the cumulative and progressive alteration of material that results in the eventual damage from the repetition of certain types of movements or pressures. Fatigue occurs from the cyclic addition and removal of stresses and loads to a structural component (a load is a force placed on a material while a stress is the response of the material to the load. E.g., lots of homework is a load that causes stress in students in response to the load). The maximum amount of stress placed on a material during fatigue is often much less than that needed to simply break the material but high enough to cause compression and relaxation to occur. Generally, the greater the stress that is applied to a

<table>
<thead>
<tr>
<th>Material</th>
<th>Load (pounds per sq. ft. of material)</th>
<th>Category</th>
<th>Description</th>
<th>Load (pounds per sq. ft. of item/material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt shingles</td>
<td>2</td>
<td>Hospital</td>
<td>Wards and rooms</td>
<td>40</td>
</tr>
<tr>
<td>Brick (4” wall)</td>
<td>40</td>
<td>Libraries</td>
<td>Reading rooms</td>
<td>60</td>
</tr>
<tr>
<td>Concrete block</td>
<td>55</td>
<td></td>
<td>Book stacks</td>
<td>125</td>
</tr>
<tr>
<td>Earth (moist)</td>
<td>100</td>
<td>Manufacturing</td>
<td>Light</td>
<td>75</td>
</tr>
<tr>
<td>Glass (¼” thick)</td>
<td>3.3</td>
<td>Offices</td>
<td>Heavy</td>
<td>125</td>
</tr>
<tr>
<td>Gypsum wallboard</td>
<td>1.8</td>
<td></td>
<td></td>
<td>50</td>
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<tr>
<td>Harwood floor</td>
<td>2.5</td>
<td>Schools</td>
<td>Classrooms</td>
<td>40</td>
</tr>
<tr>
<td>Plywood</td>
<td>1.4</td>
<td>Stores</td>
<td></td>
<td>100</td>
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<tr>
<td>Steel decking</td>
<td>2.5</td>
<td>Auditoriums</td>
<td>Fixed seating</td>
<td>50</td>
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<tr>
<td>Water</td>
<td>62*</td>
<td></td>
<td>Moveable seating</td>
<td>100</td>
</tr>
<tr>
<td>Suspended ceiling</td>
<td>1</td>
<td></td>
<td>Stage areas</td>
<td>125</td>
</tr>
<tr>
<td>Plaster (½” thick)</td>
<td>4.5</td>
<td>Garages</td>
<td>Vehicle storage</td>
<td>50</td>
</tr>
</tbody>
</table>


The distribution and transfer of loads to the external walls in a residential building and then to the ground.

Figure 18.1.6. The distribution and transfer of loads to the external walls in a residential building and then to the ground.

Figure 18.1.7. Collapse of a building wall weakened by long-term water damage to the mortar holding the bricks of the outer wall. (www.post-gazette.com/pg/11046/1125492-53.stm).
material, the shorter that material’s useful lifetime will be. Cyclic loads cause stresses that, if above a certain threshold, will ultimately weaken the material by forming microscopic cracks and fractures. As the cyclic stress-relaxation process continues, the tiny cracks continue to grow until they reach a critical size necessary to cause the entire structure to suddenly fail.

Structures, such as bridges, towers and buildings must be designed to accommodate cyclic movements and stresses safely (Figure 18.1.4). For example, the Golden Gate Bridge in San Francisco experiences cyclic (daily) thermal stress as the bridge is warmed by the sun each day and cooled each night. Because of this thermal cycling, the bridge contracts at night and expands during the day, causing the center of the span to move up and down as much as 16 ft (4.8 m) daily. Vibrations are often considered as cyclic (dynamic) loads and can rapidly weaken a structure to the breaking point through fatigue (Figure 8.1.5). A classic example is the destruction of the Tacoma Narrows Bridge (see insert box “The Last Ride of ‘Galloping Gertie’”). Cyclic vibrations can occur from earthquakes, road vibrations from traffic, trains, machinery (e.g., jackhammers, compressors, motors, jet engines, etc.) and aerodynamic wind effects, among others.

The total load placed on a structure is

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**Figure 18.1.8.** Typical brick, mortar, and wooden structure (http://www.laur.net/travel/city.php?NE=grand-island-carnegie-public-library).

