chapter 93

BRAKING SYSTEM PRINCIPLES

OBJECTIVES: After studying this chapter, the reader will be able to: • Discuss the energy principles that apply to brakes. • Discuss the mechanical principles that apply to brakes. • Discuss the friction principles that apply to brakes. • Describe how brakes can fade due to excessive heat. • Describe how deceleration rate are measured.

KEY TERMS: Coefficient of friction 1024 • Energy 1022 • Friction 1024 • Fulcrum 1023 • Inertia 1023 • Kinetic energy 1022 • Kinetic friction 1025 • Leverage 1023 • Mechanical advantage 1024 • Pedal ratio 1024 • Static friction 1025 • Weight bias 1023 • Weight transfer 1023 • Work 1022

ENERGY PRINCIPLES

Energy is the ability to do work. There are many forms of energy, but chemical, mechanical, and electrical energy are the most familiar kinds involved in the operation of an automobile. ● **SEE FIGURE 93–1.**

For example, when the ignition key is turned to the "Start" position, chemical energy in the battery is converted into electrical energy to operate the starter motor. The starter motor then converts the electrical energy into mechanical energy that is used to crank the engine.

In the example above, energy is being used to perform work. **Work** is the transfer of energy from one physical system to another—especially the transfer of energy to an object through the application of force. This is precisely what occurs when a vehicle's brakes are applied: The *force* of the actuating system *transfers* the energy of the vehicle's motion to the brake drums or rotors where friction *converts* it into heat energy and stops the vehicle.

KINETIC ENERGY

Kinetic energy is a fundamental form of mechanical energy. It is the energy of mass in motion. Every moving object possesses kinetic energy, and the amount of that energy is determined by the object's mass and speed. The greater the mass of an object and the faster it moves, the more kinetic energy it possesses. Even at low speeds, a moving vehicle has enough kinetic energy to cause serious injury and damage. The job of the brake system is to dispose of that energy in a safe and controlled manner.

Engineers calculate kinetic energy using the following formula:

$$\frac{mv^2}{29.9} = E_k$$

where:

m = mass or weight of the vehicle in pounds (lb)
v = velocity of the vehicle in miles per hour
E_k = kinetic energy in foot-pounds (ft-lb)
29.9 = a constant

Another way to express this equation is as follows.

$$\frac{\text{weight} = \text{speed}^2}{29.9} = \text{kinetic energy}$$

If a 3,000-lb vehicle traveling at 30 mph is compared with a 6,000-lb vehicle also traveling at 30 mph as shown in ● **FIGURE 93–2,** the equations for computing their respective kinetic energies look like this:

$$\frac{3{,}000\text{ lb} = 30^2\text{ mph}}{29.9} = 90{,}301\text{ ft-lb}$$

$$\frac{6{,}000\text{ lb} = 30^2\text{ mph}}{29.9} = 180{,}602\text{ ft-lb}$$

The results show that when the weight of a vehicle is doubled from 3,000 to 6,000 lb, its kinetic energy is also doubled from 90,301 ft-lb to 180,602 ft-lb. In mathematical terms, kinetic energy increases *proportionally* as weight increases. In other words, if the weight of a moving object doubles, its kinetic energy also doubles. If the weight quadruples, the kinetic energy becomes four times as great.

