A Fair Share: Doing the Math on Individual Consumption and Global Warming

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Chapter 5

Total per capita transportation emissions

- On average, each American generates 5.87 $MgCO_2e$ per year from personal transportation, with 73% of this due to the production and combustion of fuel in personal vehicles and another 8% attributable to vehicle manufacture; including infrastructure, this total increases to 6.58 $MgCO_2e$ per year. Aviation is the only other significant emissions source, at just under 1 $MgCO_2e$ per year per person (including private aviation).
- Average transportation household emissions are on the order of 14.9 and 16.4 $MgCO_2e$ without and with infrastructure, respectively.
- Given that only about two-thirds of Americans are licensed to drive, the average *driver* is responsible for 40% more transportation CO_2e than the average American (about 8.25 $MgCO_2$ per driver, from all transportation excluding infrastructure).

Before addressing various transportation modes in greater depth, I take this opportunity to summarize the per capita emissions sums derived in much more detail in the following chapters. As an overall average, gasoline combustion in personal vehicles generated (both directly and indirectly) about 4.36 $MgCO_2e$/capita in 2013, with about 80% of this total due to the tailpipe emissions, and the balance due to upstream gasoline extraction, refining, etc. Carbon equivalents attributable to the manufacture and maintenance of the light-duty fleet was on the order of 0.49 $MgCO_2e$/capita[1], and thus light-duty vehicle emissions sum to just under 5 $MgCO_2e$ per person. This is when averaging across the US populace; if we consider emissions for typical *drivers*, then we get about 6.51 $MgCO_2e$ from fuel combustion and 0.72 $MgCO_2e$ from vehicle manufacture, or over 7 $MgCO_2e$ per driver.

Including non-CO_2 forcing from high-altitude jet fuel combustion, US per capita emissions attributable to commercial aviation were on the order of 0.87 $MgCO_2e$/capita in 2015, and including private general aviation bumps this total to 0.95 $MgCO_2e$/capita. However, aviation CO_2e attributable to individuals will vary widely, given the high variation in flights per person, and there is also uncertainty in the magnitude of non-CO_2 aviation forcing.

On an overall per-capita basis, public and collective transportation, including Amtrak, intracity rail, bus, and long-distance bus travel add a trivial amount of CO_2e: Heavy bus transit systems may generate a total of 2.16 million $MgCO_2e$ (fuel-cycle only), with heavy, commuter,

[1] Derived using 123.77 billion gallons of gasoline, a fuel-cycle gasoline EF of 11.146 $kgCO_2e$/gallon, 236 million registered light-duty vehicles, and assuming 9.2 $MgCO_2e$/vehicle amortized over 14.1 years; these factors are developed in Chapter 6.

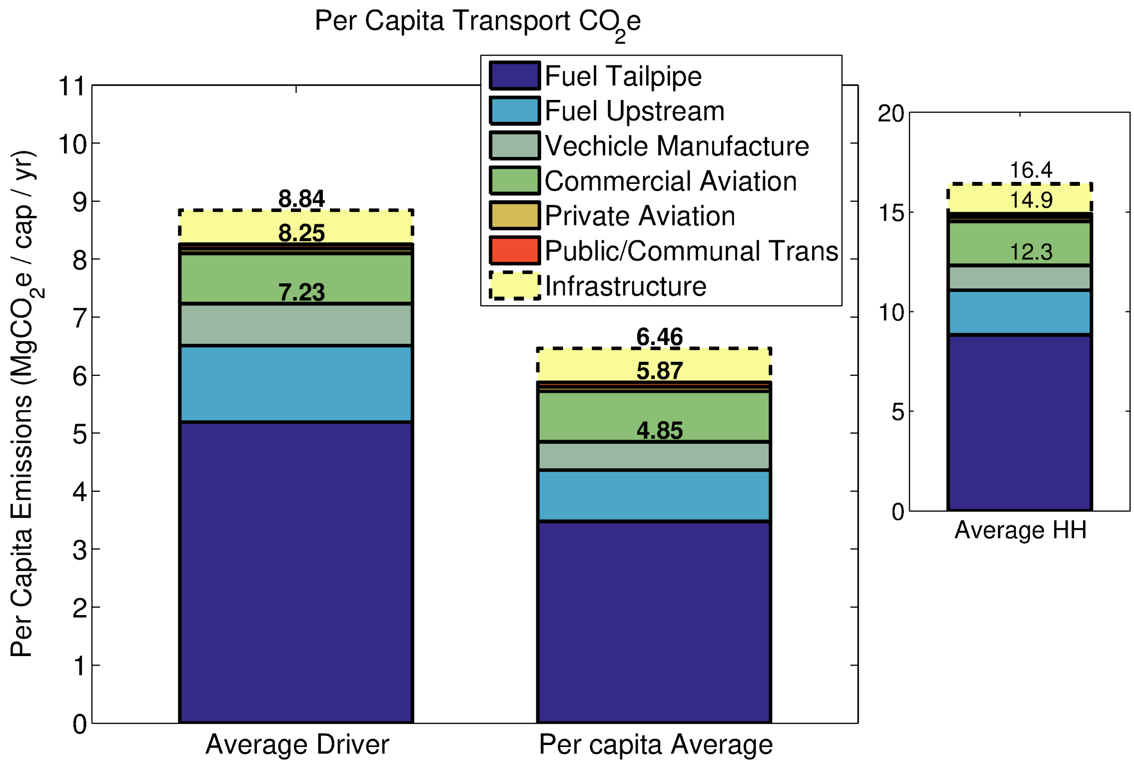

Figure 5.1: Annual US per capita emissions due to transportation, either for the average person or driver, and for the average 2.54 person US household. Numbers inset into bars give the sums for personal vehicles, everything but infrastructure, and for everything.

