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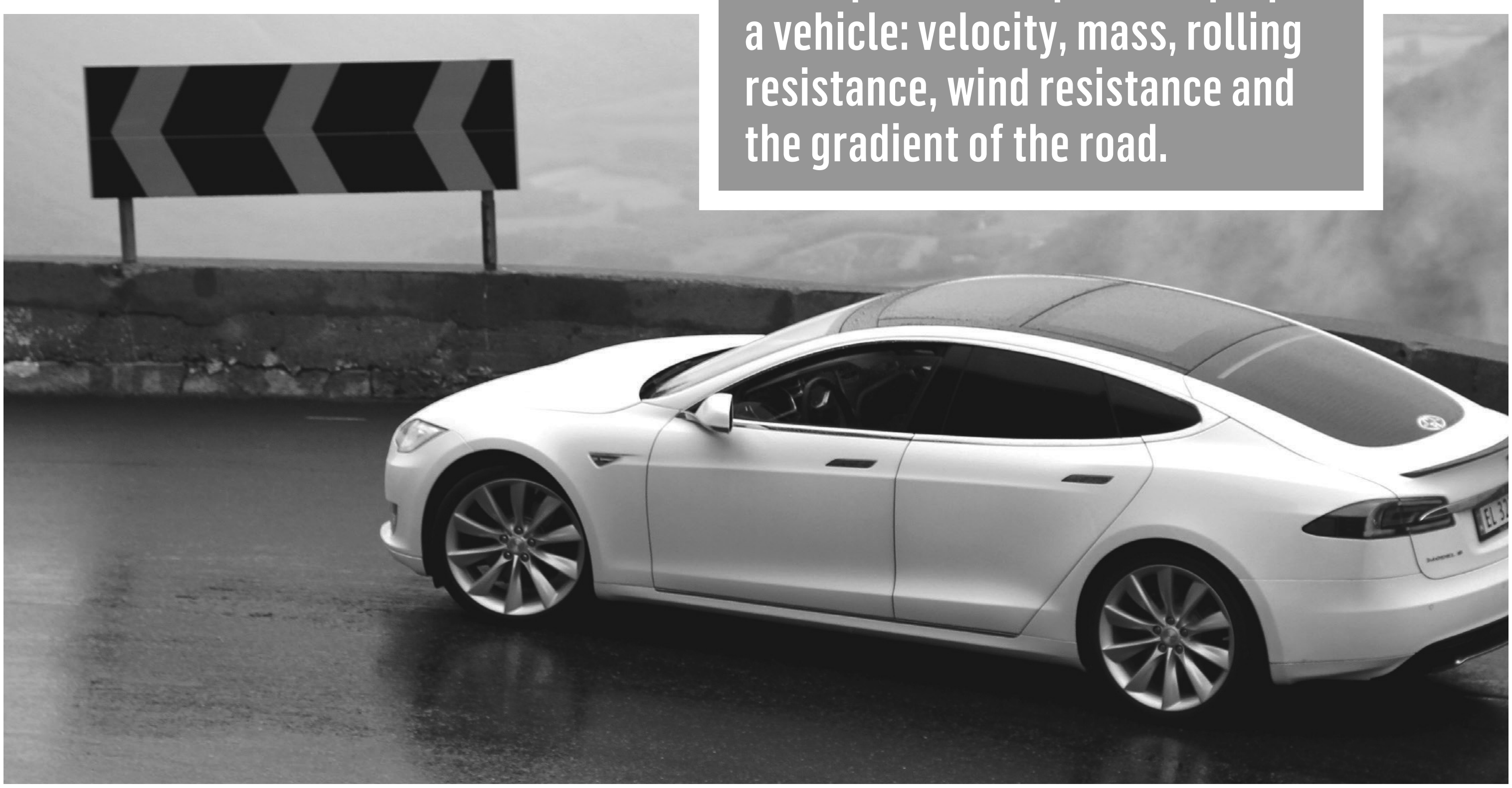

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A CLOSER LOOK AT ENERGY CONSUMPTION IN EVS

By **Jeffrey Jenkins**

When it comes to factors that affect energy consumption in EVs, the big kahunas are weight and wind resistance (aka CdA), but there are other factors that can have a surprisingly outsized effect and that tend to be overlooked, such as the use of climate control (AC, of course, but especially heat). Conversely, one factor which does not seem to affect energy consumption all that much is the use of regenerative braking.