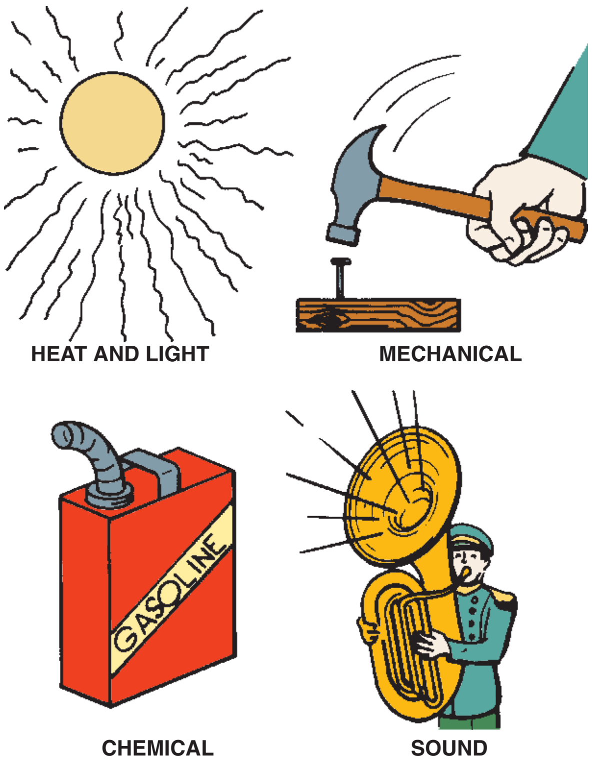

FIGURE 93–1 Energy which is the ability to perform work exists in many forms.

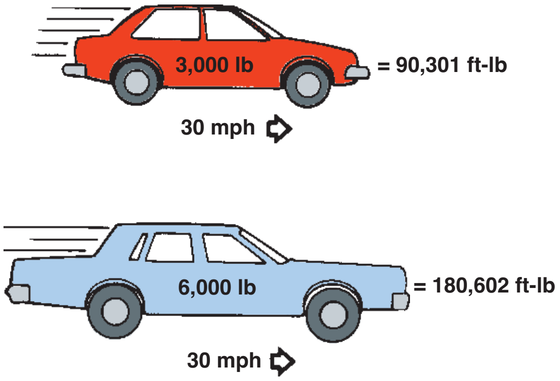

FIGURE 93–2 Kinetic energy increases in direct proportion to the weight of the vehicle.

If a 3,000-lb vehicle traveling at 30 mph is compared with the same vehicle traveling at 60 mph (● **FIGURE 93–3**), the equations for computing their respective kinetic energies look like this:

$$\frac{3{,}000\text{ lb} = 30^2\text{ mph}}{29.9} = 90{,}301\text{ ft-lb}$$

$$\frac{3{,}000\text{ lb} = 60^2\text{ mph}}{29.9} = 361{,}204\text{ ft-lb}$$

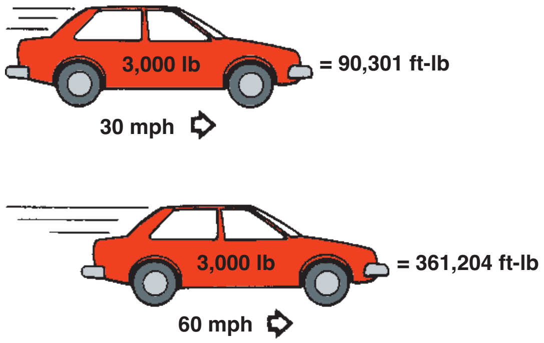

FIGURE 93–3 Kinetic energy increases as the square of any increase in vehicle speed.

The results show that the vehicle traveling at 30 mph has over 90,000 ft-lb of kinetic energy, but at 60 mph the figure increases to over 350,000 ft-lb. In fact, at twice the speed, the vehicle has exactly four times as much kinetic energy. If the speed were doubled again to 120 mph, the amount of kinetic energy would grow to almost 1,500,000 ft-lb! In mathematical terms, kinetic energy increases as the *square of its speed.* In other words, if the speed of a moving object doubles (2), the kinetic energy becomes four times as great ($2^2 = 4$). And if the speed quadruples (4), say from 15 to 60 mph, the kinetic energy becomes 16 times as great ($4^2 = 16$). This is the reason speed has such an impact on kinetic energy.

KINETIC ENERGY AND BRAKE DESIGN

The relationships between weight, speed, and kinetic energy have significant practical consequences for the brake system engineer. If vehicle A weighs twice as much as vehicle B, it needs a brake system that is twice as powerful. But if vehicle C has twice the speed potential of vehicle D, it needs brakes that are, not twice, but four times more powerful.

