.
2. When making and reporting calculations, continually carry all of the significant figures of a calculating device without rounding intermediate values, and round only the final answer.
3. Unit conversion should precede rounding.
4. Whenever possible, explicitly state the uncertainty of the results of measurements and calculations.

Suppose a vehicle skids to a stop over a distance of $d = 33.9$ m from an initial speed, $v$, on a pavement with a uniform frictional drag coefficient of $f = 0.7 \pm 0.1$. Use the minimum and maximum values of $f$ and Eq. 1.1 to calculate bounds on the initial speed. Convert the results to U.S. Customary units of ft/s.

**Solution**  The lower value of speed for $f = 0.6$:

$$v = \sqrt{2fgd} = \sqrt{2 \times 0.6 \times 9.80665 \times 33.9} = 19.973345...$$

Similarly, the initial speed for $f = 0.8$ is:

$$v = \sqrt{2 \times 0.8 \times 9.80665 \times 33.9} = 23.063233...$$

The frictional drag coefficient and its uncertainty have the fewest number of significant figures of the input values. According to the rules the final results should be rounded to one significant figure. Rounding 19.973345... to a single significant digit gives a speed of $v = 20$ m/s. Rounding 23.063235... to a single significant digit also gives a speed of $v = 20$ m/s. Both upper and lower bounds result with the same speed, $v = 20$ m/s. Clearly the result is an exaggeration of precision. Consider now another approach.
The variation of $f = \pm 0.1$ is another way of saying that because of uncertainty, $f$ can take on any value between 0.6 to 0.8. From the above discussion of significant figures and rounding, a point of view can be taken that the lower value, 0.6, for example, could be the result of rounding to one significant figure of any number from 0.55+ to 0.65- (such as 0.551, 0.642, etc.). Similarly, the upper value, 0.8, could be viewed as the result of rounding of any number from 0.75+ to 0.85- (such as 0.751, 0.842, etc.). So the full range of values of the frictional drag coefficient corresponding to the stated uncertainty and from the concepts of significant figures is $0.55 \leq f \leq 0.85$. At this point the calculations are performed as if all numbers are exact giving a speed range of $19.123022 \ldots \leq v \leq 23.773036 \ldots$ m/s. Since rounding to one significant figure here produces an exaggeration of precision (as above), rounding is done to an additional significant figure. Consequently, the final result is stated as: $19 \leq v \leq 24$ m/s, or $v = 19.5 \pm 2.5$ m/s. Precision no longer is exaggerated. An initial $\pm 14\%$ variation (0.7 $\pm$ 0.1) becomes a 12% variation of $v$ ($19.5 \pm 2.5$) through the use of Eq. 1.1.

Finally, the speed is to be converted to the U.S. Customary units of ft/s. The proper conversion factor is 1 ft = 0.3048 m (this is an exact conversion; see the following unit conversion table). Unit conversions should be done before rounding, so $19.123022 \ldots \leq v \leq 23.773036 \ldots$ m/s becomes $62.739573 \ldots \leq v \leq 77.995525 \ldots$ ft/s. Rounding again to one significant figure gives the same result, 70 ft, so another significant figure is acceptable, giving $63 \leq v \leq 78$ ft/s, or $v = 70.5 \pm 7.5$ ft/s.

Another consideration that must be kept in mind when rounding is the use or purpose of the results; for example, if the speed calculated in the last example is to be compared to a speed limit, say 25 m/s. Rounding to a number of significant digits to the right of the decimal point is superfluous. The result $19 \leq v \leq 24$ m/s is satisfactory to conclude that the calculated speed is less than the speed limit. Instead, suppose that the calculated speed is a measure of vehicle braking performance and is to be compared to a governmental regulation stated to three significant figures. Rounding to an additional significant figure leads to an exaggeration of accuracy. To compare the speed to such a regulation requires a more accurate value of friction, stated at least to two significant figures.

### A.3 Unit Conversions for Common Units

Factors in **boldface** are exact. When options exist, units in the first column printed in *italics* are preferred by the National Institute for Science and Technology. [A.3]

<table>
<thead>
<tr>
<th>To convert from</th>
<th>To</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>acre (based on U.S. survey foot)</td>
<td>square meter (m²)</td>
<td>$4.046873 \ E+03$</td>
</tr>
<tr>
<td>acre foot (based on U.S. survey foot)</td>
<td>cubic meter (m³)</td>
<td>$1.233489 \ E+03$</td>
</tr>
<tr>
<td>ampere hour (A • h)</td>
<td>coulomb (C)</td>
<td>$3.6 \ E+03$</td>
</tr>
<tr>
<td>atmosphere, standard (atm)</td>
<td>pascal (Pa)</td>
<td>$1.01325 \ E+05$</td>
</tr>
</tbody>
</table>

---

3. Note that there is no implication of the likelihood of any of the values within this range.
<table>
<thead>
<tr>
<th>Unit (source)</th>
<th>Unit (target)</th>
<th>Value</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>atmosphere, standard (atm)</td>
<td>kilopascal (kPa)</td>
<td>1.01325</td>
<td>E+02</td>
</tr>
<tr>
<td>atmosphere, technical (at)</td>
<td>pascal (Pa)</td>
<td>9.80665</td>
<td>E+04</td>
</tr>
<tr>
<td>atmosphere, technical (at)</td>
<td>kilopascal (kPa)</td>
<td>9.80665</td>
<td>E+01</td>
</tr>
<tr>
<td>bar (bar)</td>
<td>pascal (Pa)</td>
<td>1.0</td>
<td>E+05</td>
</tr>
<tr>
<td>bar (bar)</td>
<td>kilopascal (kPa)</td>
<td>1.0</td>
<td>E+02</td>
</tr>
<tr>
<td>barn (b)</td>
<td>square meter (m²)</td>
<td>1.0</td>
<td>E-28</td>
</tr>
<tr>
<td>barrel [for petroleum, 42 gallons (U.S.)]</td>
<td>cubic meter (m³)</td>
<td>1.589873</td>
<td>E-01</td>
</tr>
<tr>
<td>barrel [for petroleum, 42 gallons (U.S.)]</td>
<td>liter (L)</td>
<td>1.589873</td>
<td>E+02</td>
</tr>
<tr>
<td>British thermal unit (mean) (Btu)</td>
<td>joule (J)</td>
<td>1.05587</td>
<td>E+03</td>
</tr>
<tr>
<td>bushel (U.S.) (bu)</td>
<td>cubic meter (m³)</td>
<td>3.523907</td>
<td>E-02</td>
</tr>
<tr>
<td>bushel (U.S.) (bu)</td>
<td>liter (L)</td>
<td>3.523907</td>
<td>E+01</td>
</tr>
<tr>
<td>calorie (cal) (mean)</td>
<td>joule (J)</td>
<td>4.19002</td>
<td>E+00</td>
</tr>
<tr>
<td>candela per square inch (cd/in²)</td>
<td>candela per square meter (cd/m²)</td>
<td>1.550003</td>
<td>E+03</td>
</tr>
<tr>
<td>carat, metric</td>
<td>kilogram (kg)</td>
<td>2.0</td>
<td>E-04</td>
</tr>
<tr>
<td>carat, metric</td>
<td>gram (g)</td>
<td>2.0</td>
<td>E-01</td>
</tr>
<tr>
<td>centimeter of mercury (0 °C)</td>
<td>pascal (Pa)</td>
<td>1.33322</td>
<td>E+03</td>
</tr>
<tr>
<td>centimeter of water (4 °C)</td>
<td>pascal (Pa)</td>
<td>9.80638</td>
<td>E+01</td>
</tr>
<tr>
<td>centimeter of water, conventional (cm H₂O)</td>
<td>pascal (Pa)</td>
<td>9.80665</td>
<td>E+01</td>
</tr>
<tr>
<td>centipoise (cP)</td>
<td>pascal second (Pa • s)</td>
<td>1.0</td>
<td>E-03</td>
</tr>
<tr>
<td>centistokes (cSt)</td>
<td>meter squared per second (m²/s)</td>
<td>1.0</td>
<td>E-06</td>
</tr>
<tr>
<td>chain (based on U.S. survey foot) (ch)</td>
<td>meter (m)</td>
<td>2.011684</td>
<td>E+01</td>
</tr>
<tr>
<td>circular mil</td>
<td>square meter (m²)</td>
<td>5.067075</td>
<td>E-10</td>
</tr>
<tr>
<td>cord (128 ft³)</td>
<td>cubic meter (m³)</td>
<td>3.624556</td>
<td>E+00</td>
</tr>
<tr>
<td>cubic foot (ft³)</td>
<td>cubic meter (m³)</td>
<td>2.831685</td>
<td>E-02</td>
</tr>
<tr>
<td>cubic inch (in³)</td>
<td>cubic meter (m³)</td>
<td>1.638706</td>
<td>E-05</td>
</tr>
<tr>
<td>cubic mile (mi³)</td>
<td>cubic meter (m³)</td>
<td>4.168182</td>
<td>E+09</td>
</tr>
<tr>
<td>cubic yard (yd³)</td>
<td>cubic meter (m³)</td>
<td>7.645549</td>
<td>E+01</td>
</tr>
<tr>
<td>cup (U.S.)</td>
<td>cubic meter (m³)</td>
<td>2.365882</td>
<td>E+04</td>
</tr>
<tr>
<td>cup (U.S.)</td>
<td>liter (L)</td>
<td>2.365882</td>
<td>E+01</td>
</tr>
<tr>
<td>day (d)</td>
<td>second (s)</td>
<td>8.64</td>
<td>E+04</td>
</tr>
<tr>
<td>day (sidereal)</td>
<td>second (s)</td>
<td>8.616409</td>
<td>E+04</td>
</tr>
<tr>
<td>degree (angle) (°)</td>
<td>radian (rad)</td>
<td>1.745329</td>
<td>E-02</td>
</tr>
<tr>
<td>degree Celsius (temperature) (°C)</td>
<td>kelvin (K)</td>
<td>K = °C + 273.15</td>
<td></td>
</tr>
<tr>
<td>degree Celsius (temperature interval) (°C)</td>
<td>kelvin (K)</td>
<td>1.0</td>
<td>E+00</td>
</tr>
<tr>
<td>degree centigrade (temperature)</td>
<td>degree Celsius (°C)</td>
<td>°C = deg. cent.</td>
<td></td>
</tr>
<tr>
<td>degree centigrade (temperature interval)</td>
<td>degree Celsius (°C)</td>
<td>1.0</td>
<td>E+00</td>
</tr>
<tr>
<td>degree Fahrenheit (temperature) (°F)</td>
<td>degree Celsius (°C)</td>
<td>°C = (°F - 32)/1.8</td>
<td></td>
</tr>
<tr>
<td>degree Fahrenheit (temperature) (°F)</td>
<td>kelvin (K)</td>
<td>K = (°F + 459.67)/1.8</td>
<td></td>
</tr>
<tr>
<td>degree Fahrenheit (temperature interval)</td>
<td>degree Celsius (°C)</td>
<td>5.555556</td>
<td>E-01</td>
</tr>
<tr>
<td>Unit Description</td>
<td>Unit</td>
<td>Conversion Factor</td>
<td>Precision</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------------</td>
<td>-------------------------------------</td>
<td>-------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>degree Fahrenheit (temperature interval) (°F)</td>
<td>kelvin (K)</td>
<td>5.555 556</td>
<td>E-01</td>
</tr>
<tr>
<td>degree Rankine (°R)</td>
<td>kelvin (K)</td>
<td>K = (°R)/1.8</td>
<td></td>
</tr>
<tr>
<td>degree Rankine (temperature interval) (°R)</td>
<td>kelvin (K)</td>
<td>5.555 556</td>
<td>E-01</td>
</tr>
<tr>
<td>Denier</td>
<td>kilogram per meter (kg/m)</td>
<td>1.111 111</td>
<td>E-07</td>
</tr>
<tr>
<td>dyne (dyn)</td>
<td>newton (N)</td>
<td>1.0</td>
<td>E-05</td>
</tr>
<tr>
<td>dyne centimeter (dyn • cm)</td>
<td>newton meter (N • m)</td>
<td>1.0</td>
<td>E-07</td>
</tr>
<tr>
<td>dyne per square centimeter (dyn/cm²)</td>
<td>pascal (Pa)</td>
<td>1.0</td>
<td>E-01</td>
</tr>
<tr>
<td>erg (erg)</td>
<td>joule (J)</td>
<td>1.0</td>
<td>E-07</td>
</tr>
<tr>
<td>erg per second (erg/s)</td>
<td>watt (W)</td>
<td>1.0</td>
<td>E-07</td>
</tr>
<tr>
<td>fathom (based on U.S. survey foot)</td>
<td>meter (m)</td>
<td>1.828 804</td>
<td>E+00</td>
</tr>
<tr>
<td>fluid ounce (U.S.) (fl oz)</td>
<td>cubic meter (m³)</td>
<td>2.957 353</td>
<td>E-05</td>
</tr>
<tr>
<td>fluid ounce (U.S.) (fl oz)</td>
<td>milliliter (mL)</td>
<td>2.957 353</td>
<td>E+01</td>
</tr>
<tr>
<td>foot (ft)</td>
<td>meter (m)</td>
<td>3.048</td>
<td>E-01</td>
</tr>
<tr>
<td>foot (U.S. survey) (ft)</td>
<td>meter (m)</td>
<td>3.048 006</td>
<td>E-01</td>
</tr>
<tr>
<td>Footcandle</td>
<td>lux (lx)</td>
<td>1.076 391</td>
<td>E+01</td>
</tr>
<tr>
<td>Footlambert</td>
<td>candela per square meter (cd/m²)</td>
<td>3.426 259</td>
<td>E+00</td>
</tr>
<tr>
<td>foot of water, conventional (ftH₂O)</td>
<td>pascal (Pa)</td>
<td>2.989 067</td>
<td>E+03</td>
</tr>
<tr>
<td>foot of water, conventional (ftH₂O)</td>
<td>kilopascal (kPa)</td>
<td>2.989 067</td>
<td>E+00</td>
</tr>
<tr>
<td>foot per hour (ft/h)</td>
<td>meter per second (m/s)</td>
<td>8.466 667</td>
<td>E-03</td>
</tr>
<tr>
<td>foot per minute (ft/min)</td>
<td>meter per second (m/s)</td>
<td>5.08</td>
<td>E-03</td>
</tr>
<tr>
<td>foot per second (ft/s)</td>
<td>meter per second (m/s)</td>
<td>3.048</td>
<td>E-01</td>
</tr>
<tr>
<td>foot per second squared (ft/s²)³</td>
<td>meter per second squared (m/s²)³</td>
<td>3.048</td>
<td>E-01</td>
</tr>
<tr>
<td>foot poundal</td>
<td>joule (J)</td>
<td>4.214 011</td>
<td>E-02</td>
</tr>
<tr>
<td>foot pound-force (ft • lbf)</td>
<td>joule (J)</td>
<td>1.355 818</td>
<td>E+00</td>
</tr>
<tr>
<td>foot pound-force per hour (ft • lbf/h)</td>
<td>watt (W)</td>
<td>3.766 161</td>
<td>E-04</td>
</tr>
<tr>
<td>foot pound-force per minute (ft • lbf/min)</td>
<td>watt (W)</td>
<td>2.259 697</td>
<td>E-02</td>
</tr>
<tr>
<td>foot pound-force per second (ft • lbf/s)</td>
<td>watt (W)</td>
<td>1.355 818</td>
<td>E+00</td>
</tr>
<tr>
<td>gal (Gal)</td>
<td>meter per second squared (m/s²)</td>
<td>1.0</td>
<td>E-02</td>
</tr>
<tr>
<td>gallon [Canadian and U.K. (Imperial)] (gal)</td>
<td>cubic meter (m³)</td>
<td>4.546 09</td>
<td>E-03</td>
</tr>
<tr>
<td>gallon [Canadian and U.K. (Imperial)] (gal)</td>
<td>liter (L)</td>
<td>4.546 09</td>
<td>E+00</td>
</tr>
<tr>
<td>gallon (U.S.) (gal)</td>
<td>cubic meter (m³)</td>
<td>3.785 412</td>
<td>E-03</td>
</tr>
<tr>
<td>gallon (U.S.) (gal)</td>
<td>liter (L)</td>
<td>3.785 412</td>
<td>E+00</td>
</tr>
<tr>
<td>gallon (U.S.) per day (gal/d)</td>
<td>cubic meter per second (m³/s)</td>
<td>4.381 264</td>
<td>E-08</td>
</tr>
<tr>
<td>gallon (U.S.) per day (gal/d)</td>
<td>liter per second (L/s)</td>
<td>4.381 264</td>
<td>E-05</td>
</tr>
<tr>
<td>gallon (U.S.) per horsepower hour [gal/(hp • h)]</td>
<td>cubic meter per joule (m³/J)</td>
<td>1.410 089</td>
<td>E-09</td>
</tr>
<tr>
<td>gallon (U.S.) per horsepower hour [gal/(hp • h)]</td>
<td>liter per joule (L/J)</td>
<td>1.410 089</td>
<td>E-06</td>
</tr>
</tbody>
</table>

