# Lessons on Fuel Economy
## #1 Tires /Ernie Rogers

The purpose of this discussion is to help a car owner get the best possible fuel economy from his car, any car. Many of the ideas here are also found at www.TDIClub , a great place for fuel economy ideas. At times I may talk about parts that are difficult to change, but mostly I will suggest ideas that are easy to do. Let's talk about tires and some general principles about fuel economy. Later, I promise to write about some other topics, including air drag.

## GENERAL PRINCIPLES

It takes fuel to make power. So your car consumes fuel in proportion to the power delivered to the wheels. The power needed by the wheels is the force to keep moving multiplied by how fast you are going. We can make an equation out of this—

We'll measure the fuel flow in gallons per hour.
Define a proportionality constant for how much fuel is needed, $C_1$
Call the force to move the car F(pounds) and the speed of the car v(miles per hour).

Putting the information together, we get:

$$\text{Gallons per hour} = C_1\, F(\text{pounds})\, v(\text{miles per hour}).$$

If you divide the Gallons per hour by the v(miles per hour), you get something that is a measure of fuel economy:

$$\text{Gallons per mile} = C_1\, F(\text{pounds})$$

Gallons per mile is the inverse of miles per gallon. This little formula teaches a powerful lesson about how parts of the problem are related to fuel economy. It says you should add up all of the forces opposing the motion of the car, and multiply that total force times $C_1$, a number representing various other aspects of car efficiency such as the energy content of the fuel, the efficiency of the engine, and other losses from things like the gears and bearings, etc.

Looking at fuel economy in gallons per mile is helpful because we can see how the drag forces (and other forces) add together to cause consumption of fuel. (In Europe, the normal fuel economy units are liters per 100 km, a very nice choice.) Let's use gallons per mile for awhile, and when we want we will switch to the inverse, miles per gallon.

With fuel prices getting way out of line, we would like to lower both $C_1$ and F. Today's discussion about tires involves one part of the total F. The total force the car must fight has four parts, representing air drag, energy to turn the wheels and tires, energy for acceleration, and energy to overcome gravity when going uphill. *

$$F = \text{air drag} + \text{wheel rolling resistance} + \text{mass times acceleration} + \text{uphill grade.}$$

To summarize, $C_1$ is some constant related to the fuel and the efficiencies of various car parts (and of course they aren't always exactly constant). $C_1$ multiplied by the forces opposing the car's motion gives a good measure of fuel economy. The forces can be looked at one at a time and then added together.

## TIRES AND ROLLING RESISTANCE

The force due to energy losses by the tires is the "rolling resistance." Even choosing a set of tires has a scientific basis and can be demonstrated mathematically, for those who remember some algebra. There is a simple formula for rolling resistance, $F_{rr}$:

$$F_{rr} = C_{rr} Mg$$

This discussion will be about how to make the rolling resistance smaller. The first factor, $C_{rr}$, is the "rolling resistance coefficient," a commonly-used "constant" to indicate the efficiency of tires. Mg (mass times earth gravity) is the weight of the car. In truth, the rolling resistance coefficient can vary a little bit with speed so it's not really constant, and other things besides the tires can be involved—but let's ignore such details.

The first obvious way to lower rolling resistance is to throw away non-essential parts of your car, to lower the weight. Let's skip that option for now. That leaves finding ways to change the tire characteristics to lower their essential efficiency property, the rolling resistance coefficient. One might ask, "how much does my car's miles per gallon depend on $C_{rr}$?"

Answer: For ordinary car tires, the rolling resistance coefficient varies from about—

$C_{rr} = 0.012$ (cheap tires) to $C_{rr} = 0.0060$ (very good tires).

So, rolling resistance can change by as much as a factor of two, depending on your tires. For a modern, efficient car, the effect on fuel economy is—

Cutting Crr in half causes—
at 60 mph: 14% better mileage
at 40 mph: 20% better mileage.