INERTIA

Although brake engineers take both weight and speed capability into account when designing a brake system, these are not the only factors involved. Another physical property, inertia, also affects the braking process and the selection of brake components. **Inertia** is defined by Isaac Newton's first law of motion, which states that a body at rest tends to remain at rest, and a body in motion tends to remain in motion in a straight line unless acted upon by an outside force.

WEIGHT TRANSFER AND BIAS

Inertia, in the form of **weight transfer,** plays a major part in a vehicle's braking performance. Newton's first law of motion dictates that a moving vehicle will remain in motion unless acted upon by an outside force. The vehicle brakes provide that outside force, but when the brakes are applied at the wheel friction assemblies, only the wheels and tires begin to slow immedi-ately. The rest of the vehicle, all of the weight carried by the suspen-sion, attempts to remain in forward motion. The result is that the front suspension compresses, the rear suspension extends, and the weight is transferred toward the front of the vehicle. ● **SEE FIGURE 93–4.**

The total weight of the vehicle does not change, only the amount supported by each axle. To compound the problem of weight trans-fer, most vehicles also have a forward **weight bias,** which means that even when stopped, more than 50% of their weight is sup-ported by the front wheels. This occurs because the engine, trans-mission, and most other heavy parts are located toward the front of the vehicle. ● **SEE FIGURE 93–5.**

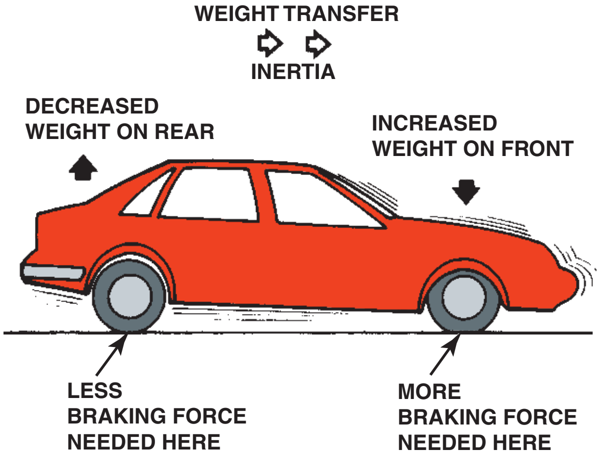

FIGURE 93–4 Inertia creates weight transfer that requires the front brakes to provide most of the braking force.

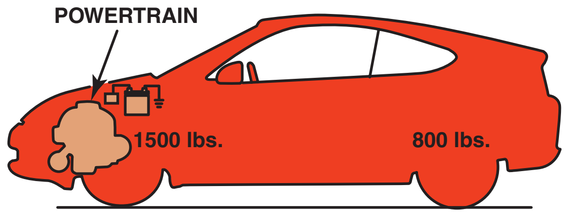

FIGURE 93–5 Front wheel drive vehicles have most of their weight over the front wheels.

TECH TIP

Brakes Cannot Overcome the Laws of Physics

No vehicle can stop on a dime. The energy required to slow or stop a vehicle must be absorbed by the braking system. All drivers should be aware of this fact and drive at a reasonable speed for the road and traffic conditions.

Front-wheel-drive (FWD) vehicles, in particular, have a forward weight bias. Whenever the brakes are applied, weight transfer and weight bias greatly increase the load on the front wheels, while the load on the rear wheels is substantially reduced. This requires the front brakes to provide 80% to 90% of the total braking force. To deal with the extra load, the front brakes are much more powerful than the rear brakes. They are able to convert more kinetic energy into heat energy.

MECHANICAL PRINCIPLES

LEVERS

The primary mechanical principle used to increase application force in every brake system is **leverage.** In the science of mechanics, a lever is a simple machine that consists of a rigid object, typically a metal bar that pivots about a fixed point called a **fulcrum.**

LEVERS IN BRAKING SYSTEMS

The levers in brake systems are used to increase force, so they are either first- or second-class. Second-class levers are the most common, and the service brake pedal is a good example. In a typical suspended brake pedal, the pedal arm is the lever, the pivot point is the fulcrum, and the force is applied at the foot pedal pad. ● **SEE FIGURE 93–6.**