and light rail transit systems together adding about 5.69 million $MgCO_2e$. Amtrak emissions sum to 1.47 million $MgCO_2e$, while the school bus system and intercity bus (motorcoach) travel generate 10.28 and 3.80 million $MgCO_2e$, respectively (fuel-cycle only). Taken together, these all sum to just 23.4 million $MgCO_2e$, equivalent to about 0.073 $MgCO_2e$/capita (in 2014).

Finally, the construction and maintenance of the transportation infrastructure also carries a non-trivial carbon cost, perhaps on the order of 0.55–0.60 $MgCO_2e$/capita for roadways, parking, and street lighting combined (around 190–200 million $MgCO_2e$ in all), while airport and rail infrastructure add almost nothing. Although individual-level choices are unlikely to directly affect these infrastructure emissions except in the aggregate and over the longer-term, it is important to at least recognize their existence. Figure 5.1 summarizes all these numbers, giving emissions for the average American, average driver (assuming all other modes are equal to the average), and the average 2.54 person household.

Chapter 6

Fundamentals and the personal automobile

- The combustion of primarily gasoline, and upstream fuel production, in light passenger vehicles generates about 1,375 million $MgCO_2e$, or about *one-fifth* of all US territorial emissions. The personal automobile is the single greatest source of greenhouse gas (GHG) emissions for a typical adult American.
- Each gallon of gasoline burned generates a little over 11 kg of CO_2e, with 80% from direct tailpipe emissions, while the other 20% is from upstream "well-to-pump" (WTP) processes, i.e. oil extraction and refining. Tar sands oil at the center of the Keystone XL controversy are associated with about twice the WTP emissions of typical oils.
- The average driver generates about 6.5 $MgCO_2e$ yearly from fuel consumption (the average vehicle generates about 5.9 $MgCO_2e$ yearly, but there are more vehicles than drivers), and the average passenger vehicle on the road gets 21.6 MPG. Additionally, about 0.7 $MgCO_2e$ per year are attributable to vehicle manufacture (for an average car), implying that a typical driver ultimately generates a full 7.2 $MgCO_2e$/year.
- There is a *hyperbolic,* not linear, relationship between MPG and GHG emissions. It follows that upgrading from a low-MPG to mid-MPG vehicle is much more beneficial than upgrading from a mid- to high-MPG vehicle.
- Fuel consumption scales essentially linearly with vehicle weight, implying that, for conventional gas-powered (non-hybrid) vehicles, size is fuel.
- Vehicle manufacturing is responsible for about 10% of lifetime vehicle emissions, with manufacturing emissions, like fuel use, scaling linearly with vehicle weight.
- Emissions from gasoline hybrid-electric vehicles are 30–45% lower than those of comparably-sized conventional vehicles, and the best hybrids are 50–60% less emitting than the average passenger vehicle; this includes the entire vehicles lifecycle.
- Electric vehicles (EVs) are *not* zero-emissions, due to the power-plant emissions from generating electricity. Emissions-intensity varies geographically, but on average most EVs are comparable to gasoline-only hybrids. The upstream emissions associated with EV battery manufacture are also non-trivial, especially for larger long-range EVs.
- "Eco-driving" techniques can reasonably improve fuel efficiency by about 10% (and at least 5%). Aggressive driving can decrease fuel efficiency by as much as 30%.
- Reducing miles driven by 10%, adopting reasonable eco-driving techniques that increase fuel efficiency by 5%, and upgrading from a typical 21.6 MPG vehicle to a 40 MPG-equivalent vehicle would together reduce an individual driver's footprint by over 50%, or about 3.7 $MgCO_2e$; if all drivers made these changes, it would be equivalent to removing 133 million of today's vehicles from the road.

Personal transportation represents the single largest component of the typical household carbon footprint, and most personal transportation-associated emissions (about 70%) come from combusting fuel in personal automobiles (including the upstream emissions associated with fuel production). Smaller portions are attributable to vehicle manufacture and air travel, while public transportation contributes virtually nothing. The energy and emissions related to the construction and maintenance of the roadway and parking infrastructure are also nontrivial, although it is difficult for an individual to directly affect such activities. Due to its dominance as a transportation mode, ubiquity, and profound influence on urban design and American culture and lifestyle, any discussion of transportation-associated emissions begins, and nearly ends, with the personal automobile.

Conventional, i.e. non-hybrid, non-electric, vehicles, account for the vast majority of vehicles already on the road as well as new-car sales, and in 2014 hybrid-electric vehicles accounted for less than 3% of overall market share[1]. While diesel is quite popular in Europe, in the US nearly all conventional vehicles are gasoline-powered, with the diesel market share similar to that of hybrids, at 2.8% in 2014[2]. Therefore, my primary focus, in terms of carbon-footprinting, is on gasoline-powered vehicles, and if not otherwise noted, all figures and results are derived using gasoline as the fuel. I do discuss extensively the potential of and lifecycle emissions associated with alternative (i.e. hybrid and electric) drive-trains, which are markedly lower than those of conventional vehicles. Indeed, I find that gasoline-only hybrid-electric vehicles have manufacturing emissions similar to conventional vehicles, while they consume 40–60% less fuel. Electric vehicles (EVs) are generally comparable to gasoline-electric hybrids in their lifecycle emissions profile, although in certain regions, especially the upper Midwest, the dirty electricity generating mix tilts the balance (in the near-term, at least) towards hybrids, and battery manufacturing for larger EVs is also a major source of emissions (hybrid batteries are one to two orders of magnitude smaller).