4. Standard value of free-fall acceleration is \( g = 9.80665 \text{ m/s}^2 \).
<table>
<thead>
<tr>
<th>Unit (US) or Metric</th>
<th>Conversion Factor</th>
<th>Prefix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>gallon (U.S.) per minute (gpm) (gal/min)</td>
<td>cubic meter per second (m³/s)</td>
<td>6.309 020</td>
<td>E-05</td>
</tr>
<tr>
<td>gallon (U.S.) per minute (gpm) (gal/min)</td>
<td>liter per second (L/s)</td>
<td>6.309 020</td>
<td>E-02</td>
</tr>
<tr>
<td>grain (gr)</td>
<td>kilogram (kg)</td>
<td>6.479 891</td>
<td>E-05</td>
</tr>
<tr>
<td>grain (gr)</td>
<td>milligram (mg)</td>
<td>6.479 891</td>
<td>E+01</td>
</tr>
<tr>
<td>grain per gallon (U.S.) (gr/gal)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.711 806</td>
<td>E-02</td>
</tr>
<tr>
<td>grain per gallon (U.S.) (gr/gal)</td>
<td>milligram per liter (mg/L)</td>
<td>1.711 806</td>
<td>E+01</td>
</tr>
<tr>
<td>gram-force per square centimeter (gf/cm²)</td>
<td>pascal (Pa)</td>
<td>9.806 65</td>
<td>E+01</td>
</tr>
<tr>
<td>gram per cubic centimeter (g/cm³)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.0</td>
<td>E+03</td>
</tr>
<tr>
<td>hectare (ha)</td>
<td>square meter (m²)</td>
<td>1.0</td>
<td>E+04</td>
</tr>
<tr>
<td>horsepower (550 ft • lb/s) (hp)</td>
<td>watt (W)</td>
<td>7.456 999</td>
<td>E+02</td>
</tr>
<tr>
<td>horsepower (boiler)</td>
<td>watt (W)</td>
<td>9.809 50</td>
<td>E+03</td>
</tr>
<tr>
<td>horsepower (electric)</td>
<td>watt (W)</td>
<td>7.46</td>
<td>E+02</td>
</tr>
<tr>
<td>horsepower (metric)</td>
<td>watt (W)</td>
<td>7.354 988</td>
<td>E+02</td>
</tr>
<tr>
<td>horsepower (U.K.)</td>
<td>watt (W)</td>
<td>7.4570</td>
<td>E+02</td>
</tr>
<tr>
<td>horsepower (water)</td>
<td>watt (W)</td>
<td>7.460 43</td>
<td>E+02</td>
</tr>
<tr>
<td>hour (h)</td>
<td>second (s)</td>
<td>3.6</td>
<td>E+03</td>
</tr>
<tr>
<td>hour (sidereal)</td>
<td>second (s)</td>
<td>3.590 170</td>
<td>E+03</td>
</tr>
<tr>
<td>hundredweight (long, 112 lb)</td>
<td>kilogram (kg)</td>
<td>5.080 235</td>
<td>E+01</td>
</tr>
<tr>
<td>hundredweight (short, 100 lb)</td>
<td>kilogram (kg)</td>
<td>4.535 924</td>
<td>E+01</td>
</tr>
<tr>
<td>inch (in)</td>
<td>meter (m)</td>
<td>2.54</td>
<td>E-02</td>
</tr>
<tr>
<td>inch (in)</td>
<td>centimeter (cm)</td>
<td>2.54</td>
<td>E+00</td>
</tr>
<tr>
<td>inch of mercury, conventional (in. Hg)</td>
<td>pascal (Pa)</td>
<td>3.386 389</td>
<td>E+03</td>
</tr>
<tr>
<td>inch of mercury, conventional (in. Hg)</td>
<td>kilopascal (kPa)</td>
<td>3.386 389</td>
<td>E+00</td>
</tr>
<tr>
<td>inch of water, conventional (inH₂O)</td>
<td>pascal (Pa)</td>
<td>2.490 889</td>
<td>E+02</td>
</tr>
<tr>
<td>kelvin (K)</td>
<td>degree Celsius (°C)</td>
<td>t/°C = T/K - 273.15</td>
<td></td>
</tr>
<tr>
<td>kilocalorie (mean) (kcal)</td>
<td>joule (J)</td>
<td>4.190 02</td>
<td>E+03</td>
</tr>
<tr>
<td>kilogram-force (kgf)</td>
<td>newton (N)</td>
<td>9.806 65</td>
<td>E+00</td>
</tr>
<tr>
<td>kilogram-force meter (kgf • m)</td>
<td>newton meter (N • m)</td>
<td>9.806 65</td>
<td>E+00</td>
</tr>
<tr>
<td>kilogram-force per square centimeter (kgf/cm²)</td>
<td>kilopascal (kPa)</td>
<td>9.806 65</td>
<td>E+01</td>
</tr>
<tr>
<td>kilogram-force per square meter (kgf/m²)</td>
<td>pascal (Pa)</td>
<td>9,806 65</td>
<td>E+00</td>
</tr>
<tr>
<td>kilometer per hour (km/h)</td>
<td>meter per second (m/s)</td>
<td>2.777 778</td>
<td>E-01</td>
</tr>
<tr>
<td>kilopond (kilogram-force) (kp)</td>
<td>newton (N)</td>
<td>9,806 65</td>
<td>E+00</td>
</tr>
<tr>
<td>kilowatt hour (kW • h)</td>
<td>joule (J)</td>
<td>3.6</td>
<td>E+06</td>
</tr>
<tr>
<td>kilowatt hour (kW • h)</td>
<td>megajoule (MJ)</td>
<td>3.6</td>
<td>E+00</td>
</tr>
<tr>
<td>kip (1 kip= 1000 lbf)</td>
<td>newton (N)</td>
<td>4,448 222</td>
<td>E+03</td>
</tr>
<tr>
<td>kip (1 kip= 1000 lbf)</td>
<td>kilonewton (kN)</td>
<td>4,448 222</td>
<td>E+00</td>
</tr>
<tr>
<td>kip per square inch (ksi) (kip/in²)</td>
<td>pascal (Pa)</td>
<td>6,894 757</td>
<td>E+06</td>
</tr>
<tr>
<td>kip per square inch (ksi) (kip/in²)</td>
<td>kilopascal (kPa)</td>
<td>6,894 757</td>
<td>E+03</td>
</tr>
<tr>
<td>Unit</td>
<td>Conversion Factor</td>
<td>Precision</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>knot (nautical mile per hour)</td>
<td>meter per second (m/s)</td>
<td>5.14444 E-01</td>
<td></td>
</tr>
<tr>
<td>lambert</td>
<td>candela per square meter (cd/m²)</td>
<td>3.183 099 E+03</td>
<td></td>
</tr>
<tr>
<td>light year (ly.)</td>
<td>meter (m)</td>
<td>9.460 73 E+15</td>
<td></td>
</tr>
<tr>
<td>liter (L)</td>
<td>cubic meter (m³)</td>
<td>1.0 E-03</td>
<td></td>
</tr>
<tr>
<td>lumen per square foot (lm/ft²)</td>
<td>lux (lx)</td>
<td>1.076 391 E+01</td>
<td></td>
</tr>
<tr>
<td>microinch</td>
<td>meter (m)</td>
<td>2.54 E-08</td>
<td></td>
</tr>
<tr>
<td>micron (μ)</td>
<td>meter (m)</td>
<td>1.0 E-06</td>
<td></td>
</tr>
<tr>
<td>micron (μ)</td>
<td>micrometer (μm)</td>
<td>1.0 E+00</td>
<td></td>
</tr>
<tr>
<td>mil (0.001 in)</td>
<td>meter (m)</td>
<td>2.54 E-05</td>
<td></td>
</tr>
<tr>
<td>mile (mi)</td>
<td>meter (m)</td>
<td>1.609 344 E+03</td>
<td></td>
</tr>
<tr>
<td>mile (mi)</td>
<td>kilometer (km)</td>
<td>1.609 344 E+00</td>
<td></td>
</tr>
<tr>
<td>mile (based on U.S. survey foot) (mi)</td>
<td>meter (m)</td>
<td>1.609 347 E+03</td>
<td></td>
</tr>
<tr>
<td>mile (based on U.S. survey foot) (mi)</td>
<td>kilometer (km)</td>
<td>1.609 347 E+00</td>
<td></td>
</tr>
<tr>
<td>mile, nautical</td>
<td>meter (m)</td>
<td>1.852 E+03</td>
<td></td>
</tr>
<tr>
<td>mile per gallon (U.S.) (mpg) (mi/gal)</td>
<td>meter per cubic meter m/ m³</td>
<td>4.251 437 E+05</td>
<td></td>
</tr>
<tr>
<td>mile per gallon (U.S.) (mpg) (mi/gal)</td>
<td>kilometer per liter (km/L)</td>
<td>4.251 437 E+01</td>
<td></td>
</tr>
<tr>
<td>mile per gallon (U.S.) (mpg) (mi/gal)</td>
<td>liter per 100 kilometer (L/100km)</td>
<td>divide 235.215 by number of miles per gallon</td>
<td></td>
</tr>
<tr>
<td>mile per hour (mi/h)</td>
<td>meter per second (m/s)</td>
<td>4.4704 E-01</td>
<td></td>
</tr>
<tr>
<td>mile per hour (mi/h)</td>
<td>kilometer per hour (km/h)</td>
<td>1.609 344 E+00</td>
<td></td>
</tr>
<tr>
<td>mile per minute (mi/min)</td>
<td>meter per second (m/s)</td>
<td>2.682 24 E+01</td>
<td></td>
</tr>
<tr>
<td>mile per second (mi/s)</td>
<td>meter per second (m/s)</td>
<td>1.609 344 E+03</td>
<td></td>
</tr>
<tr>
<td>millibar (mbar)</td>
<td>pascal (Pa)</td>
<td>1.0 E+02</td>
<td></td>
</tr>
<tr>
<td>millibar (mbar)</td>
<td>kilopascal (kPa)</td>
<td>1.0 E-01</td>
<td></td>
</tr>
<tr>
<td>millimeter of mercury, conventional (mmHg)</td>
<td>pascal (Pa)</td>
<td>1.333 224 E+02</td>
<td></td>
</tr>
<tr>
<td>millimeter of water, conventional (mm H₂O)</td>
<td>pascal (Pa)</td>
<td>9.806 65 E+00</td>
<td></td>
</tr>
<tr>
<td>minute (angle) (°)</td>
<td>radian (rad)</td>
<td>2.908 828 E-04</td>
<td></td>
</tr>
<tr>
<td>minute (min)</td>
<td>second (s)</td>
<td>6.0 E+01</td>
<td></td>
</tr>
<tr>
<td>minute (sidereal)</td>
<td>second (s)</td>
<td>5.983 617 E+01</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois) (oz)</td>
<td>kilogram (kg)</td>
<td>2.834 952 E-02</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois) (oz)</td>
<td>gram (g)</td>
<td>2.834 952 E+01</td>
<td></td>
</tr>
<tr>
<td>ounce (troy or apothecary) (oz)</td>
<td>kilogram (kg)</td>
<td>3.110 348 E-02</td>
<td></td>
</tr>
<tr>
<td>ounce (troy or apothecary) (oz)</td>
<td>gram (g)</td>
<td>3.110 348 E+01</td>
<td></td>
</tr>
<tr>
<td>ounce [Canadian and U.K. fluid (Imperial)] (fl oz)</td>
<td>cubic meter (m³)</td>
<td>2.841 306 E-05</td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td>Conversion Factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ounce [Canadian and U.K. fluid (Imperial)] (fl oz)</td>
<td>milliliter (mL)</td>
<td>2.841 306 E+01</td>
<td></td>
</tr>
<tr>
<td>ounce (U.S. fluid) (fl oz)</td>
<td>cubic meter (m³)</td>
<td>2.957 353 E-05</td>
<td></td>
</tr>
<tr>
<td>ounce (U.S. fluid) (fl oz)</td>
<td>milliliter (mL)</td>
<td>2.957 353 E+01</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois)-force (ozf)</td>
<td>newton (N)</td>
<td>2.780 139 E-01</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois)-force inch (ozf • in)</td>
<td>newton meter (N • m)</td>
<td>7.061 552 E-03</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois)-force inch (ozf • in)</td>
<td>millinewton meter (mN • m)</td>
<td>7.061 552 E+00</td>
<td></td>
</tr>
<tr>
<td>ounce (avoirdupois) per cubic inch (oz/in³)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.729 994 E+03</td>
<td></td>
</tr>
<tr>
<td>peck (U.S.) (pk)</td>
<td>cubic meter (m³)</td>
<td>8.809 768 E-03</td>
<td></td>
</tr>
<tr>
<td>peck (U.S.) (pk)</td>
<td>liter (L)</td>
<td>8.809 768 E+00</td>
<td></td>
</tr>
<tr>
<td>pennyweight (dwt)</td>
<td>kilogram (kg)</td>
<td>1.555 174 E-03</td>
<td></td>
</tr>
<tr>
<td>pennyweight (dwt)</td>
<td>gram (g)</td>
<td>1.555 174 E+00</td>
<td></td>
</tr>
<tr>
<td>pica (computer) (1/6 in)</td>
<td>meter (m)</td>
<td>4.233 333 E-03</td>
<td></td>
</tr>
<tr>
<td>pica (computer) (1/6 in)</td>
<td>millimeter (mm)</td>
<td>4.233 333 E+00</td>
<td></td>
</tr>
<tr>
<td>pica (printer’s)</td>
<td>meter (m)</td>
<td>4.217 518 E-03</td>
<td></td>
</tr>
<tr>
<td>pica (printer’s)</td>
<td>millimeter (mm)</td>
<td>4.217 518 E+00</td>
<td></td>
</tr>
<tr>
<td>pint (U.S. dry) (dry pt)</td>
<td>cubic meter (m³)</td>
<td>5.506 105 E-04</td>
<td></td>
</tr>
<tr>
<td>pint (U.S. dry) (dry pt)</td>
<td>liter (L)</td>
<td>5.506 105 E+01</td>
<td></td>
</tr>
<tr>
<td>pint (U.S. liquid) (liq pt)</td>
<td>cubic meter (m³)</td>
<td>4.731 765 E-04</td>
<td></td>
</tr>
<tr>
<td>pint (U.S. liquid) (liq pt)</td>
<td>liter (L)</td>
<td>4.731 765 E-01</td>
<td></td>
</tr>
<tr>
<td>point (computer) (1/72 in)</td>
<td>meter (m)</td>
<td>3.527 778 E-04</td>
<td></td>
</tr>
<tr>
<td>point (computer) (1/72 in)</td>
<td>millimeter (mm)</td>
<td>3.527 778 E+01</td>
<td></td>
</tr>
<tr>
<td>point (printer’s)</td>
<td>meter (m)</td>
<td>3.514 598 E-04</td>
<td></td>
</tr>
<tr>
<td>point (printer’s)</td>
<td>millimeter (mm)</td>
<td>3.514 598 E+01</td>
<td></td>
</tr>
<tr>
<td>poise (P)</td>
<td>pascal second (Pa • s)</td>
<td>1.0 E-01</td>
<td></td>
</tr>
<tr>
<td>pound (avoirdupois) (lb)</td>
<td>kilogram (kg)</td>
<td>4.535 924 E-01</td>
<td></td>
</tr>
<tr>
<td>pound (troy or apothecary) (lb)</td>
<td>kilogram (kg)</td>
<td>3.732 417 E-01</td>
<td></td>
</tr>
<tr>
<td>poundal</td>
<td>newton (N)</td>
<td>1.382 550 E-01</td>
<td></td>
</tr>
<tr>
<td>poundal per square foot</td>
<td>pascal (Pa)</td>
<td>1.488 164 E+00</td>
<td></td>
</tr>
<tr>
<td>poundal per square foot</td>
<td>pascal second (Pa • s)</td>
<td>1.488 164 E+00</td>
<td></td>
</tr>
<tr>
<td>pound foot squared (lb • ft²)</td>
<td>kilogram meter squared (kg • m²)</td>
<td>4.214 011 E+02</td>
<td></td>
</tr>
<tr>
<td>pound-force (lbf)²</td>
<td>newton (N)</td>
<td>4.448 222 E+00</td>
<td></td>
</tr>
<tr>
<td>pound-force foot (lbf • ft)</td>
<td>newton meter (N • m)</td>
<td>1.355 818 E+00</td>
<td></td>
</tr>
<tr>
<td>pound-force foot per inch (lbf • ft/in)</td>
<td>newton meter per meter (N•m/m)</td>
<td>5.337 866 E+01</td>
<td></td>
</tr>
<tr>
<td>pound-force inch (lbf • in)</td>
<td>newton meter (N • m)</td>
<td>1.129 848 E-01</td>
<td></td>
</tr>
<tr>
<td>pound-force inch per inch (lbf • in/in)</td>
<td>newton meter per meter (N•m/m)</td>
<td>4.448 222 E+00</td>
<td></td>
</tr>
</tbody>
</table>

