The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Four Billion Cars in 2050?

Posted by Stuart Staniford on February 18, 2008 - 10:00am
Topic: Environment/Sustainability
Tags: 2050, automobile, civilization, hybrids, peak oil, phev [list all tags]

The Tata Nano will sell for about $2500 (US) in the base model, and get about 51 mpg (US). Source: Wikipedia.

After taking a hiatus from my regular Monday blog spot for a couple of weeks (to focus on another obligation) I want to pick up where I left off - exploring the quantitative barriers to getting most of the way to a sustainable planetary civilization by 2050. Last time, I laid out what I was trying to do:

> This post is the start of an attempt to sketch out what an integrated solution to the world's food, energy, land, climate, and economy problems might look like. My basic goal is to get to a somewhat defensible story of how civilization could get to 2050 in reasonable shape, despite the problems of climate change, peak oil, global population growth, etc.
>
> Since it's not possible for me to entirely solve this problem in a week of part-time work, I put this out as a hasty straw-man. Feel free to point out the parts of this that don't work, or where my ignorance of some of the relevant issues shows particularly badly. Of

> course, I don't make the claim that I can predict what will happen forty years ahead. Nor do I expect the global population to pay much attention to what I think they should do. Instead, the value of a scenario is to try to think through the general issues that society faces, and the value of an **integrated** scenario is that we can think about how all the parts fit together holistically, whereas usually they get projected separately by specialists, and even the obvious interconnections get missed by decision-makers (if we try to solve our fuel problems by converting food to fuel, perhaps the price of food might go up).
>
> With that said, for the remainder of the piece I'm arrogating to myself sole authorship of all relevant international treaties and implementing legislation at the national level. Here's how I'd go about it. In this first piece, I've analyzed the overall requirements for the problem, but only fleshed out any detail on the population, economy, and energy sectors; I did not have time to write up my analysis of transportation and agriculture/land issues. I will do so in a future piece.

and some of the requirements I saw as necessary in order to consider a solution viable:

> - **Population**: The global population is able to grow and go through its demographic transition with death rates continuing to go down. No die-offs.
> - **Economy**: The world economy is able to grow on average over the period - modestly in developed countries, faster in developing countries.
> - **Carbon emissions**: The global energy infrastructure will be mainly replaced with non-carbon-emitting energy sources by the end of the period, and residual emissions will be rapidly diminishing.
> - **Fossil fuels**: I assume that peak oil is here about now but that declines will be governed by the Hubbert model (and thus will be gradual). I assume natural gas and coal are globally plentiful enough that climate policy is required to prevent their full use.
> - **Technology**: I do not assume any massive breakthroughs - no technological miracles that solve problems in ways completely unknown or untested today. However, where technological sectors have long established rates of progress in key metrics, I extrapolate the metric to continue improving at the historic rate (eg the economics of solar power, or the yields/acre of agriculture are assumed to keep improving on the historical trajectory).

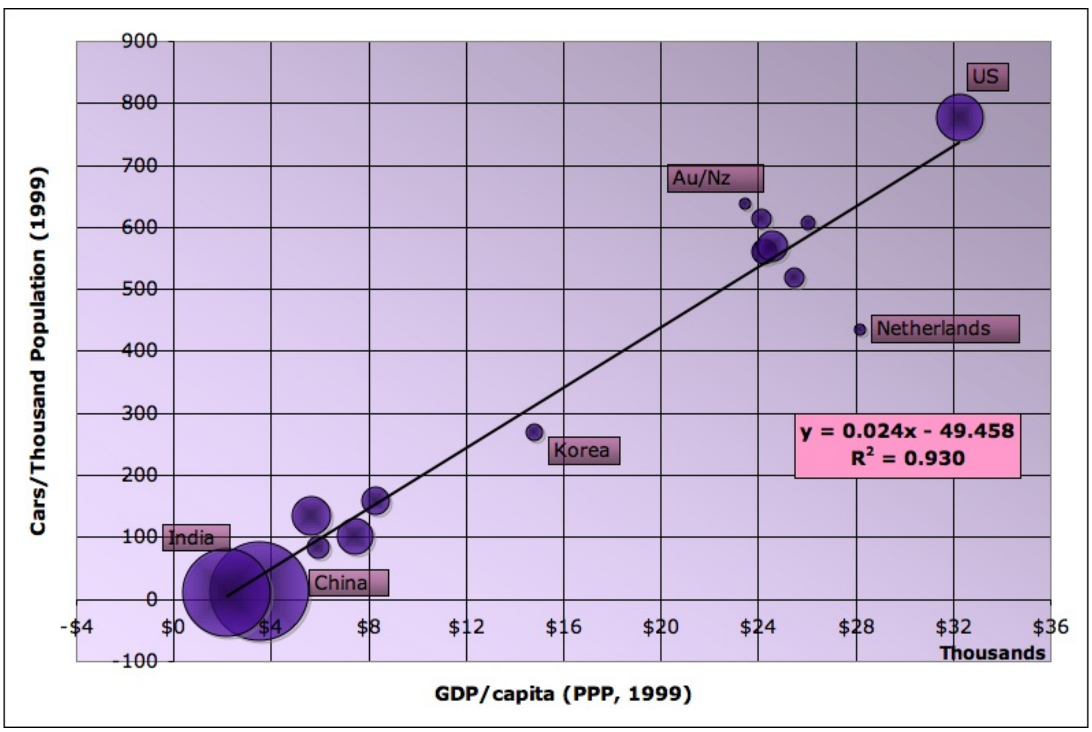
Then I looked at the energy sector and we saw that there are several potentially feasible ways to power civilization. They aren't cheap or easy, but solar, wind, and nuclear all have good to excellent EROEI and a fairly large resource that could be exploited. Solar in particular has the best learning curve historically (the rate at which price falls for each doubling of the installed base of the technology) and the highest growth curve and fewest barriers to early adoption (except cost). However, the renewable options are growing from a tiny base, and nuclear faces ongoing political resistance, so in the short term conservation and efficiency are critical requirements if we are to make it to the long term.