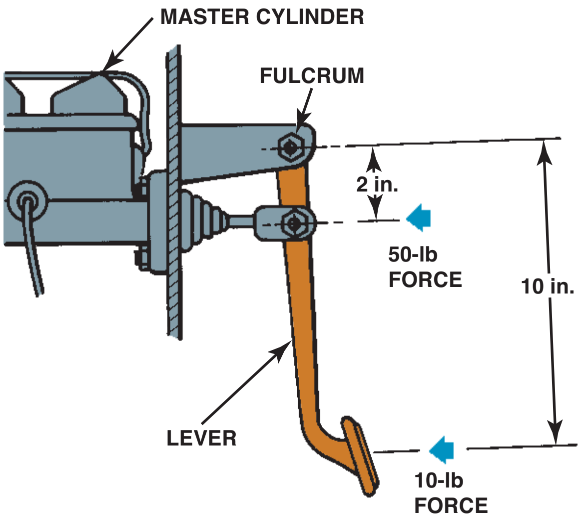

FIGURE 93–6 A brake pedal assembly is a second-class lever design that provides a 5 to 1 mechanical advantage.

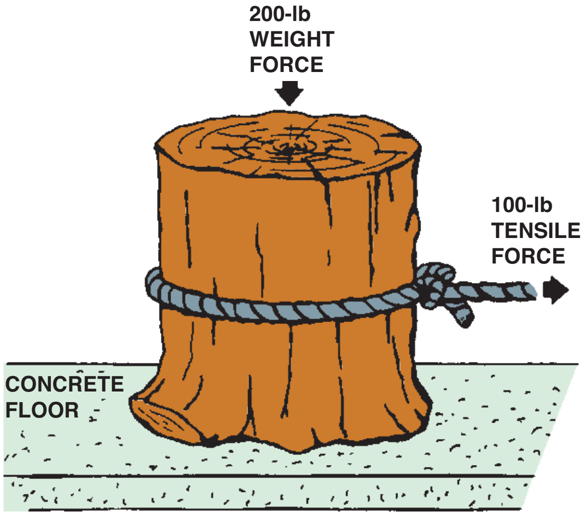

FIGURE 93–7 The coefficient of friction in this example is 0.5.

The force applied to the master cylinder by the pedal pushrod attached to the pivot is much greater than the force applied at the pedal pad, but the pushrod does not travel nearly as far.

MECHANICAL ADVANTAGE Leverage creates a **mechani-cal advantage** that, at the brake pedal, is called the **pedal ratio.** For example, a pedal ratio of 5 to 1 is common for manual brakes, which means that a force of 10 lb at the brake pedal will result in a force of 50 lb at the pedal pushrod. In practice, leverage is used at many points in both the service and parking brake systems to increase braking force while making it easier for the driver to control the amount of force applied.

FRICTION PRINCIPLES

The wheel brakes use friction to convert kinetic energy into heat energy. **Friction** is the resistance to movement between two surfaces in contact with one another. Brake performance is improved by increasing friction (at least to a point), and brakes that apply enough friction to use all the grip the tires have to offer will always have the potential to stop a vehicle faster than brakes with less ability to apply friction.

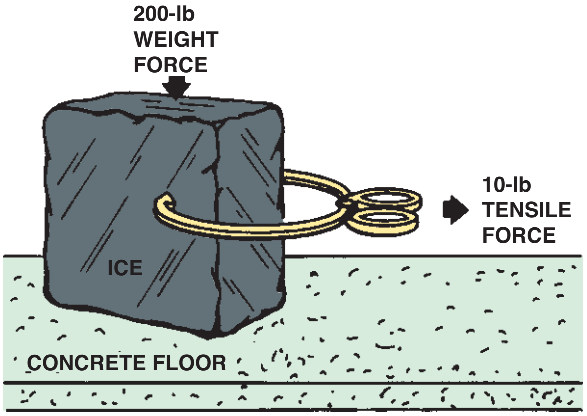

FIGURE 93–8 The type of friction material affects the coefficient of friction which is just 0.05 in this example.