5. If the local value of the acceleration of free fall is taken as the standard value \(g = 9.90665 \text{ m/s}^2\), then the exact conversion factor is 4.448 221 615 260 5 E+00.
### Appendix A

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Equivalent Unit</th>
<th>Conversion Factor</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>pound-force per foot (lbf/ft)</td>
<td>newton per meter (N/m)</td>
<td>1.459 390</td>
<td>E+01</td>
</tr>
<tr>
<td>pound-force per inch (lbf/in)</td>
<td>newton per meter (N/m)</td>
<td>1.751 268</td>
<td>E+02</td>
</tr>
<tr>
<td>pound-force per pound (lbf/lb) (thrust to mass ratio)</td>
<td>newton per kilogram (N/kg)</td>
<td>9.806 65</td>
<td>E+00</td>
</tr>
<tr>
<td>pound-force per square foot (lbf/ft²)</td>
<td>pascal (Pa)</td>
<td>4.788 026</td>
<td>E+01</td>
</tr>
<tr>
<td>pound-force per square inch (psi) (lbf/in²)</td>
<td>pascal (Pa)</td>
<td>6.894 757</td>
<td>E+03</td>
</tr>
<tr>
<td>pound-force per square inch (psi) (lbf/in²)</td>
<td>kilopascal (kPa)</td>
<td>6.894 757</td>
<td>E+00</td>
</tr>
<tr>
<td>pound-force second per square foot (lbf • s/ft²)</td>
<td>pascal second (Pa • s)</td>
<td>4.788 026</td>
<td>E+01</td>
</tr>
<tr>
<td>pound-force second per square inch (lbf • s/in²)</td>
<td>pascal second (Pa • s)</td>
<td>6.894 757</td>
<td>E+03</td>
</tr>
<tr>
<td>pound inch squared (lb • in²)</td>
<td>kilogram meter squared (kg • m²)</td>
<td>2.926 397</td>
<td>E-04</td>
</tr>
<tr>
<td>pound per cubic foot (lb/ft³)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.601 846</td>
<td>E+01</td>
</tr>
<tr>
<td>pound per cubic inch (lb/in³)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>2.767 990</td>
<td>E+04</td>
</tr>
<tr>
<td>pound per cubic yard (lb/yd³)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>5.932 764</td>
<td>E+01</td>
</tr>
<tr>
<td>pound per foot (lb/ft)</td>
<td>kilogram per meter (kg/m)</td>
<td>1.488 164</td>
<td>E+00</td>
</tr>
<tr>
<td>pound per foot hour [lb/(ft • h)]</td>
<td>pascal second (Pa • s)</td>
<td>4.133 789</td>
<td>E+04</td>
</tr>
<tr>
<td>pound per foot second [lb/(ft • s)]</td>
<td>pascal second (Pa • s)</td>
<td>1.488 164</td>
<td>E+00</td>
</tr>
<tr>
<td>pound per gallon [Canadian and U.K. (Imperial)] (lb/gal)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>9.977 637</td>
<td>E+01</td>
</tr>
<tr>
<td>pound per gallon [Canadian and U.K. (Imperial)] (lb/gal)</td>
<td>kilogram per liter (kg/L)</td>
<td>9.977 637</td>
<td>E-02</td>
</tr>
<tr>
<td>pound per gallon (U.S.) (lb/gal)</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.198 264</td>
<td>E+02</td>
</tr>
<tr>
<td>pound per gallon (U.S.) (lb/gal)</td>
<td>kilogram per liter (kg/L)</td>
<td>1.198 264</td>
<td>E-01</td>
</tr>
<tr>
<td>pound per horsepower hour [lb/(hp • h)]</td>
<td>kilogram per joule (kg/J)</td>
<td>1.689 659</td>
<td>E-07</td>
</tr>
<tr>
<td>psi (pound-force per square inch) (lbf/in²)</td>
<td>pascal (Pa)</td>
<td>6.894 757</td>
<td>E+03</td>
</tr>
<tr>
<td>psi (pound-force per square inch) (lbf/in²)</td>
<td>kilopascal (kPa)</td>
<td>6.894 757</td>
<td>E+00</td>
</tr>
<tr>
<td>quad (10¹⁵ BtuIT)</td>
<td>joule (J)</td>
<td>1.055 056</td>
<td>E+18</td>
</tr>
<tr>
<td>quart (U.S. dry) (dry qt)</td>
<td>cubic meter (m³)</td>
<td>1.101 221</td>
<td>E-03</td>
</tr>
<tr>
<td>quart (U.S. dry) (dry qt)</td>
<td>liter (L)</td>
<td>1.101 221</td>
<td>E+00</td>
</tr>
<tr>
<td>quart (U.S. liquid) (liq qt)</td>
<td>cubic meter (m³)</td>
<td>9.463 529</td>
<td>E-04</td>
</tr>
<tr>
<td>quart (U.S. liquid) (liq qt)</td>
<td>liter (L)</td>
<td>9.463 529</td>
<td>E-01</td>
</tr>
<tr>
<td>rad (absorbed dose) (rad)</td>
<td>gray (Gy)</td>
<td>1.0 E-02</td>
<td></td>
</tr>
<tr>
<td>revolution (r)</td>
<td>radian (rad)</td>
<td>6.283 185</td>
<td>E+00</td>
</tr>
<tr>
<td>revolution per minute (rpm) (r/min)</td>
<td>radian per second (rad/s)</td>
<td>1.047 198</td>
<td>E+01</td>
</tr>
<tr>
<td>rod (based on U.S. survey foot) (rd)</td>
<td>meter (m)</td>
<td>5.029 210</td>
<td>E+00</td>
</tr>
<tr>
<td>rpm (revolution per minute) (r/min)</td>
<td>radian per second (rad/s)</td>
<td>1.047 198</td>
<td>E-01</td>
</tr>
<tr>
<td>second (angle (°))</td>
<td>radian (rad)</td>
<td>4.848 137</td>
<td>E-06</td>
</tr>
<tr>
<td>second (sidereal)</td>
<td>second (s)</td>
<td>9.972 696</td>
<td>E-01</td>
</tr>
<tr>
<td>Units and Numbers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shake</td>
<td>second (s)</td>
<td>1.0</td>
<td>E-08</td>
</tr>
<tr>
<td>shake</td>
<td>nanosecond (ns)</td>
<td>1.0</td>
<td>E+01</td>
</tr>
<tr>
<td>slug (slug)</td>
<td>kilogram (kg)</td>
<td>1.459 390</td>
<td>E+01</td>
</tr>
<tr>
<td>slug per cubic foot (slug/ft²)</td>
<td>kilogram per cubic meter (kg/m²)</td>
<td>5.153 788</td>
<td>E+02</td>
</tr>
<tr>
<td>slug per foot second [slug/(ft • s)]</td>
<td>pascal second (Pa • s)</td>
<td>4.788 026</td>
<td>E+01</td>
</tr>
<tr>
<td>square foot (ft²)</td>
<td>square meter (m²)</td>
<td>9.290 304</td>
<td>E-02</td>
</tr>
<tr>
<td>square foot per hour (ft²/h)</td>
<td>square meter per second (m²/s)</td>
<td>2.580 64</td>
<td>E-05</td>
</tr>
<tr>
<td>square foot per second (ft²/s)</td>
<td>square meter per second (m²/s)</td>
<td>9.290 304</td>
<td>E-02</td>
</tr>
<tr>
<td>square inch (in²)</td>
<td>square meter (m²)</td>
<td>6.4516</td>
<td>E-04</td>
</tr>
<tr>
<td>square inch (in²)</td>
<td>square centimeter (cm²)</td>
<td>6.4516</td>
<td>E+00</td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>square meter (m²)</td>
<td>2.589 988</td>
<td>E+06</td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>square kilometer (km²)</td>
<td>2.589 988</td>
<td>E+00</td>
</tr>
<tr>
<td>square mile (based on U.S. survey foot) (mi²)</td>
<td>square meter (m²)</td>
<td>2.589 998</td>
<td>E+06</td>
</tr>
<tr>
<td>square mile (based on U.S. survey foot) (mi²)</td>
<td>square kilometer (km²)</td>
<td>2.589 998</td>
<td>E+00</td>
</tr>
<tr>
<td>square yard (yd²)</td>
<td>square meter (m²)</td>
<td>8.361 274</td>
<td>E-01</td>
</tr>
<tr>
<td>stokes (St)</td>
<td>meter squared per second (m²/s)</td>
<td>1.0</td>
<td>E-04</td>
</tr>
<tr>
<td>tablespoon</td>
<td>cubic meter (m³)</td>
<td>1.478 676</td>
<td>E-05</td>
</tr>
<tr>
<td>tablespoon</td>
<td>milliliter (mL)</td>
<td>1.478 676</td>
<td>E+01</td>
</tr>
<tr>
<td>teaspoon</td>
<td>cubic meter (m³)</td>
<td>4.928 922</td>
<td>E-06</td>
</tr>
<tr>
<td>teaspoon</td>
<td>milliliter (mL)</td>
<td>4.928 922</td>
<td>E+00</td>
</tr>
<tr>
<td>therm (EC)</td>
<td>joule (J)</td>
<td>1.055 06</td>
<td>E+08</td>
</tr>
<tr>
<td>therm (U.S.)</td>
<td>joule (J)</td>
<td>1.054 804</td>
<td>E+08</td>
</tr>
<tr>
<td>ton, assay (AT)</td>
<td>kilogram (kg)</td>
<td>2.916 667</td>
<td>E-02</td>
</tr>
<tr>
<td>ton, assay (AT)</td>
<td>gram (g)</td>
<td>2.916 667</td>
<td>E+01</td>
</tr>
<tr>
<td>ton-force (2000 lbf)</td>
<td>newton (N)</td>
<td>8.896 443</td>
<td>E+03</td>
</tr>
<tr>
<td>ton-force (2000 lbf)</td>
<td>kilonewton (kN)</td>
<td>8.896 443</td>
<td>E+00</td>
</tr>
<tr>
<td>ton, long (2240 lb)</td>
<td>kilogram (kg)</td>
<td>1.016 047</td>
<td>E+03</td>
</tr>
<tr>
<td>ton, long, per cubic yard</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.328 939</td>
<td>E+03</td>
</tr>
<tr>
<td>ton, metric (t)</td>
<td>kilogram (kg)</td>
<td>1.0</td>
<td>E+03</td>
</tr>
<tr>
<td>tonne (called “metric ton” in U.S.) (t)</td>
<td>kilogram (kg)</td>
<td>1.0</td>
<td>E+03</td>
</tr>
<tr>
<td>ton of refrigeration (12 000 Btu/h)</td>
<td>watt (W)</td>
<td>3.516 853</td>
<td>E+03</td>
</tr>
<tr>
<td>ton of TNT (energy equivalent)</td>
<td>joule (J)</td>
<td>4.184</td>
<td>E+09</td>
</tr>
<tr>
<td>ton, register</td>
<td>cubic meter (m³)</td>
<td>2.831 685</td>
<td>E+00</td>
</tr>
<tr>
<td>ton, short (2000 lb)</td>
<td>kilogram (kg)</td>
<td>9.071 847</td>
<td>E+02</td>
</tr>
<tr>
<td>ton, short, per cubic yard</td>
<td>kilogram per cubic meter (kg/m³)</td>
<td>1.186 553</td>
<td>E+03</td>
</tr>
<tr>
<td>ton, short, per hour</td>
<td>kilogram per second (kg/s)</td>
<td>2.519 958</td>
<td>E-01</td>
</tr>
</tbody>
</table>
### Appendix A

