Lessons on Fuel Economy
#2 Air Drag /Ernie Rogers

The purpose of this discussion is to show how car fuel economy is affected by air drag, which is also called "wind resistance," or aerodynamic drag. As mentioned in the first lesson about tires, you can describe the fuel economy of a car as the product of a constant (that depends on the fuel and various car parts) and the sum of forces opposing the car's motion. The total force is:

F = air drag + wheel rolling resistance + mass times acceleration + uphill grade.

Air drag is the most important because it is usually the largest force resisting a car's motion. To understand how and why it's so important, we should look at the mathematical formula for air drag. It is composed of two parts, an interference factor and an energy factor:

F_d = (Interference factor) x (Energy factor)

Remember how the wind pushes against your hand when you hold it out a car window. (Now imagine how much force is developed across the front of a car!) With your palm held toward the wind, the force is large, but if you hold your hand in a "streamlined" position, like a wing, the force is very small. These effects illustrate the interference factor, which depends on the size and shape of the car:

Interference factor = C_d A

C_d is a constant, the drag coefficient, and A is the "frontal area" of the car that pushes against the air. The combination of the two is also called the "drag area." If this number is small, you would say the car has low drag. A car that has low drag is also a car that can go fast, usually, so everyone wants low drag whether they are interested in fuel economy or not.

The kinetic energy associated with a cubic meter of air is 1/2 rho V^2, where rho is the mass of that cubic meter of air (usually written as a Greek letter, rho). The force needed to push the air out of the way of the car is proportional to this, and so it serves as the energy factor. Putting the two parts together gives a very useful formula for calculating air drag:

F_d = C_d A 1/2 rho V^2

So, let's put this in words—the force needed to overcome air drag is the combination of the drag coefficient and frontal area, the density of the air, and the velocity squared. This velocity is the velocity of the air hitting the front of the car. (To get power, you also have to multiply F by the speed of the car on the road.)

The "air speed" in this formula is the car speed plus an additional component from the wind. Even without any wind, the air drag is the largest part of the force a car has to overcome. The following table compares rolling resistance and air drag as percentages for a VW Jetta with a rolling resistance coefficient of C_{rr} = 0.009 and C_d A = 0.72 square meters. Car weight is 3553 pounds.

Comparison of Air Drag and Rolling Resistance
for a 2006 VW Jetta (No wind)

Car Speed	Air Drag	Rolling Resistance
40 mph	50%	50%
50	61	39
60	69	31
70	75	25
80	80	20

The energy loss is about evenly split at 40 mph. At 60 mph, almost 70% of the car's power is used to overcome air resistance.

Now, let's look at what happens to the air drag when a car going 60 mph drives directly into a 20 mph wind. The sum of the car speed and wind has to be squared:

No wind: 60 x 60 = 3600
20 mph wind: (60+20) x (60+20) = 6400 , an increase of 78%

Okay, there's not much you can do about it, but driving into the wind has a huge impact on fuel economy. To see exactly how much effect car speed and wind can have, here are the approximate numbers for engine power needed to drive a Toyota Prius at constant speed:

Power, P, Needed by a Prius vs. Speed and Wind

Car Speed	P (0 wind)	P (5 mph wind)	P (10 mph wind)	P (20 mph wind)
40 mph	7 hp	7.5 hp	8.5 hp	11 hp
50	11	12	13	17
60	16	18	20	24
70	23	26	28	34
80	32	36	39	47

It takes seven times as much power to drive 80 mph into a strong wind as it takes to drive at 40 mph with no wind.

By the way, a Prius engine can produce 110 horsepower. The extra margin of horsepower is useful for acceleration and for climbing steep grades, but that's a subject for another day.

Now, let's look at the way the highway fuel economy of a Prius is affected by speed and air drag. (For a Prius, $C_{rr} = 0.012$ and $C_d = 0.26$; $C_d A = 0.56$ sq.m. Electric mode is off.)

