GEOS 24705 / ENST 24705
Problem set #16
Due: Tues. May 24

Problem 1: Automobile tour

Find an automobile and take a look under the hood. Take photographs and identify and label as many parts as you can.

Everyone should muster the resourcefulness to find a car to inspect, even if you don't own one or have any friends who own one. If you go to the cab stand by the U Chicago hospital and find several cabs in line, I am sure that the last guy in line would be happy to open his hood (perhaps for $10) and let you take a look. Various gas stations that repair cars would likely let you take a peek. University employees who are parked for some reason can likely be persuaded to open their hoods.

Note that old cars are generally easier to understand than newer cars (though often dirtier). For extra credit, find a newish car and an old car and compare them. Hybrids are very complicated – you can do a hybrid too for extra credit but start by looking at a more conventional car.

Please do not feel obliged to crawl underneath a car; what you can see from the top is fine for this problem set. If you do want to crawl underneath, that's great, but do not do so unless you have first "chocked" the wheels to prevent inadvertent rolling.

Googling is fine – encouraged – to understand what you are seeing or what you should expect to see. (There are some excellent diagrams of systems in the automobile at http://www.sundevilauto.com/auto-diagrams). However, do not submit digital photographs taken by someone else. You have to go look with your own eyes.

Try to identify something from each of the areas below. If you think the car does not actually have some component, explain why you think it does not.

A. Engine block – how many cylinders does the car have? Are they vertical, horizontal, or in a V? Remember that for a four-stroke engine, each cylinder will have two valves.

B. Ignition system. Identify the spark plugs that ignite each cylinder, and find the distributor cap that sends electrical signals to the spark plugs. (Recent cars may not have this). The distributor cap should in turn be connected (eventually) to the battery which is providing power for the spark plugs.

C. Air/fuel system. The air that gets mixed with the fuel comes from outside the car. It is piped in through large tubes, passes through an air filter, and is distributed evenly to each cylinder via an "intake manifold". The air filter enclosure should be accessible and readily visible as you have to change filters frequently. Fuel is added before the air enters the cylinder. In a pre-1990 gasoline car, air and fuel are mixed in a flying-saucer-shaped carburetor sitting on top of the engine. Modern cars all operate by fuel injection; you should be able to identify the fuel injectors and the fuel lines that feed them. If you have a turbocharged car, you'll also see a compressor that pre-compresses air before it enters the cylinders. The rest of the fuel

system is typically quite difficult to see, but trace the fuel lines as far as you can.

Somewhere buried way down there is an (electric) fuel pump that moves fuel from your gas tank to the engine; this will be underneath your car at best and possibly actually inside the gas tank.

D. The electrical system of the car, which includes a battery and an alternator (a generator) turned by the engine's rotation that makes electrical power to charge the battery. (There is a picture of an alternator in the first electricity reading – car alternators are usually simple AC generators, with their output rectified to produce DC for the battery). The belt connecting the alternator to the engine should be visible from above, and you should be able to find and identify the alternator. There is an electric starter motor that turns the crankshaft when you are first getting your engine started, but this is likely impossible to see.

E. The cooling system for the engine – if 75% of fuel energy is coming out as waste heat, then something has to remove all that waste heat! The cooling system consists of tubes and hoses that circulate water (or other coolant fluid) around the engine cylinders, a radiator that lets the hot fluid cool off, a fan to blow air around the radiator, and the fan belt that uses the rotation of the engine to turn the fan. There is a water pump that circulates cooling fluid but that is usually difficult to see from above.

F. The lubrication system. At minimum you'll be able to find the "dipstick" that goes into your oil reservoir and lets you check the oil. The oil pan containing the oil might be hard to see. The oil pan is often the lowest part of the car's engine assembly (and the first thing to break if you drive over rocks or other obstacles that are too high). The oil filter is accessible, since you have to change it periodically, but it is likely only visible if you crawl under the car. (Read caution above if you want to try this). There's an electric pump to move the oil around, either in the oil pan or attached to it; again, generally not visible.

G. The transmission that connects your engine's rotating crankshaft via gears to the front axle (for front-wheel-drive cars) or to the driveshaft and rear axle (for rear-wheel-drive cars) is typically hard or impossible to see from above. You may be able to identify if your car is front-wheel or rear-wheel or all-wheel drive, though.

H. *(Optional)* If you are looking at a hybrid car, identify the electric motor/s and the generator that charges the battery (which will be much bigger than the little alternator on conventional cars).