This chapter is organized as follows. I first examine how much and for what purposes Americans drive, followed by a brief overview of historical trends in automobile use and fuel consumption in America, and the likely prospects for the future. I then move to basic concepts in MPG, emissions factors, etc. Moving to more technical discussion, I examine the tailpipe emissions that result from burning fuel in cars, and then consider in some detail the upstream, or "well-to-pump" emissions that result from oil extraction and refining. I perform an extended analysis of the upstream emissions from Canadian tar sands, which are at the center of the ongoing Keystone XL controversy.

Emissions associated with vehicle manufacture are then explored, and the potential of alternative drive-trains, i.e. hybrid-electric, plug-in electric, and fully electric vehicles is discussed. The discussion of automobiles closes with a brief examination of how driving style affects fuel economy. I also offer a brief discussion on the relationship between personal wealth and automotive transportation in America.

I would also like to briefly note the use of brand name vehicles in this chapter, as when comparing electric and hybrid vehicles to conventional vehicles I focus largely on the top-sellers, without this focus meant as any kind of endorsement. Nearly 50% of all hybrids ever sold in the US belong to the Toyota Prius family, and while market share is declining, over 40% of new hybrid sales are still in this family; the Prius also has the highest EPA MPG rating of any new gasoline-only vehicle. The Chevrolet Volt is the best-selling plug-in hybrid, and the Nissan Leaf and Tesla Model S together have accounted for the vast majority of pure EV sales.

[1] http://www.usatoday.com/story/money/cars/2014/06/09/hybrid-cars-market-share-polk/10238155/
[2] http://www.foxbusiness.com/industries/2014/07/14/can-diesel-cars-make-inroads-in-america/

6.1 How much do Americans drive?

- The average passenger vehicle travels 11,346 miles per year, while the average driver puts in 12,621 miles. At 21.6 MPG (mean for 2013), this translates into fuel-related emissions (including fuel production) of about 5.9 $MgCO_2e$/car, and 6.5 $MgCO_2e$/driver.

The primary source I rely in this section is the annual highway statistics series published by the U.S. Federal Highway Administration (FHWA), which uses data from the national Highway Performance Monitoring System, state-level data on motor vehicle registration, driver licenses, fuel use, etc., and modeling to arrive at detailed overall estimates on miles travelled on US roadways. The periodic National Household Transportation Survey (NHTS), also performed by the FHWA, is a very useful adjunct data source, as it gives a much more detailed breakdown on the daily transportation habits of Americans: where they go (work, store, pleasure), how many trips and by what mode (car, bicycle, etc.), distances for typical trips, etc. One drawback of the most recent 2009 survey [642] is that it is focused on daily travel, omitting long-distance trips. For that, we must turn to the 2001 NHTS survey [643] or other sources.

In 2013, the FHWA reported that there were 236,010,230 registered light duty vehicles in the US, each putting in 11,346 miles and burning through 524 gallons of fuel, with a total of 123,769,719,000 gallons of fuel consumed by light duty vehicles. Assuming 100% gasoline, this represents 1.1 million $MgCO_2e$ of carbon emissions from direct combustion, and 1.3795 $MgCO_2e$ when the upstream emissions that go into producing fuel are also accounted for (see Section 6.3).

I focus principally on light duty vehicles, as they mainly represent personal transportation, whereas medium and heavy duty vehicles are primarily used for commercial applications. Light vehicles accounted for 89.6% of all vehicle-miles travelled and about 75% of transportation fuel use, by volume. Note that motorcycles, officially excluded from the light vehicle category, make up about 3.44% of all vehicles but consumed only 0.28% of all fuel in 2013 (on a volumetric basis). Since the error introduced is so small, for simplicity I follow the FHWA convention and leave motorcycles out of most light vehicle calculations.

There are more (light duty) vehicles than licensed drivers, with 212,159,728 licensed US drivers in 2013, and as a consequence there is a discrepancy between miles per vehicle and miles per driver; simply dividing the number of licensed drivers by the total number of light-duty vehicle-miles suggests 12,621 miles per driver, and implies 22,088 vehicle-miles per household (using 1.75 licensed drivers per HH); dividing the total number of vehicle-miles in 2013 by 122.46 million households similarly gives an almost identical 21,867 vehicle-miles per household. It should also be noted that the 2009 NHTS suggests a slightly lower 19,850 vehicle-miles per household, but the NHTS restricted itself to daily travel, presumably omitting some long-distance trips. For simplicity, I usually assume an even 12,500 miles per driver per year for demonstrative calculations. Further, I assume a typical vehicle lifetime of 160,000 miles, equal to 12.8 years if driven 12,500 miles/yr (and 14.1 years when using 11,346 miles per year per car).