Still, if as a society we were serious and determined about solving our energy/climate problems, and we made the right investments, there seems to me little doubt that there are a number of feasible technical paths to a non-fossil-fuel energy infrastructure for civilization. Indeed, I argued that energy would likely become cheap again after a couple of decades of being expensive, once a renewable civilization was over the hump (the hump having been caused in part by failing to make more progress in the 1980s and 1990s).

However, there are many other resource constraints that we might hit along the way. So I want to continue surveying the terrain at a very high level and look at the automobile sector under the rough assumptions I outlined in Powering Civilization to 2050. In particular, how many cars might we expect by 2050, and how can we possibly power them, given that there will be less oil, not more, by that time. I think most readers would intuit that if society was wealthier in 2050, as I postulated, then if they possibly could, the planet's citizens would tend to drive more, not less.

But how much more? In my earlier scenario, I postulated a world GDP of about $350 trillion in 2006 dollars by 2050 (on a purchasing power parity - PPP - basis) which arose by assuming reduced economic growth in the near term due to problems of recession and energy constraints, but then renewed growth as those ultimately lift. Given the UN's medium population projection of 9 billion people, that gives a world GDP/capita in 2050 of about $28,000 (versus about $11,000 recently).

Now, global figures on auto ownership have proven hard to find. The best I've been able to get is some data from the EIA for a small selection of countries, and the world as a whole, for 1990 and 1999. However, it's probably enough. I combined that data with GDP data from the IMF, and UN population data to come up with the following graph:

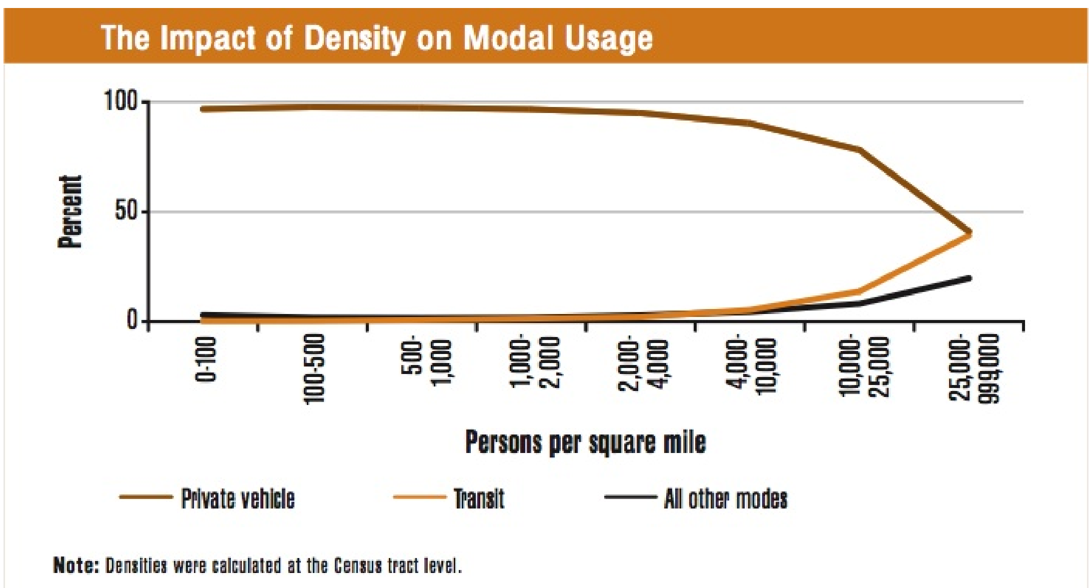


Cars per thousand population versus GDP/capita for selected countries in 1999 (using 1999 PPP dollars). Bubble area is proportional to population. Sources: Auto ownership from the EIA, GDP data from the IMF, and population data from the UN.