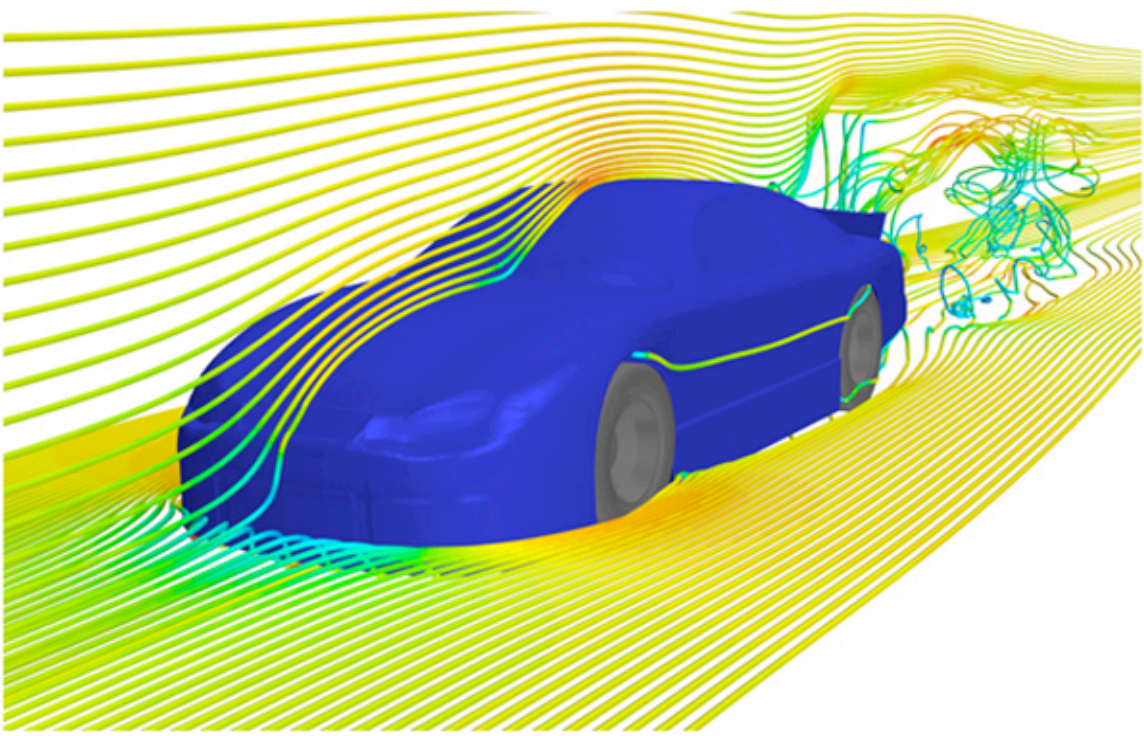
Problem 2: Air resistance and fuel economy

A wind turbine *extracts* the kinetic energy from a stream of moving air, slowing the air down in the process. A moving car does the exact opposite of a wind turbine – it bumps into stationary air and *give*s it kinetic energy, speeding the air up as it is pushed ahead of the car. Because energy is conserved, the car has to give up some of its own energy to the air to get the air moving. "Air resistance" or "aerodynamic drag" is therefore one of the important energy losses involved in driving.

You have already computed the kinetic energy / time carried by a fluid flow: $P = ½ \rho A v^3$. It would be reasonable to guess that a car with cross-section A had to exert this much energy/time to push air ahead of it. But car doesn't just stop the air, and the shape of the car can help reduce the amount of energy that must be transferred to the air. The more streamlined the car shape, the more easily the car can slice through air without disrupting it. We can account for that reduction in energy expenditure just by including a "shape factor" coefficient (call it C_d) that depends on the car shape. The drag losses of a car are then given by

$$P_{lost} = ½ \rho A v^3 C_d$$

The shape coefficient Cd can range between 1 (for a perfectly blocky car that accelerates all the air it strikes up to the speed of the car) to 0 (for a perfectly streamlined car that does not disturb the air at all). A boxy car will have higher C_d, a sleek car lower C_d. A Hummer is $C_d \sim 0.6$ while a Porsche Boxster is ~ 0.3.



Note that the Porsche has low C_d not because its designers wanted to be super-green – in fact, sports cars aren't very fuel efficient – but because they go fast, and the v^3 dependence means that aerodynamic drag matters much more at high speed. Porsche's 1900 car could be upright and square because it went slowly, but the fast Boxster has to be sleek not to have unacceptable energy losses to air

resistance. Electric cars, which are fuel-limited since batteries are so heavy, are also streamlined to keep C_d low to use less power and extend their ranges.

For any car shape, you obviously reduce your aerodynamic losses if you drive more slowly: the v^3 dependence means that fast is bad for gas mileage. You saw in class that we got smaller cars after the 1973 oil crisis when OPEC imposed an oil embargo on the U.S., shortages led to empty gas pumps, and prices spiked. "No more gasoline" signs on empty stations made U.S. very nervous suddenly about its dependence on foreign oil, and led to the introduction of the 55 mile-an-hour speed limit. The speed limit wasn't imposed for safety reasons – it was imposed in 1974 across much of the U.S. via the Emergency Highway Energy Conservation Act specifically to reduce gasoline use.