The average MPG of all light-duty vehicles in 2013 was 21.6 MPG, implying the typical passenger *vehicle* generates 5.86 $MgCO_2$/yr from fuel consumption per year, while the average *driver* likely generates about 6.51 $MgCO_2$/yr, using 12,621 miles-per-driver and assuming gasoline as the fuel. Broad historical trends in vehicle miles travelled, gasoline consumption, the number of vehicles in the US fleet, and household vehicle characteristics are summarized in Figures 6.1 and 6.2.

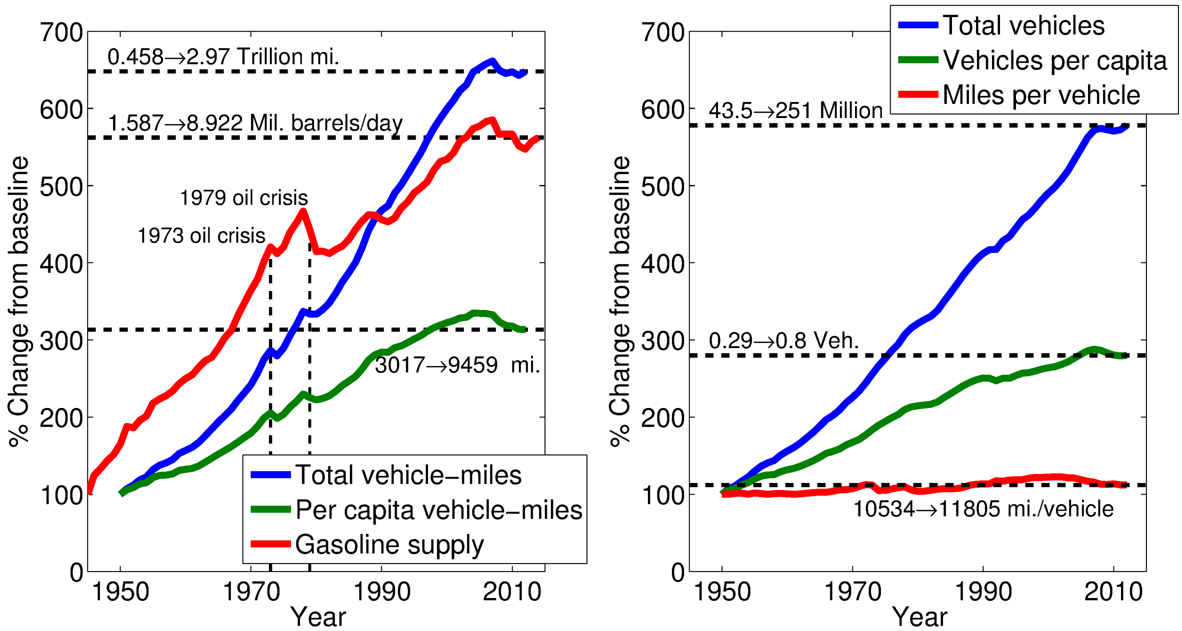

Figure 6.1: The left panel gives annual US vehicle-miles travelled, per-capita vehicle-miles travelled, and the gasoline supply, while the right panel shows total number of vehicles, vehicles per capita, and miles travelled per vehicle, from 1950 through 2012. Source: 2009 NHTS.

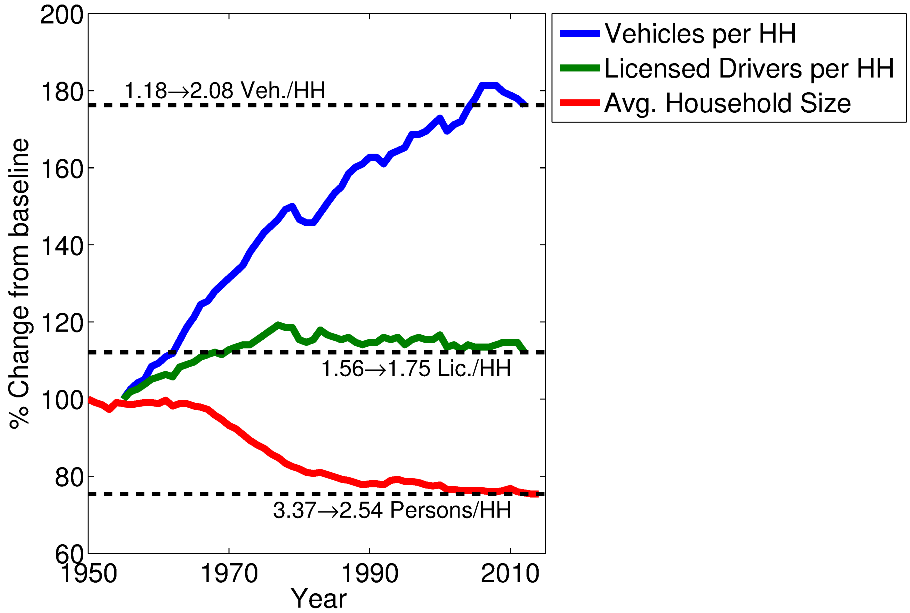

Figure 6.2: This figure shows how the number of vehicles per household has increased almost two-fold since 1955, while the number of licensed drivers per household has remained nearly flat and average household size has fallen 25%.