As you can see, at least for the available data, there is a pretty strong linear relationship between income and car ownership. 93% of the variance in the latter is explained by the former. For each additional $1000/year in average GDP per person, you get about another 25 cars per 1000 people. This strong relationship between income and car ownership seems to match the views of transportation economists, who believe that people everywhere are willing to expend a roughly constant fraction of their time and money on getting around:

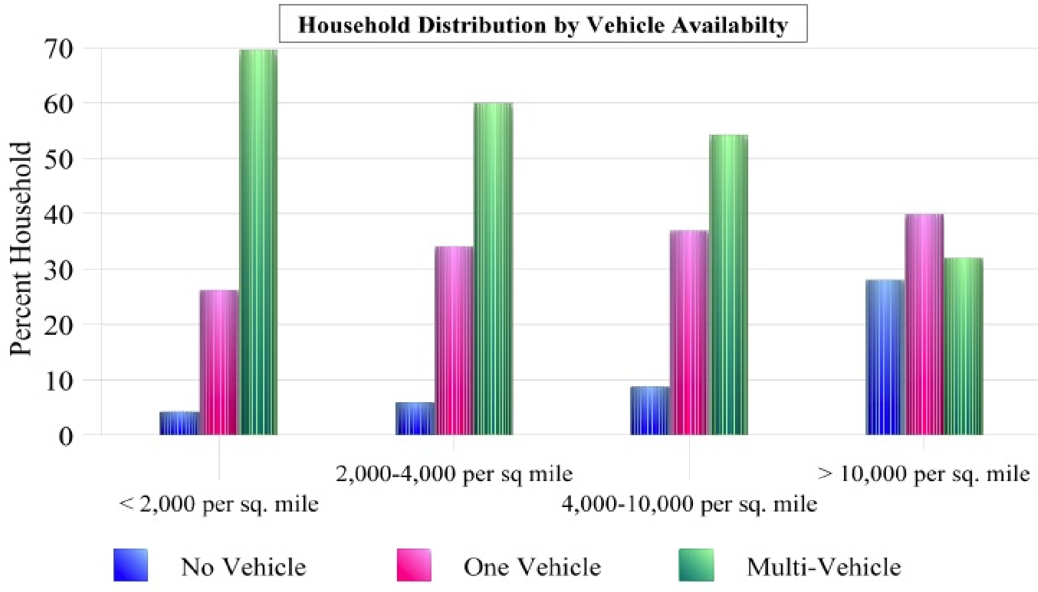
> Both travel budgets are of very rough nature only. However, since they apply to virtually all people, independent of income, space, and time, strong regularities in aggregate travel patterns are observed when we compare cross-sectional and longitudinal data of all travel surveys, including those from the developing world. The travel money budget along with country-specific characteristics of the transportation system (land-use, prices, etc.) translates disposable income into daily distance traveled. All other patterns can be largely explained by the travel time budget. Using this approach, travel patterns of countries with very different characteristics at first glance evolve on nearly uniform trajectories. Thus, despite their only rough stability, the travel budgets offer a simple, elegant framework on the basis of which average travel behavior characteristics can be approximated on aggregate levels.

While there isn't enough data above to prove this statistically, it rather looks like the major secondary variable controlling car ownership would be population density. The country with the lowest car ownership for their income level is the Netherlands, which is one of the most densely populated countries in the world, and the region with highest car ownership for income level is Australia/New Zealand, which is one of the most sparsely populated parts of the world. This matches the intuition one would get from US data, where public transportation ride share is highly correlated with population density, and auto usage inversely so:



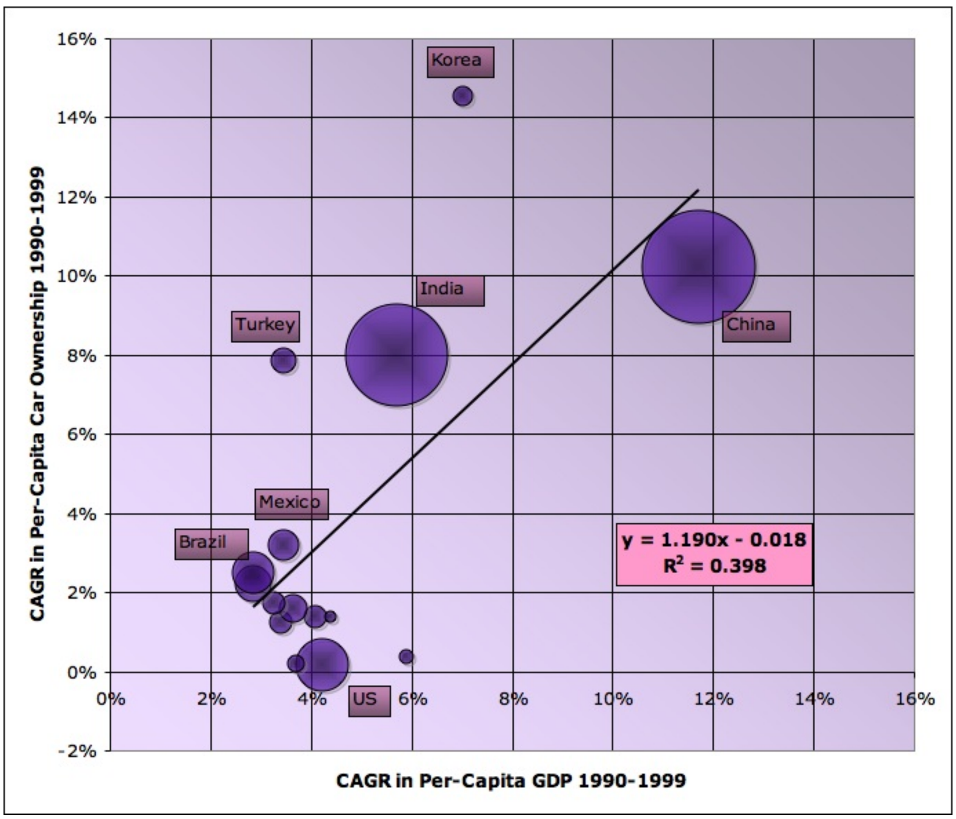
Transit and private vehicle share as a function of census tract density. Source: Commuting in America III.

