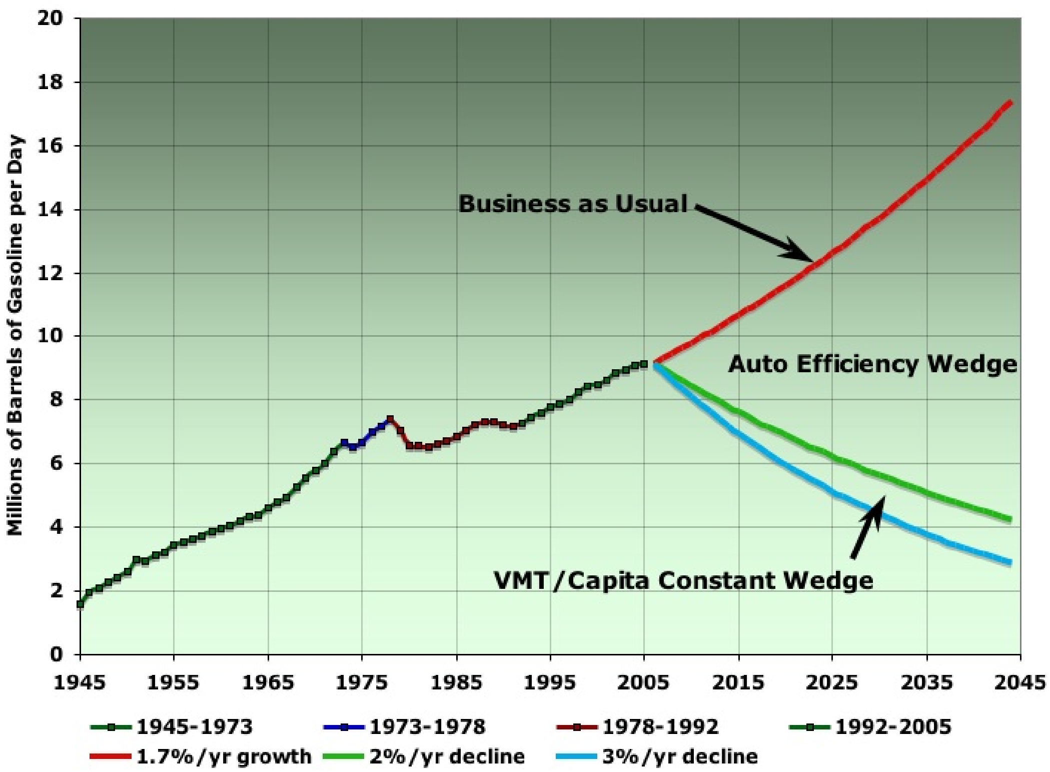
The Auto Efficiency Wedge

Posted by Stuart Staniford on February 11, 2007 - 10:28am
Topic: Demand/Consumption
Tags: automobile, fuel efficiency, peak oil [list all tags]

ED by PG: This article was originally posted December 20, 2006. Note that it has been resubmitted to reddit and digg this morning, so do help spread the word and give Stuart some more readers if you are so inclined. Send the link to someone today.

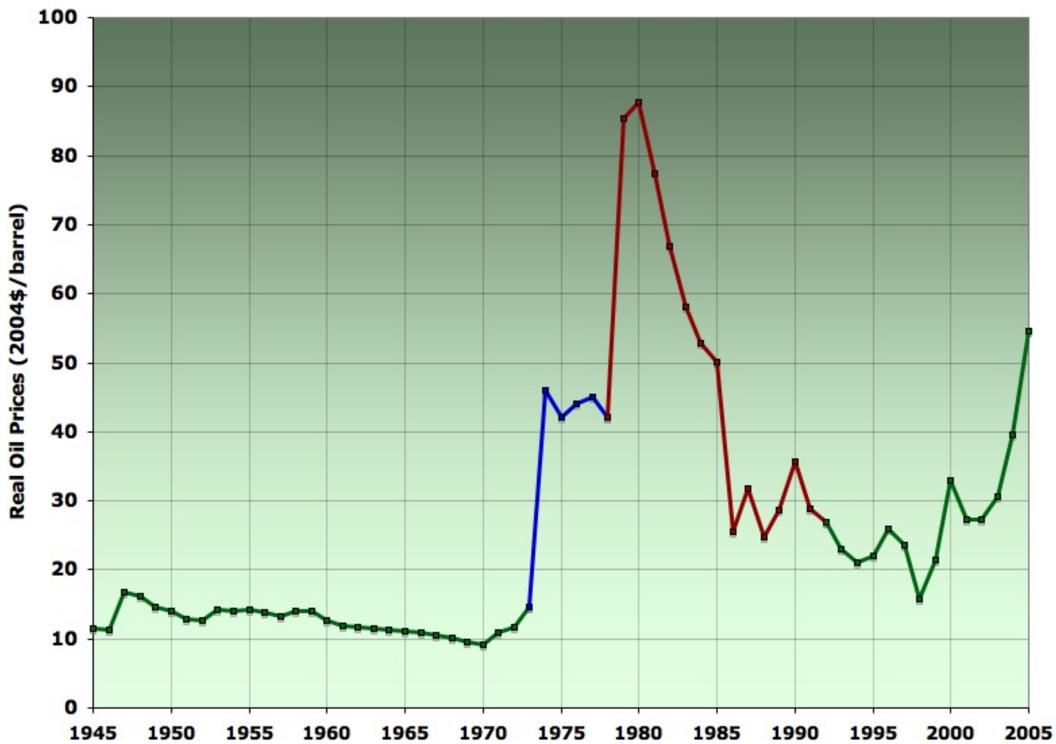


US finished motor gasoline supplied, 1945-2005, together with scenarios for 1.7% growth, and 2% and 3% declines from 2007 to 2045. Quantities expressed in millions of barrels per day. Click to enlarge. Source: US EIA for historical data. See text for scenario rationale.

In this piece, I wanted to take up a more precise consideration of how much auto efficiency improvements might contribute to solving what I called the terrible trio of energy dependence on unstable regimes, global warming, and the peaking or plateauing of liquid fuel supply. My examples are all US, but I think the lessons mostly carry over (if a little less urgently) to other developed countries.

I'll be reasoning mainly by looking at what we did in the 1970s, which was the last time we faced severe energy constraints that bled through into requiring a demand side response.

To begin with, let's refresh our memories about the history of oil prices, which tells the story of the oil shocks quite well.



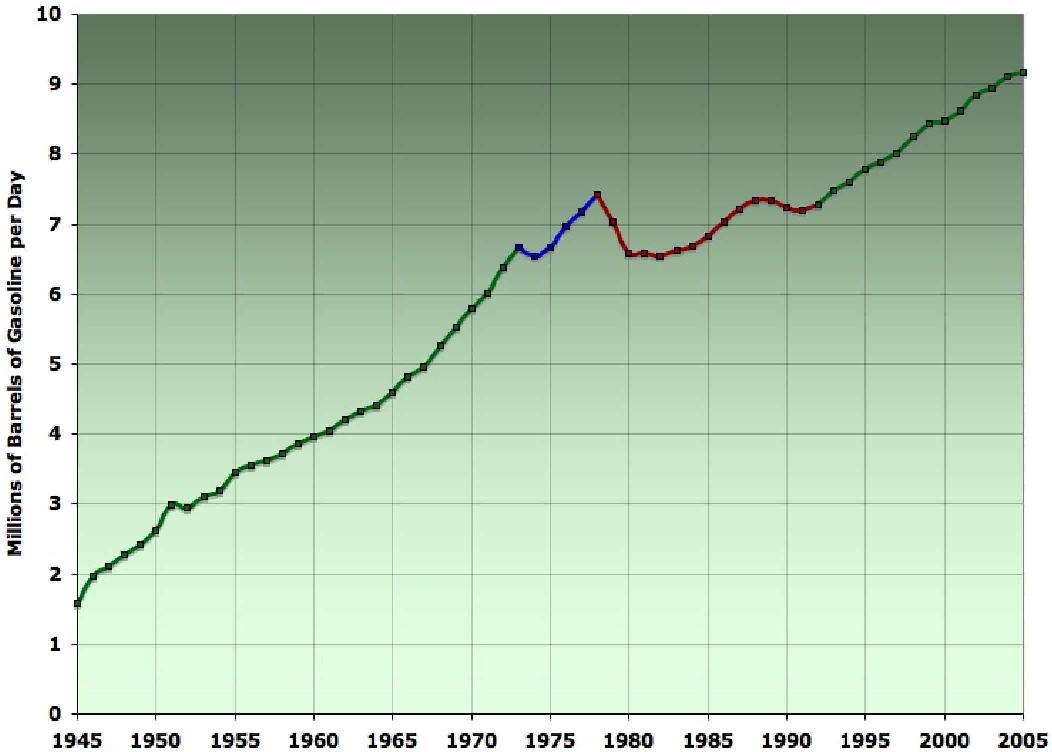
*Real oil prices, annual average, 1945-2005, expressed in 2004 dollars. Click to enlarge. Source: [BP Statistical Review of World Energy 2006](). *

In this graph, like most in this piece, I've adopted the convention of coloring 1973-1978 in blue. 1973 was the Arab oil embargo: the first oil shock. From shortly after the end of the second world war (in 1945 when the graph starts) until the early 1970s, prices were low, stable, and declining in real terms. The Arab oil embargo in '73 caused a very rapid quadrupling of prices, and they have never been anything like as low or stable since then.