6.1.1 American driving patterns

Based on the 2009 NHTS [642], the typical driver takes just over three one-way trips a day, each of which averages 9.72 miles, for a total of 28.97 daily vehicle-miles. At the household level, each day saw 5.66 vehicle-trips, summing to 54.38 vehicle-miles. Perhaps surprisingly, commuting to and from work, while the single largest driver of vehicle-miles, still accounted for only 27.8% of all vehicle miles, with the shopping, personal errands, and social/recreational categories accounting for 15.0%, 17.8%, and 24.4%, respectively.

Variation in annual vehicle-miles and fuel use

Based on publicly available survey results from the 2009 NHTS, there is very wide variation in the number of miles individuals drive: even *excluding* those that reported no daily vehicle travel in 2009, the top 20% of households drove over *ten times* as much as the bottom 20%, on average. This is also true when restricting our comparison to one-person households. The situation is very similar when examining estimated annual fuel use, and overall, miles travelled correlated well with fuel use, explaining 89% of the variation (i.e. $R^2 = 0.89$) in fuel consumption under linear regression. Variation in annual vehicle miles is summarized in Figure 6.3.

This huge variation in annual mileage, along with the fact that travel to and from work accounts for only 28% of daily travel, while 24% is recreational (2009 NHTS), and the further finding from the 2001 NHTS [643] that about 50% of long-distance trips are either for vacation or visitation, suggests that it is within the power of individuals to rather dramatically cut their annual driving and fuel consumption. Failing that, higher mileage conventional vehicles and alternative drive-trains, i.e. hybrids and electric vehicles, can reduce driving-associated emissions by 40–60% compared to typical vehicles (and by as much as 75% compared to the worst conventional vehicles). *Ideally, these two strategies (i.e. decreased miles and increased efficiency) should be pursued in tandem, rather than in opposition.*

6.1.2 Historical fuel economy, and emissions

Broad historical trends in fuel economy from 1923 have been documented in detail by Sivak and Schoettle [203], who found the entire US vehicle fleet to average about 14 MPG in 1923, with this number slowly decaying over the subsequent decades to a nadir of 11.9 MPG in 1973 (passenger cars hit their low point of 13.4 MPG in 1973). The 1970s heralded a new age of resource-limitation, with the decade seeing domestic US oil production peak in 1970, and global oil crises in 1973 and 1979. New energy efficiency standards, the Corporate Average Fuel Economy (CAFE) standards, were adopted in 1975, along with a "gas-guzzler" tax for especially inefficient cars [204], and the fuel economy of new vehicles increased dramatically from the late 1970s through the early 1980s, with corresponding downward trends in vehicle weight and horsepower [205].

This trend of increased MPG largely stalled in the early 1980s, with 1987 a high water mark for MPG (at 22.0), and new vehicle MPG then proceeded to stagnate for nearly two decades. Vehicle horsepower and weight both increased markedly over this period, which also saw a dramatic expansion in SUV and other light truck market share. The trend of decreasing MPG did not reverse until 2005, and in 2009, average MPG finally exceeded the 1987 level [205]. In 2014, the average new passenger vehicle averaged about 24.2 MPG [205], implying that, over the course of nearly three decades, fuel economy ultimately increased by a remarkably scant 10%.

It does appear that the widespread adoption of light trucks (mainly SUVs, but also pickups, vans, and minivans) for personal transportation contributed to the decline in fuel economy seen

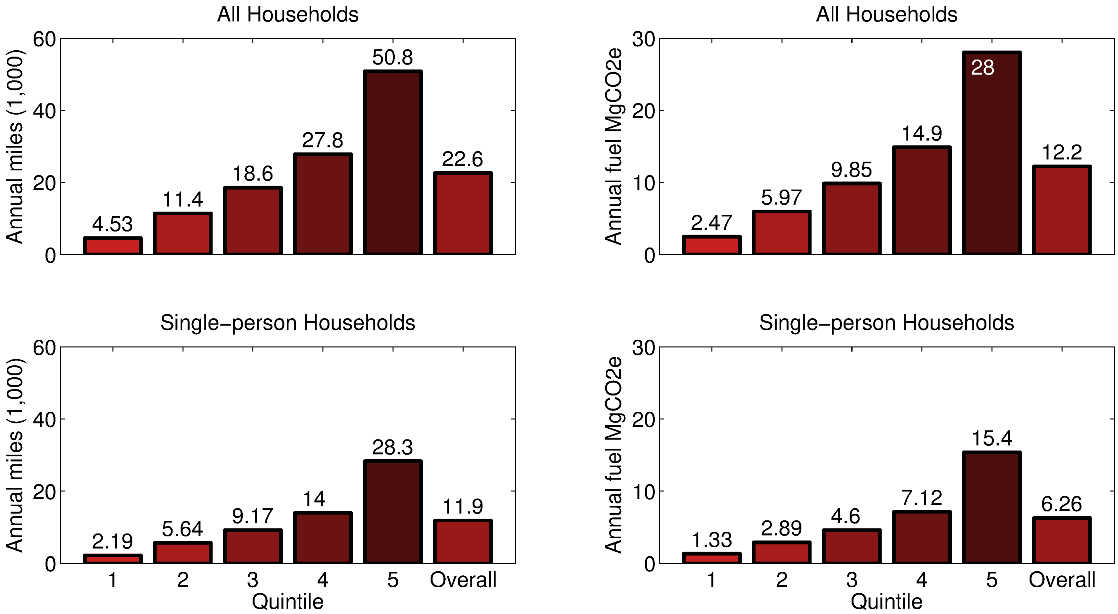

Figure 6.3: Variation in daily vehicle miles travelled among US households that reported any daily vehicle travel, based on the 2009 NHTS. The left panels give the mean miles (in 1,000s) travelled for each quintile, along with the overall mean. The right panels show the corresponding fuel-related emissions (including upstream fuel-production) in $MgCO_2e$. The top panels use data for all households, while the bottom are restricted to single-person households.