First, though, two terms that are confused or even used interchangeably way too often are power and energy. Power is a measure of the rate at which work can be done while energy is a measure of the amount of work done. Ignoring the effect of wind resistance (which would otherwise disprove what comes next), it will take the same amount of energy to drive a 2,000 kg vehicle a distance of 1 km whether it is going 1 kph or 2 kph or even 10 kph. Yes, the higher speed requires more power, but it is applied for an inversely lower amount of time, and energy is power * time.

Power

There are five primary factors that go into determining how much power is required to propel a vehicle: velocity (aka speed), mass (aka weight, at least as long as the vehicle remains on planet Earth), rolling resistance, wind resistance and the gradient of the road. The latter four components are used to determine the total drag force opposing the vehicle's motion, and speed should be self-explanatory. The relevant physics equation that combines all these factors together is deceptively simple:

$$P = F * v$$

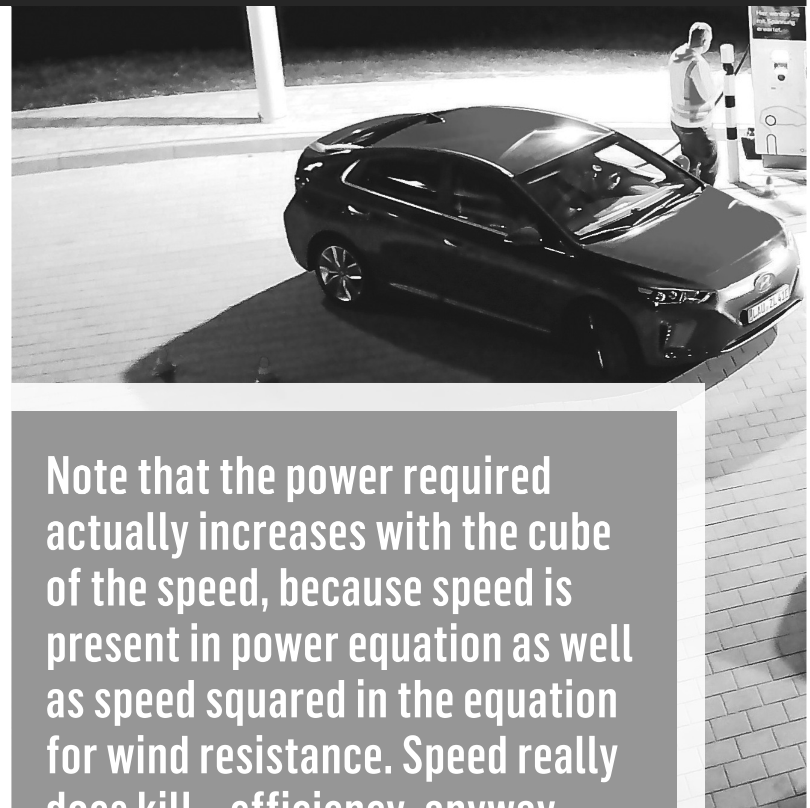
Where P is power (in watts, W), F is the total drag force acting on the vehicle (in Newtons, N), and v is the velocity (in meters per second, m/s). The components that make up the total drag force need to be evaluated for the above equation to be useful, however. Also note that the power required actually increases with the cube of the speed of the vehicle, because speed is present in the power equation above as well as speed squared in the equation for wind resistance. Speed really does kill…efficiency, anyway.

Drag forces

The easiest drag force to evaluate is rolling resistance, Fr, which is simply vehicle mass (in kilograms, kg) * gravitational acceleration of your particular planet (9.81 m/s^2 for Earth) * coefficient of friction, Cf (a dimensionless number, usually between 0.01 and 0.02 for most tires and roads):

$$Fr = m * 9.81\ m/s^2 * Cf$$

For example, a 2,000 kg vehicle and a coefficient of friction between tires and road of 0.015 results in a drag force from rolling resistance of 294 N, or a mere 30 kg of force (1 N = 0.102 kg-f). This isn't much force to overcome, though rolling resistance does increase dramatically if tires are underinflated. Conversely, overinflating the tires to reduce rolling resistance isn't really worth



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the reduced tire life and increased risk of a blowout.