I've also colored the period 1978-1992 in red. 1979 brought the Iranian revolution, shortly followed by the Iran-Iraq war. Prices doubled again from the mid-seventies values, and stayed high, though steadily declining, through about 1985. By 1986, prices entered a new regime of fluctuating in the $20s and $30s until the runup in price of the last few years (which I believed to be probably caused by the onset of a plateau in global production).

As we'll discuss below, 1992 was when the period of rapid fuel economy increases initiated by the oil shocks ended.

Let's now look at how total gasoline used in the US evolved in response to this history.

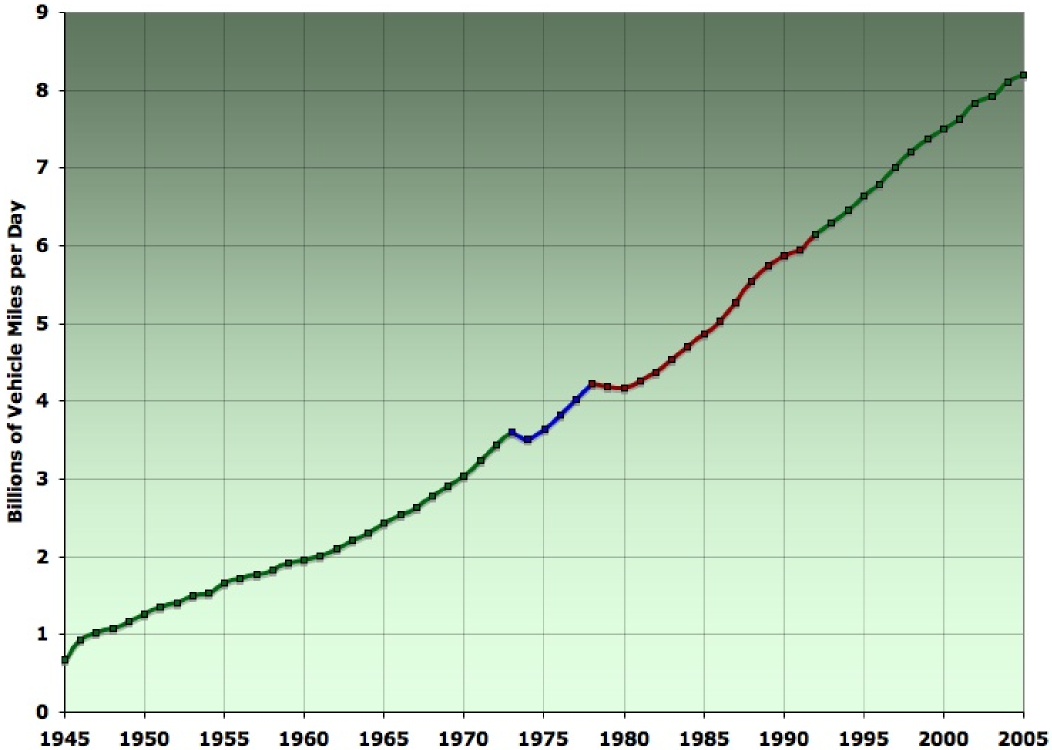


US finished motor gasoline supplied, 1945-2005, expressed in millions of barrels per day. Click to enlarge. Source: US EIA.

We see strong and steady growth prior to 1973. 1973 saw only a minor blip downwards, but growth rapidly resumed. However, following the Iranian revolution, gasoline usage dropped sharply, and then began growing again only very slowly and hesitantly, and did not exceed the 1978 value until the 1990s. Since 1992, gasoline usage has been steadily increasing, though at a slower pace than in the 1950s and 1960s.

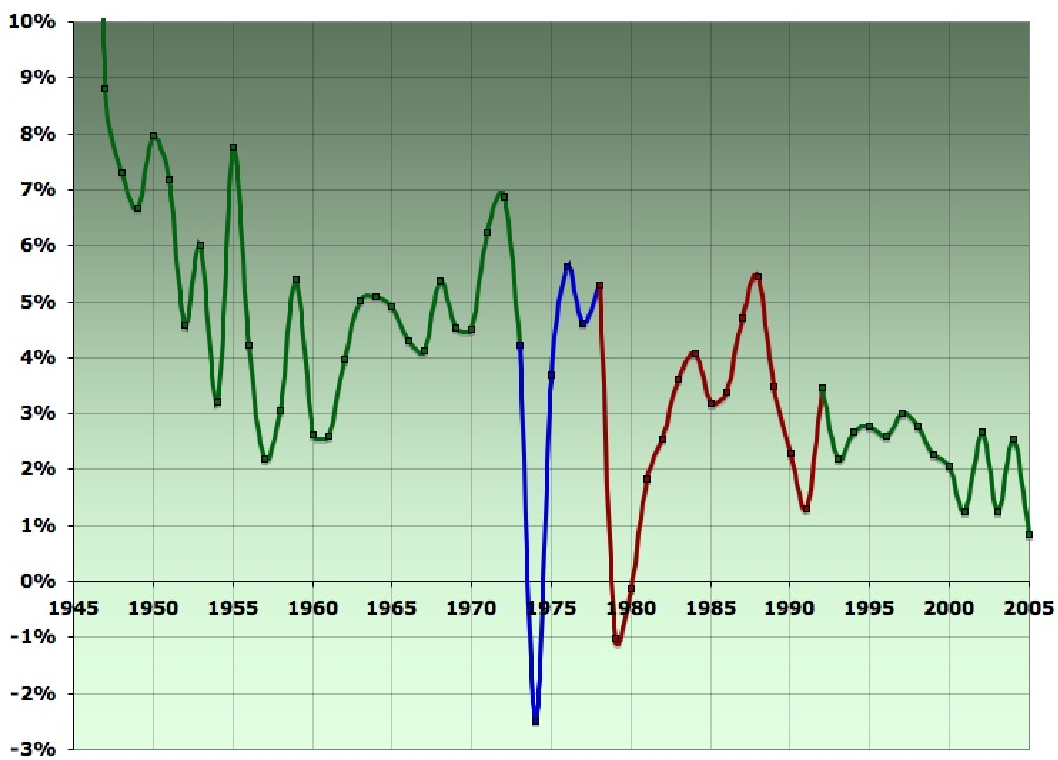
It's useful to decompose gasoline usage as a product of two things: the total amount of miles driven, and the fuel efficiency of the vehicles doing the driving. Miles driven is mainly a function of the physical layout of society (where houses, schools, offices, factories etc are located, and thus how far people have to drive to get to them), and human behavior (how often people decide to go to a particular destination, and whether they choose to go alone, share a ride, or to take some form of transportation other than driving). Fuel efficiency is mainly a function of vehicle technology, with a small component of driving behavior mixed in (we'll see an example of how small below).

Here is the total number of miles driven (expressed in billions of miles/day) in the US on all roads by all vehicles. Again we are looking from the end of WWII until last year.



US vehicle miles traveled (all vehicles, all roads), 1945-2005, expressed in billions of miles per day. Click to enlarge. Source: FHWA [Highway Statistics](#) series.