from the late 1980s through the early 2000s. This can be seen in Figure 6.5, which shows that the gap between the average new *car* and new *vehicle* (i.e. cars+trucks) MPG grew markedly from the 1980s to a peak in 2004. The year 2004 also represents a local nadir in MPG, being the lowest new vehicle MPG since 1980. However, average car MPG also decreased during this period, as these also vehicles grew larger and more powerful. This may be partly due to the increasing popularity of car-based SUVs (also known as "crossover" SUVs), which tend to have fuel economy better than truck-based SUVs, but still worse than most other cars.

Figure 6.5 also shows the share of new vehicles sales that are pickup trucks/SUVs, as well as the average household size. Strangely enough, even as Americans have continued to favor larger vehicles over the last 40 years, household size continues to fall, and jobs where a heavier-duty work vehicle may be necessary make up a smaller portion of employment (e.g. construction or farming). Furthermore, while in 1970, 26.4% of the US population lived in rural areas, this percentage fell to 19.3% by 2010 (per the US Census), so massive rural demand seems unlikely to explain the shift to SUVs either.

Vehicles with fuel economy comparable to today's hybrids have, in fact, been available for nearly 30 years. The 1986 GM Sprint has a revised EPA rating of 48 MPG city/highway combined, and the original 2000 Honda Insight achieved 53 miles per gallon (EPA revised estimate). This was not exceeded until 2016, when the Toyota Prius Eco posted a combined 56 EPA rating.

New fuel efficiency standards, through CAFE, were established by the Energy Independence and Security Act of 2007, while the EPA was compelled to regulate carbon dioxide emissions under the Clean Air Act by the *Massachusetts v. EPA* Supreme Court decision. This led to the establishment of a goal of a CAFE fleet-average 54.5 MPG for new cars and light trucks by 2025 [206]. However, since fuel consumption under CAFE standards is measured using highly outdated standards, MPG is grossly inflated, and this 54.5 figure translates into an actual fuel

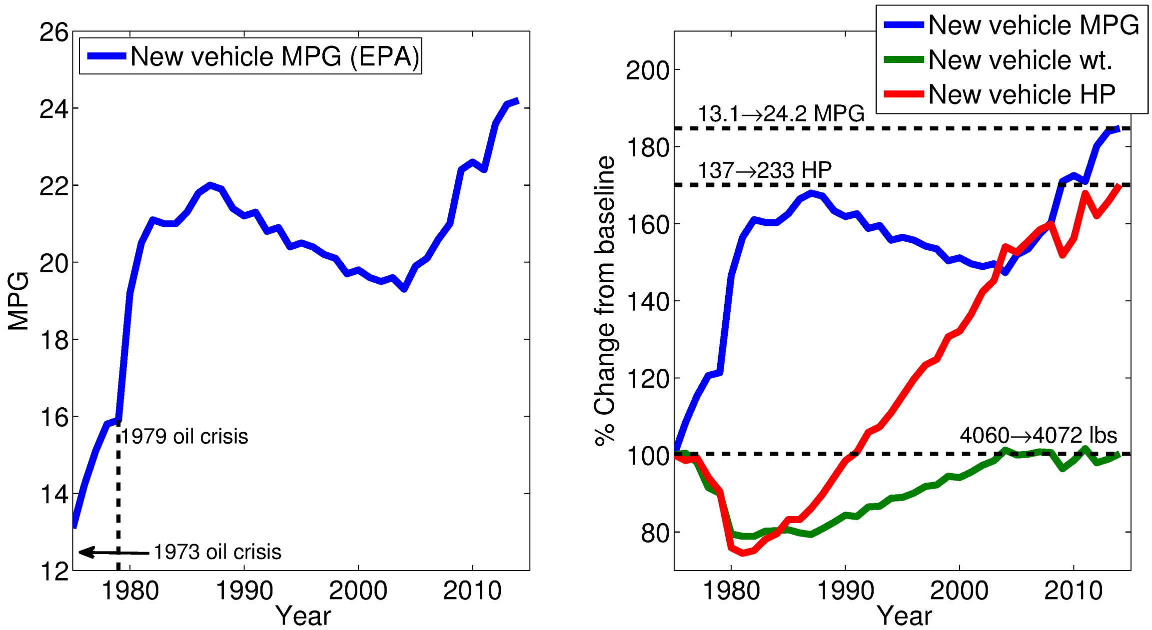

Figure 6.4: New passenger vehicle MPG from 1975 through 2014, per the EPA [205]. The right panel shows how weight and horsepower reductions accounted for most of the decrease in fuel consumption in the early 1980s, following the initial adoption of CAFE standards. Weight and horsepower trends reversed, however, correlating with the drop in MPG through the 1990s. The later plateau in weight (and a slow-down in the power trend) imply that improvements in car and engine technology explain the more recent fuel economy gains (since about 2004).

economy of 35–40 MPG. Given the very recent reductions (2016–2017) in gasoline prices and the continued strong performance of the light truck and SUV market, it remains to be seen whether these standards will actually be met.