COEFFICIENT OF FRICTION The amount of friction between two objects or surfaces is commonly expressed as a value called the **coefficient of friction** and is represented by the Greek letter μ (mu).

$$\frac{F_t}{G} = \mu$$

$$\frac{\textbf{Tensile force}}{\textbf{Weight force}} = \textbf{Coefficient of friction}$$

SURFACE FINISH EFFECTS The effect of surface finish on the friction coefficient can be seen in ● **FIGURE 93–7.**

In this case, 100 lb of tensile force is required to pull a 200-lb block of wood across a concrete floor. The equation for computing the coefficient of friction is as follows.

$$\frac{100\text{ lb}}{200\text{ lb}} = 0.5$$

The friction coefficient in this instance is 0.5. Now take the same example, except assume that the block of wood has been sanded smooth, which improves its surface finish and reduces the force required to move it to only 50 lb. In this case the equation reads as follows.

$$\frac{50\text{ lb}}{200\text{ lb}} = 0.25$$

The friction coefficient drops by half, and it would decrease even further if the surface finish of the floor were changed from rough concrete to smooth marble.

It is obvious that the *surface finish* of two connecting surfaces has a major effect on their coefficient of friction.

FRICTION MATERIAL EFFECTS Taking the example above one step further, consider the effect if a 200-lb block of ice, a totally different type of material, is substituted for the wood block. In this case, it requires only a 10-lb force to pull the block across the concrete. ● **SEE FIGURE 93–8.**

The equation reads as follows.

$$\frac{10\text{ lb}}{200\text{ lb}} = 0.05$$

The coefficient of friction in this example decreases dramatically to only 0.05, and once again, even further reductions would be seen if the floor surface were changed to polished marble or some other similar smooth surface.

It is obvious that the *type* of materials being rubbed together have a very significant effect on the coefficient of friction. The choice of materials for brake drums and rotors is limited. Iron and steel are used most often because they are relatively inexpensive and can stand up under the extreme friction brake drums and rotors must endure.

The brake lining material, however, can be replaced relatively quickly and inexpensively, and therefore does not need to have as long a service life. Brake shoe and pad friction materials play a major part in determining coefficient of friction. There are several fundamentally different materials to choose from, and each has its own unique friction coefficient and performance characteristics.

FRICTION CONTACT AREA

For *sliding* surfaces, such as those in wheel friction assemblies, the amount of contact area has no effect on the amount of friction generated. This fact is related to the earlier statement that brake friction materials always have a friction coefficient of less than 1.0. To have a friction coefficient of 1.0 or more, material must be *transferred* between the two friction surfaces. The amount of contact area does not affect the coefficient of friction, but it does have significant effects on lining life and the dissipation of heat that can lead to brake fade.

Tires are an example where contact area makes a difference. All other things being equal, a wide tire with a large contact area on the road has a higher coefficient of friction than a narrow tire with less contact area. This occurs because the tire and road *do not* have a sliding relationship. A tire conforms to and engages the road surface, and during a hard stop, a portion of the braking force comes from shearing or tearing away the tire tread rubber. The rubber's tensile strength, its internal resistance to being pulled apart, adds to the braking efforts of friction. A racing tire making a hard stop on dry pavement, for example, has a friction coefficient of 1.0 or better. The transfer of material between the two surfaces can be seen as skid marks on the pavement.

STATIC AND KINETIC FRICTION

There are actually two measurements of the coefficient of friction, the **static friction** coefficient and the **kinetic friction** coefficient. The static value is the coefficient of friction with the two friction surfaces at rest. The kinetic value is the coef-ficient of friction while the two surfaces are sliding against one another.

The coefficient of static friction is always higher than that of kinetic friction, which explains why it is harder to *start* an object mov-ing than to *keep* it moving. In the example shown in **FIGURE 93–9,** it takes 100 lb of tensile force to start the wooden block sliding, but once in motion, it takes only 50 lb to keep it sliding.