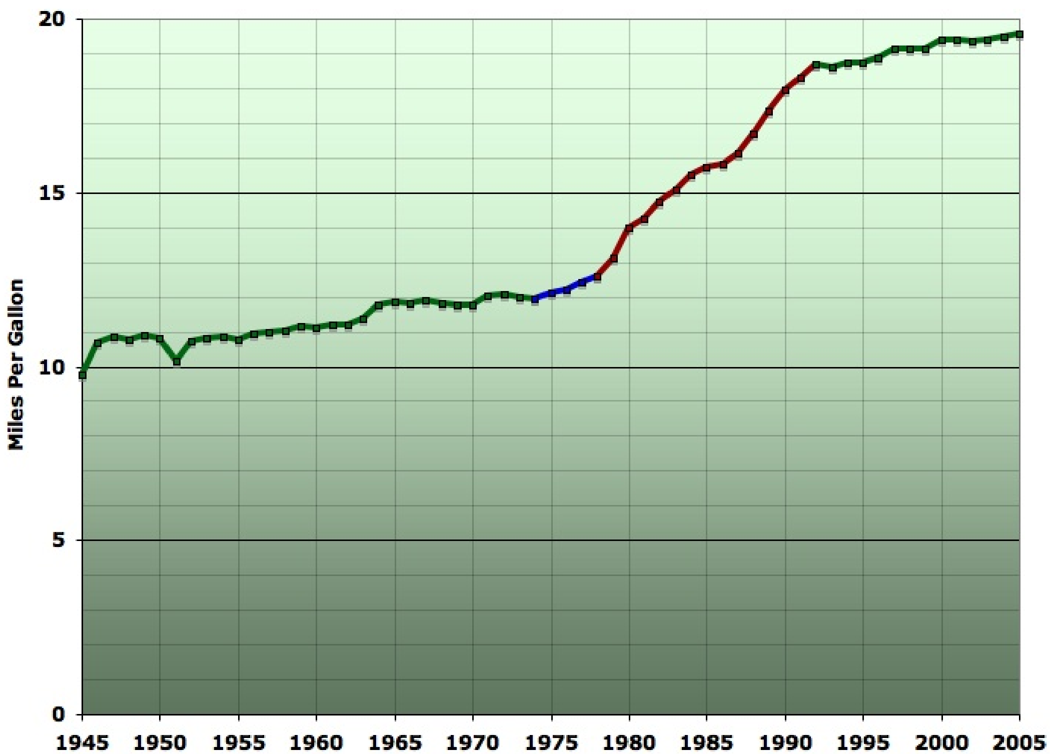
The oil shocks made rather less impact on the human behavior and land use components. VMT only dipped down very slightly, following each increase in price, and then resumed growth quickly, even when prices stayed high. We can see this more clearly by looking at the changes in VMT on a year on year basis.



Year on prior year percentage change in US vehicle miles traveled (all vehicles, all roads), 1945-2005. Click to enlarge. Source: FHWA [Highway Statistics](#) series.

As you can see, the effect of the Arab oil embargo was essentially gone after 1974: growth in VMT resumed at about 5% per year in the mid seventies, much as it had been in the fifties and sixties. This is **despite** the fact that prices did not go down again in 1974, but stayed at the $40 level ($2004) through 1978. However, 1978 caused a more profound transformation - miles only actually shrank in two years (1979 and 1980), but growth was depressed for several more years after than, and didn't reach the 5% mark again until the late eighties. It has been consistently lower than that since (which I discuss below). Anyway, the second '70s oil shock drove the point home more strongly than the events of 1973 and caused a multi-year shaving of VMT growth (but very little and brief actual reduction in the absolute level of driving).

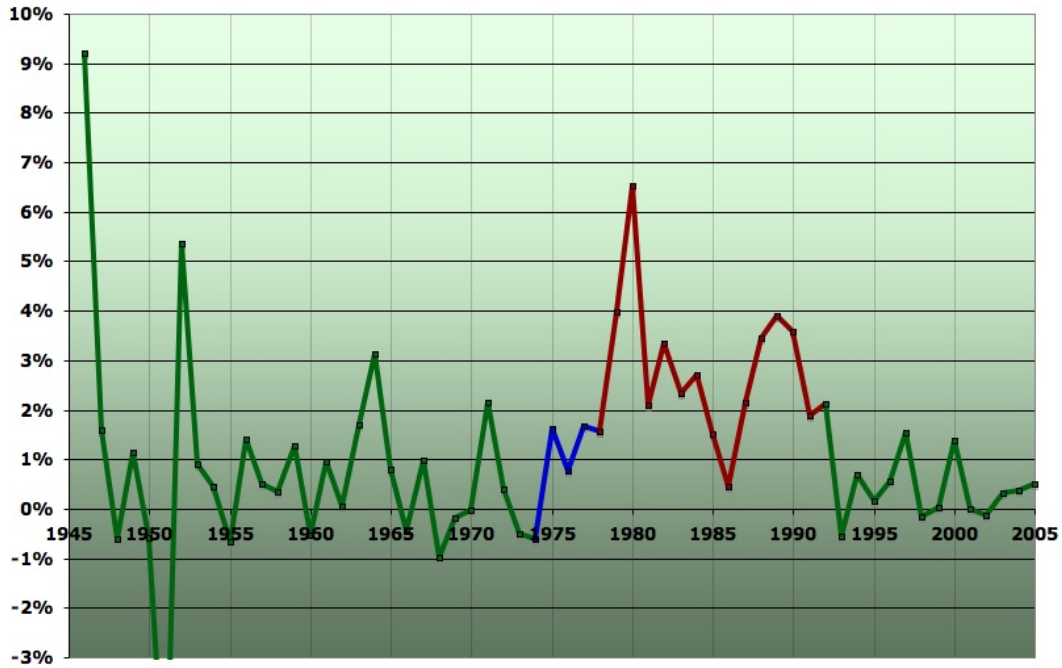
The fuel efficiency response to the oil shocks was much stronger than the VMT response. The next graph is an approximate estimate of gasoline vehicle fuel efficiency derived by taking total gasoline supplied numbers from the EIA, and dividing them into VMT statistics (corrected for non-gasoline vehicles[1]) . Note that this is **not** the fuel efficiency of new vehicles supplied, but rather the achieved fuel efficiency of the entire gasoline fleet in actual use that year.



Estimated fuel efficiency for all deployed gasoline vehicles in the United States by year, 1945-2005. Click to enlarge. Source: Author's approximate calculations based on FHWA [Highway Statistics](#) series for vehicle miles traveled data, and [US EIA](#) for data on finished motor gasoline supplied. See text for details.

Fuel efficiency was trending up very slowly from 1945, but had only reached 12mpg by 1973. It starts up slightly faster in the blue region between 1973 and 1978, but then really starts to take off after 1978, climbing to almost 19mpg by 1992. Since then it has resumed a very slow rise, similar to the pre 1973 years. It never went down again. Thus the oil shocks clearly caused a large and permanent change in the fuel efficiency of the US vehicle fleet.

We can see this in more detail if we look at a graph of year-on-year percentage changes throughout this period:



Year on prior year percentage change in estimated fuel efficiency for all deployed gasoline vehicles in the United States by year, 1945-2005. Click to enlarge. Source: Author's approximate calculations based on FHWA [Highway Statistics]() series for vehicle miles traveled data, and [US EIA]() for data on finished motor gasoline supplied. See text for details.