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>torr (Torr)</td>
<td>pascal (Pa)</td>
<td>$1.333224 \times 10^2$</td>
</tr>
<tr>
<td>watt hour (W•h)</td>
<td>joule (J)</td>
<td>$3.6 \times 10^3$</td>
</tr>
<tr>
<td>yard (yd)</td>
<td>meter (m)</td>
<td>$9.144 \times 10^{-1}$</td>
</tr>
<tr>
<td>year (365 days)</td>
<td>second (s)</td>
<td>$3.1536 \times 10^7$</td>
</tr>
<tr>
<td>year (sidereal)</td>
<td>second (s)</td>
<td>$3.155815 \times 10^7$</td>
</tr>
<tr>
<td>year (tropical)</td>
<td>second (s)</td>
<td>$3.155693 \times 10^7$</td>
</tr>
</tbody>
</table>
Common Terms and Acronyms in Accident Reconstruction

The terms defined here are for the convenience of the readers, both those learning accident reconstruction as well as those already familiar with the field. Not all terms included in the list are used in this book.

18-wheeler: A tractor, semitrailer with a total of 18 wheels; see tractor, semitrailer.

A, B, C, D, pillars and posts: The vertical pillars and posts of a light vehicle forming the major vertical structural members of the body; see Fig. B1. Pillars typically are at window height; posts are below window height. From front to rear, the A post/pillar is the most forward member, the B post/pillar is the second most forward vertical member, etc.

Figure B1.
Pillars and posts.
AACN: Automatic Advanced Crash Notification, General Motors term for ACN (see also ACN).

AADT: Average Annual Daily Traffic.

AASHTO: American Association of State Highway and Transportation Officials.


ABS: Antilock Braking System.

ACAT: Advanced Collision Avoidance Technology.

ACC: Adaptive Cruise Control.

acceleration: Change in linear or angular velocity or speed with respect to time.

accelerometer: An electromechanical sensing device with an output signal proportional to acceleration.

accident investigation: The process of observation, acquisition, and documentation of physical evidence and other information regarding an accident or crash.

accident reconstruction: A procedure carried out with the specific purpose of estimating in both a qualitative and quantitative manner how an accident occurred using engineering, scientific, and mathematical principles and based on evidence obtained through accident investigation.

accident scene: A place where a traffic accident occurs, both during and immediately following the accident, and before vehicles and participants have departed; see accident site.

accident site: A place where a traffic accident occurred, after vehicles and participants have departed the scene; see accident scene.

accident, vehicle: An event in which one or more vehicles undergo unexpected action(s), usually involving contact with another vehicle or other object, producing injury, death, and/or property damage; an accident is an unstabilized situation which includes at least one harmful event; see crash.

ACM: Airbag Control Module (Chrysler), control module for airbags and related restraint systems, see RCM and SDM.

ACN: Automatic Crash Notification System.

acoustic levels: see sound levels.

ADA: Americans with Disabilities Act.

ADR: Accident data recorder; see EDR.
AE: Algorithm Enable


aggressivity: The inertial and structural properties and characteristics of a vehicle that relate to the severity of injuries to occupants in the other vehicle in a crash.

agricultural commodity trailer: Trailer designed to transport bulk commodities from harvest sites to process or storage sites.

air bag: A device in the interior of a vehicle that inflates and acts between an occupant and an interior vehicle surface to prevent injury in a crash; see supplemental restraint system.

angular acceleration: The time rate of change of angular velocity.

angular velocity: The time rate of change of rotational displacement.

animation: The process by which the movement of objects is illustrated.


approach speed: Speed of a vehicle just prior to the first significant event such as contact in an accident; see closing speed.

aquaplaning: See hydroplaning.

area of impact: Area encompassed by the interface between colliding objects projected onto the road; see point of impact.

articulated vehicle: A vehicle comprised of two or more distinct, interconnected bodies such as a tractor, semitrailer.

asphalt: See bituminous pavement.


BAC: Blood Alcohol Concentration.

backlite header: The structural body member which connects the upper portions of the rearmost driver and passenger pillars and forms the top edge of the backlite (back window) [B.1].

backlite: The rear or back window which spans from the driver’s to passenger’s side of the vehicle [B.1].

barrier equivalent velocity (BEV): The forward speed and corresponding kinetic energy with which a vehicle contacts a flat fixed rigid barrier at 90° with no rebound; see also equivalent energy speed (EES).
Appendix B

**BAS**: Brake Assist System

**BCM**: Body Control Module.

**BEV**: Barrier Equivalent Velocity, or Battery Electric Vehicle.

**bicycle model**: A two-wheeled vehicle used conceptually in vehicle dynamics studies to represent a four-wheeled vehicle where the side-to-side extent of the vehicle is neglected for simplicity.

**bituminous pavement**: A pavement comprising an upper layer or layers of aggregate with a bituminous binder (asphalt, coal tars, natural tars, etc.) and surface treatments such as chip seals, slurry seals, sand seals, and cape seals.

**black box**: See event data recorder.

**blacktop**: See bituminous pavement.

**BMP**: BitMaP, digital photograph file format.

**bobtail**: A term used to refer to a truck tractor being driven without a semitrailer.

**brake slip**: See wheel slip.

**braking distance**: The distance taken to bring a vehicle to rest during brake application in straight forward motion; see stopping distance.

**braking force, peak**: The largest force that can be developed during brake application as wheel slip is varied over the range of free-rolling slip to locked-wheel slip.

**braking force**: The force over the contact surface between a tire and a road in the direction of heading of the braked wheel that develops as a result of brake application.

**BTO**: Brake Throttle Override.

**BTS**: Bureau of Transportation Statistics.

**BTSI**: Brake Transmission Shift Interlock.

**Btu**: British thermal unit.

**bus**: A vehicle designed to transport more than 15 passengers, including the driver.

**CAA**: Clean Air Act.

**CAD**: Computer Aided Design (often referring to drafting software).

**CAFE**: Corporate Average Fuel Economy.

**CAN**: Controller Area Network, a type of communication bus (see also GMLAN).
CCD: Charge Coupled Device (such as the sensor in a digital camera).

CCM: Cruise Control Module.

CDR: Crash Data Retrieval System; a system used to image crash data from certain light vehicles.

center of gravity (cg): That point of a body through which the resultant force of gravity (weight) acts irrespective of the orientation of the body.

center of impact: See impact center.

center of mass: See center of gravity.

central impact: An impact in which the contact impulse passes through the center of gravity; see oblique impact.

CDL: Commercial Driver’s License


change in momentum: The difference of the momentum (product of mass and velocity) of a mass from one time to another; the difference of the momentum of a mass between the beginning and end of contact with another mass; the difference in the momentum of a system of bodies; see also conservation of momentum.

change of velocity: The difference between velocity vectors at two points in time; see also \( \Delta V \), delta-V.

CHB: Crash Imminent Braking.

CHOP: a broad shallow gouge in a road surface, beginning with an even, regular, deeper side and terminating in scratches and striations on the opposite shallower side; a depression in pavement made by a strong, sharp metal edge moving under heavy pressure [B.2], more commonly occurring at an impact event as opposed to post-impact trajectory.

clearance lamp: Light used on the front or rear of a motor vehicle to indicate overall width or height.

closing speed: The magnitude of the relative velocity between two vehicles at a given point in time as they approach each other; the relative velocity between two vehicles as they approach each other at the beginning of an accident; normal component of the closing velocity; see approach speed.

closing velocity: The magnitude of the relative velocity between two vehicles at a given point in time as they approach each other; the magnitude of the relative velocity between two vehicles at the beginning of a crash; the vector difference between the velocity of the vehicle and the vehicle/object struck immediately before impact.
CMV: Commercial Motor Vehicle.

CO: Carbon monoxide.

CO$_2$ (CO$_2$): Carbon dioxide.

**coefficient of friction:** A number representing the resistance to sliding of two flat surfaces in contact; defined as the ratio of the resistance force to the normal force between the surfaces; see frictional drag factor.

**coefficient of restitution:** The ratio of the relative normal velocity at the time of separation to the relative normal velocity at the time of initial contact between the point area of contact of two colliding bodies.

**coefficient of rolling resistance:** The ratio of the force of resistance to rolling with zero slip to the vertical load of a wheel or vehicle; see rolling resistance.

**collision deformation classification (CDC):** A classification of the extent of deformation to an automobile, utility vehicle, pickup, and van from a crash [B.3].

**collision:** Sudden contact of a vehicle with an object or another vehicle, usually resulting in visible damage; see impact, crash.

**common contact point:** See impact center

**common velocity conditions:** Two independent conditions applicable to a collision where at the time of separation the relative normal velocity component is zero (no restitution) and the relative tangential component of velocity is zero (sliding has ended).

**compatibility, vehicle:** Disparities in structural crashworthiness of different sized vehicles due to varying structural geometries, such as different heights of vehicles’ front and side structures; a tendency of some vehicles to inflict more damage on another vehicle in a crash.

**concrete pavement:** A solidified pavement with an upper layer of aggregate (such as sand and stone) mixed with Portland cement paste binder.

**conservation of momentum:** The principle of physics for vehicles in dynamic contact stating that in the absence of external forces, the sum of the preimpact momentum is equal to the sum of the postimpact momentum of the vehicles.