Well, this is very, very good. The tires on my own car were the best I could find (I think), and I measured their rolling resistance coefficient as $C_{rr} = 0.0065$. You should be able to find several tire makes with $C_{rr}$ = to 0.009 or better. It's an unfortunate state of affairs that, at least so far, tire manufacturers seem intent on keeping their $C_{rr}$ values a secret. That could mean taking the time to evaluate tires for ourselves. We need to change that. Some tire properties that affect efficiency are things you can change without buying new tires. Let's talk about them. Here is a list of tire properties that are expected to affect $C_{rr}$:

## Tire Properties

Profile (P, given as a percentage)
Tire pressure (p), which is connected to--
Contact patch area
Diameter (D) : related to P, tire width (w) and wheel rim diameter (d)
Rubber stiffness (depends on temperature)
Rubber internal friction (depends on temperature)

Here is some of the information you can find on the walls of my tires:

Michelin Energy MXV4 S8 205/60 R16 91V Max Press = 44 psi

The first part says something about the design and materials of construction. I know that the Energy MXV4 S8 tires have a rubber composition with very low internal friction, and that means very efficient. The tire size, 205/60 R16, can be used to calculate the approximate diameter of the tire. It tells me that the tire width is $w = 205$ mm. The tire profile, which indicates the ratio of height to width, is $P = 60\%$. The tire has radial cord placement, and the mating wheel rim diameter is $d = 16$ inches. Here's how to calculate the tire diameter:

$$D = 2 ( w/25.4 ) P + d$$

So my tire diameter is: $D = 2(205/25.4)(0.60) + 16 = 25.7$ inches.

"91V" indicates the load and speed rating of the tire. The maximum pressure, as I understand it, is the maximum safe gauge pressure when the tire is "cold," or about 70 degrees F, give or take 10 degrees. Tire pressure changes with temperature, but not a lot. If the pressure is set to 35 psi at 70 degrees F, then the pressure will be 34.1 psi at 60 degrees and 35.9 psi at 80 degrees. So, a good rule of thumb would be to increase tire pressure setting by 1 psi for every 10 degrees F above 70 F, and set the pressure 1 psi lower for every 10 degrees below 70 degrees F.

Of course, once you have driven your car for a few miles and the tires have begun to heat up (because they have internal friction, the thing we hate), you really don't know the air temperature inside the tires. That's why tire pressure should be measured "cold," before you have driven more than about two miles.

Following are my impressions about how tire characteristics affect Crr, and then also their effect on mileage.

### Profile

The experience of many drivers indicates that a tire's efficiency declines with its profile number. I believe this is consistent with theory, since a long flexible wall allows more give in the tire with less local flexing. Alternate flex and rebound of the walls and tread as a tire rolls is the main source of energy loss in a tire. I think the lowest profile a tire can have and be very efficient is P = 55%.

## Tire Pressure and Contact Patch Area

A car is held up entirely by the air pressure in its tires, except for just a few pounds used to deflect the tire rubber a very small amount. Each tire forms a flat spot on the ground, called the "contact patch." This portion of the tire transmits just enough force to exactly balance the load it supports. From this, you can calculate the area of the contact patch:

$$mg = \text{(Contact Area) (Gauge Pressure)}$$

$mg$ is the weight supported by the tire, which equals the product of its contact area and its pressure. The amount of flexing of the tire is about proportional to the area of the contact patch. That means the tire rolling resistance increases as the tire patch area increases. Experience shows, however, that rolling resistance doesn't increase in proportion to the contact area. The explanation is that a tire remains cooler at higher pressure, and the cooler rubber loses somewhat more energy than warmer rubber, all else being equal.

Many of us that are intent on obtaining the best fuel economy we can will operate our cars with somewhat higher tire pressure than is recommended by the car manufacturer. I set my tires at 40 psi cold, or about 10% below the maximum pressure stated on the tires by the tire maker. I have had no problem with uneven tire wear at the higher pressure (for good-quality tires), and the tires are found to last much longer than you would expect. The downside is that the high pressure makes the ride too bumpy for some people's tastes.

## Diameter

Tire diameter affects a lot of different aspects for a car. In most cases, increasing tire diameter makes things better.

Increasing D provides:

- Lower rolling resistance
- Higher engine efficiency
- Longer tire life
- Smoother ride and improved control.