There's a similar pattern in vehicle ownership - households in areas with the highest population density (over 10,000 persons/mile) are much more likely to have no car, and much less likely to have lots of cars:



Number of private vehicles per United States household as a function of population density in 2001. Source: [2001 NHTS Summary of Travel Trends](#).

This is somewhat encouraging for keeping the car count down, since the average world citizen in 2050 is likely to live in a very dense city in what we today call the developing countries (a lot of them will be pretty developed by 2050 under my assumptions). However, the discouraging thing is that those countries are growing the fastest economically, and that means rapid growth in car ownership also:



Annual growth rate in cars per thousand population versus annual growth rate in GDP/capita between 1990 and 1999 (using current PPP dollars). Bubble area is proportional to population. Sources: Auto ownership from the [EIA](#), GDP data from the [IMF](#), and population data from the [UN](#).

Whereas high car ownership is entirely a function of being a wealthy developed country, high **growth** in car ownership comes from being a low income but fast growing country. Particularly striking is Korea, with an extraordinary 14% growth rate average in car ownership over the decade of the 1990s. Korea was a middle-income rapidly-industrializing country, which obviously leads to a lot of car buying. These days, China and India, with a third of the world's population, are working their way into that status.

So let's try to roughly guesstimate the number of cars people might buy if they **weren't** resource constrained under this scenario, and then look at the resource constraints that might prevent them from having that many cars. I'll do the guesstimation three different ways which should give us a rough sense of the ballpark.

The first method is to note that the $28k/person/yr GDP in 2050 (expressed in 2006 dollars) would be about $23k in 1999 dollars. On the straight line in the ownership versus GDP graph above, that would place us at around the 500 cars/person mark. However, if we figure the average citizen is at Netherlands densities, we might knock 200 cars/person off that total to come out around 300 (give or take). With 9 billion people, that's about 3 billion cars in round numbers.

Another way to get to it is to notice that in the growth rate comparison, the average elasticity is a little more than 1 (ie 1% growth in income/capita leads to 1% growth in car ownership/capita). The EIA says that global car ownership in 1999 was 122 per 1000 people, which was 730 million cars. This source says there were a little less than 1 billion cars in 2006, so let's figure 1 billion in 2007. So car ownership grew 4%/year, and the global economy averaged 4.3% growth over the same period. Close enough to an elasticity of 1. So if we extrapolate that out to 2050, we go from 150 cars/person and $75 trillion today to $350 trillion and thus about 700 cars/person in 2050. If we again knock a couple of hundred off for high density city effects, we would get down to around 500 cars/1000 people, or about 4.5 billion cars. This is effectively to say that another 40 years of economic growth at something like current rates would place the world average roughly at current European levels of car ownership, which sounds reasonable if only we can find some way to power that many cars.

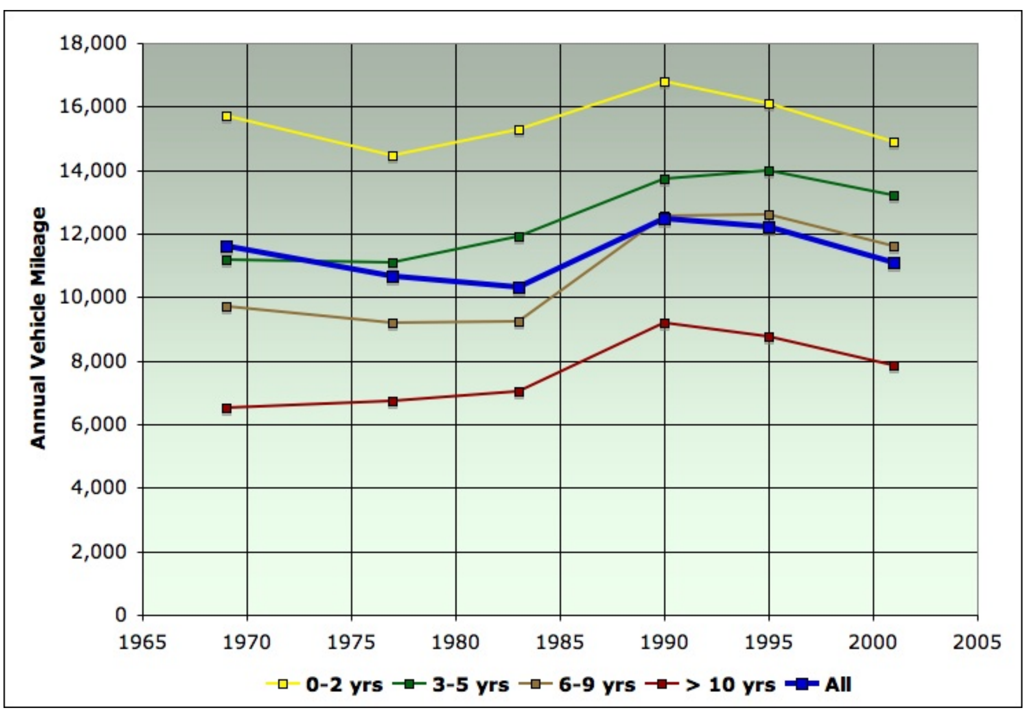
The third method is to use some data from here which show production of autos (rather than ownership). Production from 1997 to 2005 grew at an average rate of 2.43%. If we apply *that* growth rate to ownership and extrapolate to 2050, we get 2.8 billion vehicles on the road at that time.