Next is the contribution from wind resistance, which is proportional to the square of speed, v (in m/s), air density, ρ (1.2 kg/m^3 for air at 20° C at sea level), drag coefficient, Cd (typically in the range of 0.3 to 0.4), and the frontal area of the vehicle, A (in m^2). The relevant equation to find the drag force from wind resistance is:

$$Fw = 0.5 * v^2 * \rho * Cd * A$$

For example, a vehicle traveling at 90 kph (25 m/s) with a Cd of 0.35 and a frontal area of 2.2 m^2 requires a force of 288.75 N to overcome wind resistance; at 120 kph that force increases to 513.33 N, or nearly double!

The last drag force is from a change in elevation, which is the only one which can actually assist the vehicle (aside from the unlikely scenario in which a tailwind is strong enough to propel the vehicle all on its own). This equation is a little less straightforward and requires some trigonometry. If the incline of the road is not given in degrees, then converting to such is the first step. In the US, grade is given as a percentage rise vs. a horizontal run, and these figures correspond to the opposite and adjacent sides of a right triangle (the vehicle itself drives along the hypotenuse) so to convert percentage grade into degrees

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first change percentage into decimal format (e.g., 10% = 0.1) then take the arctangent of the resulting number to get the slope in degrees (e.g., arctan(0.1) = 5.71°).

With the slope in degrees the following equation can be used to find the drag force from a change in elevation:

$$Fs = m * 9.81\ m/s^2 * \sin(\Theta)$$

Where Fs is the drag force from a slope in N (Fs is a positive number if going up the slope and a negative number if going down), m is the vehicle mass in kg, 9.81 m/s^2 is the gravitational acceleration of Earth, and Θ is the slope in degrees. For example, a 2,000 kg vehicle going up a 10% grade experiences a drag force of 1,952 N (or 199 kg-f).

Putting all the above together in another example should help solidify an understanding of the concepts:

Example: a 2,175 kg vehicle with 2.34 m^2 of frontal area and a Cd of 0.24 traveling at 110 kph on a road with a 5% grade:

$$Fr = 2{,}175 * 9.81 * 0.015 = 320.0\ N$$
$$Fw = 0.5 * (110 / 3.6)^2 * 1.2 * 0.24 * 2.34 = 314.6\ N$$
$$Fs = 2{,}175 * 9.81 * \sin(2.86°) = 1{,}064.6\ N$$
$$P = (320.0 + 314.6 + 1064.6) * (110 / 3.6) = 51{,}920\ W$$

And if the road is flat? Now the power required is 19,390 W. Slope is no joke!

Weight

Weight also has a direct impact on the amount of energy it takes to change speed. It probably goes without saying, but the heavier the vehicle the more energy will be expended to increase its speed. The relevant formula for determining such is:

$$K = 0.5 * m * v^2$$

Where K is energy (in Joules, J, aka W-s), m is mass (aka weight, in kg) and v is velocity (aka speed, in m/s). For example, to increase the speed of a 2,000 kg vehicle by 72 kph requires 400 kJ (or 0.111 kWh). That might not seem like much, but it can add up surprisingly quickly

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in stop-and-go traffic, and the ability of EVs to recapture some of this energy via regenerative braking is one reason why they deliver superior "fuel" efficiency in city driving compared to their ICE counterparts.

Regen

While regenerative braking can recapture some of every positive change in speed, keep in mind that energy must be fully converted twice when regen is used, so it incurs twice the losses.

Using the above equation for kinetic energy for a 1,000 kg vehicle decelerating from a speed of 100 kph gives a result of 384 kW-s (kilowatt-seconds). Divide by 3,600 to convert seconds to hours and that gives us a rather paltry 0.11 kWh of recovered energy - assuming 100% efficiency.

Multiply 0.11 kWh by the price for electricity ($0.11 per kWh) and the resulting savings is $0.0121. Still, you can't make gasoline by braking in an ICE vehicle so any energy recaptured by regen is better than nothing.

