

Air resistance and rolling resistance losses

GEOS24705 notes

EJM 5/24/2014

About half of the mechanical work output by a car engine goes to the replacing the kinetic energy lost to air resistance and to the rolling resistance of tires against the road surface. If you had perfect tires and drove your car in a vacuum you'd need to output only half the mechanical work that you otherwise would, and so would have higher gas mileage. Reducing losses to air resistance and rolling resistance are therefore possible strategies for increasing vehicle fuel economy.

Rolling resistance. 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 the "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. Now, you can derive some scientific insight from the observation that generally, people who start to slip on ice DO fall on their behinds. That tells you that in a given system, the 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.

Once you get moving, kinetic friction necessarily leads to dissipation of kinetic energy. The surfaces "scraping" past each other convert some kinetic energy to heat. (You can see this when you rub your hands together: your palms get warm because of the kinetic friction between the two moving surfaces.)

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, the wheel 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.*

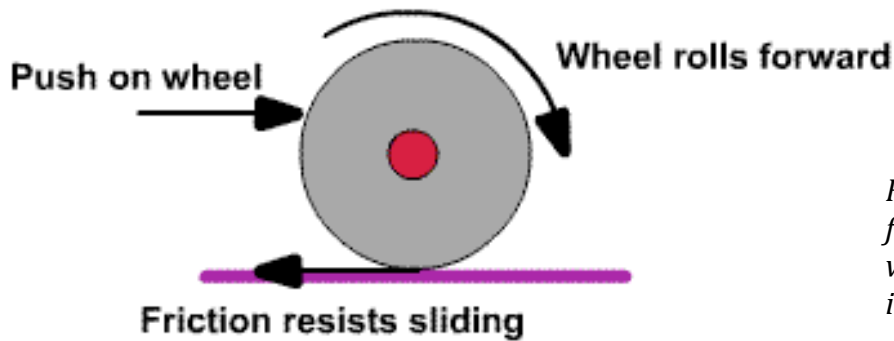


Figure: static friction allows a wheel to roll instead of sliding.

*Kinetic friction, on the other hand, 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.

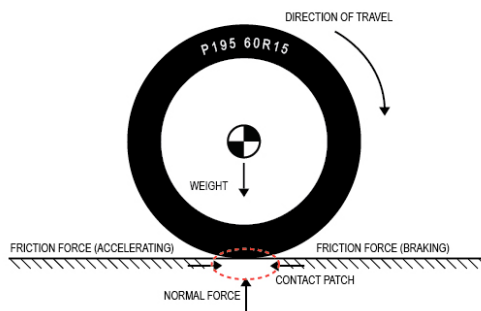


Figure: kinetic friction causes energy losses while rolling.

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.

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 no one has yet been able to develop a magical combination with high coefficient of static friction and low coefficient of kinetic friction.

How does kinetic friction translate into energy losses? The force of rolling resistance is proportional to the car's weight (mg) times a coefficient C_{rr} that captures the deformation of the tire and the stickiness of the tire against the road:

$$F = C_{rr} * m * g$$

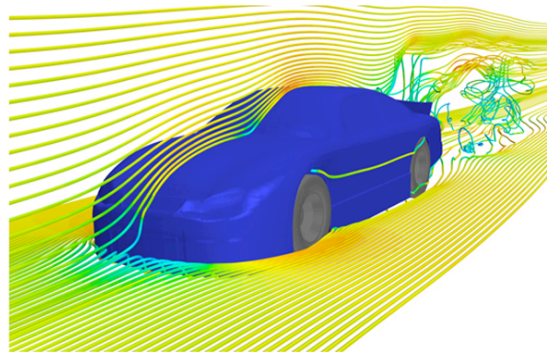
The power dissipated by kinetic friction is the force of kinetic friction multiplied by the speed (power = energy/time = force*distance/time): so $P_{lost} = C_{rr} m g v$

Air resistance: 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 *gives* 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. That energy loss is terms “air resistance” or “aerodynamic drag”.