**contact damage:** Deformation sustained in a vehicle from physical engagement with another vehicle or object; see induced damage, residual crush, dynamic crush.

**contact patch:** The area or region of mutual contact between a tire and the surface over which it rests or moves.

**contact point:** The point of intersection of the resultant contact impulse with the intervehicular contact surface of each of two colliding vehicles; see impact center.
contact surface: See intervehicular contact surface.

coordinate system, vehicle: See three-axis vehicle coordinate system.

cornering coefficient: See sideslip coefficient.

CPR: Crash Pulse Recorder, a device that measures acceleration during a crash; see accelerometer.

CRAF: Civil Reserve Air Fleet.

crash duration: The period of time defined by the moment when two vehicles come in contact until that time when they separate.

crash pulse: The shape of the intervehicular force curve during the crash duration.

crash reconstruction: See accident reconstruction.

crash: An event in which one or more vehicles make unintended contact with another vehicle or other object producing injury, death, and/or property damage; see accident, impact, collision.

CRASH3: An acronym for Calspan Reconstruction of Speeds on the Highway, Version 3; a method of reconstruction that uses the calculation of the crush energy of a collision and an approximate postimpact trajectory spinout simulation.

crashworthiness: The characteristics of a motor vehicle which represent occupant protection of that vehicle in a specific collision.

critical speed formula: A formula, $v_{cr} = \sqrt{fgR}$, that calculates the speed of a vehicle from its radius of curvature, $R$, frictional drag coefficient, $f$, and acceleration of gravity, $g$.

critical speed: The maximum speed at which a vehicle can traverse a path with a specific radius of curvature without loss of directional control; the speed of a vehicle undergoing a sudden turn maneuver at which the tires leave visible sideslip marks.

crumple zone: That portion of the front or rear of a vehicle designed to absorb energy of a collision for the protection of the occupants.

crush area: Area defined by the original vehicle exterior and a crush profile.

crush equivalent speed: See energy equivalent speed, EES.

crush profile: The geometric shape in a specified plane (e.g., vertical, horizontal) which describes the vehicle damage resulting from an impact.

crush stiffness coefficient: An empirical quantity used in the calculation of the energy dissipated in a collision and associated with each vehicle's velocity change, $\Delta V$; see CRASH3.
**crush stiffness**: See crush stiffness coefficient.

**CTE**: Coefficient of Thermal Expansion.

**curb weight**: The weight of a motor vehicle with standard equipment and maximum fuel capacity.

**CVT**: Continuously Variable Transmission.

**delta-t** \((\Delta t \text{ or } \Delta \tau)\): A time interval associated with an event such as vehicle-to-vehicle contact; the time duration of impulse.

**delta-v** \((\Delta V)\): The difference or change of a velocity vector over a time interval; the difference in the velocity vector of the center of gravity of a vehicle between separation and first contact in a crash.

**departure velocity**: See separation velocity.

**deployment** (event): Actuation of a supplementary restraint, based on an enabling algorithm, following which acceleration and other data are recorded and made available to an event data recorder.

**deployment level** (event): An acceleration level sufficient to cause the GM SDM’s crash-sensing algorithm to “enable” and anticipate a collision severity which otherwise warrants a deployment for that vehicle but a deployment had been previously commanded.

**decibel**: A logarithmic measure of the level, \(L\), of a time-varying signal, \(s(\tau)\), relative to a reference value \(s_{ref}\).

\[
L = 10 \log \frac{s^2}{s_{ref}^2}
\]

where \(s^2\) is the mean square value of the signal.

**DGPS**: Differential Global Positioning System.

**direction of principal force** (DOPF): See principal direction of force, PDOF.

**divot**: A piece of turf or sod torn up by dynamic contact.

**DLC**: Diagnostic Link Connector, may also be seen as Data Link Connector.

**DOE**: U.S. Department of Energy.

**DOI**: U.S. Department of the Interior.

**DoT, DOT**: United States Department of Transportation; see NHTSA.
**drag factor**: An equivalent acceleration expressed as a fraction of the acceleration of gravity, $g$; also see frictional drag coefficient.

**drag sled**: A weighted device (whose bottom surface is covered with a portion of tire tread) which is pulled along a roadway surface and provides a sliding friction coefficient of that device and roadway surface by computing the ratio of the pull force to its weight.

**dwt**: Deadweight tons.

**drop axle**: An unpowered auxiliary axle on a truck that can be raised or lowered to change the vertical load distribution of permanent axles (also called tag axle).

**DTC**: Diagnostic Trouble Code.

**dual wheels**: The use of two closely spaced wheels on one side of an axle, typically used on trucks and semitrailers.

**DXF**: Drawing Exchange Format, graphical format for drawings made with CAD programs.

**dynamic crush**: The deformation formed by the external surface of a vehicle at any time during an impact, usually measured relative to the corresponding as-manufactured undeformed surface; see crush area, crush profile, static crush, residual crush.

**eccentric impact**: See oblique impact.

**ECE**: Economic Commission for Europe (United Nations).

**ECI**: Electronic Conductive Immunity.

**EDS**: Explosive Detection Systems.

**EDR**: Event Data Recorder; a function within a vehicle module (ACM, PCM . . . ) which has the capability to save certain crash data parameters after primary functions are completed.

**elastic deformation**: Deformation which is fully recovered after an applied force is removed.

**elastic impact**: An idealized impact where the kinetic energy at separation equals the kinetic energy at the initiation of contact; a fully elastic impact is an impact where the coefficient of restitution is equal to one.

**electronic control module (ECM)**: See Electronic Control Unit (ECU).

**electronic control unit (ECU)**: The computer in a vehicle that controls vehicle system operation, including functions such as engine operation, On Board Diagnostics (OBD), Stability Control, Safety System Operation, etc.
**electronic data recorder (EDR):** See event data recorder.

**EMC:** Electromagnetic Compatibility.

**EMI:** Electromagnetic Interference.

**energy equivalent speed (EES):** The speed and corresponding kinetic energy with which a vehicle must contact a fixed rigid object with no rebound for equivalence to conditions of another collision; for example, the energy may be equal to a specified level of residual crush; EES is a preferred term, broader than barrier equivalent velocity (BEV), equivalent barrier speed (EBS), and equivalent test speed (ETS).

**energy equivalent velocity:** See energy equivalent speed and equivalent barrier speed.

**engine control module (ECM):** An electronic device in a vehicle (especially heavy trucks) that controls engine operation.

**EPA:** U.S. Environmental Protection Agency.

**EPS:** Electronic Power Steering.

**ERI:** Electronic Radiated Immunity.

**ESD:** Electrostatic Discharge.

**ESC:** Electronic stability control.

**ESP:** An acronym for Chrysler’s Electronic Stability Program (see ESC).

**equivalent barrier speed (EBS):** The forward speed and corresponding kinetic energy with which a vehicle must contact a flat, fixed, rigid barrier at 90° with no rebound for equivalence to conditions of another collision; for example, the energy may be equal to a specified level of residual crush; see also equivalent energy speed (EES).

**equivalent test deformation:** See EES.

**equivalent test speed (ETS):** ISO term and is a non-preferred term, see EBS and EES.

**ETC:** Electronic Throttle Control (can also mean: electronic toll collection).

**ETMS:** Enhanced Traffic Management System.

**EU:** European Union.

**EVC:** Electronic Vehicle Control.

**event data recorder (EDR):** An onboard electronic module or device capable of monitoring, recording, and displaying precrash, crash, and postcrash data and information from a vehicle, event, and driver.
EXIF: Exchangeable Image File Format (photographs).

FAA: Federal Aviation Administration.

FAF: Freight Analysis Framework.

farm tractor: A powered farm vehicle designed to pull farm implements (such as a plow, farm trailer, manure spreader, etc.)

FARS: Fatality Analysis Reporting System.

FARs: Federal Aviation Regulations.

FHWA: U.S. Federal Highway Administration.

first contact position: The position, or location, at an accident scene (measured relative to a coordinate system fixed to the earth) of a vehicle, pedestrian, or other object at the time it first has contact with another body in a collision.

first contact velocity: The velocity of the center of gravity of a vehicle, pedestrian, or other object at its first contact position.

fixed object: A stationary object such as a guardrail, bridge railing or abutment, construction barricade, impact attenuator, tree, embedded rock, utility pole, ditch side, steep earth or rock slope, culvert, fence, or building [B.4].

flip: Movement of a vehicle from a place where the forward velocity of a part of the vehicle suddenly is stopped by an object below its center of gravity such as a curb, rail, or furrow with the result that the ensuing rotation lifts the vehicle from the ground.

FMCSA: Federal Motor Carrier Safety Administration.

FMCSR: Federal Motor Carrier Safety Regulations.

FMEA: Failure Modes and Effects Analysis.

FMVSS: Federal Motor Vehicle Safety Standard; see NHTSA.

forward projection pedestrian collision: A frontal collision of vehicle and pedestrian or cyclist where the initial contact area is at or above the height of the center of gravity of the pedestrian or cyclist and where a single impact with the frontal geometry of the vehicle causes the pedestrian or cyclist to be projected straight forward relative to the vehicle.

four point transformation: A photogrammetric technique whereby points positioned on a surface reasonably approximated by a plane with unknown locations can be located through the use of four additional points whose locations are known; see photogrammetry.
FRA: Federal Railroad Administration.

friction: Resistance to sliding over a contact surface between two materials.

friction coefficient: See coefficient of friction.

frictional drag coefficient: An average, uniform (constant) value of a sliding friction coefficient applied to a specific sliding event such as when an object slides from an initial speed to a stop over a distance, \(d\), or during a speed change, \(\Delta V\).

frictional drag factor: See frictional drag coefficient.

frontal impact: An impact or collision involving the front of a vehicle.

FTA: Federal Transit Administration, also Fault Tree Analysis.

full trailer: A towed vehicle with a fixed rear axle and a front axle that pivots and is made to be pulled by a powered tow vehicle (an example is a farm trailer).

furrow: A channel in a loose or soft material, such as snow or soil, made by a vehicle tire or some other part of a moving vehicle.

GA: General Aviation.

GAW: Gross Axle Weight is the total weight carried by an individual axle (front and rear) including the vehicle weight and cargo.

GAWR: Gross Axle Weight Rating is the maximum allowable weight that can be carried by a single axle (front or rear).

GCW: Gross Combined Weight is the weight of a loaded vehicle plus the weight of a fully loaded semitrailer.

GCWR: Gross Combined Weight Rating is the maximum allowable weight of a vehicle and loaded semitrailer.

GHG: Greenhouse Gas.

GIF: Graphics Interchange Format, digital photograph file format.

GIS: Geographic Information Systems.

glare: Interference to a driver’s vision due to natural or artificial, direct or reflected light.

gouge or gouge mark: Pavement or ground scar deep enough to be easily felt with the fingers; see Fig. B6 and also chop and groove.

GMLAN: A General Motors implementation of the Controller Area Network (CAN) type serial communication protocol.
GPS: Global Positioning System.

groove: A long, narrow, pavement gouge or a channel in a pavement.

gross vehicle weight rating: The upper limit of combined weight and cargo for a vehicle established by design, regulation, or both

gross vehicle weight: The combined weight of a vehicle and its cargo.

GVWR: See Gross Vehicle Weight Rating.

HAPs: Hazardous Air Pollutants.

heading angle, \( \psi \): The angle between a reference axis fixed in the vehicle and a reference axis fixed in the roadway, giving a measure of vehicle yaw rotation or directional orientation relative to the roadway; see Fig. B2 [B.5].

head-on impact: Frontal impact where the PDOF is at or near zero degrees.

heavy truck classifications: See truck classifications.

HEV: Hybrid Electric Vehicle.

HELP: Heavy Vehicle Electronic License Plate.


HPMS: Highway Performance Monitoring System.

Figure B2. SAE coordinate system showing the vehicle heading angle, \( \psi \), and vehicle sideslip angle, \( \beta \).
HSI: Human-System Integration.

HSR: High-Speed Rail.

HTF: Highway Trust Fund.

HV: Heavy Vehicle.

hydroplaning: A phenomenon where a layer of fluid (usually water) on a roadway separates the load-bearing surface of one or more tires of a moving vehicle from the road surface and causes a full loss of traction (longitudinal) and steering (transverse) force components.

IBET: Intermodal Bottleneck Evaluation Tool.

illumination: Placement or existence of natural or artificial light on an area presented to a driver.

impact center: The point of intersection of the contact impulse and the intervehicular contact surface for an impact; see contact point.

impact force (lever arm) moment arm: See impulse moment arm.

impact velocity: The velocity of an object’s center of gravity relative to a coordinate system fixed in the earth during an impact; see preimpact velocity, postimpact velocity.

impact: The striking of one body against another; short-duration, high-force contact of two objects; a collision of a vehicle with another vehicle, a pedestrian, or some other object; see collision, crash.

impulse moment arm: The perpendicular distance from an object’s center of gravity to the line of action of an impulse; see Fig. B3; see also impact force moment arm.
impulse ratio: The ratio of the tangential and normal impulse components in planar impact mechanics; see impulse.

impulse: A combination of force, \( F \), and time, \( \tau \), defined as a mathematical integral, \( \int F \, d\tau \), of the force over a specific time duration.

induced damage: Residual deformation caused without direct contact by virtue of being adjacent to deformation caused by direct contact; see residual crush.

initial contact: The point in time and space when two objects begin to touch or interact with no significant force. The beginning of an impact.

INS: Immigration and Naturalization Service.

intervehicular contact surface: A single, planar surface that represents the average (over time and space) deformed contact surface between two vehicles or a vehicle and barrier.

intervehicular crush plane: See intervehicular contact surface.

intrusion: Reduction of the pre-crash space within the passenger space compartment [B.6].

IPCC: Intergovernmental Panel on Climate Change.


