On cars of the future

John S. Reid

This is a spin-off piece from the 'the numbers game'. I've put it in a separate section because the subject has strayed from meteorology and is largely about energy constraints on the capabilities of future cars. I've just watched the race of electric motorcycles around 1 lap of the Isle of Man TT course (about 37 miles) with the podium places all being won with an average speed of over 100 mph. This sort of result might lead people to think that electric vehicles will replace today's carbon-based transport with little further change, but it won't happen. Read on to find out why.

1) Will battery electric cars be able to provide a private transport experience comparable to today's petrol or diesel cars?

Answer: no!

The idea: work out how much energy is available to a modern car engine in its fuel and compare this with the energy required to power an electric motor as an alternative power source.

First, some figures relevant to carbon-based car transport. How much energy is stored in the petrol tank of a typical car? Petrol has an energy content of 9.7 kWh l^{-1}. A 60 litre tank will therefore contain 586 kWh of energy. If the car uses 8 litres per 100 km it will therefore run for 750 km on one complete tank and with an average speed of 50 km h^{-1} over a mixture of town and out-of-town roads will run for 15 hours. That's a use of 4 l h^{-1} or an average expenditure of chemical energy at the rate of close to 40 kW. Car engine efficiencies are quoted at around 20%, making the average mechanical power delivered about 8 kW. A car with an engine of only 8 kW output would take you back to the motoring days of the 1930s. Engine power use is very 'spiky' with hill climbing and quick accelerations requiring much more than the average power. Let's take car and engine as having a mass of about 1500 kg, about a Ford Fiesta unloaded. For example to drive a 1.5 tonne car at 100 km h^{-1} up a 6^{o} slope requires an extra mechanical power of about 45 kW over and above the power needed to drive at the same speed on the flat. (My own car has an engine capable of producing over 100 kW in a car with kerb weight about 1.75 tonnes). Clearly for most of the time the full power of the engine is not nearly used. To get back to the fuel, the 60 litre tank holds just over 40 kg of fuel that can be filled and paid for in about 5 minutes and cost about £80 at current prices.

[One often sees 'green' advice that we should make ours car as light as possible by taking out all unnecessary 'stuff' that people carry around in their cars. Most 'stuff' we keep in our cars weighs a small fraction of the weight of a typical car, say 1500 kg. In my experience the petrol consumption of a car doesn't change much with its loading even when a few hundred kg of passengers are added and this makes physical sense. The engine does most of its work against air resistance and this doesn't change when a car is loaded up. With a heavier car, more work is done (and hence more fuel used) only during periods of acceleration and when hill climbing. If neither of these occupy most of the journey then fuel use won't change much with load.]

Electric engines are significantly more efficient at converting the input (electric) power to mechanical power than petrol engines are at converting chemical energy. They aren't conspicuously smaller and lighter (witness the comparable size of electric and diesel locomotives). However a car of the same size will need the same power to move it through the air at a given speed and if an electric engine were substituted for a petrol engine in the same chassis then any weight saving would not be huge since most of the weight of the car is not in the engine in any case. The efficiency gain of the electric engine is the big advantage it has. There is also a secondary advantage that an electric motor can act as a brake when needed and convert mechanical energy back into electric current that can be fed into storage. To produce a comparable performance to a petrol car in the same chassis would need an electric engine of something like 60 kW. That's 120 amps at 500 volts, for example. Even an electric motor using an average of 10 kW for 15 hours, the running time of the petrol car, is beyond any battery the car could reasonably carry. The battery capacity would need to be 150 kWh. Standard lead-acid technology offers about 40 Wh kg^{-1} and lithium-ion technology perhaps 3 times this value and hence we're talking about 1 tonne of lithium-ion batteries. Remember that only about 40 kg of petrol is needed to keep a modern car going for 15 hours! Even if new technology succeeded in inventing a significantly lighter battery, to re-charge it with 150 kWh in say 3 hours (about 100 times the time it takes to fill a tank with petrol) would require a DC supply of 230 volts at over 200 amps. Swapping 1 tonne of batteries in and out of the car for a re-charge, like new horses for the stage-coach, isn't a feasible alternative either. On the positive side, 150 kWh of electricity at current prices will cost the consumer about £20.