You have already computed the kinetic energy / time carried by a fluid flow: $P = \frac{1}{2} \rho A v^3$. 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 , for “coefficient of drag”) that depends on the car shape. The drag losses of a car are then given by

$$P_{\text{lost}} = \frac{1}{2} \rho A v^3 C_d$$

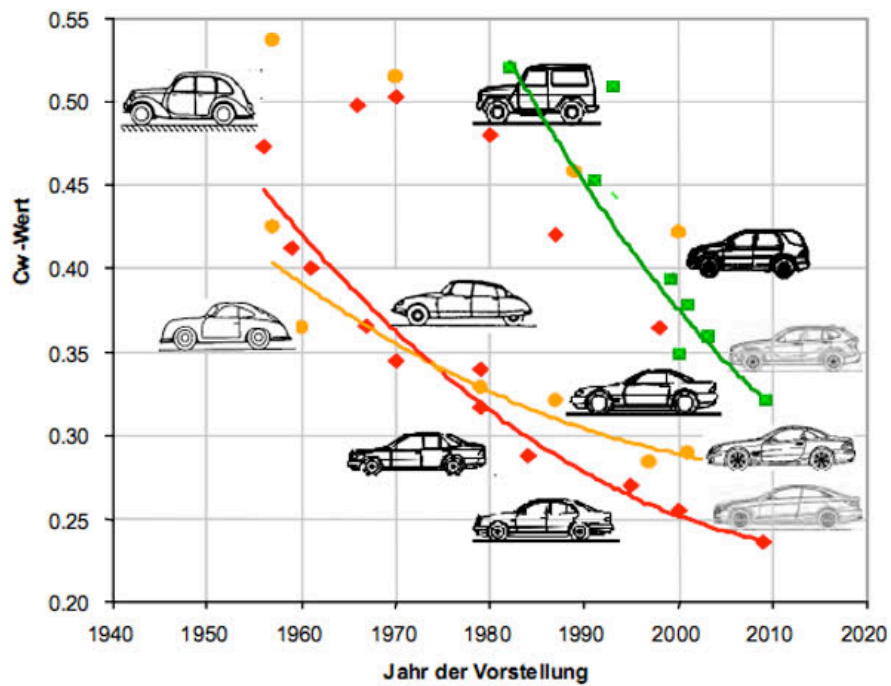
The shape coefficient C_d can in theory range between 1 (accelerating all the air a car strikes up to the speed of the car) to 0 (not disturbing the air at all). A boxy car will have higher C_d , a sleek car lower C_d . A Hummer H2 has $C_d \sim 0.6$ while a Porsche Boxster is ~ 0.3 .



Automobile performance.

Both coefficients of both rolling resistance and drag coefficients have generally decreased for passenger cars over time. That is, tires have become less “sticky” (lower C_{rr}) and cars have become sleeker (lower C_d) (see figures below). Both reductions may be motivated by fuel economy but also by performance considerations. This is especially true for C_d , because air resistance depends on v^3 - -- aerodynamic drag matters much more at high speed -- and cars have gotten much faster. Energy losses quickly become unacceptable as speeds rise. If your engine's power is mostly going just to maintain speed, you have no leftover power to accelerate. Porsche's 1900 car could be upright and square because it went slowly, but the fast Boxster has to be sleek.

Both types of losses may get increasing attention because of new mandated improvements in fuel economy and because of the constraints of electric cars, which are fuel-limited since batteries are so heavy. Electric cars have a high premium on keeping losses low to extend their range between charges.



Figures: Above, caption translates as “The evolution of the Cww-value for different automobile categories: red: sedans/coupes, yellow: sports cars, green: SUVs. Source unknown. Below, rolling resistance for tire samples from 1982-2005, from “Tires and Passenger Vehicle Fuel Economy”, the National Research Council, available at <http://onlinepubs.trb.org/onlinepubs/sr/sr286.pdf>