ISTEA: Intermodal Surface Transportation Efficiency Act.

ITS: Intelligent Transportation System.

JPEG: Joint Photographic Experts Group, digital photograph file format.

KPH: Kilometers Per Hour (also km/h).

leading edge: The foremost part of a vehicle with respect to the vehicle’s motion and attitude.

light vehicle: An automobile, passenger van, pickup truck, or sport utility vehicle.

LNG: Liquefied Natural Gas.

LPG: Liquefied Petroleum Gas.

LTV: Light Trucks and Vans.

LV: See light vehicle.

MAIT: Multidisciplinary Accident Investigation Team (NHTSA).

maximum crush depth: Deepest part of a crush profile; see dynamic crush or residual crush.
**maximum engagement**: The point in time when the maximum dynamic crush occurs.

**MDB**: Moving Deformable Barrier.

**MMUCC**: Model Minimum Uniform Crash Criteria.

**moment of inertia**: A physical property of a body that represents its resistance to rotational acceleration.

**MPG**: Miles Per Gallon.

**MPH**: Miles Per Hour.

**MTBE**: Methyl-tertiary-butyl-ether.

**MTC**: Mechanical Throttle Control.

**MUTCD**: Manual on Uniform Traffic Control Devices.

**NASS**: National Automotive Sampling System.

**NCAP**: New Car Assessment Program (DoT, NHTSA).

**NDR**: National Driver Register.

**neutral steer**: When a vehicle, traveling on a circular path at constant speed and a constant front wheel steer angle, is accelerated it will remain on a path with the same radius, tend to increase its radius, or tend to decrease its radius; these are defined as neutral steer, understeer, and oversteer, respectively; see oversteer and understeer.

**NHTSA**: National Highway Traffic Safety Administration; see DoT.

**NO2 (NO₂)**: Nitrogen dioxide.

**NOX**: Nitrogen oxides.

**NPTS**: Nationwide Personal Transportation Survey.

**NTL**: National Transportation Library.

**NTSB**: National Transportation Safety Board.

**OBD**: On Board Diagnostics.

**oblique impact**: An impact in which the contact impulse does not pass through the center of gravity; see central impact.

**occupant compartment**: That portion of a vehicle’s interior designed for the use of passengers during operation of the vehicle.

**ODI**: Office of Defects Investigation (NHTSA).
offset: The distance between the longitudinal heading axes of two vehicles in frontal contact; see Fig. B4; see overlap.

**Figure B4.** Illustration of offset and overlap.

OPEC: Organization of Petroleum Exporting Countries.

ORC: Occupant Restraint Controller, see event data recorder (EDR).

OTR: Over The Road.

overhang, front rear: The longitudinal dimension of a vehicle from the center of the front/rear wheels to the foremost/rearmost point on the vehicle including bumper, bump guards, tow hooks, and/or rub strips if standard equipment.

overlap: The length of mutual contact damage; see Fig. B4; see offset.

override: A condition in a collision where the main structural members such as a bumper of the striking vehicle are above the main structural members such as frame rails of the struck vehicle; see Fig. B5; see underride.

**Figure B5.** Illustration of override in a collision.

oversteer: When a vehicle, traveling on a circular path at constant speed and a constant front wheel steer angle, is accelerated it will remain on a path with the same radius, tend to increase its radius, or tend to decrease its radius; these are defined as neutral steer, understeer, and oversteer, respectively; see neutral steer and understeer.

PCM: Powertrain Control Module; also Pulse Code Modulation (a way of digitally transmitting analog data).
PAR: Police Accident Report.

PCR: Police Crash Report.

PDOF: See principal direction of force.

PDR time: See perception-decision-reaction time.

perception-decision-reaction time: The time required by a person to complete a response to an event or stimulus; see reaction time.

PFD: Personal Flotation Device.

PHEV: Plug-In Hybrid Electric Vehicle.

photogrammetry: The process of determining the quantitative dimensional information of objects in two or three dimensions through the process of recording, interpreting, and transforming measurements from a flat photographic image.

pitch, roll, yaw: Terms that distinguish rotations of a vehicle about three perpendicular axes with origin at the vehicle's center of gravity; pitch is rotation about the horizontal, side-to-side axis; roll is rotation about a horizontal front-to-rear axis; and yaw is rotation about the vertical axis; see Fig. B7; see yaw angle.

planar impact: An impact in which all forces, moments, and motion takes place in a plane.

plastic impact: An impact with little or no rebound at the end of impact; a perfectly plastic impact is where the coefficient of restitution is equal to zero.

PM-10: Particulate matter of 10 microns in diameter or smaller.

PM-2.5: Particulate matter of 2.5 microns in diameter or smaller.

PMT: Passenger-Miles of Travel.

point mass: An idealized concept from mechanics where an object is considered to have mass but no extent, no finite dimensions, and as a consequence, its rotation is irrelevant; see rigid body.

point of contact: The point of intersection of the contact impulse and the intervehicular contact surface during an impact; see also impact center, first contact position, PDOF, DOPF.

postcollision trajectory, postimpact trajectory: The path of a vehicle from the time of separation to its rest position.

postcrash damage: Damage existing to a vehicle after it came to rest, including damage that may result during rescue, towing, and salvage operations.
**postimpact speed**: The magnitude of the velocity of an object in a collision at the time of separation, or end of contact; see postimpact velocity and separation speed.

**postimpact velocity**: The velocity of an object in a collision at the time of separation, or end of contact; see postimpact speed and separation speed.

**PNG**: Portable Network Graphics, digital photograph file format.

**preimpact velocity**: The velocity of a vehicle in a collision at the instant of its initial contact.

**principal direction of force (PDOF)**: The direction of the line of action of the contact impulse in a planar collision expressed in degrees, measured clockwise from the longitudinal axis of a vehicle; see Fig. B3.

**PRNDL**: Park-Reverse-Neutral-Drive-Low (shift mechanism sequence).

**PTC**: Positive Train Control.

**PUV**: Personal-Use Vehicle.

**radius of gyration**: The square root of the quotient of the moment of inertia and the mass of a rigid body; see moment of inertia.

**RCM**: Restraint Control Module (Ford).

**reaction time**: See perception-decision-reaction time.

**residual crush**: The permanent deformation formed by the nominal external surface of a vehicle caused by an impact, usually measured relative to the corresponding as-manufactured undeformed surface; see crush area, crush profile.

**rest position**: The location of the center of gravity of a vehicle following an accident measured relative to a coordinate system fixed in the earth.

**reverse projection photogrammetry**: The photogrammetric procedure of inserting a transparency that contains outlines of transient and fixed objects into a camera for the purpose of determining the position and orientation of the camera at the time the original photograph was taken to facilitate the re-location of the transient information.

**RFG**: Reformulated gasoline.

**RFI**: Radio Frequency Interference.

**rigid body**: A concept from mechanics where an object is considered to have mass and dimensions (such as length, width, radius, etc.) that remain constant and which provide resistance to rotation; see point mass, moment of inertia.

**roll out**: Part or all of a postimpact trajectory in which little or no sideslip of a vehicle’s wheels occur; see spinout.
**roll**: See pitch, roll, yaw, and yaw angle.

**rollbar**: A structural member placed over the occupant compartment of a vehicle to protect the occupants against the effects of roof crush during vehicle rollover: also used in some busses and construction machinery.

**rolling resistance**: The retarding force of a freely rolling wheel due to interaction with a contact surface, parallel to the heading axis of a wheel of a moving vehicle; also:

- a force opposite to the direction of travel resulting from deformation of a rolling tire [B.7, B.8]
- several resistances to motion that may be classified as due to friction in the wheel bearings, friction in the tire walls and tread as they flex when rolling along the road surface, deformation of road surface, impact resistance due to irregularities of road surface, and churning of air by wheels [B.9].

**rollover**: Vehicle motion where its wheels leave the road surface and at least one side or top of the vehicle contacts the ground; see flip and vault.

**ROPS**: Rollover Protection System.

**ROR**: Run-Off-the-Road.

**SAE coordinate system**: See three-axis vehicle coordinate system.

**SAI (SA)**: Sudden Acceleration Incident (Sudden Acceleration).

**scrape**: A mark on a surface that is wider than it is deep that can usually be felt with fingers.

**scratch**: A light and usually irregular scar made on a hard surface, such as paving, by a sliding metal part without great pressure [B.2]. Scratches are visible but not normally distinguishable to the touch.

**Figure B6.** Examples of scuff marks (broad, dark, sweeping marks on surface) and gouge marks (light-colored marks into surface).

**SCTG**: Standard Classification of Transported Goods.

**scuff marks**: Relatively short marks made by a moving tire on a road or other surface in an erratic fashion with no specific, consistent features; for example, acceleration scuff, impact scuff, flat tire mark; see Fig. B6; see yaw marks, skid marks.
Glossary

**SDD**: Sudden Deceleration Data (Cummins Engines).

**SDM**: Sensing and Diagnostic Module; an electronic device in a vehicle that captures and stores information in the event of a crash in which air bags may or may not deploy; see EDR.

**second impact**: An impact between an occupant and an interior surface of a vehicle caused by and following an impact between the vehicle and another object.

**secondary impact**: A second or subsequent impact between the same two vehicles during the crash.

**semi**: See tractor, semitrailer.

**semitrailer**: A semitrailer is a towed vehicle equipped with one or more axles to the rear of its laden center of gravity and whose front end forms part of a pivot joint attached to a truck tractor or other powered tow vehicle (examples are truck, cargo, recreational, boat, and livestock trailers).

**separation speed**: The speed at the time of loss of contact of two vehicles in a collision, can refer to the speed of the centers of gravity or of the contact point.

**separation velocity**: The vector velocity at the time of loss of contact of two vehicles in a collision can refer to the speed of the centers of gravity or at the contact point.

**service brake system**: The primary brake system used for slowing and stopping a vehicle.

**SI System of Units**: Metric system, (Système International d’Unités).

**side rail**: The outermost edge on the side of a vehicle’s roof connecting the upper ends of the A, B, C, and D pillars.

**sideslip angle, tire**: See tire slip angle.

**sideslip angle, vehicle**: The angle between the vehicle’s heading and its velocity vector ($\beta$ in Fig. B2); see sideslip.

**sideslip coefficient**: The slope of the initial linear portion of the lateral force-slip angle curve of a tire.

**sideslip stiffness**: See sideslip coefficient

**sideslip**: Lateral/transverse translation of a vehicle perpendicular to its heading; see Fig. B2; see tire slip angle.

**sideswipe collision**: A collision of a vehicle where sliding (relative tangential motion) over the intervehicular contact surface does not end at or before separation; see common velocity conditions.
**simulation**: The use of mathematics and mechanics, usually done using a computer, to represent, reproduce or model a physical process.

**SIR**: Supplemental Inflatable Restraint.

**skid**: Motion over a surface of a vehicle with its wheels locked from rotation.

**skid number**: A number representing tire-pavement frictional drag determined by measurements made according to standard equipment, conditions, and procedures and usually stated as 100 times a friction coefficient.

**skidmark**: A friction mark on a pavement made by a tire that is sliding without rotation and, if along the heading axis of the tire, displays a tread pattern.

**sliding friction coefficient**: See coefficient of friction.

**slip angle, tire**: See wheel sideslip angle.

**slip speed**: The speed of a single wheel in the direction of its heading at a given value of longitudinal wheel slip.

**slip stiffness**: See wheel slip coefficient

**SLIP**: See wheel slip, sideslip.

**SO2 (SO2)**: Sulfur dioxide.

**SOC**: State of Charge (electric vehicles).

**sound level**:  

\[ L_p = 10 \log \frac{p^2}{P_{ref}^2} \]  

Sound Pressure Level, where \( s^2 \) is the mean square acoustic pressure and \( P_{ref} = 2 \times 10^{-5} \text{ N/m}^2 \)

\[ L_{ref} = 10 \log_{10} \frac{W}{W_{ref}} \]  

Sound Power Level, where \( W \) is the acoustic power and \( W_{ref} = 1 \times 10^{-6} \text{ W} \)

**speed**: The rate of change of vehicle displacement with respect to time; the magnitude of velocity.

**spinout**: A descriptive term for postimpact vehicle motion including significant yaw rotation; see postimpact trajectory.

**static crush**: See residual crush.

**stiffness coefficient**: See crush stiffness coefficient.
**stopping distance**: The distance taken by a driver to bring a vehicle to rest in straight forward motion by braking, including the distance traveled during perception-decision-reaction time prior to brake application; see braking distance.

**STRAHNET**: Strategic Highway Network.

**striations**: Periodic stripes that appear transverse to the tire marks from a yawing vehicle.

**superelevation**: A side-to-side slope of a road measured in degrees or percent.

**supplemental restraint system**: An interior vehicle device that inflates when actuated by accelerometers and/or crash sensors and acts between an occupant and an interior vehicle surface to prevent injury due to sudden contact; see air bag.

**SUV**: Sport Utility Vehicle.

**tag axle**: See drop axle.

**tandem axles**: The use of two closely spaced axles, front-to-rear, usually for buses, heavy trucks, and trailers.

**TAU**: Throttle Actuation Unit.

**TEA-21**: Transportation Equity Act for the 21st Century.

**three-axis vehicle coordinate system**: Fig. B7 shows the standard, three-dimensional vehicle coordinate system.

**throw distance**: The distance a pedestrian is propelled (in the direction of vehicle motion at impact) between the location of the pedestrian at first contact and pedestrian's rest position.
TIFF (TIF): Tagged Image File Format, digital photograph file format.

tire marks: General term for marks on a surface generated by tires; can be scuffs, skids, yaw marks, prints, etc.

tire slip angle (also tire sideslip angle): See wheel slip angle.

total station: An electro-optical device, usually mounted on a tripod, used to make position measurements such as in-site surveys.

tractor, semitrailer: A truck tractor (cab) with two or more axles pulling a semitrailer; see Fig. B8.