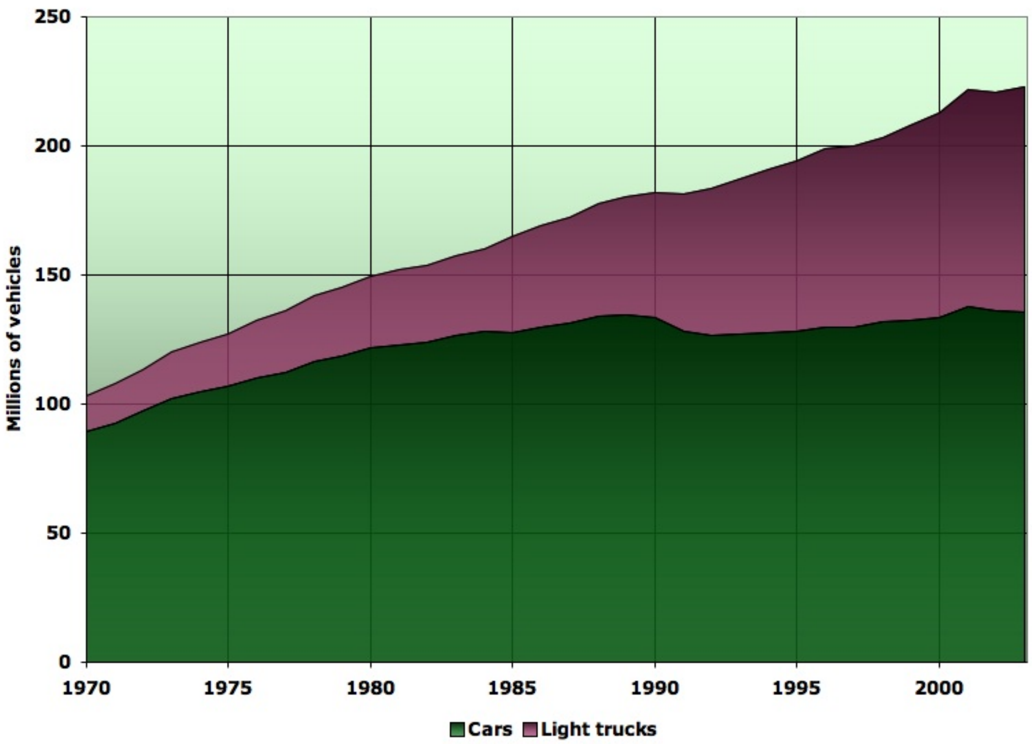
Prior to 1973, percentage increases oscillate generally in the 0%-1% band. Overall, from 1945 to 1973, the compound annual growth rate in fuel efficiency was 0.7%/year. After 1978, increases are much higher, fluctuating mostly over 2%, and reaching a high of a 6.5% gain from 1979 to 1980. On average, from 1978 to 1992, fuel economy grow at a compound annual growth rate of 2.8%/year - a major contribution to the situation. From 1992-2005, however, progress has stalled, with average annual growth of only 0.3%/year.

One thing that struck me as very surprising is the lack of impact of the 55mph speed limit. This was adopted in 1973, and one might have expected it to make an abrupt and significant contribution to the solution. However, fuel economy increases between 1974 and 1977 were only very slightly higher than those of earlier years and it is rather hard to discern a major effect (eg a big spike up in the fuel economy growth rate in 1974 is not evident at all - there is not even a modest response until 1975). Nor is there any sign of a decline in fuel economy when the policy ended in 1995. Overall, I find very little evidence that the 55mph speed limit had much effect at all - presumably compliance was too poor for the theoretical benefits to emerge in practice.

In thinking about the post-peak future, then, it seems clear that the 2.8%/year average growth in fuel economy achieved 1978-1992 has to be taken as a lower bound on what the economy could do in response to high fuel prices. Obviously, the response faded away, but that is clearly not because we are anywhere close to the technical limits of fuel economy, but rather because the price stimulus faded away. There are 50mpg vehicles on the road now that are acceptable to at least some current consumers, and the next generation Prius (available in 2008) [is rumored to achieve close to 100mpg]() while improving acceleration from the present version. While not everyone will drive a Prius, the mix of cars does shift towards compacts and subcompacts when oil gets expensive. And of course, the 2008 Prius is very unlikely to be the end of auto-engineer's ingenuity when sparked by high gas prices. All in all, there seems no reason to suppose that the gasoline powered fleet could not run four or five times more efficiently than the current approximately 20mpg fleet, and probably more eventually. It's just a matter of how quickly we can/will get there.

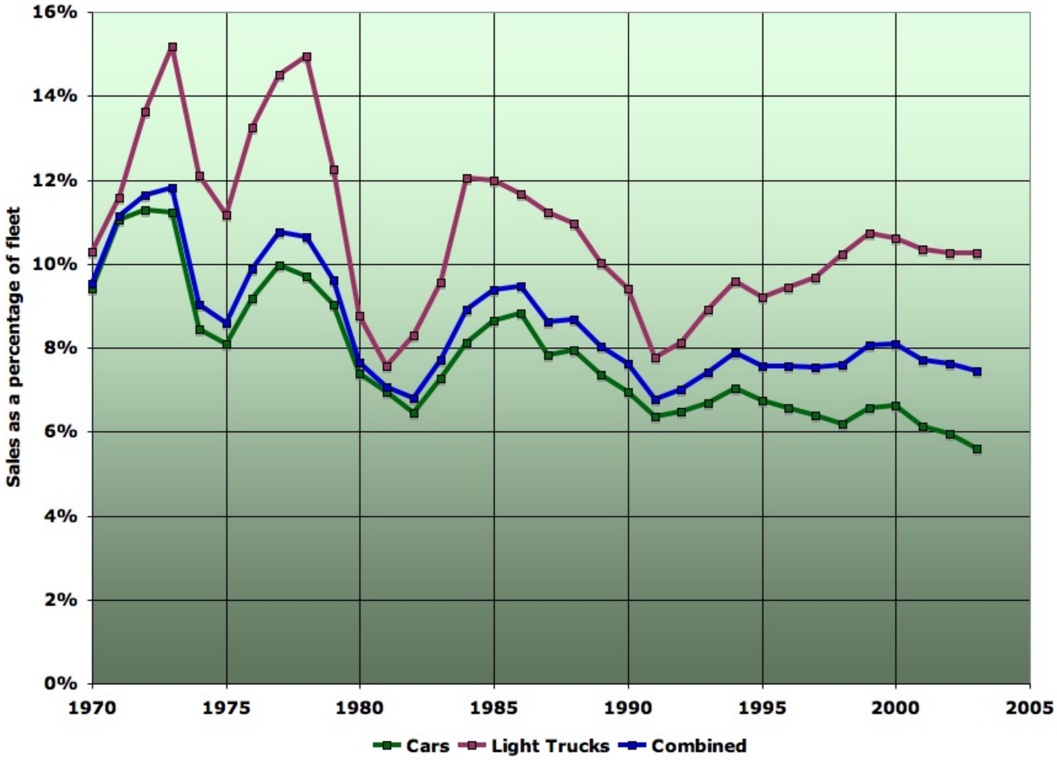
It is tempting to take the 6.5%+ annual improvement in fuel economy achieved from 1979 to 1980 as a best case for the annual improvement in fuel economy that could be achieved on a sustained basis if we really, really had to. There are some significant uncertainties however that make me uncomfortable with this. Let me outline both those uncertainties before giving my rationale for my eventual choice. With the available data, it's hard to understand in detail how the adaptation that year was achieved - it's a stunningly high figure given that in recent years only 8% of the auto fleet has been sold annually (that is sales of new cars is 8% of the size of the fleet, roughly).

Let's review the summary data. Here's the overall size of the fleet of both cars and light trucks (ie SUVs, minivans, and pickups):



Total population of US cars and light trucks, 1970-2003. Click to enlarge. Source: [Transportation Energy Data Book](), Tables 4.1 and 4.2.

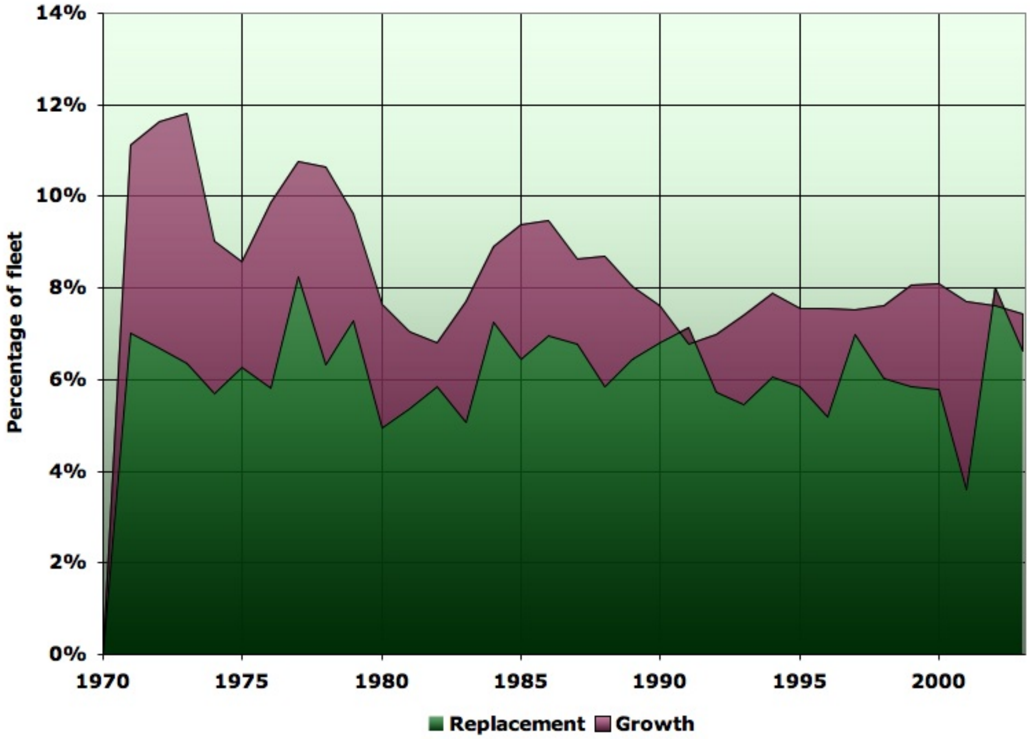
Clearly visible is the gradual secular trend towards light trucks and away from cars. The oil shocks are not a profound feature of that trend. Now, however, let's look at sales, expressed here as a percentage of the fleet size in the year of sales:



New sales of US cars and light trucks as a proportion of the existing fleet, 1970-2003. Click to enlarge. Source: [Transportation Energy Data Book](), Tables 4.1, 4.2, 4.5, and 4.6.

