CREW CHIEF NOTES: The Science of Safety

Introduction

The most dangerous event in racing is when a car hits another car or part of the track. Collisions are a very important part of science, whether they are between billiard balls or atoms. We can think about collisions in terms of energy *and* force: The two ways of thinking complement each other. Using both concepts allows students to see the relationships of these concepts to each other, and to think about the same problem in terms of two conceptually different frameworks.

This Note provides a brief review of force and energy, then shows how the two concepts relate to each other and to safety in auto racing.

Review: Energy

We generally can classify energy into a limited number of types: For example, kinetic energy, potential energy and electromagnetic energy. There are other types of energy, but they don't come into play in racing very frequently.

Kinetic energy is the energy of motion. Any moving object has kinetic energy, but there are a number of different kinds of kinetic energy.

Potential energy is the ability to make something happen. A raised hammer, a cat crouched back ready to pounce, or a compressed spring are all examples of potential energy.

Electromagnetic energy is energy that is carried by electromagnetic waves. Light and radio waves are examples of electromagnetic energy.

Units

The unit of energy is the ft-lb or joule. In SI units,

$$joule = \frac{kg\ \ m^2}{s^2}$$

Translational Kinetic Energy

We commonly treat objects in elementary physics as though they were point masses: All of the mass of a race car, for example, is treated as being concentrated at the car's center of mass. The translational kinetic energy *KE* of an object with mass *m* and speed *v* is

$$KE = \tfrac{1}{2}\, mass \times (speed)^2$$

$$KE = \tfrac{1}{2} mv^2$$

We usually call this just 'kinetic energy' because we often neglect other types of kinetic energy.

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Rotational Kinetic Energy

When we limit ourselves to treating objects as point masses, we may overlook other types of kinetic energy. In general, you can describe the motion of a car by the motion of its center of mass and the motion of the car about the center of mass. For example, a race car has rotational kinetic energy when it spins. The rotational kinetic energy KE_{rot} of a car with moment of inertia I and rotational speed ω is

$$KE_{rot} = \tfrac{1}{2}\, moment\ of\ inertia \times \left(rotational\ speed\right)^2$$

$$KE_{rot} = \tfrac{1}{2} I\omega^2$$

The moment of inertia measures how difficult it is to start an object rotating, just as the mass is an indication of how difficult it is to start an object moving.

Heat

Temperature measures the motion of the atoms in a solid, liquid or gas. The higher the temperature of a material, the more motion there is on an atomic scale and thus the more kinetic energy the object has. The units of temperature are Kelvin or degrees Celsius (metric) or degrees Fahrenheit (British).

The ***heat capacity*** is a property of a specific object. The heat capacity measures how much energy it takes to increase the temperature (i.e. the kinetic energy of the atoms) of that object. The units of heat capacity are J/K or ft-lb/°F. The heat capacity of an object depends on how much mass the object has because the more atoms or molecules there are, the more energy it can take.

The ***specific heat capacity*** is a property of a type of material and measures the amount of energy needed to raise a standard amount of the material by a specific temperature increment. For example, the specific heat capacity in the metric system is the amount of energy needed to raise the temperature of one gram of material by one degree Celsius.

The difference between heat capacity and specific heat capacity is that heat capacity refers to an object and specific heat capacity refers the material from which an object is made. For example, rubber as a material has a specific heat capacity, but a tire (which is made of a fixed mass of rubber) would be described by its heat capacity. Two tires made of the same rubber but having different masses could have different heat capacities, even though the rubber from which they were made has the same specific heat capacity.

Sound

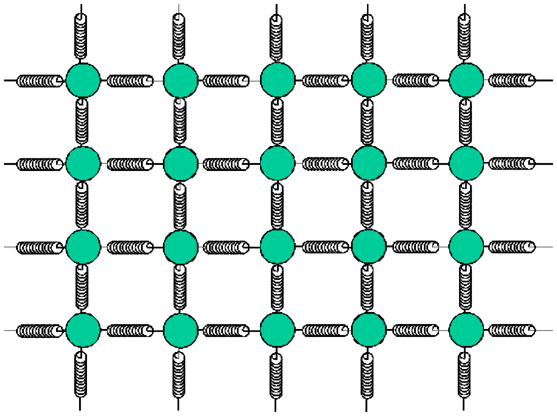
Sound is the motion of molecules, which makes sound a type of kinetic energy. As sound propagates, more and more molecules are involved, which means that the energy of the sound wave is distributed over more and more molecules. Each individual molecule increases its energy by a small amount. It is much more difficult to quantify the energy contained in a sound wave; however, the energy increases the larger the amplitude of the sound wave or the higher the frequency. The energy you experience from a sound wave also depends on how close you are to the sound source.

Elastic Potential Energy (Springs)

The elastic potential energy of a spring with spring constant k compressed or stretched an amount Δx is

$$\text{Elastic Potential Energy} = \frac{1}{2}\text{spring constant} \times \left(\text{change in length}\right)^2$$

$$PE_{elastic} = \frac{1}{2} k \left(\Delta x\right)^2$$



Energy in Atomic Bonds

Bonds between atoms store energy. You can think of the atoms in a solid, for example, as being held together by springs. Changing the equilibrium state of the material requires energy to stretch, compress or even break the chemical bonds holding together the atoms.

