Fuel Economy Factors - Part 1: The Role of Aerodynamic "Drag"

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This is a guest post from Will Stewart. Will is a systems engineer in the DC area and previously has written several guest posts on The Oil Drum, including a series on Passive Solar Design.

As oil production falls and volatile oil prices in concert with a struggling economy induce a pattern of demand suppression/destruction, mobility choices will narrow and Vehicle Miles Traveled (VMT) will decline. What should governments at all levels be proactively preparing for? What should individuals and their families be preparing for in advance? The choices are broad: at a high level, land use planners could refine cities into a series of compact, carfree urban districts interconnected with mass transit. For the existing built-out suburban and exurban communities, however, such choices are limited. Aside from telecommuting, transportation choices will increasingly include biking, carpooling/vanpooling, bus rapid transit, and other efficient means of transportation. Travel between cities and countries will also undergo a transformation, with air travel becoming less and less affordable.

This series will cover current and projected land-based vehicle energy efficiency and a high level overview of the factors that determine it, such as aerodynamic drag, weight, efficiency of motive force (e.g., engine, motor), rolling resistance, driver behavior, drivetrain losses, parasitic losses, environmental factors, Passenger Miles Traveled (PMT), etc. In this first article of the series, we will focus on energy losses associated with aerodynamic drag losses, or more succinctly, "drag".

Tri Sled Avatar, a velomobile

Bus rapid transit in Cleveland

Drag is a force working against an object whenever that object moves through a fluid (i.e., a liquid or a gas) and is highly dependent on the object's velocity, Coefficient of Drag (Cd), and cross sectional area. We can express these dependencies in a simple formula;

$$F_d = -0.5\rho v^2 A C_d$$

where;

$\mathbf{F_d}$ = the force of drag,

$\boldsymbol{\rho}$ = the density of the fluid. At sea level, dry air is 1.2 kg/m3 at 20°C and 1.29 kg/m3 at 0°C.

v = the speed of the object relative to the fluid,

A = the cross sectional area of the vehicle,

$\mathbf{C_d}$ = the drag coefficient

Multiple connected vehicular objects (e.g., trains, articulated buses, and trucks with multiple trailers) have more complex calculations, due to the drafting effect of multiple objects in succession. The distance between each is a major determinate for calculating the aggregate drag force. [1]

Coefficient of Drag (Cd)

This is a dimensionless number that describes how 'smoothly' an object can move through a fluid. The "rougher" the surface of the object, the more turbulence is induced, hence the higher the Cd; conversely, the more streamlined the object is, the lower the number (golfballs are an exception). Table 1 has general values for many common objects.

Table 1: Example Drag Coefficients

C_d	**object or shape**
2.1	rectangular box
1.0~1.4	skydiver (horizontal)
1.0~1.3	person standing
0.9	bicycle
0.7~1.1	formula one race car
0.7~0.9	tractor-trailer, heavy truck
0.6	bicycle with faring
0.6~0.7	tractor-trailer with faring
0.5	sphere
0.35~0.45	suv, light truck
0.25~0.35	typical car
0.05	airplane wing, normal operation
0.15	airplane wing, at stall
0.020~0.025	airship, blimp, dirigible, zeppelin

Air flow around a vehicle can be separated into *laminar flow* and *turbulent flow*. Laminar flow is a steady movement of air in one direction. Turbulent flow, on the other hand, is noted by swirling eddy pockets that increase drag. A real world understanding of the difference can be realized by anyone who has held their hand out of a moving car window, changing the angle of their hand.

Cd will vary depending on the speed range, so we would want to focus on values that have merit in the ranges we are examining. Since drag is proportional to the square of the speed, the faster a vehicle travels, the lower the efficiency of distance traveled vs. energy input.

Figure 1 shows where laminar flow separates from the vehicle shape, marking turbulent flow points.