So all three methods come out somewhere in the range of a few billion vehicles on the road in 2050. Whether it's 3, 4, or 5 we can't know, but clearly it would take something on the order of a major economic collapse somewhere along the way for there to still only be 1 billion cars on the road then. (For example, Soviet car ownership declined from 357 per thousand people in 1990 to 134 per thousand people in 1999, so that's what a major economic collapse can do). Let's take 4 billion as a reasonable working number, with the understanding that this is ± 25% (at least). Is there any way that many cars could be built and powered? Let's first look at powering them, and then building them.

Running Four Billion Cars

The Tata Nano will sell for about $2500 (US) in the base model, and get about 51 mpg (US). Source: Wikipedia.

Ok, so I don't think we need to spend very long on the idea that that many cars could be run primarily on oil. Let's try to roughly figure what kind of oil that might need. I don't have global mileage numbers, but in the US, vehicles do a fairly stable 10-12000 miles/year:



US annual vehicle mileage for vehicles of varying age grades. Source: 2001 NHTS Summary of Travel Trends .

Older vehicles do less, newer vehicles do more. Part of this might be income related, and since the average world citizen in 2050 will still not quite have achieved today's US income level, and will live in a denser city than today's average US resident, let's figure 10,000 miles/vehicle. So we're looking at somewhere in the neighborhood of 40 trillion vehicle miles per year. If we take the Toyota Prius/Tata Nano as exemplifying 2050 average fuel economy - about 50mpg - then we'd need a little over 50mbd of gasoline/diesel to run the 4 billion cars, even under the assumption they were pretty efficient. This won't work at all. In my scenario, we'd be down to about 35mbd of total oil production by 2050, and we'd want most of that for other things (aviation, heavy machinery, petrochemicals etc).

I don't really see doing too much supplementation of this with biofuels. Even the 1mbd of biofuels the world is already producing is causing a lot of problems, and it has the potential to get much worse quickly. Although cellulosic ethanol in theory could help, in reality most of the good agricultural land on the planet is already in use, and expansions onto the remaining land will tend to create far more carbon emissions than they save. (See two recent Science papers by Fargione et al, and Searchinger et al which are pretty convincing on this point).

So to run 4 billion cars, we should be looking at more like an average fleet economy of 200mpg to 250mpg, to keep the fuel bill down around 10mbd. That makes it likely that most of the energy would have to be coming from something other than liquid fuel.

There are two basic possibilities. The first is the hydrogen economy, in which renewable/nuclear power is used to produce hydrogen via electrolysis. The hydrogen is then used to power vehicles (and other things). I'm deeply sceptical about this whole idea. My objections are not primarily technical (though there are technical concerns) but rather based on the market diffusion problems.

Generally, diffusion of a new technology requires that there be early adopters who see value in it, then a larger group of less early adopters who are willing to do it once the worst bugs have been worked out, then the bulk of customers who only convert once the technology is really well established and their friends are starting to do it, and then finally the holdouts who cling to the old way of doing things until it becomes really not viable. This is the mult-stage diffusion process that has to occur.

Hydrogen has the huge problem of requiring a new infrastructure. So there need to be both early adopters on the infrastructure side (investors willing to fund hydrogen pipelines, gas stations owners willing to put in a hydrogen pump, etc), and early adopters on the consumer side (people willing to buy hydrogen cars). And in the early stages, both of these kinds of early adopters are going to have a miserable time because there won't be enough of the other kind close by. (I buy a hydrogen car, but have to drive 100 miles to buy hydrogen, or I open a hydrogen station and I lose my shirt because there are only three hydrogen car owners in my city).

Now, if hydrogen cars were the only way to get around at a decent speed, people would find a way to get over these hurdles (after all, cars succeeded in displacing horses). But hydrogen cars will have the problem that there are already lots of gasoline cars on the road. Gasoline of course is expensive and likely to get more so over time. But hydrogen is even more expensive and, even in my scenario, is not likely to get cheap for decades. In the meantime, a hydrogen car is at a serious disadvantage to a gasoline car. Therefore, they won't get adopted any time soon.

The other story, which I think is a lot more appealing, is that the present trend to hybrid gasoline/electric cars moves onto a plugin-hybrid stage in which the car has a larger battery and motor and gets plugged in to the electric grid at night or during the day at work. This has a far less serious adoption barrier. We already have distribution infrastructures for electricity and liquid fuel, so the only early adopter needed is the buyer of the plug-in hybrid. To the extent the grid needs to get expanded over time due to increased electricity usage by plug-ins, this will be done on the basis of clearly proven demand trends and can be a relatively low-risk decision. The speed of adoption of plugins will essentially be controlled by the relative prices of electricity and liquid fuels (including any carbon emission surcharges and governmental incentives).