Fuel Economy of a Prius vs. Speed and Wind

Car Speed	MPG (0 wind)	MPG (5 mph)	MPG (10 mph)	MPG (20 mph)
40 mph	74 mpg	67 mpg	60 mpg	49 mpg
50	60	54	49	40.5
60	49	45	40.5	34
70	40.5	37	34	28
80	34	31	28	24

There are a lot of lessons to be learned from this table. It was done for a particular car, but the wind and speed effects are about the same no matter what kind of car you have. So, let's take a look at the numbers. Is it just the air speed and air drag that affect fuel economy? What about the engine RPM, or the tire speed? Let's see.

At 60 mph and no wind, you have the same wind speed as at 50 mph and a 10 mph headwind. They both give the same 49 miles per gallon. And, a 60 mph car speed plus a 20 mph headwind gives the same mileage as going 80 mph with no wind, 34 mpg. This shows fairly well that wind resistance is the ONLY thing that makes fuel economy change with speed.

By the way, the numbers in the table were obtained by just calculating the sum of air drag and rolling resistance, and multiplying by a constant factor for efficiency of the car parts, including the engine. But, they match very closely with actual driving tests for most cars. My, how very simple car physics really is. Of course, there are plenty of things that aren't quite that simple, but their effects are smaller. One example is the tires. When a car goes faster, the tires get hotter, and that changes their rolling resistance.

Okay, air drag is the reason you get better mileage when driving slower. How about making up a rule-of-thumb for this effect? Look at the columns in the table for zero wind and five mph wind speed. The 5 mph wind column shows the same effect as driving 5 mph faster. 67 is about 10% less than 74; 54 is 10% less than 60, and on down. There's a rule for us: speeding up by 5 mph cuts fuel economy by 10%. What happens if you go 10 mph faster? Let's apply the rule we already have:

74 x 0.9 x 0.9 = 60 mph
And 67 x 0.9 x 0.9 x 0.9 = 49

It's amazing. Fuel economy goes down another 10% for each 5 mph increase. (The rule works best starting from near 60 mph.) Okay, let's try it another way, if you multiply 49 mpg (at 60 mph) by 140%, do you get the miles per gallon at 40 mph, 20 mph slower? If you multiply by 60%, do you get the miles per gallon at 80 mph?

49 x 1.40 = 67 mpg
49 x 0.60 = 29 mpg

Well, it's not quite as accurate, but darn close. Okay, so now the GREAT FUEL ECONOMY SECRET is out! Driving slower gives a fantastic improvement in mileage. Going just 5 mph slower on the highway gives as much improvement as you can get from millions of dollars spend on engineering to make the car more efficient.

Well, alright, what are the prospects for improving fuel economy through engineering, to reduce aerodynamic drag coefficient? Prospects are tremendous. Look at the following table of drag coefficients that I found--

Drag Coefficient Data for Some Cars

- 2.1 - a smooth brick
- 0.9 - a typical bicycle plus cyclist
- 0.7 to 1.1 - typical values for a Formula 1 car (downforce settings change for each circuit)
- 0.7 - Caterham Seven
- > 0.6 - a typical truck
- 0.57 - Hummer H2, 2003
- 0.51 - Citroën 2CV
- > 0.5 - Dodge Viper
- 0.44 - Toyota Truck, 1990-1995

- 0.42 - Lamborghini Countach, 1974
- 0.42 - Triumph Spitfire Mk IV, 1971-1980
- 0.42 - Plymouth Duster, 1994

- 0.39 - Dodge Durango, 2004
- 0.39 - Triumph Spitfire, 1964-1970

- 0.38 - Volkswagen Beetle
- 0.38 - Mazda Miata, 1989

- 0.374 - Ford Capri Mk III, 1978-1986
- 0.372 - Ferrari F50, 1996

- 0.36 - Eagle Talon, mid-1990s
- 0.36 - Citroën DS, 1955
- 0.36 - Ferrari Testarossa, 1986
- 0.36 - Opel GT, 1969
- 0.36 - Honda Civic, 2001
- 0.36 - Citroën CX, 1974 (the car was named after the term for drag coefficient)