The relatively high static friction is harder to overcome than the somewhat lower kinetic friction. The static and kinetic friction coefficients for several combinations of materials are shown in **CHART 93–1.**

The difference between static and kinetic friction explains why parking brakes, although much less powerful than service brakes, are still able to hold a vehicle in position on a hill. The job of the parking brakes is relatively easy because the stationary vehicle has no kinetic energy, and the brake lining and drum or disc are not moving when they are applied. To start the vehicle moving, enough force would have to be applied to overcome the relatively high static friction of the parking brakes. The service brakes, however, have a much more difficult job. The moving vehicle has a great deal of kinetic energy, and the fact that the brake friction surfaces are in relative motion means that kinetic friction makes them less efficient.

FRICTION AND HEAT

The function of the brake system is to convert kinetic energy into heat energy through friction.

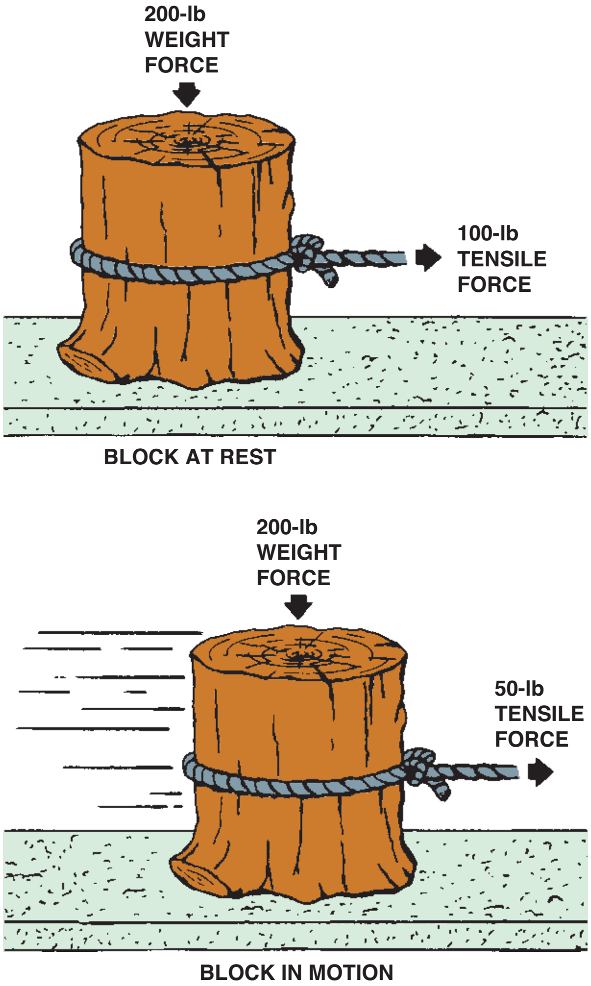

FIGURE 93–9 The static coefficient of friction of an object at rest is higher than the kinetic (dynamic) friction coefficient once in motion.

	COEFFICIENT OF FRICTION	
CONTACTING SURFACES	STATIC	KINETIC
STEEL ON STEEL (DRY)	0.6	0.4
STEEL ON STEEL (GREASY)	0.1	0.05
TEFLON ON STEEL	0.04	0.04
BRASS ON STEEL (DRY)	0.5	0.4
BRAKE LINING ON CAST IRON	0.4	0.3
RUBBER TIRES		
ON SMOOTH PAVEMENT (DRY)	0.9	0.8
METAL ON ICE	–	0.02

CHART 93–1

Every combination of materials has different static and kinetic friction coefficients.

It is the *change* in kinetic energy that determines the amount of temperature increase, and kinetic energy increases proportionately with increases in weight, and as the square of any increase in speed. If the weight of the vehicle is doubled to 6,000 lb, the change in kinetic energy required to bring it to a full stop will be 180,602 ft-lb.

The thicker and heavier the brake rotors and drums, the more heat they can absorb. Some of the heat is absorbed by the brake drums and rotors, some goes into the shoes and pads, and some is conducted into the wheel cylinders, calipers, and brake fluid. In addition, the front brakes provide 60% to 80% of the total braking force and they receive a similar percentage of the average temperature increase. The increase at each axle is divided evenly between the two wheel friction assemblies unless there is unequal traction from one side to the other, or there is a problem within the brake system itself.