6.2 Basic concepts

6.2.1 MPG: city, highway, and combined

Fuel consumption, which is jointly determined by MPG and miles driven, accounts for 90% of vehicle-related emissions, an obvious but deeply important fact. As I discuss later, the MPG rating of a diesel vehicle is equivalent (from a CO_2e standpoint) to an 11% lower MPG under gasoline, and the EPA's MPGe ratings for electric vehicles are are not comparable to gasoline engine MPGs in terms of emissions; the MPG_{GWP} metric, which is explained in Section 6.6.3, does compare electric vehicle emissions to gasoline vehicles, and is determined using upstream emissions from electricity generation.

The EPA gives all vehicles produced in the US with a gross vehicle weight under 8,500 lbs a city, highway, and combined MPG rating; the former two are determined by running a vehicle through a series of standardized duty cycles. The combined MPG rating is a (weighted) harmonic mean of city and highway MPG, with city and highway MPG weighted 55 and 45%, respectively. The *harmonic*, and not the arithmetic mean is the appropriate average, and the logic is explained in a moment.

In determining how many emissions one can expect to generate through driving, it is most appropriate to use the combined MPG rating (in the absence of a log of actual MPG achieved). Using the higher highway MPG rating will invariably underestimate one's personal emissions.

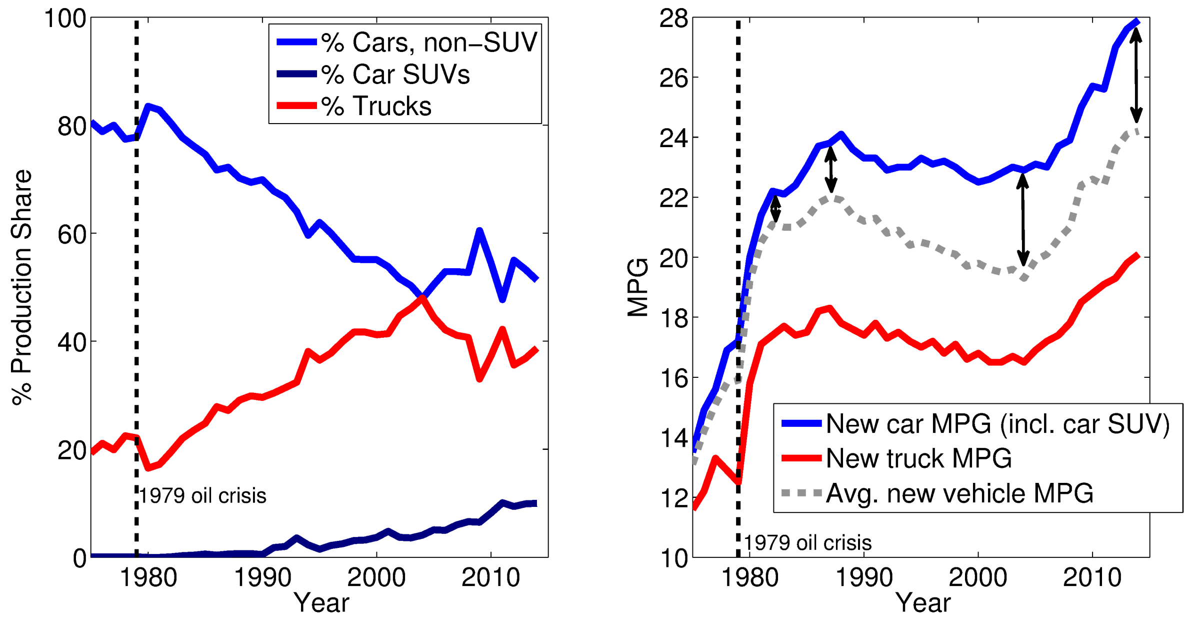

Figure 6.5: New car, car-based SUV, and light truck (pickup, van, SUV) market shares from 1975 through 2014 (passenger-vehicles only) [205]. The right panel shows MPG disaggregated into car- and truck-based vehicles, with the average (gray line) being "pulled" toward the truck curve (red line) as the truck market share increased through the early 2000s.

Throughout this chapter, I use the EPA's combined MPG ratings for all calculations that consider a specific vehicle model.

6.2.2 The hyperbolic relationship between MPG and emissions

The US FHWA estimated an average MPG of 21.6 for all light duty vehicles in the US, in 2013. New vehicles get slightly better MPG, with the EPA estimating an average 27.9 MPG for new cars, 20.1 for trucks, and 24.2 MPG for new cars and trucks combined, in 2014 [205]. It is probably common to assume that the effect of MPG on one's carbon footprint is linear. In other words, one might assume that the difference between 30 MPG and 20 MPG is the same as 20 MPG versus 10 MPG. However, the relationship is not *linear* but *hyperbolic*. That is, in evaluating fuel use, it is much better to think of the gallons of gas consumed per 100 miles travelled than the miles travelled per gallon of gas. For example, cars getting 10, 20, and 30 MPG will consume 10, 5, and 3.3 gallons of gas to travel 100 miles, respectively. This more clearly demonstrates that, at the lower MPG range, even small changes in MPG have a dramatic effect on fuel consumption and hence carbon emissions, while the effect is much diminished at higher ranges. For example, going from 40 to 50 MPG changes fuel consumption from 2.5 to 2 gallons per 100 miles, only a tenth of the fuel saving achieved by a 10 to 20 MPG improvement (10 to 5 gallons per 100 miles). This general hyperbolic pattern is illustrated in Figure 6.6. Figure 6.7 illustrates how small increases in MPG have a far more profound effect on fuel consumption at the lower MPG range than at higher levels.