Three things stand out. Firstly, the light truck sales/fleet ratio is higher than that of automobiles, reflecting mainly the fact that the light truck fleet is growing faster. The "combined" line is closer to the car line (since there are more cars in the population). Secondly, in the past, the sales/fleet ratio was typically higher (with the combined ratio being around 10%-12%, versus the 8% in more recent years). Probably this is because cars last longer these days. Thirdly, the oil shocks are clearly visible as sharp drops of several percentage points in the sales/fleet ratio (reflecting the fact that the oil shocks triggered or worsened serious recessions, and car sales go down in recessions).

Since in 1979-1980 the sales to fleet ratio was down at around 7.5%, it's very hard to see how substitution of old vehicles with new could have given rise to a 6.5% rise in fuel economy. To get a better lock on this, we need to understand how many sales went to fleet replacement, versus fleet growth. By looking at year on year changes in fleet size, as well as sales, I came up with the following breakdown into the proportion of the fleet that gets replaced each year, and the proportion that is involved in growing the fleet:



Sales of US cars and light trucks as a proportion of the existing fleet, broken down into a segment used to replace scrapped cars, and a portion used to grow the fleet. 1970-2003. Click to enlarge. Source: [Transportation Energy Data Book](), Tables 4.1, 4.2, 4.5, and 4.6[2].

Note that the couple of times the "growth" number went negative is because the fleet shrank slightly in those years. As you can see, the "replacement" proportion is much more stable at around 6% of the fleet (give or take a percentage point), with most of the volatility in the growth line.

Still, this makes the 6.5% fuel economy gain in 1980 all the more interesting, since only about 5-6% of the fleet was replaced in 1979 and 1980. There are two possibilities that I can think of. One is that scrappage mainly affects vehicles that are **much** worse than the average fuel economy, while new cars bought during an oil shock are **much** better than the average fuel economy. However, we know the new fuel economy stats, and there's no way to explain all the fuel economy gain this way. So perhaps there must also be internal rearrangement of the fleet. That is to say, high mileage drivers sell gas-guzzlers to low-mileage users, and/or pick the highest-mileage vehicle available to them for longer trips.

All in all, I feel that I don't understand this number well enough to assume it could be sustained. However, I note that in 1979 there was a 4% improvement in deployed fuel economy, and then again in 1989 there was a 3.9% increase. Plus several other years achieved improvents in fuel economy over 3.5%. Therefore, I feel that 4%/year is a reasonable estimate for the economy's sustained ability to improve fuel economy when it's under very great pricing pressure to do so.

Some might argue that there is a case for assuming the post peak-oil the economy will be very different and capable of much larger responses. However, I notice that the replacement rate for the vehicle fleet has been pretty stable at around 6% for several decades and in oil shocks changed only slightly (and that **down**, rather than up). Thus I think the case for assuming that we can improve fuel economy faster than that after peak oil is poor. (Not that it definitely couldn't happen - the uncertainties are considerable - but it seems unwise to plan on it).

In short, then, after lots of detailed analysis, my best guess for the potential size of the fuel efficiency wedge remains the same as my first SWAG of 4%/year.

To make clearer what that would look like, suppose hypothetically that we began increasing fuel economy at 4%/year starting in 2007 over 2006. Here's the picture:

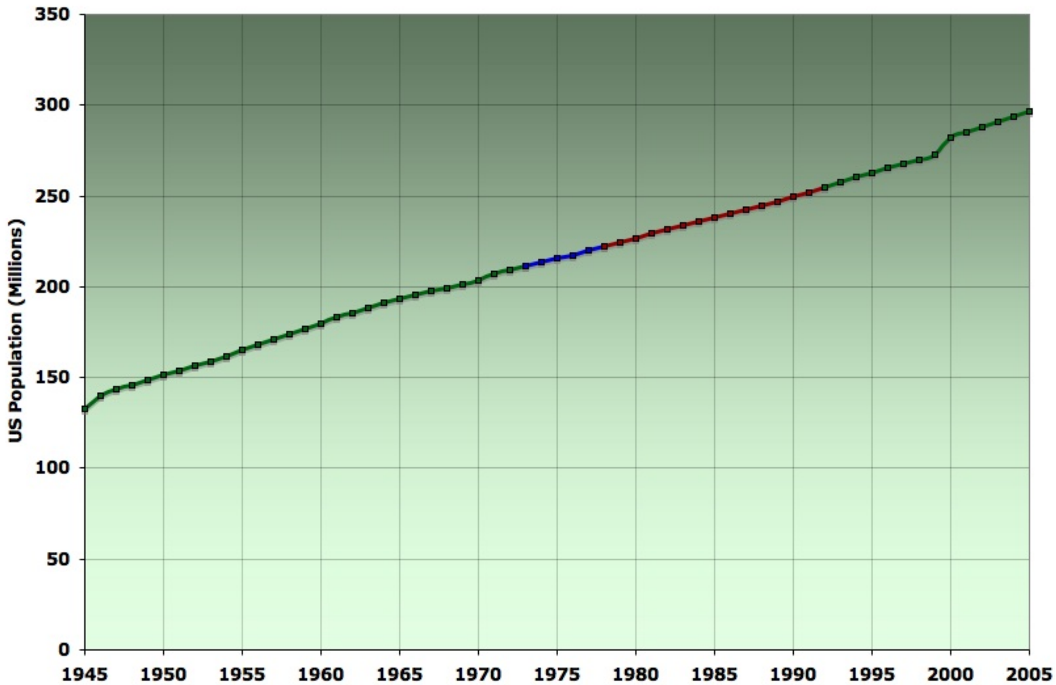
Hypothetical fuel economy (miles/gallon) to 2050 with a 4% growth rate starting in 2007. Click to enlarge.

Clearly, it would take sustained major pricing pressure to make people do this. However, I have also put the current nominal fuel efficiency of the current model Prius, and the rumored efficiency of the 2008 Prius on the chart. We wouldn't reach the former level as a fleet average until about 2030, and the latter level wouldn't be reached until after 2040. So clearly, there is no technical barrier whatsoever to a number of decades of 4% fuel economy growth. And that ought to be long enough to solve the large-scale plugin hybrid problem. So I'm quite willing to assume sustained 4%/year increases out past mid-century.

To achieve higher than around 4%/year gains, it seems to me that it is likely market mechanisms would not suffice. The key to going faster would be retiring more old inefficient vehicles and replacing them with new highly efficient ones. Gas taxes would be one method, but I suspect that what might be a lot more politically acceptable is something like a government tax break for people who retire an inefficient vehicle and replace it with one that's at least X% more fuel-efficient (this would create more benefit than the current hybrid tax-break, since it would encourage retirement of bad vehicles, as well as purchase of good ones). However, I cannot currently estimate how cost-effective such a program would be. A more muscular approach would be to create sunset dates for low fuel-efficiency vehicles enforced through the existing smog-testing infrastructure. All vehicles that failed the current fuel economy bar would be forcibly retired, and the bar would be raised each year. It would require considerable political will to create the conditions under which such legislation would be passed.

Next, I'd like to make some more analysis of what is the business-as-usual case from which one should be deducting this as a wedge. For this, we need to go back to the VMT statistics. I would like to now break VMT down into a product of two factors, both growing. The first is the US population, and the second is the VMT/capita.