Conservation of Energy

The principle of conservation of energy says that energy is never created or destroyed, but is instead transformed from one type of energy to another.

Review: Forces, Momentum and Work

Momentum

The momentum *p* of an object depends on its mass *m* and speed *v*

$$\text{momentum} = (\text{mass})(\text{speed})$$

or

$$p = mv$$

The SI unit of momentum is $\frac{\text{kg} \times \text{m}}{\text{s}}$ while the British unit is lb-s.

Force and Momentum

The change in momentum is called the impulse which is the product of the force *F* and the time Δt over which the force acts.

$$\text{Change in momentum} = (\text{force}) \times (\text{time over which force acts})$$

$$\Delta p = F\ \Delta t$$

Work

The work *W* done when using a force *F* to move an object a distance *d* is

$$\text{work} = (\text{force}) \times (\text{distance})$$

or

$$W = F\,d$$

Work and energy have the same units: joules or ft-lbs.

Review: The Relationship between Work and Energy

Kinematics and energy are often taught as distinct units, which can make it difficult for students to see the relationships between the quantities.

The amount of work it takes to change an object’s speed is equal to the change in the object’s kinetic energy. The work is the product of the force times the distance, so

$$\text{Change in kinetic energy} = \text{Work done}$$

$$\Delta KE = W$$

This is the work-energy theorem. We can take this a step further and relate the kinetic energy to the kinematics quantities force *F* and distance *d*.

$$\text{Change in kinetic energy} = (\text{Force})(\text{distance})$$

$$\Delta KE = F\ d$$

Going one more step, we can use the relationship that the force is the change in momentum over the change in time to more directly link kinematics and energy quantities.

$$\Delta KE = \frac{\Delta p}{\Delta t} d$$

Racing and Safety

Safety from a Force Perspective

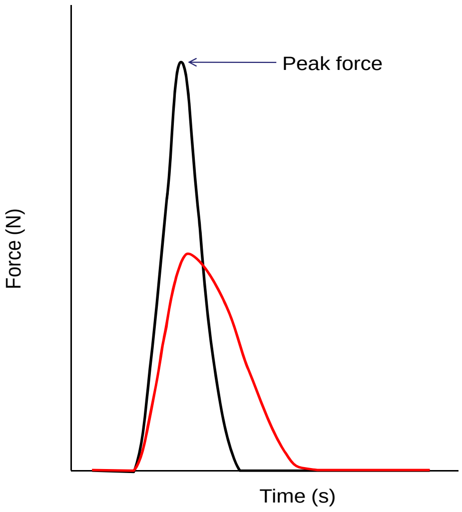
A car going 180 mph comes to a stop. The change in momentum is the same, regardless of the manner in which the car comes to a stop. A car coming into the pits slows from 180 mph to a stop. So does a car that hits a wall going 180 mph; however, the force the car experiences is very different if it comes to a stop because of an accident than if it comes to a stop by braking.

Compare two cars going 180 mph. One comes in to pit and takes 30 seconds to decrease its speed and come to a complete stop. The other hits the track wall and comes to a stop in 0.2 seconds. The change in momentum is the same for both cars.

$$\Delta p = F\ \Delta t$$

Since Δp is the same, the product of *F* and Δt must remain constant. A quick stop (small Δt) produces a larger force. A longer stop (large Δt) produces a smaller force.

Safety researchers study the force on the car as a function of time. The area under the curve of a plot of *F*(*t*) is the change in momentum. Students without calculus can count squares under the graph to approximate the change in momentum. Any two stops with the same initial and final speeds must have the same areas under the two curves. In the figure to the right, the black curve represents a stop occurring over a shorter time, which is why the peak force is larger. The red curve represents a longer stop and less peak force. Airbags work on this principle: By lengthening the time over which a person comes to a stop, the peak force is reduced. Padded dashboards work the same way.



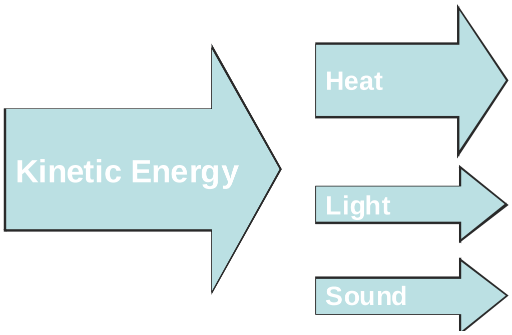
The ***peak force*** is the maximum force experienced. A large peak force, even if experienced for a very short time, can cause injury. A smaller force might be applied over a longer time and not cause as serious an injury. Many of the safety devices used in auto racing are designed specifically to decrease the peak force experienced by the driver, and to control which parts of the driver's body experience the majority of the force.

You can think about safety in terms of distance as well. The change in kinetic energy when a car comes to a stop is equal to the work done in stopping the car. If the car is to stop over a shorter distance, the force will be larger. A smaller force is required to stop the car over a longer distance. This is one reason that an accident involving a car rolling is less serious than an accident in which a car comes to a stop by hitting a wall. When the car gradually slows down over 200 feet, the force the driver feels is also spread out.