In this scenario, power for cars will be predominantly coming from electricity by 2050, which I have already argued could be plentiful if we make the necessary infrastructure investments. So then the issues become whether it might be feasible to build that many plug-in hybrids.

Building Four Billion Plugin Hybrids

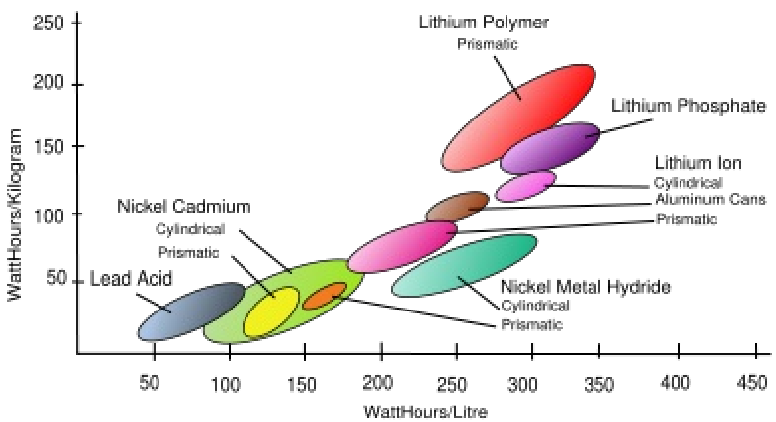
I stress of course that I'm not proposing that we make any crash program to build plugins. I'm simply proposing that as the economy grows and people, particularly in developing countries, get wealthier and want more cars, we create incentives to shift the car population gradually to hybrids and then plugin hybrids. Such incentives are already in place in a number of countries (eg the hybrid tax credit in the US). If this is done sufficiently, we would end up with a few billion plugin-ins by 2050. Market forces will do a lot of the work, since electricity is already cheaper per unit energy than liquid fuel, and the gap is likely to widen over time.

So then the question is what other resource constraints might we run into along the way, given that energy is not one in my scenario (at least not in the long term). Some things are fairly clearly not problems. The bulk of the car is made from steel, perhaps aluminum in future (lighter), and plastics. Iron and aluminum are the two most common metals in the earth's crust and are unlikely to be serious resource constraints this century. Plastics will be available from oil as long as we can mostly stop burning the oil in automobiles. The necessary roads can be made from concrete, and we are very unlikely to run out of limestone to make the cement, or sand and gravel.

Two issues seem to me to be potentially pressing - lithium for batteries and copper for motor wiring. I will examine lithium in detail now, but defer copper, which is a more general concern, to a future piece. (Roughly speaking, those familiar with the copper issue can imagine that it comes down to an argument about how much copper usage can be substituted by much more plentiful aluminum).

Lithium

The best battery chemistries known for future automobiles all appear to involve lithium. Lithium-based rechargeable batteries have more energy density per unit weight, as well as carrying more energy per unit volume:



Energy density (weight and volume) for various battery technologies. Source: Wikipedia.

For these reasons, lithium is coming to dominate a number of rechargeable battery markets (laptops, cordless power tools) and it seems reasonably forseeable that it would also dominate the plug-in hybrid market. So in this section, I want to take up the question of whether we would run out of Lithium before 2050. An important analysis for considering this issue is The Trouble with Lithium which seemed quite alarming when I first read it, though now I have run the numbers myself, I am more sanguine. It's also useful to read the most recent USGS commodity summary, as well as the longer 2006 Minerals Yearbook entry on Lithium. Also, Costs of Lithium-Ion Batteries for Vehicles has much useful data. I also recommend this nice overview presentation on mineral resource limitations on Earth in general (though some of the graphs are dated).

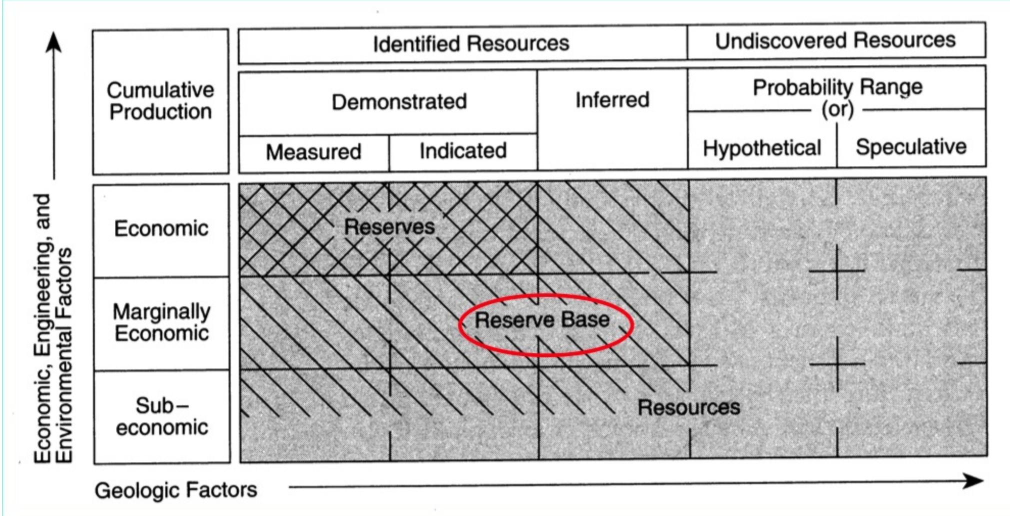
The concerns raised in Trouble With Lithium are two-fold. One is that the best and cheapest sources of lithium are limited to a few geographic regions (principally certain high desert regions of South America and Tibet) and that therefore the world would be as vulnerable to political problems with these regions as it is now with oil and the Middle East. The second is that the expansion of lithium mining required to support a plug-in hybrid world would be enormous relative to present day production. There is some validity to both these concerns, but let's first look at the total amount of lithium available, see if that's enough, and then come back to the potential bumps along the way.