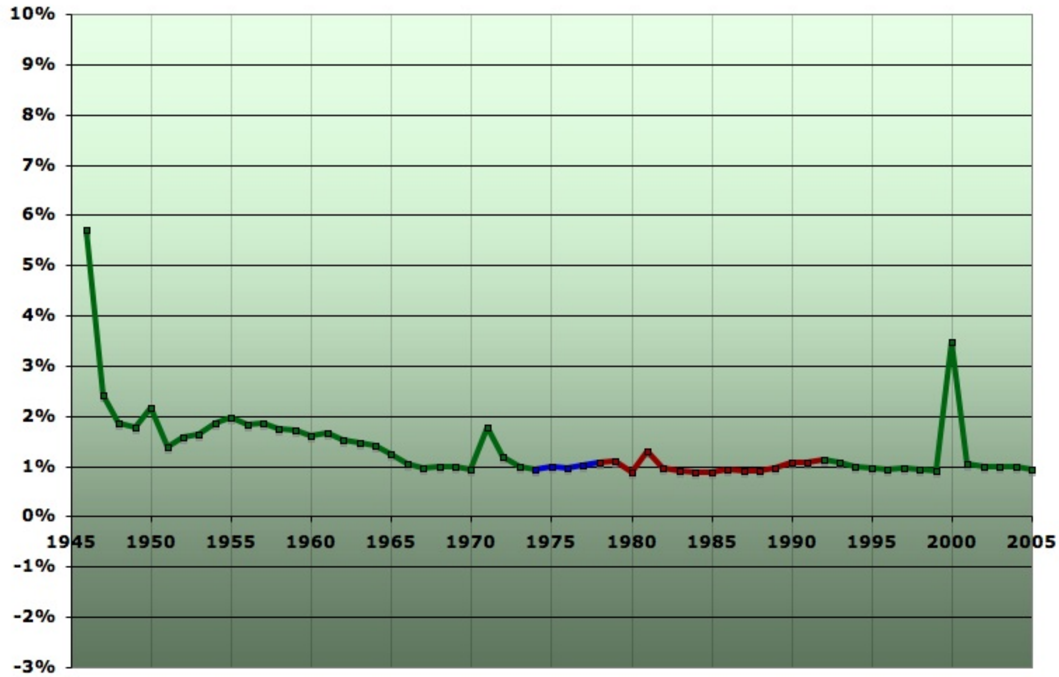
Let's take population first. It has the merit of being very boring in its behavior:



US population, 1945-2005. Click to enlarge. Source: US Census Bureau estimates via [Texas State Library and Archives](#).

As you can see, with the exception of a couple of anomalies, most notably in 2000, the growth has been very smooth and linear. I have not been able to track down what happened in 2000, but my guess is that there was some change in the Census Bureau's estimation methodology, rather than an actual sudden step in population. Henceforth I will treat that year as an outlier to be ignored.

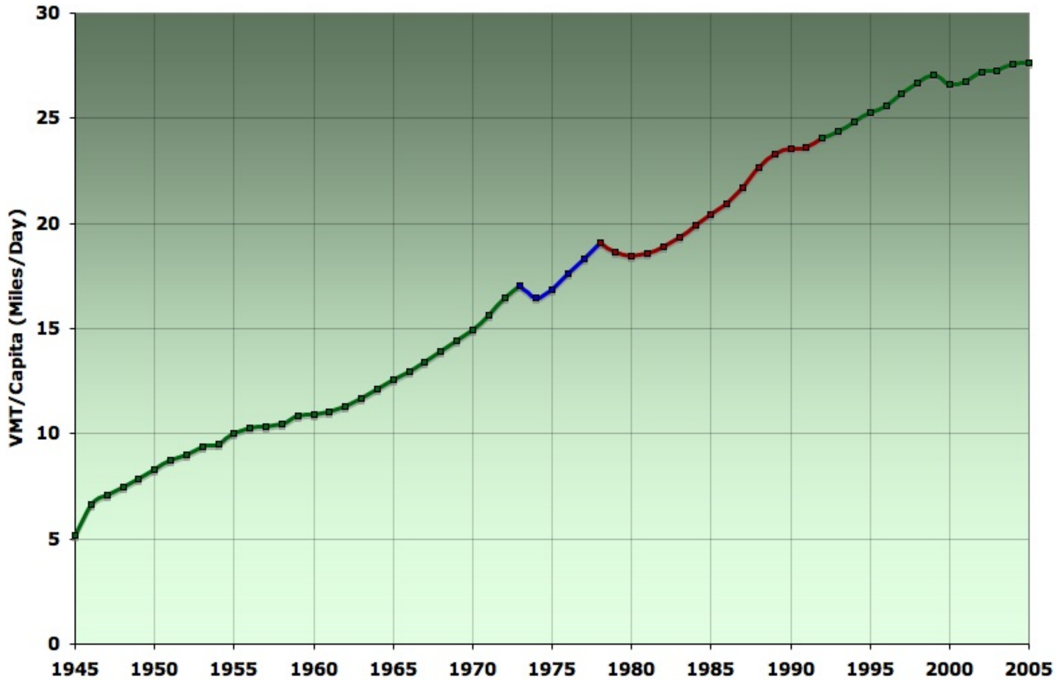
We can get a more precise sense of past growth by looking at the year-on-prior-year percentage change in population.



Year on prior year change in US population, 1945-2005. Click to enlarge. Source: US Census Bureau estimates via Texas State Library and Archives.

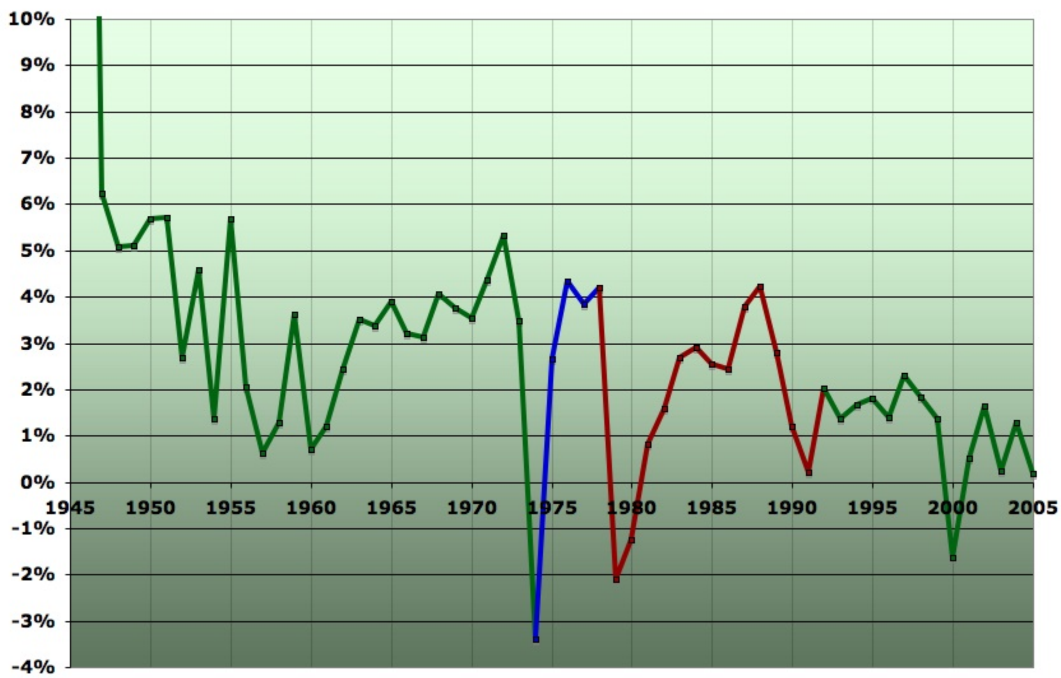
Population growth dropped to 1%/year about forty years ago, and has been very stable there ever since. The 1970s oil shocks had no impact at all on population growth, and nor has much of anything else that's happened since about 1965. It seems, then, that any projection other than "about 1%/year" going forward would be rather hard to justify. The demographers at the Census Bureau believe it will drop gradually to about 0.8%/year over coming decades, but the difference seems small enough that I will stick with the numerically more convenient 1%.

If we now divide the population out of the VMT growth, we get the following graph for VMT per person (this is all vehicle miles by all vehicles on any road in the US, divided by every man, woman, mewling infant, etc).



US vehicle miles traveled (all vehicles, all roads) per capita, 1945-2005, expressed in miles per day. Click to enlarge. Source: FHWA [Highway Statistics] series for VMT, and US Census Bureau estimates via [Texas State Library and Archives] for population.