It bears mentioning that along with regen, the two other reasons EVs excel in city driving are that they don't need to idle their motor while stopped, nor do they need to use energy over and above what is required to deliver good acceleration performance. In the bad old days of carburetors and the first port fuel injection systems, there was a pump that literally sprayed a dollop of fuel every time the accelerator pedal was pressed, just to make sure the engine didn't run too lean and stumble (of course, the engine could also stumble from running too rich).

Climate control

The final factor that can affect energy consumption - sometimes dramatically so - is cooling or heating the cabin. Many first-generation EVs used a conventional automotive AC system, except that the compressor was driven by its own electric motor, rather than by a belt to the traction motor. Using a dedicated motor is a more costly solution, but it is far superior, as the compressor always runs at its optimal speed, allowing it to be more efficient, and cooling isn't lost every time the vehicle is stopped, since the traction motor doesn't idle in an EV.

One huge disadvantage of the conventional automotive AC system is that it only pumps heat in one direction; there was no need for it to operate bidirectionally (i.e., as what is commonly thought of as a "heat pump") because the ICE is a profligate producer of waste heat which comes at no additional burden to the engine or fuel economy. In contrast, the efficiency of the EV inverter

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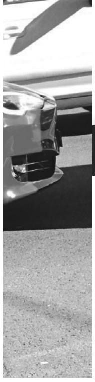
and motor combination - the only potential sources of waste heat of any magnitude - is typically in the high 90s and the losses directly scale with power output, so you might get a reasonable amount of waste heat climbing hills all day, but very little driving the speed limit on any limited-access highway in the US.

So, heating the cabin in an EV requires an additional source of heat. Many early designs used resistance heating, as it is cheap, simple and 100% efficient at converting electricity into heat. That last spec sounds impressive, except that the typical compressor-type heat pump can move around 2 - 4 W of heat for every 1 W of electrical input power; the so-called "Coefficient of Performance" in refrigeration/HVAC parlance. This is also why switching from almost any kind of furnace to a heat pump tends to save quite a bit of money heating a home. Another bonus of the heat pump operating as a heater (rather than as an AC) is that waste heat produced by the compressor is useful, so the COP tends to be 1 higher in heating mode compared to cooling.

For a more concrete example, the average vehicle needs somewhere in the range of 4-8 kW of heating/cooling capacity, depending on interior volume, exposed glass area, insulation R value, outside temperature, etc. If heating is via electrical resistance then that will be a direct 4-8 kW of additional drain on the battery, whereas if it is supplied by a modern heat pump system with a COP of 4.0 in heating mode, then only 1-2 kW will be drawn (with 1.33-2.67 kW drawn in cooling mode, as COP will then be 3.0). Using the previously worked example for vehicle power demand, 19.4 kW was required to travel at 110 kph on the flat, so an additional draw of 2 kW for climate control would be equivalent to increasing the speed by nearly 6 kph or decreasing the range by 10%. Bumping the draw up to 8 kW for an electric resistance heater would be equivalent to increasing speed to 130 kph or cutting range by 40%!



Efficiency

Last to be considered is the question of how changes in the efficiency of some of the major drivetrain components affect energy consumption. The inverter seems to receive a lot of the focus here, but there really isn't much room for improvement - 98% is already achievable using state-of-the-art 600 V IGBTs, and to get to 99%, say, would require cutting losses in half…good luck with that. The traction motor is a juicier target as it typically operates with an efficiency in the 80-90% range, but improving motor efficiency invariably results in a bigger (and costlier) motor. Still, higher efficiency in both these components can have positive effects in other areas, such as reduced cooling complexity/cost and, of course, even a small efficiency boost can add up to significant energy savings over the life of the EV.

Using the same example as above, if the average efficiency of the motor is improved from 90% to 95% (easy to achieve for an industrial motor operating at a fixed load; a rather more heroic achievement for a traction motor in an EV), then the power would drop from 21.56 kW to 20.42 kW (assuming 19.4 kW required at 100% efficiency), which works out to a savings of around $0.125 per hour if energy costs $0.11 per kWh. Guesstimating a 5,000 hour operational life for the EV (e.g., 300,000 km at an average speed of 60 kph), that works out to a lifetime savings of $625, minus whatever it cost to achieve the efficiency improvement (a figure which may very well exceed the savings).