**Figure 18.1.9.** Unusual architectural designs are possible through the careful direction of the internal loads within the building to the Earth (www.globalconstructionwatch.com/page/2/).

**Figure 18.1.10.** Examples of building trusses used to carry and distribute loads (www.fermco.com/roof_trusses.html).
ultimately transferred to the earth, but structures are designed to distribute and transfer their loads in a variety of ways. For example, a typical residential home transfers the loads from the roof, floors and most of its contents to the outer walls of the structure and then to the ground, as shown in Figure 18.1.6. Damage to these outer load-bearing walls often leads to the partial or total collapse of the building, as illustrated in Figure 18.1.7. For example, many buildings constructed in the late 1800’s to early 1900’s were simple “box” structures built primarily of locally produced materials such as brick, mortar (the bonding material used to hold bricks together, usually cement or lime) and wood. The design most frequently employed used outer brick walls, held together with inexpensive lime mortar, to transfer the weight of the structure to the ground, coupled with horizontal wooden beams (joists) that fitted into notches in the brick walls to hold and transfer the weight of the floors and contents to the outer walls. These buildings often had flat, gently sloping roofs constructed of wooden beams and planking covered with felt and tar to aid rainwater run-off (Figure 18.1.8). Over long use and lack of maintenance, however, rainwater can penetrate at the juncture of the roof’s brick walls and the flat wooden decking. The rainwater runs down along the inside wall of the building, often undetected behind the framed interior walls of the building. During this long-term process, the chemical components of the mortar gradually leach away, thereby weakening the outer load-bearing walls. At some point when enough of the strength of the mortar has been removed, the wall suddenly collapses (Figure 18.1.7) without any visible warning to the occupants of the building since the damage is largely hidden behind the interior walls.

Various structures deal with the distribution and transference of loads in different ways. Some modern skyscrapers, for example, consist of a massive central core that supports most of the weight of the floors, allowing complex outer shapes and unusual architectural designs while others

Milwaukee’s Miller Baseball Park Crane Collapse

On July 14, 1999, while placing a 1,000,000 pound section for the roof of new baseball stadium under construction in Milwaukee, Wisconsin, the crane – known as “Big Blue” – collapsed, killing three people and causing millions of dollars in damages. Big Blue was an enormous crane over 500 feet tall carrying 2.4 million pounds of counterweights and run by three operators. The crane was designed to be well able to handle this load – so why did it collapse?

The forensic engineering company of ESI was called in to investigate the collapse (www.esi-website.com/projects/miller-park.php). The engineers investigated many things about the accident including:

- The materials used in the crane;
- The physical evidence remaining within the wreckage;
- The winds present at the time of the collapse;
- The loads placed on the crane and roof;
- The strength and stiffness of the crane;
- The ground supporting the crane;
- The effects of roof load dynamics on the crane;
- The standards in the U.S. and worldwide.

From their detailed analysis, the forensic engineers determined that the cause of the accident was the result of the unfortunate combination of a number of smaller factors that all added together. No one factor was sufficient by itself to cause the collapse, but when all were taken together, led to the observed tragedy. These factors included: the wind speed and direction, the strength of the soil underneath the massive crane, the flexibility of the crane, the design of the crane, and the actions of the three operators.
use a combination of internal and external support structures (Figure 18.1.9). For example, suspension bridges transfer the weight through the support towers while rigid bridges use various types of trusses to distribute and transfer the weight. Many different truss support designs have been devised, depending upon the structure’s load requirements and building materials available, such as shown in Figure 18.1.10.

Architects and engineers usually design structures with a large capacity to hold both expected and unplanned loads. The factor of safety (FS) of a structure describes its ability to withstand loads beyond those anticipated from the total of static and dynamic loads. The FS is usually given by a ratio of the largest load that a structure can endure to the expected actual load (design load):

$$\text{Factor of Safety} = \frac{\text{Material Strength}}{\text{Design Load}} \quad \text{(Eq. 18.1)}$$

A factor of safety value of two indicates that the structure should be able to hold about twice the expected load before failure would occur. Engineers usually use a “worst case” scenario when calculating the factor of safety for a structure. Required factors of safety values for structural components vary but often

---

**The Loss of the Space Shuttle Challenger**

NASA’s flagship program for many years was its space shuttle program, the goal of which was to provide a rapid, inexpensive and reusable space-delivery system for exploration and economic development. The enormously successful shuttle program ultimately flew 135 missions from 1981 until mid-2011 before being retired to allow the development of other space vehicles.