Back in the late 40s, we managed on less than 10 miles of daily vehicle movement per person. Now it's up over 25 miles per person. It was climbing until the last year when high oil prices (presumably) have caused it to level out. The oil shocks in the 1970s loom a little larger in the per-capita signal than in the overall total (not surprising in light of the fact that population growth was completely unpeturbed by oil shocks, so all the effect on VMT comes from the per-capita factor, rather than the population multiplier). Let's look more closely at the year-to-year changes:



Year on prior year changes in US vehicle miles traveled (all vehicles, all roads) per capita, 1945-2005. Click *to enlarge. Source: FHWA Highway Statistics series for VMT, and US Census Bureau estimates via Texas State Library and Archives for population.*

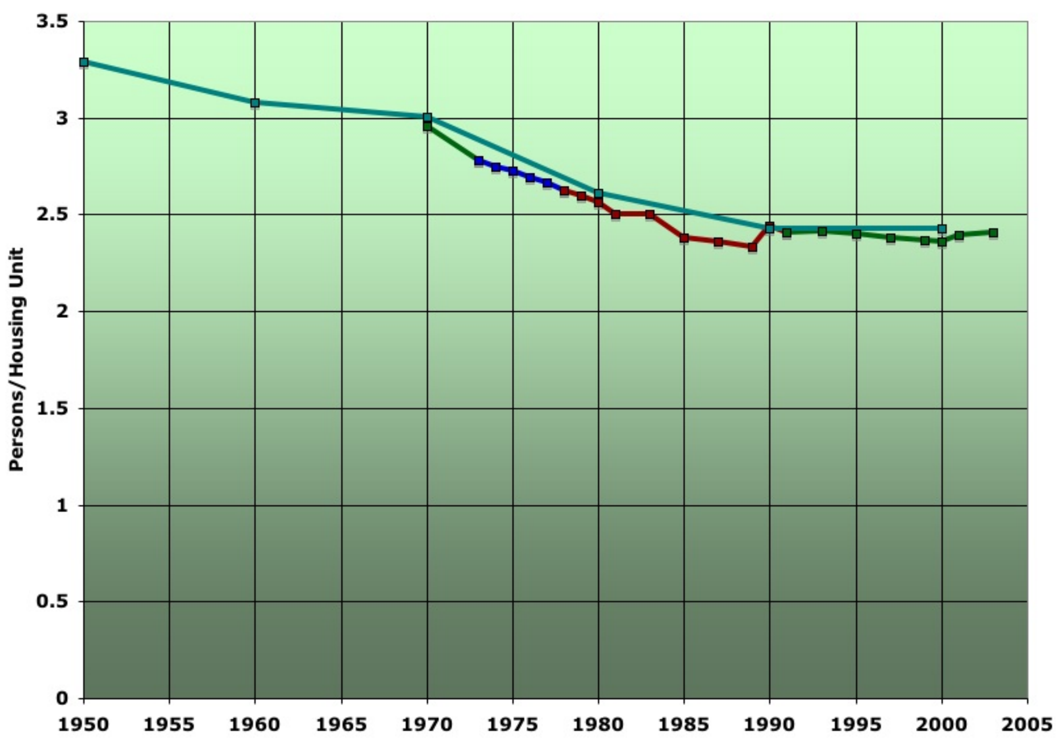
Hmmm. The oil shocks are very visible, but as we noted before, did not have very long-lived effects on VMT growth. The 73 shock (which apparently mostly just primed people to respond to the 79 shock), causes a dip in the curve that is really over by 1975. However, the 79 shock takes several years, to overcome, with VMT/capita growth not back to normal until 1983.

However, there's another interesting and important thing expressed in this picture, and that is that VMT per capita growth was significantly lower in the 1990s than it was in the 1980s, and also in the 1950s and 1960s. To quantify the issue, here are the compound annual growth rates for a couple of regions of the graph:

Years	Growth
1950-1973	3.2%/yr
1973-1983	1.7%/yr
1983-1993	2.3%/yr
1993-2003	1.1%/yr

What's going on here? The growth in VMT/capita was lower in the 90s even than in the period 1973-1983 when there were oil shocks. This matters because we want to know if this decline would continue in the future even if we had no oil supply/carbon emission problems, or if it would rebound.

Here is likely one piece of the explanation. The next graph shows the ratio of people to housing units in the US. This is, roughly, the average number of people in a household, but also incorporates the effects of empty units, vacation homes, etc:



Number of housing units per capita, 1950-2003, from two sources. Click to enlarge. Source: Department of

Housing and Urban Development for housing unit statistics, and US Census Bureau estimates via Texas State Library and Archives for population. Teal line uses housing unit estimates from Census Bureau Decennial Census of Housing, which doesn't quite match the HUD numbers, but the trend seems much the same.

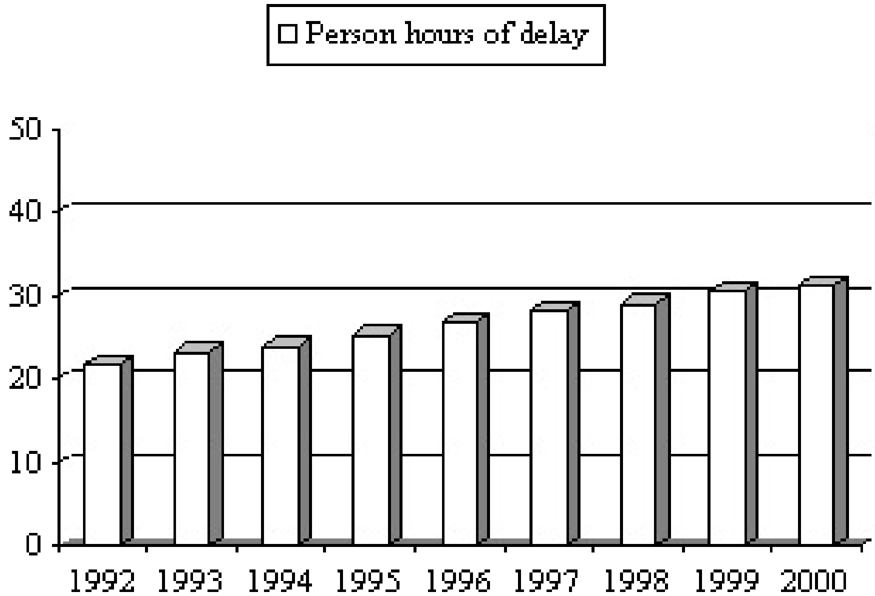
As you can see, people/unit declined steadily from the end of the second world war through the end of the 1980s. This probably primarily reflects the increasing trend towards divorce and the demise of the extended family as a living unit. However, it also no doubt got an assist from more vacation homes. Likely, demographic factors also played a role (from 1945 through much of the 1960s, the baby boomers were kids at home, and after that they moved out). Obviously, to the extent people are spreading out into more housing units, they are going to tend to use more VMT each, though it's not a linear matter (Eg consider a couple with two kids who divorce and get 50% custody. The two kids still only need to be taken to school once each. However, the two small households are likely to make nearly twice as many grocery runs as the one big household. The number of jobs held is likely to go up also, on average).

In the 1990s, people/unit stabilized and has been pretty much flat ever since. This could have a lot to do with the slowing in the growth of VMT/capita. To the extent this is a permanent social change, then VMT/capita might continue to grow at a lower rate in the future (even in the absence of oil/carbon constraints). Another possibility to consider is that people/household might actually start to go up again in the future, especially in the face of a tighter economy; adult children might be slower to leave home, aging relatives might be more likely to live with family as nursing home expenses continue to escalate, divorce may seem less economically feasible, etc. However, given that the seventies oil shocks caused no densification whatsoever, it is probably unrealistic to expect anything more than an extremely gradual rise.

Besides people/unit, another likely factor in the 1990s is congestion. As the FHWA describes the matter:

> During this period, growth in highway and mass transit systems in the United States did not expand at the same pace as the growth in travel demand. In the case of highways, total mileage in lane miles increased only 0.2 percent nationally during the entire period, from 8.11 million miles in 1992 to 8.25 million miles in 2000. As a result, travel per lane mile increased on all systems and, in particular, at faster rates on rural routes. While most travel now occurs in urban areas, approximately 77 percent of lane miles are on rural, local-owned highways.