![Figure B8. Illustration of an automobile riding under the rear of a semitrailer.](image)

tractor trailer: A truck tractor (cab) with two or more axles pulling a trailer.

tractor: See truck tractor or farm tractor.

trailer: A trailer is a towed vehicle equipped with two axles; the front axle is attached to the tow vehicle and pivoted for turning, whereas the rear axle is fixed.

trailing edge: The term used to describe that portion of a vehicle component (such as door, window, fender, quarter, etc.) which is closest to the rear of the vehicle. The rearmost part of a vehicle with respect to a vehicle’s motion and attitude.

trajectory: The path of the center of gravity of a body as it moves through space; usually associated with coordinates of the center of gravity as a function of time; see Fig. B2.

TRB: Transportation Research Board.

trip point: That location along a ground surface at which the motion of a vehicle component is suddenly halted followed by a flip, rollover, or vault.

truck classifications: Trucks are classified according to their GVWR

<table>
<thead>
<tr>
<th>Class</th>
<th>GVWR range, lb</th>
<th>Class</th>
<th>GVWR range, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 6,000</td>
<td>2</td>
<td>6,001 - 10,000</td>
</tr>
<tr>
<td>3</td>
<td>10,001 - 14,000</td>
<td>4</td>
<td>14,001 - 16,000</td>
</tr>
<tr>
<td>5</td>
<td>16,001 - 19,500</td>
<td>6</td>
<td>19,501 - 26,000</td>
</tr>
<tr>
<td>7</td>
<td>26,001 - 33,000</td>
<td>8</td>
<td>33,001 and above</td>
</tr>
</tbody>
</table>
**truck deformation classification (TDC):** A classification system used to appropriately describe a collision-damaged truck. It consists of seven alphanumeric characters arranged in specific order to form a descriptive composite of the vehicle damage [B.6].

**truck tractor:** A motor vehicle designed for pulling semitrailers. Basic types are cab-over-engine and conventional.

**TSA:** Transportation Security Administration.

**TSB:** Technical Service Bulletin.

**TSC:** Transportation Systems Center (NHTSA).

**UA:** Unintended Acceleration.

**underride:** A condition in a collision where the main structural components of one vehicle are below the main structural components of the other vehicle; see Fig. B8; see override.

**understeer:** When a vehicle, traveling along a circular path on a flat, level surface with a constant speed and a constant front-wheel steer angle is accelerated, it will remain on a path with the same radius, tend to increase its radius, or tend to decrease its radius; these are defined as neutral steer, understeer, and oversteer, respectively; see neutral steer and oversteer.

**USGS:** U.S. Geological Survey.

**UST:** Underground Storage Tank.

**V2I:** Vehicle To Infrastructure (electronic communication).

**V2V:** Vehicle To Vehicle (electronic communication).

**VCE:** Vehicle Control Electronics.

**VIIC:** Vehicle Information Integration Consortium.

**V-MAC:** Vehicle Management and Control Unit (Mack Trucks).

**vault:** A roll or pitch motion of a vehicle made following loss of ground contact.

**vehicle coordinate system:** See Figs. B2 and B7; see three-axis vehicle coordinate system.

**vehicle length:** The maximum dimension measured longitudinally between the foremost point and the rearmost point in the vehicle, including bumper, bumper guards, tow hooks, and/or rub strips, if standard equipment [B.1]. Also known as overall length (OAL).

**vehicle width:** The maximum dimension measured between the widest point on the vehicle, excluding exterior mirrors, flexible mud flaps, and marker lamps, but including
bumpers, moldings, sheet metal protrusions, or dual wheels if standard equipment [B.1]. Also known as overall width (OAW).

**velocity**: The rate of change of displacement with both a magnitude and direction; the magnitude of velocity is referred to as speed.

**velocity-time curve** (*v*-*τ* or *v*-*t* curve): A graphical depiction of velocity of the center of gravity of a vehicle as it changes over time.

**vmt**: Vehicle-miles of travel.

**VOC**: Volatile Organic Compounds.

**VOQ**: Vehicle Owner Questionnaire (NHTSA).

**VRTX**: Vehicle Research and Test Center (NHTSA).

**wheel base**: The perpendicular distance between axes through front and rear wheel centerlines of a vehicle. In case of dual axles, the distance is to the midpoint of the centerlines of the dual axles.

**wheel slip angle** (also **wheel sideslip angle**): The angle between a wheel’s heading axis (x axis) and direction of the velocity vector of the center of the wheel.

**wheel slip coefficient**: The slope of the initial linear portion of the longitudinal force-wheel slip curve of a tire.

**wheel slip**: The ratio of the forward velocity of a tire at the road contact patch to the forward velocity at the center of the wheel (for braking) or the ratio of the forward velocity of a tire at the center of the wheel to the forward velocity at the road contact patch (for traction or acceleration).

**windshield header**: The structural body member which connects the upper portions of the left and right A-pillars and is above the top edge of the windshield.

**WOT**: Wide Open Throttle.

**wrap pedestrian collision**: A frontal collision of vehicle and pedestrian or cyclist where initial contact occurs at a point below the center of gravity of the pedestrian or cyclist and where the frontal geometry of the vehicle allows the pedestrian to move rearward relative to the vehicle and strike another portion of the vehicle, such as a windshield. The latter impact causes the pedestrian or cyclist to develop an airborne trajectory followed by an impact with the ground.

**WWC**: Windshield Wiper Control.

**yaw angle**: The angle between the heading of a vehicle and a fixed reference; see Fig. B2.
**yaw mark**: A tire mark caused by a sideslipping tire, often showing a striped pattern called striations.

**yaw moment of inertia**: The moment of inertia about a vertical axis of a vehicle; see moment of inertia, radius of gyration.

**yaw rate**: Angular velocity about the z-axis; see Fig. B2.

**yaw**: See pitch, roll, yaw, and yaw angle.
Chapter 1


References


Chapter 2


Chapter 3


Chapter 4


References


Chapter 5


References


Chapter 6


References


Chapter 7


Chapter 8


8.9. Test performed in Wildhaus (Switzerland) by DEKRA (Germany) and Winterthur Insurance (Switzerland), 1995.


Chapter 9


Chapter 10


10.19. @RISK, Palisade Corporation, Newfield, NY, 1998.
References

Chapter 11


**Chapter 12**


References


Chapter 13


Appendix A


**Appendix B**


Bibliography of Vehicle Dynamics Books


Acceleration equations, 51
  constant acceleration, 51–53
  rotational acceleration, 55
Accident reconstruction, braking distance vs.
  stopping distance, 59
Accident site
  documentation of, 88
  rollover accident, information about,
    110–111
Airbags, 189–191
Antilock braking systems (ABS), 39–40
Articulated vehicles
  collisions, 193–224
    examples, 197–198, 209–224
    impact equations, 198–205
    validation of, 206–222
  results of analysis, 221t
  spreadsheet appendix, 222–224
Bakker-Nyborg-Pacejka model, 31–33
Calculations
  terminology, 3
  uncertainty in, 1–15
Close-range photogrammetry, see Photogrammetry for accident reconstruction
Coefficient of friction, 22–23, 43n
  dry pavement, 45, 46t
  wet pavement, 45, 47t
Coefficient of restitution, 134, 136, 141–143,
  142t, 147, 153, 189, 237
  mass equivalent collision, 143–144
  stiffness equivalent collision, 142
Collisions, articulated vehicles, 193–224; see also Impulse-momentum
  examples, 197–198, 209–224
  impact center, 199, 202
  impact equations, 198–205
    validation of, 206–222
  planar impact mechanics, assumptions
    about, 195–198
  results of analysis, 221t
  spreadsheet appendix, 222–224
Collisions, frontal vehicle-pedestrian,
  244–258
  analysis model, 249
    pedestrian motion, 249
    vehicle motion, 252
  forward projection model, 248
  hybrid wrap model, 248
Collisions, frontal vehicle-pedestrian
(continued)
reconstruction model, 254–258
speed reconstruction approaches, 247
throw distance, 247, 252, 254, 255f,
examples, 253–254, 257
types of contact, 245–246
values of physical variables, 252–254
pedestrian-ground drag
coefficient, 253–254
variables for vehicle-pedestrian
throw model, 251
Collisions, light vehicles, analysis of, 129–
162, see also Impulse-momentum
controlled collisions, 139–144
barrier collisions, 139–141
coefficients of restitution 141–144,
example, 140–141
low-speed in-line, 186–189
example, 189
quantitative concepts, 131
example, 131–132
RICSAC collisions, 158–162
sideswipe collisions, 137–139
example, 137–139
using a solution of the planar impact
equations, 171–172
using a spreadsheet solution of the
planar impact equations, 172–185
vehicle collisions with rotation,
164–168
Collisions, railroad grades, 299–319
insertion loss, sound pressure level,
316–319, 317f, 318f
locomotive horn sound levels, 313–319
calculation of, 313–316
example, 316
Railroad Highway Grade Crossing
Handbook equations, 309–312
clearing sight distance, 311–312,
313f
stopping distance, 309–311
stopping sight distance, 311
sight distance for stopping before a
crossing, 304–307
example, 307–309
sight triangle for clearing a crossing,
300–304
example, 304–305
sound pressure level, calculation
example, 318–319
train-vehicle converging example,
303–304, 307–309
Collisions, road intersections, 299–319, see
also Collisions, railroad grades
sight distance for stopping before an
intersection, 304–307
sight triangle for clearing an
intersection, 300–304
Common-velocity conditions, 230
Conservation of energy, 98–99
Conservation of momentum, 129–130
Controlled collisions, 139–144
barrier collisions, 139–141
coefficients of restitution 141–144,
example, 140–141
Conversion nomograms, 41f, 42f
Coordinate system, 15–17, 16f
Coulomb, Charles Augustin de, 22
Coulomb’s laws, 22–23
CRASH program, xv, 141
CRASH3, 150, 157, 176, 195, 227–235
assumptions of model, 230
Critical speed, 69–83
calculated vs. measured, 80
defined, 69
drawbacks to sophisticated formulas,
70–71
equation, 70, 73
use of in example, 119
examples, 74–75, 82, 119
Crush energy, 225–243
arbitrary number of crush
measurements, 243
average crush, rigid barrier tests,
236–241
assumptions of model, 230
 crush stiffness coefficient, 225, 236–
241
example, 236
side crush, 243
vehicle-to-vehicle collisions,
241–243
equation, 225
nonlinear models, 243
planar impact mechanics, 155–158
for calculating ΔV, 232–235
principal direction of force, 228–229
Crush stiffness coefficients, 225, 236–241
side crush, 243
vehicle-to-vehicle collisions, 241–243
Crush surface, 155
angle, 151–152, 166, 171–172
Curved motion, 63

Driver control modes, 77

Edge dropoff, 79
EDSVS, 322
EDVSM (Engineering Dynamics Vehicle Simulation Model), 322
EDVTS, 322
Effective drag factor equation, 90
Equations
acceleration, 51–56
constant acceleration, 51–53
rotational acceleration, 55
articulated vehicle impact equations, 198–205
validation of, 206–222
constant mass, 131
crush energy, 225
effective drag factor, 90
forward-motion performance, 54–59
notation for, 56
frictional drag coefficient, 1
of motion, 51, 99–101
photogrammetry,
collinearity equations, 287
coplanarity equations, 287
projection equations, 285–287
planar vehicle motion, differential equations, 338–340
Railroad Highway Grade Crossing Handbook equations, 309–312
clearing sight distance, 311–312, 313

stopping distance, 309–311
stopping sight distance, 311
solution equations, 134–135
sound pressure level, 313
system equations, 134
vehicle fall, 64–68
velocity of a vehicle, estimating, 1

Event data recorders, 189–192
crash data, 191–192

Examples
articulated vehicle collision, 197–198, 209–224
controlled collision, 140–141
critical speed, 74–75, 82, 119
crush energy, 157–158, 236, 237–142
crush stiffness coefficient, 236
low-speed in-line collision, 189
mean and standard deviation, 11
pedestrian throw distance, 253–254, 257
perception-reaction time, 9
preimpact speed, 165–168
quantitative concepts, 131–132
railroad grade and road intersection collisions, 304–305, 307–309, 316, 318–319
rollover accidents
pretrip phase, 91–95
trip phase, 105
roll phase, 108
sideswipe collisions, 137–139
straight-line motion
braking distance, 57–58
pitch angle of vehicle, 68–69
speed when distance is known, 60–62
stopping time and distance, 62–63
uniform grade, 53
vertical force and frictional drag coefficient, 58–59
uncertainty, 5, 7, 82
vehicle dynamic simulation, 326–338
vehicle-pedestrian wrap collision, 253–254
Federal Motor Carrier Safety Regulations (FMCSR), 44
Force diagram, 96
Forward-motion performance equations, 54–59 notation for, 56
Forward projection collisions, see Collisions, frontal vehicle-pedestrian
Friction, coefficient of, 22–23, 43n
  dry pavement, 45, 46t
  wet pavement, 45, 47t
Friction circle, 27–31, 76–77
  actual, 30
  idealized, 28–30
Friction ellipse, 27–31
  idealized, 28–30
Frictional drag coefficient, 22–23, 30, 37, 39–46, 76
  equation for, 1
  for heavy vehicles, 41–46
  for light vehicles, 40–41
  for combined trip and roll phase, 108t
Grade and equivalent drag coefficients, 54
HVOSM (Highway Vehicle Obstacle Simulation Model), 322
Hydroplaning, 46–49
Impact center (point C), 155, 199, 202
Impulse-momentum, 95–96, 98–99, 102, 131
  controlled collisions, 139–144
  barrier collisions, 139–141
  coefficients of restitution 141–144, 142t
  planar impact mechanics, 144–158
  applications of, 164–168
  and articulated vehicles, assumptions about, 195–198
  coefficient of restitution, 147, 153–154
  crush energy, 155–158
  crush energy example, 157–158
  crush surface, 155
  impact center (point C), 155
  impulse ratio, 153–154
  overview of, 150–153
  sideswipe collision, 154
  solution equations, 148, 171–172
  spreadsheet solution, 172–185
  point-mass theory, 132–138
  coefficient of restitution, 134, 136
  common velocity conditions, 137–139
  critical impulse ratio, 136–137
  frictionless point-mass collisions, 136
  preimpact speed examples, 165–168
  sideswipe collisions, 137–139
  solution equations, 134–135
  system equations, 134
theory, 129–224
Impulse ratio, 134, 147, 153
  critical, 136–137, 149
Insertion loss, sound pressure level, 316–319, 317t, 318t
Lateral tire forces, 25–27, 26f
  modeling of, 31–37
Locomotive horn sound levels, 313–319
  calculation of, 313–316
  example, 316
Longitudinal tire forces, 23–24
  modeling of, 31–37
  peak, 47–48
Low-speed in-line (central) collisions, 186–189
Measurements, uncertainty in, 1–15
  terminology, 3
Modified Nicolas-Comstock model, 33, 78
Monte Carlo method, 257
Motion, equation of, 51
National Highway Traffic Safety Administration (NHTSA), 87, 98
Neutral stability position, 98
New Car Assessment Program (NHTSA), 87, 139
Newton’s laws of motion, 51, 54–56, 64, 146
  second law, 74, 131, 132, 147, 323
  third law, 200, 242
Nicolas-Comstock model, modified, 33, 78