The best estimates available are these (expressed as thousands of tonnes of elemental lithium).

Variable	Quantity (KT Li)
Reserves	6,200
Reserve Base	13,400
2005 Production	21.4
2006 Production	23.5
2007 Production	25

As you can see, there is not an urgent lithium problem - reserves/production is currently about 250. (As far as I know, no-one has raised a serious question about the validity of lithium reserve numbers). However, this is with hardly any cars containing lithium batteries. How does four billion of them change the picture?

Let's take a moment to look at the definition of reserves and reserve base:



Schematic of various categories of reserves and resources. Source: Resource Limitations on Earth.

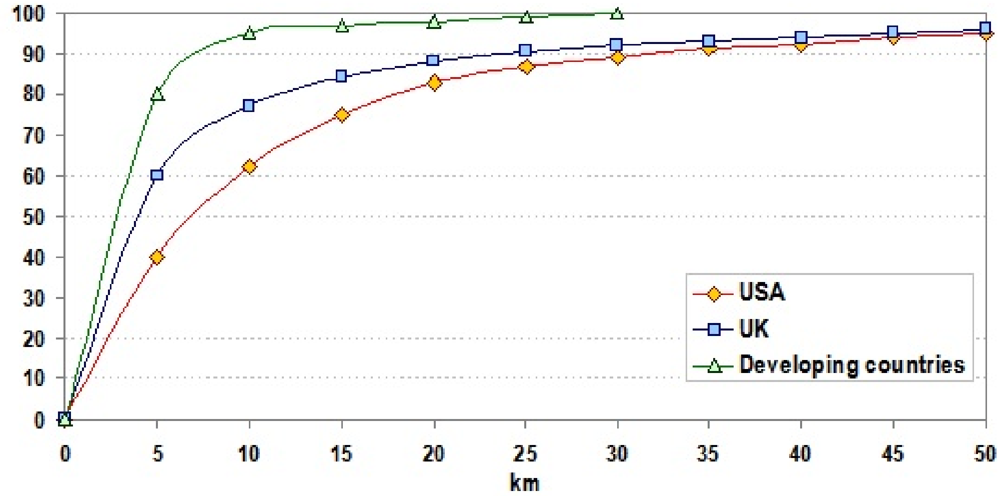
Basically, *reserves* are the material that we know where it is today, and we believe with high confidence that we know how to get it out of the ground profitably at today's prices with today's technology. The *reserve base* additionally includes known or reasonably inferred deposits of material that are technically recoverable but marginally economic. After that, we get into resources that either haven't been discovered, or are sufficiently dilute or inaccessible that no practicable way is known to extract them at near current prices.

Thinking about 2050, it seems to me that the reserve-base is the best guesstimate of how much lithium might be available if really needed (ie if we haven't figured out a better idea in the meantime). This allows for improvements in extraction technology and/or higher prices (manageable by a wealthier society), but we aren't getting out into "lithium from seawater" territory - the "reserve base" is lithium in known deposits.

Furthermore, since cars are 95% recycled even now, it seem reasonable to assume that long before 2050 we can pretty much be recycling all or nearly all of the lithium. So the calculation I'm going to assume (and I freely admit this is just a rough back-of-the-envelope sort of exercise) is to just divide the 13.4 MT of lithium reserve base by the 4 billion cars, which gets us an average of 3.3kg of lithium per car. Now, currently, it takes 0.3kg of lithium to get 1 kWhr of battery capacity, so that 3.3kg of lithium represents about 11 KWhr of electricity storage.

A reasonable assumption is that a plugin would require about 0.2 kWhr/mile. Thus the 11 KwHr average battery is 55 miles of all-electric range, or about 90 km. Now if we assume that they all get charged at night (figuring that the extra charging during the day for some cars is cancelled by others that can't or don't charge at night) then we can basically treat this as the maximum amount of daily mileage that can be covered by electricity, rather than liquid fuel.