Theory suggests that rolling resistance is proportional to one over the tire diameter. The reason for this is that there is less deflection of the rubber to get the needed contact area. In addition, most cars obtain best engine efficiency at lower engine RPM than you get with standard transmission gearing and normal-sized tires. That's because car companies make cars the way people like them—with lots of acceleration—"perky," as I might say. Engine RPM is lowered for a given speed when you increase tire diameter.

The standard factory tire size for my car was 205/55 R16, with a tire diameter of 24.9 inches. Changing the profile from 55% to 60%, to tire size 205/60R16, increased my tire diameter by 0.8 inches, a 3.2% increase in diameter. This small change has given about a 5% increase in fuel economy for my car. So far, I have driven 55,000 miles on these larger tires, and the tread wear has only been 3/32 of an inch. I still have at least another 3/32 of rubber before I need to think about replacing my tires. (The original tread depth was 9/32: the tires now have 5/32 to 6/32.) Michelin Energy tires are not known for giving long wear, unless you have larger-than-normal tires, as I do.

Pluses and minuses of increasing tire diameter: better mileage, tire life and handling, but less perky at the stop sign. Your speedometer and odometer may be less accurate, or sometimes better. Either way, don't be fooled by the change with the gauges, this could cost you a ticket—lower your indicated speed proportionately and be mindful that the odometer is reading lower, and you should be pleasantly surprised with the higher mileage you obtain. By the way, experiments indicate that the width of the tires does not seem to affect fuel economy

## Rubber Internal Friction and Stiffness

Some kinds of rubber are much more "efficient" than others. Remember super-balls? They were so surprising because they could bounce up almost as high as they fell. The ratio of <bounce up> to <fall> is the "coefficient of restitution" of the ball's rubber. This is the efficiency with which the material returns strain energy as it rebounds. "Internal friction" is a common term for this kind of energy loss. The amount of energy lost by the tire rubber in each rotation is proportional to the amount of flexing, and that in turn is proportional to the weight of the car (for all four wheels combined). This is why rolling resistance is proportional to the car's weight. These days, many tire companies put additives in the rubber to lower its internal friction.

Now, about stiffness. Remember, I said the weight of the car is held up entirely by the air pressure in the tire? Having stiffer rubber in the tire doesn't have any practical effect in holding up the car. But, the deflection energy is proportional to stiffness. And a part of that energy is not returned when the rubber rebounds. The effect on mileage is plain to see—tires made of stiff rubber have high Crr, and result in lower miles per gallon.

Let's look one logical step further while we are still here. Rubber gets softer in hot weather and becomes stiff in the cold. So, we might expect that car fuel economy could increase in hot weather, and this is usually observed to be true. (Engines usually run more efficiently when hot also.) The most efficient energy-saving tires are made of softer rubber, with comparatively flexible sidewalls and tread.

## Summary

For best fuel economy from your wheels and tires---

1. Buy only top-quality tires that are known to have high efficiency. The rolling resistance coefficient should be Crr = 0.009 or less. Sporty low-profile tires have higher Crr.

2. Buy tires with a slightly larger diameter, but be sure that they don't rub other car parts on turns or bouncy roads. Choosing higher-profile tires is a good way to increase diameter.

3. Keep tire pressure higher than normal, up to 10% below sidewall stated pressure, and check tires regularly to be sure the pressure is up. It's best to check tire pressure cold. Add one psi to pressure for each 10 degrees above 70 deg. F.

Suppose you are ready to buy a new set of tires. How do you choose? It's best if you can know the Crr for the tires. Here is an idea. First, ask if the tires you are buying have a satisfaction guarantee. This is partial compensation for not knowing what their "official rolling resistance coefficient" is. Most dealers or tire companies will offer a 30-day satisfaction guarantee. Now, you can drive on them and see how your mileage changes. If you don't get satisfactory results, you can take them back. You can also measure the rolling resistance coefficient of the tires yourself. That will be a good topic for another lesson.

Ernie Rogers

---

* In the introductory section, the components of force are spelled out in words. Here is the algebraic equation including all four parts:

$$F = \mathrm{Cd}\ A\ 1/2\ \text{rho}\ V^2 + \mathrm{Crr}\ Mg + M\,a + Mg\ (\text{grade\%}/100)$$

The first term, the aerodynamic drag, will be the topic of another lesson.