PC-Crash, 322
Peak friction, 39
Pedestrian collisions, see Collisions, frontal vehicle-pedestrian
Perception-decision-reaction time, 59–60, 299, 301
  examples, 9, 303, 308–309, 316
Perception-reaction time, see Perception-decision-reaction time
Peterbilt vehicles, frictional drag coefficient, 44
Photogrammetry for accident reconstruction, 259–298
  close-range, 259
  defined, 259
  planar photogrammetry, 260, 274–281
  assumptions about, 275
  example, 276–277, 278–281
  field example, 279–281
  image and object planes, 298f
  obtaining coordinates, 275–276
  projective relation, 297–298
  quality of photograph used, 276
  reverse projection photogrammetry, 260–274
  analog approach, 263
  defined, 261
  full-frame photographs, importance of, 262–263
  landmarks, importance of, 262
  overlays, 263–265
  practical difficulties, 271–272
  procedure, 263–268
  requirements, 261–263
  seven degrees of freedom, 267t
  size of image, choosing, 264
  size of viewable area, determining, 266–267
summary of main steps, 268–269
three-dimensional photogrammetry, 281–297
  accuracy of, 282
  collinearity equations, 287
  coordinate system, 284
  coplanarity equations, 287
  example, residual crush, 291–296
  fundamentals, 283
  mathematical basis, 284
  multiple image considerations, 287
  practical use of, 288–290
  projection equations, 285–287
Planar impact mechanics, 144–158
  applications of, 164–168
  and articulated vehicles, assumptions about, 195–198
  coefficient of restitution, 147, 153–154
  crush energy, 155–158
  crush energy example, 157–158
  crush surface, 155
  impact center (point C), 155
  impulse ratio, 153–154
  overview of, 150–153
  sideswipe collision, 154
  solution equations, 148, 171–172
  spreadsheet solution, 172–185
Planar photogrammetry, 260, 274–281
  assumptions about, 275
  example, 276–277, 278–281
  field example, 279–281
  image and object planes, 298f
  obtaining coordinates, 275–276
  projective relation, 297–298
  quality of photograph used, 276
Point-mass theory, 132–138
  coefficient of restitution, 134, 136
  common velocity conditions, 137–139
  critical impulse ratio, 136–137
  frictionless point-mass collisions, 136
  preimpact speed examples, 165–168
  sideswipe collisions, 137–139
  solution equations, 134–135
  system equations, 134
Postimpact speed, calculating, 164
Principals direction of force, 176–177, 181, 191, 228–229

Railroad grade collisions, see Collisions, railroad grades

Railroad Highway Grade Crossing
   Handbook equations, 309–312
      clearing sight distance, 311–312, 313f
      stopping distance, 309–311
      stopping sight distance, 311

Reaction time, see Perception-reaction time

Reconstruction applications, 163–192; see also Impulse-momentum
   airbags, 189–191
   event data recorders, 189–191
   low-speed in-line (central) collisions, 186–189
   point-mass collision applications, 164–168
   planar impact mechanics applications, 164–168
      using a solution of the planar impact equations, 171
      using a spreadsheet solution of the planar impact equations, 172–185
   vehicle collisions with rotation, 164–168

Reconstruction techniques
   CRASH program, xv, 141, 150, 157
   SMAC, 141, 195

Reverse projection photogrammetry, 260–274
   analog approach, 263
   defined, 261
   full-frame photographs, importance of, 262–263
   landmarks, importance of, 262
   overlays, 263–265
   practical difficulties, 271–272
   procedure, 263–268
   requirements, 261–263
   seven degrees of freedom, 267f
   size of image, choosing, 264
   size of viewable area, determining, 266–267
   summary of main steps, 268–269

RICSAC collisions, 158–162
   RICSAC 7, 180
   RICSAC 9, 172–179
      test conditions, 176f

Rigid barrier tests, 139, 142f, 236–241

Rigid-body impact theory, 144
   application of, 168–171

Road intersection collisions, see Collisions, road intersections

Roadway, superelevation, 74–75

Rollover accidents, reconstruction of, 85–128
   conservation of energy, 98–99
   documentation of accident site, 88
      example, 117–126
      detailed analysis, 120–125
      speed analysis, 117–120
   phases of, 85
      pretrip phase, 89–85, 118–120
      example, 91–95
      roll phase, 106–117, 108f
      accident scene, gathering
         information about, 110–111
      analysis of rolling vehicle, 109–110
      example, 108
      frictional drag coefficients, 108f, 109f
      inspection of accident vehicle, 111–115
      police report and photographs, importance of, 110–111
      speed analysis, 107–109
      rollover reconstruction tools, 115–116
      validation of reconstruction method, 106
   SAE recommended practice, 87
   scratch patterns, 113
   segmented method, 94
   static stability factor, 87, 98
   test methods, 86–88
   tire marks, 90–94
   trip phase, 95–105
      analysis of vehicle trip, 96–101
      complex vehicle trip models, 101–102
      constant force trip model, 99
      difficulties applying trip models, 101–102
drag factors, 104
example, 105
frictional drag coefficients, 108
reconstruction of, 102–105
rim contact, 105–106
vehicle drag factor, 89–90
vehicle dynamics simulation, 92–93
vehicle roll rate, 126–127, 128
vehicle sideslip angle, 89–90, 90
Rollover reconstruction tools, 115–116
Rollover Resistance Rating system (NHTSA), 98
Rollover tests, 81, 86–88
Rounding of numbers, 343–344
Runge-Kutta-Gill numerical integration, 323

Scratch patterns, evaluating, 113–114
SI units
metric vs. customary units, 342
use of, 341
Sideswipe collisions, 137–139
example, 137–139
Sight distance for stopping before a crossing, 304–307
example, 307–309
Sight triangle for clearing a crossing, 300–304
example, 304–305
Significant figures, 342
consistency of, 344–345
SMAC, 141, 195, 322
Sound pressure levels, 313–319
example of calculation, 318–319
insertion loss, 316–319, 317, 318
Speed, critical, 69–83
calculated vs. measured, 80
defined, 69
drawbacks to sophisticated formulas, 70–71
equation, 70, 73
use of in example, 119
examples, 74–75, 82, 119
Static stability factor, 87, 98
Steering forces, combined with tire forces,
modeling of, 31–37
Bakker-Nyborg-Pacejka model, 31–33
Modified Nicolas-Comstock model, 33–37
Stopping distance, 59–63
calculating distance from speed, 60
calculating speed from distance, 60–61
Straight-line motion, 51–68
equation of motion, 51
examples
braking distance, 57–58
pitch angle of vehicle, 68–69
speed when distance is known, 60–62
stopping time and distance, 62–63
uniform grade, 53
vertical force and frictional drag
coefficient, 58–59
stopping distance, 59–63
calculating distance from speed, 60
calculating speed from distance, 60–61
uniform acceleration and braking
motion 51
equations of acceleration, 51–56
grade and equivalent drag
coefficients, 54
vehicle fall equations, 64–68
vehicle forward-motion performance
equations, 54
notation for, 56

Three-dimensional photogrammetry, 281–297
accuracy of, 282
collinearity equations, 287
coordinate system, 284
coplanarity equations, 287
example, residual crush, 291–296
fundamentals, 283
mathematical basis, 284
multiple image considerations, 287
practical use of, 288–290
projection equations, 285–287
Tire forces, 15–49
acceleration slip vs. braking slip, 20
contact patch, 17
coordinate system, 15–17
friction, 22
Tire forces (continued)
lateral force, 25–27, 26f
  modeling of, 31–37
longitudinal force, 23–24
  modeling of, 31–37
  peak, 47–48
rolling resistance, 17, 18f
slip force, 17–27, 18f
  longitudinal, 19–20
Tire forces, combined with steering forces,
  modeling of, 31–37
  Bakker-Nyborg-Pacejka model, 31–33
  Modified Nicholas-Comstock model, 33–37
Tire mark striations, 90
Tire model, important aspects, 322
Tire rims
  contact with roadway, 105–106
  evaluating deformation, 113
Tire sideslip, 71–72
Tire treads
  depths, 48t
Tire yaw marks, 69–83
  curved, 76
  estimation of speed, 69
defined, 71
guidelines for measuring, 76
radius from, 73, 77
severe, 77–78
vs. skid marks, 72
Tires, evaluating deformation, 113
Treads, tire, see Tire treads

Uncertainty
  of articulated vehicle reconstructions, 217
  of critical speed calculations, 79–83
  design of experiments, 12–13
differential variations, 5–7, 79–80
distribution-free methods, 13
examples, 5, 7, 82
norm, defined, 6n
propagation of error, 5
sensitivity coefficients, 6
statistical distributions, 8–9
  arbitrary functions, 9–11
  linear functions, 8–9
  statistical variations, 81–82
  upper and lower bounds, 4–5
Uncertainty, epistemic, 13
Uncertainty, parametric, 1
Uncertainty, modeling, 1
Unit conversion, 346–354
VCRware, 322
VDANL (Vehicle Dynamics Analysis Nonlinear), 322
VDM RoAD (Vehicle Dynamics Models for Roadway Analysis and Design), 322
VdynVB, 322
Vehicle drag factor, 89–90
Vehicle dynamic simulation, 92–93, 321–340
  conditions applied, 323–325
  defined, 321
  examples, 326–338
  planar vehicle dynamics simulation, 322
  planar vehicle motion, differential equations, 338–340
  Runge-Kutta-Gill numerical integration, 323
tire model, important aspects, 322
tire side-force stiffness coefficients, 325
  for heavy vehicle, 326
  for light vehicle, 325
vehicle dynamic simulation vs. vehicle dynamics, 321
Vehicle fall equations, 64–68
Vehicle roll rate, 126–127, 128t
Vehicle sideslip angle, 89–90, 90f
Velocity of a vehicle
  calculating ΔV with planar impact mechanics, 232–235
  ΔV, 225–243
  estimating, 2
  predicted, 95t
Volvo vehicles, heavy, frictional drag coefficient, 44

Yaw marks, see Tire yaw marks
About the Authors

Raymond M. Brach
Raymond M. Brach, PhD, PE, is a consultant in the field of accident reconstruction and a professor emeritus of the Department of Aerospace and Mechanical Engineering, University of Notre Dame. He is a fellow member of SAE International. Other professional memberships include the American Society of Mechanical Engineers (ASME), The Acoustical Society of America (ASA), The Institution of Noise Control Engineers (INCE), and the National Association of Professional Accident Reconstruction Specialists (NAPARS). He was granted a PhD in Engineering Mechanics from the University of Wisconsin, Madison, and a BS and MS in Mechanical Engineering from Illinois Institute of Technology, Chicago. His specialized areas of teaching and research include mechanical design, mechanics, vibrations, acoustics, applications of statistics and quality control, vehicle dynamics, accident reconstruction, and microparticle dynamics. He is a licensed professional engineer in the state of Indiana. In addition to more than 100 research papers and numerous invited lectures, he has authored Mechanical Impact Dynamics published by Wiley Interscience in 1991 and is a coauthor of Uncertainty Analysis for Forensic Science, Lawyers and Judges Publishing Company, 2004.

R. Matthew Brach
R. Matthew Brach, PhD, PE, is an engineering consultant with the firm Brach Engineering, LLC. His principal areas of professional activities include vehicle impact analysis, vehicle dynamics, and automotive accident reconstruction. He has a PhD in Mechanical Engineering from Michigan State University, East Lansing (1995), an MS in Mechanical Engineering from the University of Illinois at
About the Authors

Chicago (1986), and a BS in Electrical Engineering from the University of Notre Dame (1982). He served as an adjunct professor in the Mechanical Engineering Department at Lawrence Technological University, Southfield, Michigan from 1994 to 2000. He is a member of SAE International, the American Society of Mechanical Engineers (ASME), the Institute of Electrical and Electronics Engineers (IEEE), and the National Association of Professional Accident Reconstruction Specialists (NAPARS). He is a licensed professional engineer in the states of Indiana and Michigan. He is the author of technical papers covering a range of topics that includes nonlinear vibrations, automotive engine mount design, vehicular accident analysis methodologies, and tire forces.