In conclusion, it really takes a lot of power to push a car over the landscape at a reasonable speed. A tank of petrol (or diesel) contains a phenomenal amount of energy and is up to the challenge. For an electric car, the cost of electricity and the efficiency of electric motors are not the issue. The issue is delivering the electricity. Storing externally generated electricity on-board is a huge problem requiring for a comparable performance to today's average car a power to weight ratio of battery not achieved in mass production and perhaps not achievable at all; also needed are minimum mass vehicles, maximum aerodynamic efficiency and even then the re-charging problem for a battery capable of the performance of a typical petrol car is likely to be an application killer. Battery powered electric vehicles look set to occupy the large short-haul, moderately low-speed niche. Externally generated electricity, where the electricity does not need to be stored on-board or stored only in small quantities, makes sense for long-distance transport in the context of electric trains, or variations on this theme, or cable-ways where the entire traction force is provided externally. The energy required to propel a closely coupled train of cars across country is much less than the energy required to propel them as separate cars. This seems to me to lead to the inevitability of road trains.

In short, if society is to keep cars much as we now know them, then chemical energy rules. The options on the table that could deliver are biofuels, hydrogen power and fuel cells. Of course it's not just cars that use the high energy-density of chemicals. Think of agricultural machinery such as tractors and combine harvesters, forestry machinery, building machinery and a wide variety of industrial machines, pneumatic tools, landscaping tools from chain saws to the mower that keeps the golf-course in shape. You can't do much in these contexts with a battery-pack machine or even a cable plugged into the electric mains. Developing carbon-neutral alternatives to today's options will take decades of work.

2) The 'ultimate car' will always have to overcome air resistance and hence use energy to get from A to B. Estimate the power needed and fuel consumption of such a car travelling on the flat at 110 km h^{-1}, at 80 km h^{-1} and at 50 km h^{-1}.

Answer: the power needed for 110 km h^{-1} travel is 9.41 kW; other figures are given below.

The 'ultimate car' is one that would use no energy in the absence of air resistance. Braking, for example, would be achieved by converting kinetic energy into electric energy or mechanical energy and storing it (in a battery or flywheel) for re-use. Such technology already exists but it's not 100% efficient. The 'ultimate car' would have so little internal friction that if it rolled downhill in the absence of air resistance it would climb up the next hill to the same height, like a ball bouncing up to the height it is dropped from. This is a technological target rather than something likely to be achieved. There is, though, no obvious way of eliminating air resistance for a car that travels through the countryside. How much energy is used overcoming air resistance?

The power, P, needed to travel at speed v through air of density ρ is given by $P = \frac{1}{2}\rho v^3 ACd$, where A is the effective cross-sectional area of the car and Cd the drag coefficient. Modern cars have a lower drag coefficient than boxy vintage cars. A decent figure is Cd = 0.28, though no doubt the 'ultimate car' would be a bit less. A generally useful car has to be big enough to accommodate several passengers and luggage so let ACd = 0.66 m^2, a value typical of a reasonably sized modern car. The density of air is about 1 kg m^{-3}, making $P = 0.33v^3$.

We can now calculate the power needed to push the car through the air at the 3 representative speeds in the question (near enough 70 mph, 50 mph and 30 mph). For example, 110 km h^{-1} ≡ 30.56 m s^{-1}. Hence the power needed is 9.41 kW. At 80 and 50 km h^{-1} the power needed is 3.62 kW and 884 W respectively. The first conclusion is that travelling at speed is power greedy. A 10 kW electric motor to achieve 110 km h^{-1}, for example, is quite a sizeable piece of kit.