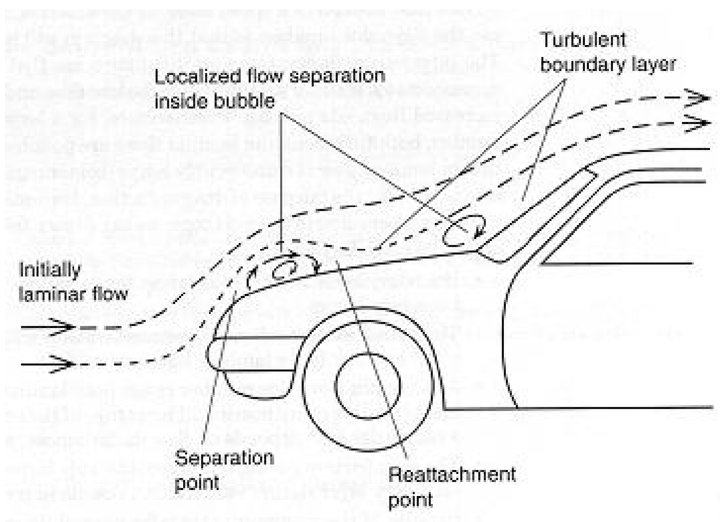


Figure 1: Example sources of vehicle frontal turbulence

While much design and marketing focus is placed on the streamlining of the vehicles front half, the rear half and undercarriage are equally important (or more so). Figure 2 shows the effects of different vehicle rear configurations and their affects on turbulence.

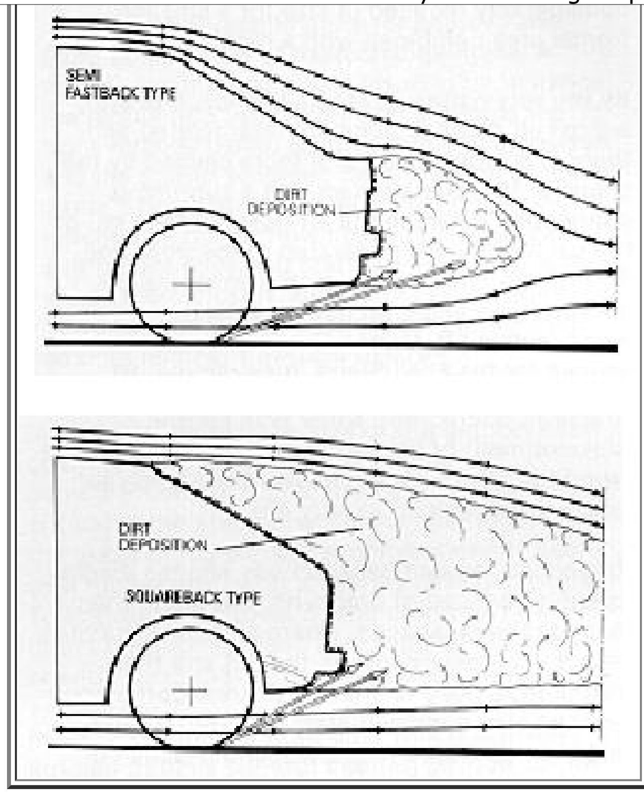


Figure 2: Variation in drag of different rear configurations

Some manufacturers have been smoothing the underside of vehicles in order to further reduce Cd even further (e.g., Toyota Prius and Honda Insight), with aftermarket vendors offering similar products for several other models.

In order to predict a vehicle's Cd, manufacturers often simulate wind turbulence with modeling software applications to quickly evaluate "what if" changes to a model design, allowing greater improvements before the physical prototying stage.