The key to safety from a force perspective is increasing the time (and thus the distance) over which the car comes to a stop. Although it may not seem very substantive, the SAFER (Steel and Foam Energy Reducing) barriers doubled the amount of time a car spends in contact with a track wall. That reduces the peak force by half, which can make the difference between a driver being sore and a driver being injured.

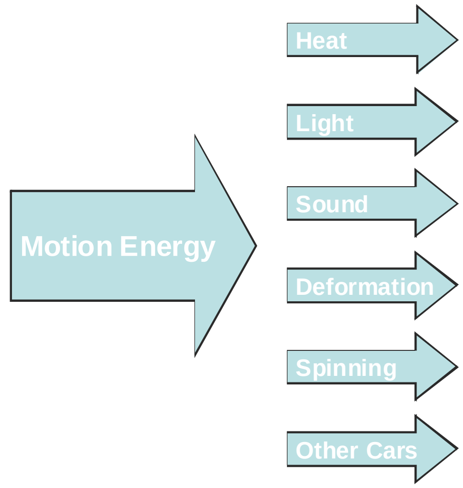
Safety from an Energy Perspective

When the driver puts on the brakes to come into the pits, all of the kinetic energy of the moving race car must be converted into other forms of energy. As shown to the right, the majority of the kinetic energy is converted into heat (from the friction between the pads and the brake rotors and also between the tires and the track), with the remainder converted into light (the rotors often get hot enough to glow) and sound (the brakes may squeal). There is always heat due to friction between the tires and the track, but if the car slides coming into the pit, there will be additional heat and perhaps additional sound energy if the tires screech. This situation is schematically illustrated in the figure to the right.



The transformation of energy in the case of a controlled stop in the pits

In the case of a collision, energy can still be transformed into sound (a car hitting another car or the wall), heat (produced by friction between two cars sliding against each other), and light (sparks from metal hitting metal, or from a piece of metal being dragged on the track). There are additional transformations involved in a crash however:



The transformation of energy is slightly different in the case of a crash. There are other types of energy involved and the distribution of energy may be different depending on the type of crash.

Rotational kinetic energy. When we talk about the kinetic energy of a racecar, we usually think of the translational kinetic energy of the car's center of gravity (CG). If a car spins, some of the translational kinetic energy may be changed into rotational kinetic energy. During a spin, additional friction is produced between the tires and the track, producing additional heat. Both of these decrease the translational kinetic energy.

Motion of other objects. It takes work to change the speed or the direction of another car. If car A hits car B, causing it to change direction or speed, that requires transferring some of car A's kinetic energy to car B. Car A's kinetic energy decreases while car B's kinetic energy increases by a corresponding amount.

If parts of the car come off the car and move independently of the car's center of mass, they carry kinetic energy away from the car. If the part has a high mass, it can be dangerous: This is why NASCAR requires very strong tethers on the rear axle, hood, decklid and wing that connect these parts to the car's chassis. If, for example, the hinges holding on the hood are broken, the hood will stay attached to the car. If it fell off, it would create hazards for other drivers or spectators.

Deformation: When a fender is crushed, two types of energy are involved in the deformation. First the atoms in the part of the fender that is crushed have to be moved, and that requires energy. Although each atom has a small mass, there are a lot of atoms in a fender. Second, the chemical bonds that hold the atoms together must be disturbed or even broken. Some bonds take more energy to break than others, which is why some materials break before others.

The key to safety in terms of energy is controlling how the kinetic energy of the racecar is converted into other forms of energy. A racecar going 180 mph has about nine times as much kinetic energy as a passenger car going 60 mph, so there is much more kinetic energy to be converted. As much energy as possible should be transferred to things other than your driver. You'd also like to make sure that as much of the conversion as possible involves things you can easily fix, like crumpled sheet metal as opposed to a smashed engine.

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The Numbers

The NASCAR car has a minimum weight of 3450 lbs (1565 kg). When you add in a typical 150-lb driver, the total weight is about 3600 lbs (1633 kg). Compare this with the corresponding street vehicles.

Car	Weight (lb)	Mass (kg)
2009 Toyota Camry	3680 (1)	1669
2009 Ford Fusion	3160 (2)	1433
2008 Dodge Avenger	3738 (3)	1696
2008 Chevy Impala	3674 (4)	1667

Compare the kinetic energy of a stock car to that of a passenger car:

$$KE_{car} = \tfrac{1}{2}(1678\,\text{kg})(27.0\,\tfrac{\text{m}}{\text{s}})^2 \qquad KE_{stockcar} = \tfrac{1}{2}(1633\,\text{kg})(80.5\,\tfrac{\text{m}}{\text{s}})^2$$

$$= 6.11 \text{ x } 10^5\,\text{J} \qquad = 5.29 \text{ x } 10^6\,\text{J}$$

Using the numbers for a passenger car, if you come to a stop in 90.0 m, you'd feel a force of $6.79\text{x}10^3$ N, whereas you would feel $5.88\text{x}10^4$ N

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