Which allows us to make use of this data on the cumulative distribution of daily miles:

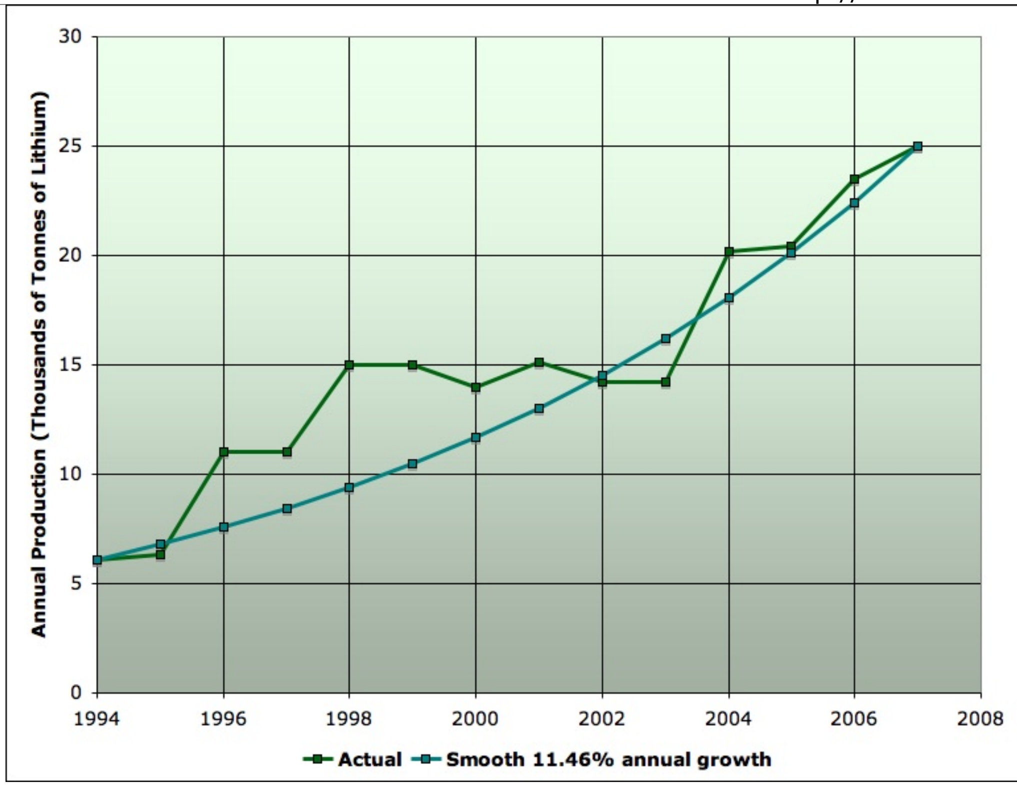


Cumulative distribution of personal daily travel distance in the US, UK, and an estimate for developing countries. Source: The Geography of Transport Systems, summarizing data from Regularities in Travel Demand: An International Perspective.

The average world citizen in 2050 is probably going to do a little less mileage than the US/UK numbers (given very dense cities). Thus more than 95% of vehicle days would be covered on electricity alone, and therefore it's pretty comfortable that the 50mbd of oil requirement (assuming 50mpg) would fall below 10mbd.

(Obviously, powering even more cars after 2050 would require at some point that we find more lithium, figure out how to extract it from seawater profitably, discover some better battery technology, or somehow otherwise work around the problem. I'm willing to live with this - who knows what 40 years of innovation will come up with. We wouldn't be worried about peak oil if it was 40 years off, and so I'm not going to worry about running out of lithium then -- we have to leave our children something to do...).

Now, let me go back to the other concerns raised in Trouble with Lithium. The author, William Tahil, spends a lot of time concerned about the disconnect between the current production of lithium and the amount required to turn out all of today's car production with lithium batteries, or convert all of today's cars on the road to lithium. But these are not reasonable models for the time path of lithium/plugin adoption occurring. Instead, the right way to frame the question is to assume that the market for lithium-ion batteries in plugins grows gradually over time, and then look at the required growth rate in lithium production and see if it looks outrageous. In my case, for a first quick calculation, I'm just going to look at what constant growth rate is required to produce a cumulative 13.4MT of lithium by 2050, and then compare that to recent history. Here is the recent history:



Recent history of global lithium production (exclusive of the US). Source: USGS. Note that the USGS doesn't publish US production because there is only a single US producer. The US will not be a major factor in lithium production going forward.

The darker green curve is actual lithium production. The compound annual growth rate from 1994 to 2007 is 11.46%, and the implied smooth curve is shown. Now, it turns out that if we were to assume that growth rate going forward, then we would mine almost 26 million tonnes by 2050. To get only the reserve-base number of 13.4 million tonnes, the average growth rate in lithium production between now and 2050 should be 9.35%. This doesn't seem an obviously outrageous growth rate.

The second major objection Tahil raises is the geographic concentration of lithium that will thus give some countries a lot of leverage over global supplies. He is undoubtedly right, but this will be only one of many such world problems, and far from the most serious. The world is going to be ever more dependent on the Middle East for oil in coming decades. The world will be critically dependent on Asia for a lot of manufactured goods. Asia and the Middle East will be critically dependent on big food exporters like the US and Brazll to eat. If we don't trade, we are all going to be in a world of hurt. In this context, concentration of lithium exports doesn't seem like the worst problem (at least if lithium exports stop, it only hurts the ability to build new cars, not run the existing ones).

In conclusion, these stylized facts seem to be roughly true:

- With the existing known reserve base of 13.4 million tonnes of lithium and less than 10 mbd of oil, we could run 4 billion cars in 2050.
- If we assume most residents of the planet are living in dense cities in the third world with degrees of public transportation comparable to dense western cities today, then 3-5 billion cars should be enough to satisfy people's aspiration for automobile transport by that time.

Oh, and I think we could reasonably hope that the darn things will drive themselves by 2050!

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