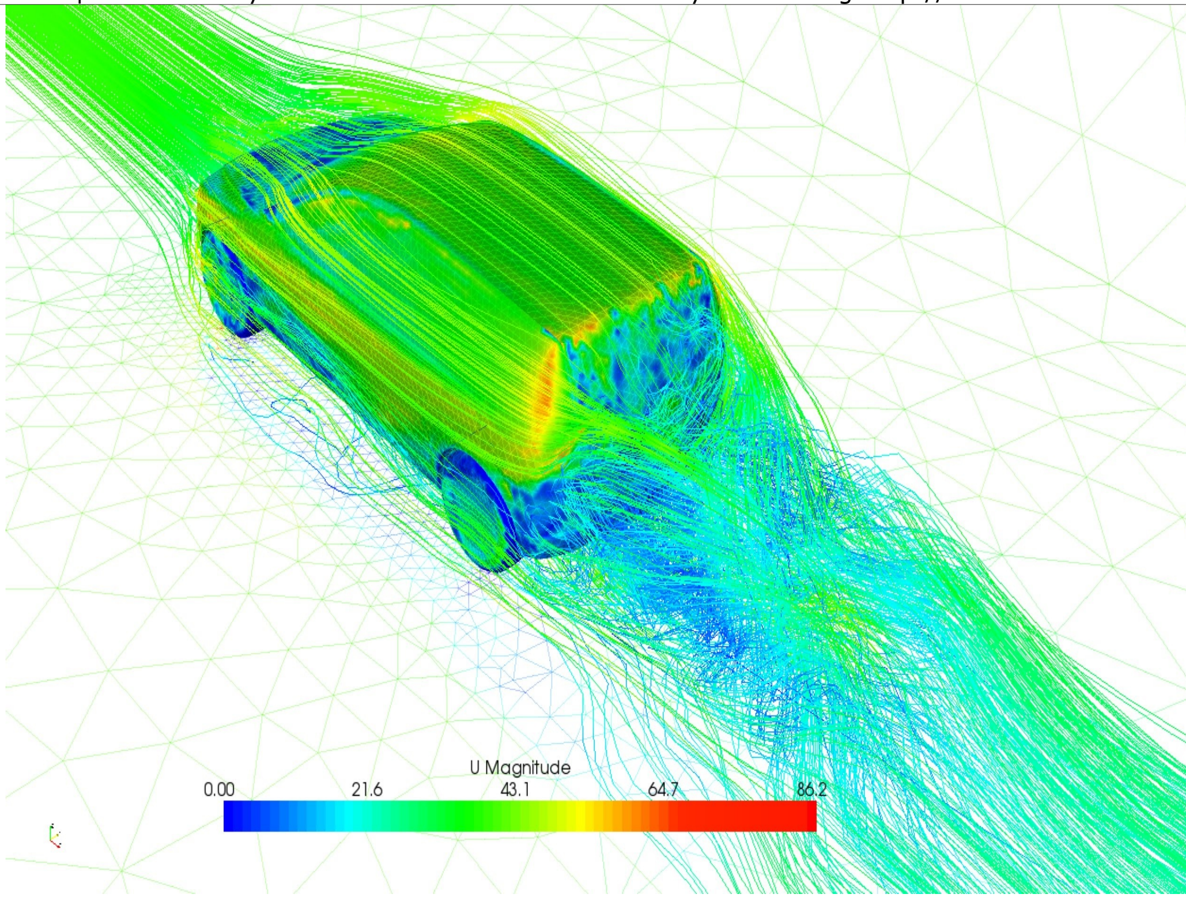


Figure 3: Simulation of vehicle aerodynamics

Once the model has been simulated satisfactorily, production mockups are incrementally created and tested in the wind tunnel to collect actual data to validate the modeling and to zero in on any final improvements.

Figure 4: Wind Tunnel testing of the new VW Polo

A significant leap forward in *human powered vehicle* Cd improvement came through the introduction of fully faired recumbent bikes, commonly called velomobiles [2][3], though their history has been fraught with obstacles. Due to their aerodynamic superiority, fairings and recumbents were banned from bicycle racing for providing too much of an advantage, so they languished outside the borders of bicycle competition for decades. The design of velomobiles now includes wind tunnels testing, with one example (the Reflex 700) achieving a 'head-on' Cd of 0.012. The designer of the Reflex (Don Elliot) reports that during wind tunnel testing at a 25 degree angle, it registered forces similar to a tacking sailboat. This effect resulted in an apparent benefit during the 1999 World Solar Cycle Contest where "the riders said they actually stopped pedalling in the gusting cross winds and still maintained speed."