In this problem, you'll decide whether the 55 mph speed limit was a practical way of reducing our dependence on foreign oil.

Assumptions: you can assume you have a middle-of-the-road car with C_d ~ 0.4 and an overall fuel economy of ~27 miles per gallon when driving ~55 mph on the freeway. Make reasonable estimates about car size.

A. Compute your gasoline consumption in gallons per hour if you are driving at 55 mph. Check if it's consistent with your intuition.

B. Now convert units to state your total power consumption in W.

C. Compute your power loss to aerodynamic drag at 55 mph (from the equation in this section).

D. What fraction of your gasoline consumption goes to aerodynamic drag? Is that consistent with the rule-of-thumb division of "where the energy goes" stated in class?

E. Now compute what the power loss to aerodynamic drag would be if you increased speed to 70 mph.

F. What fractional change in gasoline consumption per mile results from driving 70 mph instead of 55 mph?

G. Was the Emergency Highway Energy Conservation Act a plausible way of reducing oil usage significantly?

H. *(Optional)* How fast can a Boxster drive before it exceeds the aerodynamic losses of a Hummer driving at 55 mph?

I. *(Optional)* From aerodynamics alone, how much worse is the gas mileage of a Hummer than that of a Boxster, if both are driven at 55 mph? Assume all else about the cars is equal. (In practice other factors also make the Hummer less efficient).

J. *(Optional)* Formula One racing cars are intended to go very fast, in races where fuel consumption matters, but they don't act like Boxsters – instead, they have have drag coefficients close to 1. Aerodynamically they seem more "blocky" even than Hummers. Presumably this is a deliberate design choice (and the engineers are good). Why was it chosen?

Problem 3: Rolling resistance

Background. There are two kinds of friction important for wheels. "Static friction" is what keeps two non-moving bodies from slipping against each other when you apply an external force. We sprinkle sand on icy sidewalks to increase the static friction, so that people don't slip. The force of "kinetic friction" on the other hand is what you'd need to apply to keep two surfaces moving relative to each other. Think of static friction as a thin layer of glue that has a breaking point that allows motion, and kinetic friction as "stickiness" that you have to push through to keep moving. A person who leans back while standing on ice starts to slip if the forward force he's applying to his foot exceeds the static frictional force that would keep him standing. He *keeps* slipping and falls on his behind only if the force he's applying to the ice also exceeds the kinetic frictional force. This is generally what happens, though because coefficient of kinetic friction is usually less than that of static friction. Once you "break through" the static friction and start moving, you keep moving.

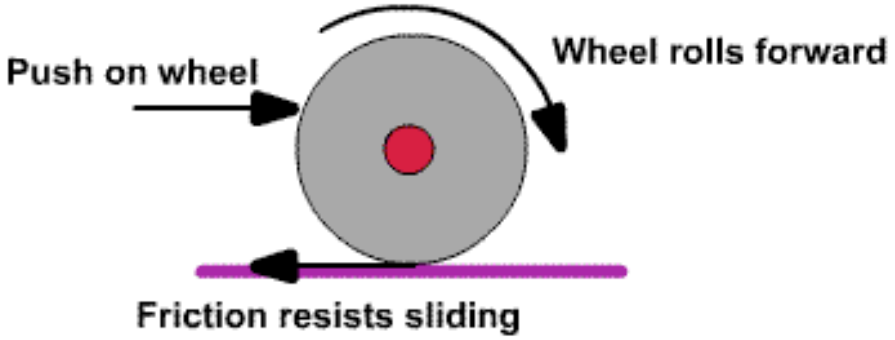
One you get moving, kinetic friction necessarily leads to dissipation of kinetic energy. The surfaces "scraping" past each other convert some kinetic energy to heat. When you rub your hands together, your palms get warm because of the kinetic friction between the two moving surfaces. In summary:

The force of static friction keeps stationary things from moving when you push on them.

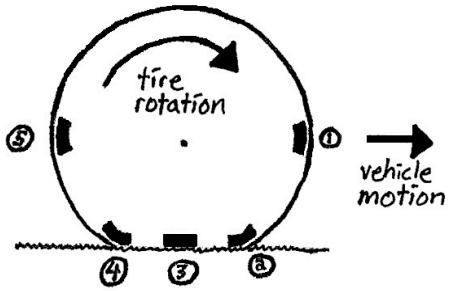
The force of kinetic friction is the push you must apply to keep moving things in motion.

Static friction is relevant to moving wheels because one point on the wheel is in fact stationary with respect to the road. Imagine a wheel with a perfectly circular tire that makes contact with the road only at one point. The wheel rolls *around* that contact point – the contact isn't sliding across the ground. (If you haven't thought about how rolling works before, this may seem counterintuitive, but think on it).