Petrol has an energy content of 9.7 kWh l^{-1} implying that 1 hour at 110 km h^{-1} would use 9.41/9/71 = 0.97 litres if the engine were 100% efficient. Today's engines are about 20% efficient and hence would use some 4.8 litres to travel the 110 km in 1 hour. You can work out that at 80 km h^{-1} the car would need only 2.6 litres to travel 110 km and at 50 km h^{-1} only 1 litre to travel 110 km. These then become target figures for a manufacturer to aim for. They can be bettered by more efficient engines, but there isn't likely to be a huge improvement here for thermodynamic reasons. They can be bettered with lower drag but again there are limitations, for the vehicle has to be practical.

The conclusion is that one can aim for quite an efficient car that will travel along the flat at speeds up to 110 km h^{-1} but there is a non-trivial limit on what can be achieved, due to air resistance.

3) How do hills affect the power requirements of a car?

Answer: they affect it even more than air resistance. See below for numbers.

The above doesn't mention real details such as wind and hills. In a real journey a car's engine does work against gravity going up hill, as well as work against air resistance, and gravity does some of the work going downhill. This doesn't invalidate the argument above. What one can gain from gravity going downhill one has to give back going up hill. The force needed to push our car through the air at 110 km h^{-1} is not very much (308 N). For a car of mass 1700 kg, including occupants, this force is the same as the component of weight down a slope of just 1 in 100. The car would free-wheel down such a slope at 110 km h^{-1} but going up the same slope at 110 km h^{-1} it would use twice as much power, namely about 19 kW. Going up a 1 in 10 slope at 110 km h^{-1} would need just over 100 kW of power (9.4 kW working against air resistance and 94 kW against gravity). 100 kW is quite achievable in a modern 2-litre car, petrol or diesel, but for a battery powered electric car, 'forget it'. The excess power provided by gravity going down a steep hill is converted into electricity in our 'ultimate car' (or stored as flywheel energy for later use).

Gravity is clearly the big issue for cars in terms of both speed attainable and fuel consumption. A car of mass 1700 kg with a 10 kW engine can only climb a 1 in 10 hill (and plenty of hills are steeper) at 21.7 km h^{-1} (13.5 mph). This takes us back to small-car motoring in the 1920s and 1930s. Of course, halve the mass and you can more or less double the speed but 4 passengers and luggage may well clock up 400 kg and the car must be comfortable inside, be strong enough to meet safety standards and include the weight of engine and fuel so the total mass is unlikely to be halved by medium-term developments. This discussion leads me to three conclusions.

a) I think that hybrid electric/(petrol, diesel, lpg or hydrogen) cars are here to stay, for one needs the power of chemical fuel to climb hills (and in the medium term before we get car trains, to overtake!). They are not a half-way house to all electric propulsion.
b) Regenerative braking is the biggest unexploited resource for improving the efficiency of cars. At present some of the large potential energy of a car at the top of a hill is wasted if you have to brake on the following downhill. Braking is a frequent requirement in town driving. Braking is currently energy wasted. Regenerative braking to convert this energy to electrical energy for later use with the electric motor in the car is a technology that could bring big energy savings over current practice. Some cars do have this but at the moment it doesn't capture a large proportion of the kinetic energy.
c) From the foregoing, my 'concept car' of the future has a hydrogen fuel tank powering a combustion engine for hill climbing and high speed acceleration (the hydrogen being produced by the electrolysis of water where electricity is cheap) and an electric motor of about 10 kW for cruising on the flat and for acting as a dynamo to convert unwanted kinetic energy to electricity when braking is needed. I said 'an electric motor' but on reflection I expect car manufacturers will take a leaf out of the commuter train makers who use a system of distributed electric motors on each carriage. Cars may have smaller electric motors on each wheel, doing away with the need for a drive shaft and even the cumbersome and expensive differential gearing now on the 'driven' axle. If that were the case then there may even be advantages to having more than 4 wheels. For example, the combustion engine, if present, could just drive the auxiliary wheels for the spike of power when needed.

JSR