Figure 5: Velomobile fairings can reduce a typical cyclist's Cd from 0.9 to 0.012

Figure 6: Even freight bikes are becoming more aerodynamic

Area

Coefficient of drag is important, though only one aspect of the drag force equation. Another equally important variable is *cross sectional area* of the vehicle with regard to the direction of the travel (and prevailing wind). This area is typically the frontal area of the vehicle, or the outline of the vehicle when viewed from the front. Per the equation above, we see that drag is proportional to the cross sectional area, so vehicle designers and serious cyclists take measures to reduce this area as much as possible.

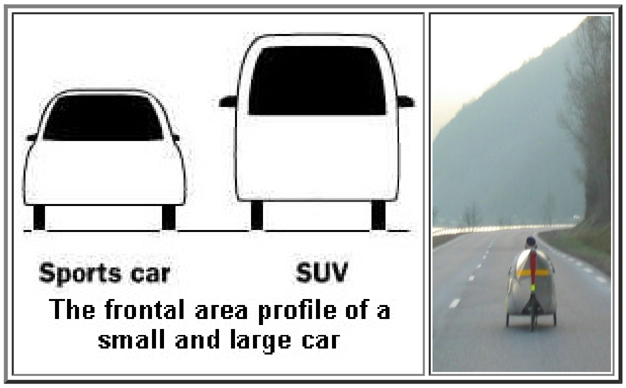
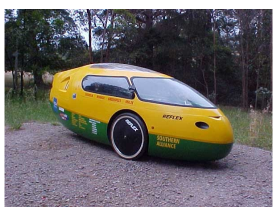
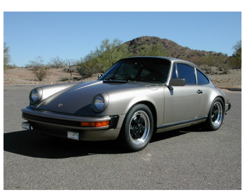
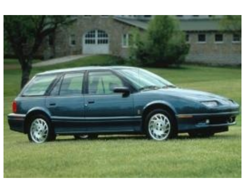


Figure 7: Cross sectional area differences between car, SUV, and velomobile

A common indicator of the drag of a vehicle is the product of the coefficient of drag (Cd) and the cross sectional area (A), which gives us **CdA**. This term provides a quick means of assessing the aerodynamic qualities of a vehicular body or cyclist form. Table 2 below shows the CdA of some selected vehicles.

Table 2: Examples of vehicle CdA

 0.019 m^2 Varna Diablo racing bicycle	 0.079 m^2 Reflex 700 velomobile	 0.092 m^2 Quest velomobile	 0.13m^2 Cambridge University's Endeavor
 0.18 m^2 Bug-E	 0.18 m^2 Monotracer	 0.199 m^2 Volkswagen "1-Liter"	 0.211 m^2 Aptera

 0.22 m^2 Loremo	 0.23 m^2 Twike	 0.2-0.3 m^2 Racing cyclist in aero tuck*	 0.3-0.35 m^2 Super bikes*
 0.36 m^2 GM EV-1	 0.37 m^2 Chevy Volt	 0.47 m^2 2000 Honda Insight	 0.50 m^2 1992 Opel Calibra
 0.54 m^2 2004 Toyota Prius	 0.54 m^2 2001 Audi A2 1.2 TDI	 0.55-0.7 m^2 typical upright cyclist*	 0.6-0.7 m^2 typical unfaired motorcycle*
 0.58 m^2 1994 Porsche 911	 0.59 m^2 1992 Chevrolet Corvette	 0.59 m^2 1999 Lotus Elise	 0.63 m^2 2007 BMW 335i
 0.64 m^2 1993 Saturn station	 1.07 m^2 2006 Ford Escape	 1.08 m^2 1994 Ford	 1.61 m^2 1994 Land Rover

wagon	hybrid	Windstar	Discovery
 2.46 m^2 2003 Hummer H2	 ~2.6 - 4.2 m^2 Typical bus*	 ~5.0 - 7.0 m^2 typical tractor trailer*	 ~8.5 - 10.5 m^2 High Speed Rail*

* - Typical values, though outliers exist

Up Next

The next part of this series will cover velocity and rolling resistance (with at least one surprise)...

References

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