On January 28, 1986, a “routine” launch of the shuttle Challenger, however, ended in disaster. Seventy-three seconds into the launch, the spaceship exploded, completely disintegrating over the Atlantic Ocean and killing all seven crewmembers onboard. This disaster led NASA to halt all shuttle flights for 32 months until a complete investigation could be completed and design changes implemented to prevent any similar problems with the other shuttles in the future.

The problem, of course, was that the space shuttle was an enormously complicated vehicle with millions of parts. Complicating this was the fact that the shuttle used over 1.3 million pounds of explosive liquid oxygen and 2.2 million pounds of solid rocket fuel. Within all this complexity and explosive chemicals, investigators needed to find the “needle in the haystack”.

After an extensive recovery effort and investigative process, the cause of the failure was found to come from a single O-ring in the solid rocket booster engine on the shuttle (See below). The O-ring formed a flexible joint in the design of the powerful solid rocket boosters that could usually withstand high temperature. But it was found that the weather on the day of the launch was unusually cold, causing the O-ring to crack. Once in flight, the crack opened to allow hot gases from the booster engine to cut through the rocket explosively igniting the entire remaining fuel supply. The failure of this one, relatively small component, therefore, was the cause of the loss of the entire shuttle vehicle and crew.
range between 3 and 10 or more, meaning that the structure should hold at least three to ten times the expected total load for the structure. For example, if the total load (dynamic plus static) on a structure is calculated to be 100,000 pounds, then a FS value of three means that the structure’s design must be specified to handle at least 300,000 pounds of load. Structures in areas of earthquake, hurricane and other potentially high dynamic load environments may require even greater factors of safety. Evaluating the designed factor of safety for structural components along with accurately estimating the expected total loads on a structure are key steps in forensic structural failure analysis. Looking at how a structure failed can point to either design or construction flaws (or both) that somehow compromised the safety requirements of the structure. An engineer may use a FS value of 5 for a building component but, during construction, a substitute material might be used that only has a FS value of 3 for the given application. For example, in the catastrophic collapse of the Skywalk in the Hyatt Regency Hotel in Kansas City, Missouri, a modified design was substituted during construction that compromised the FS of the suspension system holding up the skywalk. The result was a collapse that killed 114 people and cost over $120 million in claims and damages.

A second safety value that engineers use when making their designs, called the Margin of Safety (MoS), describes the ratio of the strength of the structure to the required strength of the structure. There are several operational definitions of MoS that depend on the specific engineering application (e.g., civil, aerospace, mechanical, etc.) but most relate to the ratio of the load that the structure is able to take before it fails to the load that it is required to withstand, usually by law or common practice, and is often given by the equation (Eqn. 18.2):

\[
\text{Margin of Safety (MoS)} = \frac{\text{actual load capacity}}{\text{load capacity required}} - 1 \quad \text{(Eqn. 18.2)}
\]

For example, a MoS of zero means that the component exactly meets the required load capacity and a value of below zero means that it did not meet the requirement. Note that the required load capacity in the MoS calculation may already have a factor of safety several times larger than the expected actual load for the structure – it is the load capacity not the total of dynamic and static loads placed on the structure that is used in this calculation. In determining MoS, it is also the legal load capacity required that is used in the calculation. This may seem confusing but the legal capacity is basically a measure of the amount of load that a structure can withstand compared to the legal requirements of what it must withstand.