Without getting into the debate over whether this reflects a lack of political will to build highways, or the impossibility of solving the problem by building more highways, the effect was that congestion went up:

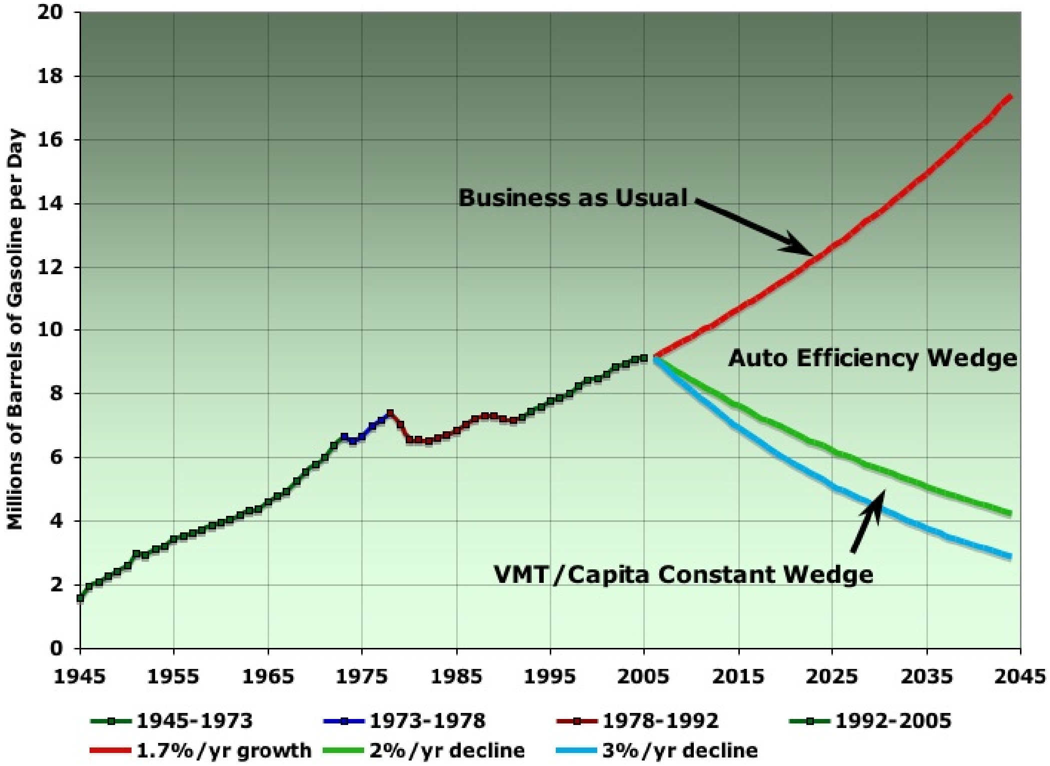


Annual number of delay hours per person due to highway congestion. Click to enlarge. Source: Federal Highway Administration [Fiscal Year 2003 Performance Plan](#).

Presumably, this has a deterrent effect on traveling and has contributed to the slower growth in VMT/capita.

For my purposes here, I am going to assume that "business-as-usual" going forward, in the absence of energy issues, would have been continued 1%/year growth in VMT/capita (cf the 1.1%/yr growth in this quantity from 1993-2003). Combining this with the 1%/yr growth in population, we would anticipate 2%/year growth in VMT. Since, as above, fuel economy has been increasing at 0.3%/year since 1992, our overall business-as-usual in gasoline usage would be 1.7%/year growth.

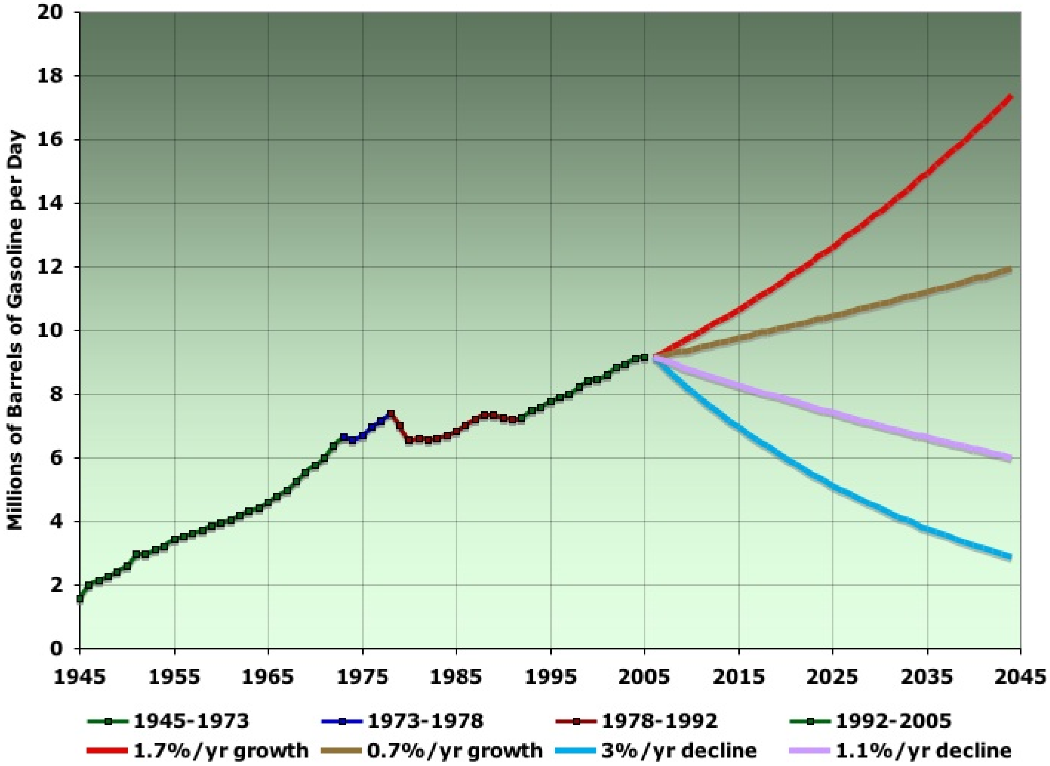
This next graph shows that 1.7% growth in gasoline usage out through 2045 (the end of my expected lifetime :-). I also show what would happen if VMT growth was identical, but fuel economy increases by 4%/year instead of only 0.3%/year.



US finished motor gasoline supplied, 1945-2005, together with scenarios for 1.7% growth, and 2% and 3% declines from 2007 to 2045. Quantities expressed in millions of barrels per day. Click to enlarge. Source: [US EIA](US EIA).

As you can see, it makes an enormously dramatic difference. The most aggressive scenario on the graph shows what would happen if, in addition to improving fuel economy by 4%/year, we also could hold VMT/capita constant from here on out (instead of it growing at 1%/year as under the business as usual scenario). That's better still, but stabilizing VMT/capita is not nearly as useful as getting fuel economy moving upward as fast as possible.

Finally, to aid your intuition for growth and decline processes a little further, my last graph shows the business as usual and 3% decline scenarios with two different ones in-between. The 0.7%/year growth is what you'd get if you just capped VMT/capita growth but only continued the recent history of 0.3% fuel efficiency. The 1.1%/year decline would come from business-as-usual VMT/capita growth together with 2.8%/year annual increases in fuel efficiency (the same as was actually achieved on average from 1978 to 1992).



US finished motor gasoline supplied, 1945-2005, together with scenarios for 1.7% growth, 0.7% growth and 1.1% and 3% declines from 2007 to 2045. Quantities expressed in millions of barrels per day. Click to enlarge. Source: US EIA.

Footnotes

1. The approximation comes in that it is not straightforward to allocate vehicle miles between gasoline vehicles and diesel vehicles from the available statistics. My approach from 1966 on is to assume that all passenger cars and all "two axle four wheel trucks" run on gasoline, and larger trucks and buses run on other fuels. Prior to 1996, the "two axle four wheel" trucks are not broken out from other trucks, and I linearly interpolated that post 1966 data backward to estimate the proportion of larger trucks. My procedure is unlikely to be perfect (some cars and light trucks run on diesel and some larger trucks burn gasoline), but the error is probably modest, and probably fairly stable over time. In recent years, FHWA has made their own estimate of deployed fleet fuel economy via methods they don't document enough to reproduce. Their estimates are about 1/2mpg higher than mine. Theirs may well be more accurate, but are not available throughout the period of interest.
2. There is some uncertainty in the allocation of this quantities between neighbouring years, since it is not clear whether the fleet totals in the TEDB are for the beginning or end of the year, or an average. Here it is assumed that they are end of the year totals.