DECELERATION RATES

Deceleration rates are measured in units of "feet per second per second" (No, this is not a misprint). What it means is that the vehicle will change in velocity during a certain time interval divided by the time interval. Deceleration is abbreviated "ft/sec^2" (pronounced "feet per second per second" or "feet per second squared") or meters per sec^2 (m/sec^2) in the metric system. Typical deceleration rates include the following.

- Comfortable deceleration is about 8.5 ft/sec^2 (3 m/sec^2).
- Loose items in the vehicle will "fly" above 11 ft/sec^2 (3.5 m/sec^2).
- Maximum deceleration rates for most vehicles and light trucks range from 16 to 32 ft/sec^2 (5 to 10 m/sec^2).

An average deceleration rate of 15 ft/sec^2 (3 m/sec^2) can stop a vehicle traveling at 55 mph (88 km/h) in about 200 ft (61 m) in less than 4 seconds. During a standard brake system test, a vehicle is braked at this rate 15 times. Temperatures at the front brake pads can reach 1,300°F (700°C) or higher, sometimes reaching as high as 1,800°F (980°C). Brake fluid and rubber components may reach 300°F (150°C) or higher.

REVIEW QUESTIONS

1. What is kinetic energy?
2. How is mechanical advantage used in the braking system?
3. What is the coefficient of friction?
4. Why do brakes fade due to excessive heat or water?

CHAPTER QUIZ

1. All of the following are correct statements about braking *except*:
 a. Kinetic energy must be absorbed by the braking system.
 b. Kinetic energy of a vehicle doubles when the speed doubles.
 c. The heavier the vehicle, the greater the kinetic energy when moving.
 d. If the vehicle weight is doubled, the kinetic energy of a moving vehicle is doubled.

2. Technician A says that the front brakes do most of the braking because the front brakes are larger. Technician B says that due to weight transfer, most of the braking force needs to be done by the front brakes. Which technician is correct?
 a. Technician A only
 b. Technician B only
 c. Both Technicians A and B
 d. Neither Technician A nor B

3. The brake pedal assembly uses a mechanical lever to ______________.
 a. Increase the driver's force on the brake pedal applied to the master cylinder
 b. Increase the distance the brake pedal needs to be depressed by the driver
 c. Decrease the driver's force on the brake pedal applied to the master cylinder
 d. Allow for clearance between the brake pedal and the floor when the brakes are applied

4. The friction between two surfaces is affected by all *except* ______________.
 a. Speed difference between the two surfaces
 b. Surface finish
 c. Frictional material
 d. Heat

5. Technician A says that the thicker or heavier the disc brake rotor, the more heat can be absorbed. Technician B says that the faster the vehicle is traveling when the brakes are applied, the greater the amount of heat created in the brake system. Which technician is correct?
 a. Technician A only
 b. Technician B only
 c. Both Technicians A and B
 d. Neither Technician A nor B

6. All of the following are types of brake fade *except* ____________.
 a. Mechanical fade
 b. Lining fade
 c. Gas fade
 d. Rotor fade

7. Brake fade caused by water can occur ______________.
 a. Only if the vehicle is driven in water above the centerline of the axle
 b. Whenever it rains and the roads are wet or damp
 c. Due to moisture in the air on a humid day
 d. Whenever driving through water puddles or during a severe rainstorm

8. What can the driver do to reduce the possibility of brake fade caused by heat?
 a. Ride the brakes to keep the shoes and pads against the drum or rotor
 b. Pump the brake pedal while descending a steep hill
 c. Select a lower transmission gear
 d. Shift the transmission into neutral and allow the vehicle to coast down long or steep hills

9. Maximum deceleration rates for a typical passenger car or light truck range from ______________.
 a. 1 to 3 ft/sec
 b. 5 to 10 ft/sec
 c. 16 to 32 ft/sec^2
 d. 200 to 250 ft/sec^2

10. Disc brake pads can reach temperatures as high as ______________.
 a. 300°F (150°C)
 b. 1,000°F (540°C)
 c. 1,300°F (700°C)
 d. 2,000°F (1,093°C)