**Forensic System Failure Analysis:** Sometimes, the catastrophic failure of an engineered system is brought about by the failure of just one or several smaller components that make up the entire system. Such failure can result in a significant loss of life, property or revenue and may involve criminal or civil litigation focused upon evidence of improper design, illegal construction or poor operation practices. Forensic failure analysis investigations may also provide information specifically for insurance claims where the underlying cause of the failure needs to be determined before a proper settlement can be completed. Insurance investigations rarely ever make it into court and are typically settled between the parties but nonetheless may require the same level of forensic investigation as those cases that do find their way into court. System failure analysis investigations may require that forensic engineers explore the causes of failure for vehicles, machinery or industrial processes (e.g., chemical manufacturing productions). These failures may be due to a wide range of causes that include improperly designed or poorly constructed systems, undetected wear and stress faults, poor maintenance practices, over-taxing a system or component beyond its engineered capabilities (exceeding the designed Margin of Safety), physical damage from impacts, accidents, corrosion, fire and human error in the operation of the item. This type of analysis requires an intimate understanding and working knowledge of the key features and use practices for the failed system or component. The investigation often employs a combination of digging out background information (e.g., blueprints, maintenance logs, legal requirements and standards, etc.), carrying out detailed site investigations, completing computer modeling simulations, and running multidisciplinary laboratory analyses before a reasonable answer is reached.
Failure analysis is most often focused upon determining the root cause, or failure mechanism, responsible for the observed problem. Engineers frequently use a technique known as reverse engineering to help in determining these root causes. **Reverse engineering** refers to starting with a finished product or end result and then carefully “taking it apart” in a piece-by-piece fashion to determine how it works and was constructed. For example, an engineer may start with a finished and working clock and take it completely apart to learn the secrets of its operation and design. Engineers and scientists in industry may do this with a competitor’s product to see how the competition solved a particular problem or made a better product. Forensic reverse engineering specifically deals with beginning at the point of the failure and then working backwards to the root cause of the failure, examining the design, manufacturing process and functioning of each component individually and collectively. By understanding both the expected operation as well as the role that each component played in the observed failure can help lead backwards through the sequence of events that led to the failure.

System failure analysis may also play a central role in investigations that involve piecing together intentionally designed criminal devices, such as bombs and weapon systems, that have been used to destroy much larger structures, such as a building, ship or aircraft. The incredibly detailed, difficult and time-consuming task of piecing together the remains of an airplane that exploded in mid-air, for example, may be the only way to locate the exact position within the aircraft where the explosion originated. Determining this location may aid in identifying whether the explosion was caused by an intentionally detonated device, a mechanical failure (e.g., material flaw, fatigue or stress failure, etc.), an unexpected impact (including a firearm discharged within the craft followed by explosive decompression), or through human error (e.g., an improperly closed door, misaligned cargo weight, or a wrench inadvertently left in an engine during repairs). If the investigation is able to identify the characteristic features that arise from the detonation of an explosive device onboard, locating the position of the device precisely within the structure may allow it to be traced back to its point of origin and creator. A classic example of this was presented earlier in the case of the “Lockerbie Bombing Crime Scene” in Chapter 2.3. Investigators were able to pinpoint the exact location of the bomb, hidden within a transistor radio case in a suitcase in the forward cargo hold of the aircraft. Knowing this, they were able to trace the suitcase and its contents back to the point when it was placed onboard the aircraft. Eventually, investigators were able to trace the suitcase and its bomb back to the perpetrators responsible for the crime through an amazing example of investigative determination, diligence and skill.

A component failure analysis may also provide the only detailed description possible of the sequence of events that led to an observed catastrophic result. Analyses of these types helped investigators piece together how the events unfolded that lead to the destruction of the World Trade Center in New York City, the Oklahoma City bombing, and the explosion of the space shuttle *Challenger* (see inset box “The Loss of the Space Shuttle *Challenger*”), among many others.
Forensic Engineering and Crime Scene Reconstruction

Each engineering discipline can make important contributions to creating a crime scene reconstruction that sheds light onto the sequence of events that occurred during the commission of a criminal act. In chapter two (section 2.3), the use of common engineering tools, such as computer aided-design (CAD) programs and total surveying stations (Figures 18.1.11 and 18.1.12), were described as important modern applications of technology to criminal investigations. These and other engineering techniques are rapidly changing the way crime scenes are processed, analyzed and presented to juries.

There is probably no place where the practical use of engineering tools and expertise in crime scene reconstruction is more evident, however, that in vehicular accident investigations.