Since you're exerting force on the wheel, you need static friction to make sure that stationary point in fact stays stationary. Think of starting a car from a standstill. You put a big force on the wheel to get it turning. Why shouldn't the wheel just spin in place? Without friction, it would spin, but if static friction is big enough to keep the wheel stuck at its contact point, then the wheel has to roll forward instead. That's the desired operation, and is usually what happens when we get in a car and push the accelerator, but most of us have experienced static friction failure before: think of trying to start a car on ice. Static friction is the driver's friend.



Kinetic friction is ***not*** the driver's friend. Kinetic friction produces irritating losses of energy. It comes into play only because real-world tires aren't perfectly circular but deform. (The ground or road may be soft and deform as well). Any deformation means there is contact between the road and parts of the tire that other than the stationary point. That means that as the tire rolls forward, it is constantly "scraping" some parts of the tire along the road and losing energy as heat.



What you'd ideally do is make your tires and road surfaces out of some special combination of materials that produces very large static friction (to keep wheels from spinning out) but very small kinetic friction (to prevent losses while driving). Unfortunately however the two types of friction tend to go together, and that magic material combination doesn't seem to exist.

In this problem you'll predict a formula for power lost to rolling resistance, i.e. to the kinetic friction between the car and the road. Remember:

* The ***force*** of "kinetic friction" is related to the deformation of the tire and to the stickiness of the tire against the road.

* The ***power dissipated*** by kinetic friction during rolling depends both on the force of kinetic friction and on how the tire and road are moving relative to each other.

A. Write down all the factors that you think the power dissipated (P) might be related to. Write them all down, but then you can combine anything that has to do with the properties of the tire itself, or the road, into a coefficient Crr.

B. Decide whether the power dissipated likely linear with each factors.. or should the factors be squared? Etc. Once you decide, you can just write down your equation (P = ….). If you are just guessing, say so, but make a reasonable guess. We'll discuss in class.

C. We said in class that in normal driving for a car, losses to air resistance and losses to rolling resistance were about similar. What if you slow down to bicycle speed, though? Based on your formula in B, would you then care about air resistance or rolling resistance equally, or more about air resistance, or more about rolling resistance? Is this consistent with your intuition for how bicycles are differently designed?

D. *(Optional)* Derive the power loss to kinetic friction more exactly than your guess above. First, write down force the car exerts on the ground – the "normal force". Then write the force of friction, which is proportional to the normal force.

E. *(Optional)* Now, write an equation that explains how power dissipated (energy/time) is related to whatever force is causing that dissipation.

F. *(Optional)* Combine E and F to produce the formula for power dissipated from rolling resistance. Is it the same as your guess in B?

G. *(Optional)* Look at the specs for some actual tires: see tire properties collected by tha California Energy Commission at http://saturn.lynnautorepair.com/2009%20Rolling%20Resistance%20Efficiency%20Ratings%20for%2077%20Tires

   The tires are ranked by a coefficient of kinetic friction that is proportional to C_{rr}, lowest friction at the top of the page and highest at the bottom. You might think the tires with the lowest rolling resistance would be the most desirable and would cost more, but scanning the prices you'll realize that there isn't systematic variation in price along the page. So – why would someone want to pay good money for a tire at the bottom of the page that has more energy losses? Relate your answer to the other tire information provided here.

H. *(Optional)* Use the thinking you developed in the questions above to explain why tires for bicycle racing look so different from those for auto racing. What are the considerations driving the design choices?

Michelin Pro3 Race tire, 116 psi

Pirelli PZero Formula 1 race tire: ~15 psi

Problem 4 *(optional):* Automobile history virtual tour

Take a virtual tour through the early history of the automobile in the U.S. at this terrific website: http://earlyamericanautomobiles.com/1890a.htm (and links to other decades). Pick three different time periods, read the pages on the autos from each period, pick a feature or features to focus on, and evaluate the evolution of that feature.

You might want to consider

- Basic design and architecture: how do you steer, where is the engine, how are the wheels suspended, etc.
- Relative fraction of steam vs. electric vs. gasoline powered cars. (You should see the oddballs go away as the industry standardizes)
- Diversity of companies represented, and company lifetimes. Again, watch diversity diminish, though of course this collectors' website will be biased to finding examples of oddballs instead of giving a statistically representative sample.

Problem 5 *(optional):* Automobile history remedial education

Dig up some information on automobile history that I don't know but should

- Who was Audi? Where does the "Mercedes" in "Mercedes-Benz" come from?
- When did all those Italian companies start? (Maserati, Lamborghini, Ferrari). Were they technological innovators or did they just package German inventions? What is their relation to the foundational German/Austrian companies?
- How did Japanese automobile manufacturing get going in the 1970s-80s? Was it state-subsidized, or purely private?