- 0.355 - NSU Ro 80, 1967\

- 0.34 - Ford Sierra, 1982
- 0.34 - Ferrari F40, 1987
- 0.34 - Chevrolet Caprice, 1994-1996
- 0.34 - Chevrolet Corvette Z06, 2006
- 0.338 - Chevrolet Camaro, 1995

- 0.33 - Dodge Charger, 2006
- 0.33 - Audi A3, 2006
- 0.33 - Subaru Impreza WRX STi, 2004
- 0.33 - Mazda RX-7 FC3C, 1987-91
- 0.33 - Citroen SM, 1970

- 0.32064 - Volkswagen GTI Mk V, 2006 (0.3216 with ground effects)

- 0.32 - Toyota Celica,1995-2005

- 0.31 - Citroën AX, 1986
- 0.31 - Citroën GS, 1970
- 0.31 - Eagle Vision
- 0.31 - Ford Falcon, 1995-1998
- 0.31 - Mazda RX-7 FC3S, 1986-91
- 0.31 - Renault 25, 1984
- 0.31 - Saab Sonett III, 1970

- 0.30 - Audi 100, 1983
- 0.30 - BMW E90, 2006
- 0.30 - Porsche 996, 1997
- 0.30 - Saab 92, 1947

- 0.29 - Dodge Charger Daytona, 1969
- 0.29 - Honda CRX HF 1988
- 0.29 - Subaru XT, 1985
- 0.29 - BMW 8-Series, 1989
- 0.29 - Porsche Boxster, 2005
- 0.29 - Chevrolet Corvette, 2005
- 0.29 - Mazda RX-7 FC3S Aero Package, 1986-91
- 0.29 - Lancia Dedra, 1990-1998
- 0.29 - Honda Accord Hybrid, 2005
- 0.29 - Lotus Elite, 1958
- 0.29 - Mercedes-Benz W203 C-Class Coupe, 2001 - 2007

- 0.28 - Toyota Camry and sister model Lexus ES, 2005
- 0.28 - Porsche 997, 2004
- 0.28 - Renault 25 TS, 1984
- 0.28 - Saab 9-3, 2003

- 0.27 - Infiniti G35, 2002 (0.26 with "aero package")
- 0.27 - Mercedes-Benz W203 C-Class Sedan, 2001 - 2007
- 0.27 - Rumpler, 1921
- 0.27 - Toyota Camry Hybrid, 2007

- 0.26 - Alfa Romeo Disco Volante, 1952
- 0.26 - Hotchkiss Gregoire, 1951
- 0.26 - Mercedes-Benz W221 S-Class, 2006
- 0.26 - Toyota Prius, 2004
- 0.26 - Vauxhall Calibra, 1989

- 0.25 - Dymaxion, 1933
- 0.25 - Honda Insight, 1999

- 0.24 - Audi A2 1.2 TDI, 2001

- 0.212 - Tatra T77 a, 1935

- 0.20 - Loremo Concept, 2006
- 0.20 - Opel Eco Speedster Concept, 2003

- 0.195 - General Motors EV1, 1996
- 0.19 - Alfa Romeo BAT Concept, 1953
- 0.19 - Dodge Intrepid ESX Concept , 1995
- 0.19 - Mercedes-Benz "Bionic Car" Concept, 2005 [2] (based on the boxfish)

- 0.16 - Daihatsu UFEIII Concept, 2005
- 0.16 - General Motors Precept Concept, 2000

- 0.14 - Fiat Turbina Concept, 1954

- 0.137 - Ford Probe V prototype, 1985

Figures given are generally for the basic model. Faster and more luxurious models often have higher drag, thanks to wider tires and extra spoilers.

With current cars hovering around Cd = 0.30, you can see we have a long way to go.

Ernie Rogers