Forensic Vehicular Accident Reconstruction: The past one hundred years has seen an extraordinary explosion in the availability and use of motorized vehicles worldwide. Cars and trucks come in all sizes, shapes and designs to fit an enormous range of practical and recreational uses. In the United States alone, there is nearly one vehicle for every person in the country with over 250 million registered passenger vehicles reported in the US in 2007 (US DoT survey, excluding buses, motorcycles and trains) (Figure 18.1.13).

During the early 20th century, the number and severity of vehicular accidents rapidly grew as the density of vehicles swelled, higher speeds became possible and the extensive new high-speed roadways were constructed. A 2004 estimate reported that about 1.2 million people were killed worldwide and 50 million injured through vehicular accidents (WHO report on road traffic injury prevention). Traffic fatalities are the leading cause of deaths worldwide among children in the 10 to 19 year-old age group and for the 5 to 35 year-old population in the US. These accidents arise from a variety of causes that include human, vehicular, environmental, and road design factors, as shown in Figure 18.1.14.

Figure 18.1.12. A computer-based 3D CAD rendering of a crime scene prepared from the data taken from the laser scanner shown in Figure 18.1.11. The figure can be viewed and analyzed from any angle or perspective, including determining bullet trajectories and blood spatter evidence (www.policemag.com/Channel/Technology/Articles/Print/Story/2004/11/The-Next-Dimension.aspx).

Figure 18.1.13. Number of passenger vehicles by country per 1,000 persons of driving age (J.D. Power).
Because of this range of contributing causes, there is usually a need to determine the exact circumstances and contributing causes in a vehicular accident. Fortunately, this type of information may often be best provided through an engineering approach to the reconstruction of the vehicular accident.

Many tools and techniques may be employed when investigating a vehicular accident to answer a number of key questions including:

- the relative positions of the vehicles and surroundings;
- the speed of the vehicle(s);
- the direction and trajectory of the vehicles and passengers (especially if passengers were thrown from the vehicle) both before and after the impact;
- the point and angle of impact;
- the items involved in the impact (e.g., vehicles, people, trees, telephone poles, etc.);
- the actions of the drivers (e.g., when and where the brakes were applied);
- the start and end points of the collision.

As it turns out, each of these questions can usually be addressed with a high degree of accuracy using several basic principles of physics and engineering. Most approaches to vehicular accident reconstruction usually begin with a consideration of energy and momentum.

**Energy and Momentum:** Vehicular accidents involve bodies in motion that collide, transfer energy and eventually come to rest. The movements of all objects, such as vehicles, are best described through the application of some simple and basic ideas of physics and engineering. Two terms are of particular importance in these descriptions: energy and momentum.

In previous chapters, concepts about energy and especially the conversion of energy between its various forms were presented. Kinetic energy, heat, light, sound, chemical, work, and even mass \((E = mc^2)\) are some of the examples of the different forms that energy may take. **Kinetic energy** is the energy associated with the motion of an object and is given by the very simple expression:

\[
\text{Kinetic Energy (KE)} = \frac{1}{2} mv^2 \quad \text{(Eqn. 18.3)}
\]

(where \(m\) is the mass and \(v\) is the velocity of the object)

This relationship should make common sense, we understand intuitively that when an object moves faster, it has greater energy. Similarly, as an object increases in mass at a certain speed, the energy associated with its motion likewise increases. From the equation (Eqn. 18.3), however, it can be seen that when the velocity of an object doubles, its energy quadruples – the energy increases as the square of the velocity.
traveling at 40 mph has four times the kinetic energy as the same car traveling at 20 mph and will require four times the distance to stop. For example, a car going 20 mph will skid about 19 ft before coming to a complete stop while the same car going 40 mph (double the speed) will require about 76 feet to stop (Figure 18.1.15). When you add in a person’s average reflex time to react and apply the breaks, the total stopping distance at 40 mph is about 164 ft.

The transfer of energy between forms is governed by the physical law of the **Conservation of energy** that says that, while energy may be converted between its different forms, the total energy of an isolated system **must remain constant**. For example, when an object in motion strikes an immovable object, the kinetic energy of the moving body is changed mostly into heat, light, sound and work energy – the products we observe from a collision. This is called an inelastic collision, where some or all of the kinetic energy is converted into other forms of energy (see inset box “Collision Definitions”). During an emergency stop or collision, the kinetic energy of a vehicle is **irreversibly** converted into work energy in a one-way process – it cannot be converted backwards into kinetic energy later. **Work (W)** is defined simply as the product of the force applied to an object times the distance that the object moves from the action of force. **Force (F)**, the impetus used to move the object, is given by the product of an object’s mass times its acceleration. The two equations that mathematically define work and force are:

\[
W = F \cdot d \quad \text{(Eqn. 18.4)}
\]

(\text{where } F \text{ is the force and } d \text{ is the distance through which the object is moved)}

\[
F = m \cdot a \quad \text{(Eqn. 18.5)}
\]

(\text{where } F \text{ is the force, } m \text{ is the mass, and } a \text{ is the acceleration)}

When a car rapidly applies and locks its brakes until it stops, the car’s initial kinetic energy is **completely** converted into work, frictional heat, or other forms of energy. When the car stops, it has zero kinetic energy - all of its initial kinetic energy has changed into other forms of energy. This is a statement of the idea of **conservation of energy** where the total energy of the system before the brakes were applied (when the car is moving at a given speed) must be equal to the total energy after it has completely stopped. This can be stated using several simple equations (Eqn. 18.6 – 18.8):

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### Physics Brain Teaser

**Question**: If a bulldozer pushes with all of its power against a wall that is cannot budge, even a little bit, does the bulldozer do any work?

**Answer**: No, since the object being pushed did not move through any distance, no work was done. Remember \( w = f \cdot d \) and if \( d \) (distance) is zero, then the product is zero – no work done.

### Collisions Definitions

**Elastic Collision**: a collision where the amount of kinetic energy is the same before and after the collision.

**Inelastic Collision**: a collision where some or all of the kinetic energy is converted into other forms of energy, such as work or thermal energy.

**Force (F)**: the impetus given to an object and calculated as mass times acceleration.

**Work (W)**: the movement of a mass through a distance and defined as force times distance.

**Gravitational acceleration (g)**: a constant on Earth indicating how fast an object is accelerated by gravity.

**Frictional coefficient (f)**: A numeric value that indicates the resistance an object encounters when moving over a surface.

### Other Abbreviations:

- \( m \) = mass
- \( v \) = velocity
- \( d \) = distance
- \( K \) = crush coefficient for the car
- \( x \) = crush depth measured
- \( S \) = speed at start of skid
The three equations above all say exactly the same thing but in slightly different ways – they all say that energy has been conserved – we’ve neither lost nor gained any energy, just changed it into different forms as the car stops.

When the brakes of a vehicle are quickly applied, such as during an accident, a major way that the kinetic energy of the vehicle can be reduced is through skidding (Figure 18.1.16). A skid occurs when the tires of a vehicle stop rotating (or rotate very slowly) while the car continues to move forward. During this process, some of the rubber from the tires is abraded away from the tire’s surface, leaving behind a dark streak of rubber on the surface of the road. Eventually, friction (and any collision) brings the car to a stop. The measured length of a vehicle’s skid marks can be used to provide an estimate of the vehicle’s minimum speed when it began to skid using the physics we’ve learned so far.

We consider that the energy transferred when a skidding car stops goes into friction. The work done through skidding, like all other forms of work, is then determined simply by the force times the distance traveled times a frictional coefficient (a value that relates to how well energy can be transferred between the two “rubbed” surfaces, in this case the car’s tires and the road surface). The energy done as work in this irreversible process (cannot go backwards into kinetic energy), is given by:

\[ E_{\text{work}} = F f d \]  
(Eqn. 18.9)

Since we know from Eqn. 18.5 that force also equals mass times acceleration, \( F = m g \) (in this, case the acceleration must be replaced by the constant of gravitational acceleration, \( g \), because of the action of gravity), we can substitute \( m \) times \( g \) into equation 18.9 for force to get

\[ E_{\text{work}} = (m g) f d \]  
(Eqn. 18.10)

So, finally we can put it all together. During skidding, a car starts with a certain amount of kinetic energy (Eqn. 18.3) that is entirely converted into the work energy of the skid that brings the car to a stop (Eqn. 18.10). Since all the initial kinetic energy of the car is transferred to the work energy of the skid (KE at the end of the skid is zero), we can set these two equations for KE (Eqn. 18.3) and \( E_{\text{work}} \) (Eqn. 18.10) equal to each other, or:
Eqn. 18.3 = Eqn 18.10
Energy initial kinetic = Energy skid work
\( \frac{1}{2} m v^2 = m g f d \)  
(Eqn. 18.11)
(Eqn. 18.12)

If we simplify this with the use a little algebra and solve this equation for \( v \) (velocity), we come up with:

\[ v = (2 g f d)^{\frac{1}{2}} \]  
(Eqn. 18.13)

**EQUATION FOR SPEED AT START OF SKID**  
(from skid without impact)

The equation above (Eqn 18.13) gives us a very easy way to calculate the minimum velocity necessary for a car to skid the measured distance (\( d \)) [note: \( g \) and \( f \) in the above equations are constants: \( g = 32.17 \text{ ft/s}^2 \) and \( f \) is 0.75 for dry pavement; \( f \) depends upon the surface being skidded over and, to a small extent, on the characteristics of the tires involved]. Equation 18.13 is sometimes called the “skid formula”.

An example of how it can be readily used to determine the speed of a vehicle at the beginning or at any point along a skid is given in the inset box “Example of Skid Mark Calculations”.

It is important to note that this formula works only when the vehicle skids to a stop without hitting anything. If a collision with a heavy object occurs, such as another vehicle or roadway object, then a more complicated formula must be used that takes into account the fact that some of the kinetic energy of the skidding car is transferred to the object struck in the collision, energy that is not transferred to the work of the skid through friction.

One common method to determine the amount of energy transferred upon collision uses a *crush depth* measurement. For example, based on measurements from test vehicles, a particular type of car might be found to require 4,500 pounds of force to crush in the front of the vehicle by a distance of one inch (Figure 18.1.17). This means that 4,500 pounds of force derived from the car’s kinetic energy must...
be used to cause the one-inch indentation. By measuring both the length of the skid marks and the amount of crush observed on a vehicle, the speed of the vehicle can be determined at all points along the vehicles path. In this case, all of the kinetic energy of the car is still transferred away as it comes to a stop, but the transferred energy is now distributed between the frictional work of the skid and the energy necessary to cause the observed crush. The revised equation which is used to calculate the speed of the vehicle at the beginning of the skid when some of the kinetic energy is used to crush in the car is shown in Eqn. 18.14:

\[
\text{Kinetic Energy} = \text{Skid Energy + Crush Energy} \quad (\text{Eqn 18.14})
\]

\[
\frac{1}{2} mv^2 = m g f d + Kx \quad (\text{Eqn 18.15})
\]

(where K is the measured crush coefficient for the car, x is the crush depth measured from the crashed car, and m is the mass of the car (not the weight) that is calculated by \( m = \frac{F}{g} \) where F is the force weight of the vehicle)

Crush energy is simply the amount of kinetic energy transferred from the car to the impacted structure (e.g. another vehicle or bridge abutment) which caused the observed indentation in the struck object. Once again, if we use a little algebra and solve this equation for \( v \) (velocity), we come up with:

\[
v = \left[ 2 g d f + 2 \left( \frac{K}{m} \right) x \right]^{\frac{1}{2}} \quad (\text{Eqn 18.16})
\]

**EQUATION FOR SPEED AT START OF SKID**
(with impact and crush factor)

![Simplified Formulas](http://x.vceinc.com/tag/skid-marks/)

An example of how Eqn 18.16 can be used to determine the speed of a vehicle involved in a collision at the beginning of a skid is given in the inset box “Example of Skid Mark Calculations with a collision”.

Using the appropriate formula for a given situation, it is relatively easy to determine if the vehicle was traveling faster than the posted speed limit prior to the accident – information that may carry important legal implications. These equations (Eqn. 18.13 for skids without a collision and 18.16 for skids with a collision) can be simplified even further by combining all the constants together to given the most common form of the equations employed by police investigators, shown in the box called “Simplified Formulas”.

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**Figure 18.1.17.** Measuring the crush distance from a collision in order to calculate the speed of the striking vehicle prior to the collision (http://x.vceinc.com/tag/skid-marks/).