This hyperbolic relationship means that, when calculating average MPG, we must use the harmonic mean and not the arithmetic mean, as noted previously. For example, consider a household that has a large truck averaging 10 MPG, and a small car that gets 40 MPG, each driven 12,000 miles per year. Intuitively, we might assume that the average MPG for the household is 25 MPG (the arithmetic mean), but in fact it is only 16 MPG (the harmonic

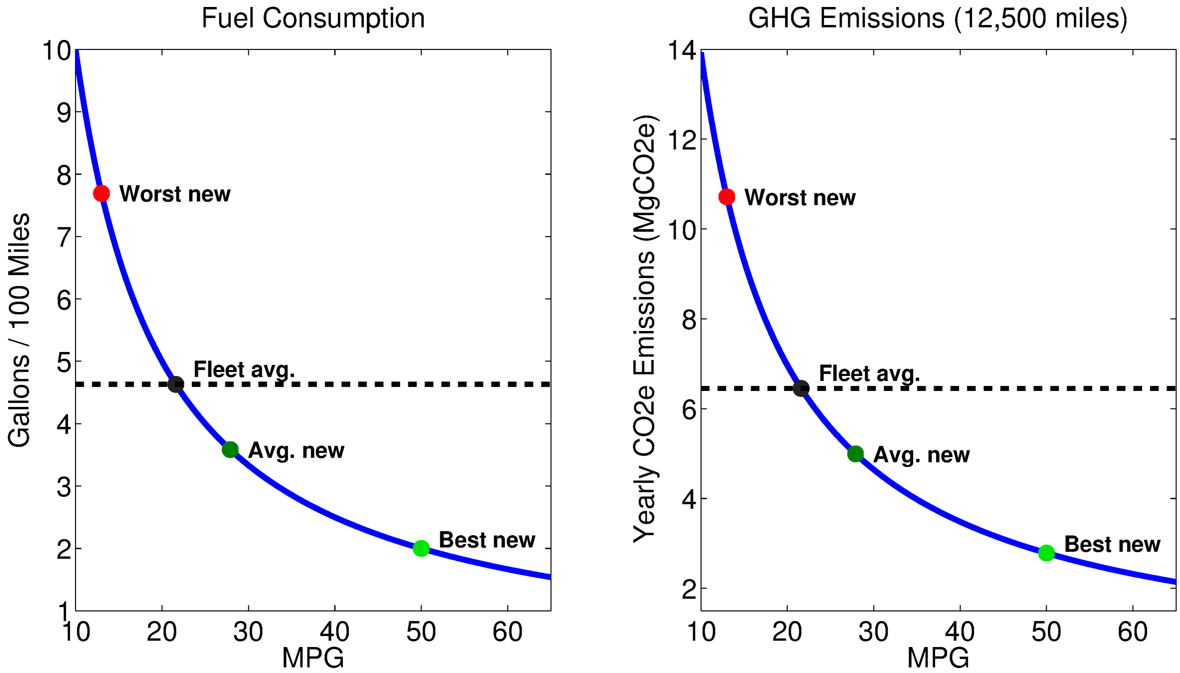

Figure 6.6: The hyperbolic relationship between MPG and fuel consumption (left panel), assuming 12,500 miles per year. Since the amount of fuel consumed is directly proportional to GHG emissions, there is an identical hyperbolic relationship between MPG and carbon emissions, as shown in the right panel.

mean). To see that this is true, it is easier to consider gallons of gas consumed: 1,200 gallons of gas are consumed by the truck (12,000 miles / 10 MPG), and 300 gallons of gas are consumed by the car (12,000 miles / 40 MPG), giving a total of 24,000 miles and 1,500 gallons of gas. Dividing, we see that the household fleet actually got only 16 MPG (and corresponding to annual emissions of 16.7 $MgCO_2e$). Suppose that, aghast at this calculation, our household shifted their driving habits to 6,000 truck miles, and 18,000 car miles. The average fleet MPG then becomes about 23 MPG, lowering emissions by 30% to 11.7 $MgCO_2e$, an improvement but still weighted towards the inefficient truck MPG; if all miles were travelled in the car, fleet emissions would fall 60% relative to baseline, to 6.7 $MgCO_2e$. These calculations are meant to further emphasize the fact that low MPG vehicles have a seemingly disproportionate effect on fleet MPG and fuel consumption, and our collective priority should be to increase fuel efficiency, and to decrease miles driven, at the *lower* end of the MPG scale.

6.2.3 Operational emissions as a function of MPG and miles driven

Figure 6.8 shows annual fuel-cycle (tailpipe plus well-to-pump) emissions as a function of miles driven and vehicle MPG, using gasoline as the fuel. In Section 6.5.2, I add estimated emissions from vehicle manufacture and disposal ("vehicle-cycle") to the table, which increases per annum emissions by 10–15% for any given cell. The latter table is probably better referenced for overall carbon footprinting purposes.

6.2.4 A note on "fuel consumption" versus "fuel economy"

It should be noted that the term "fuel economy," which corresponds to the familiar vehicle MPG ratings, is *not* synonymous with "fuel consumption," which refers to the number of gallons

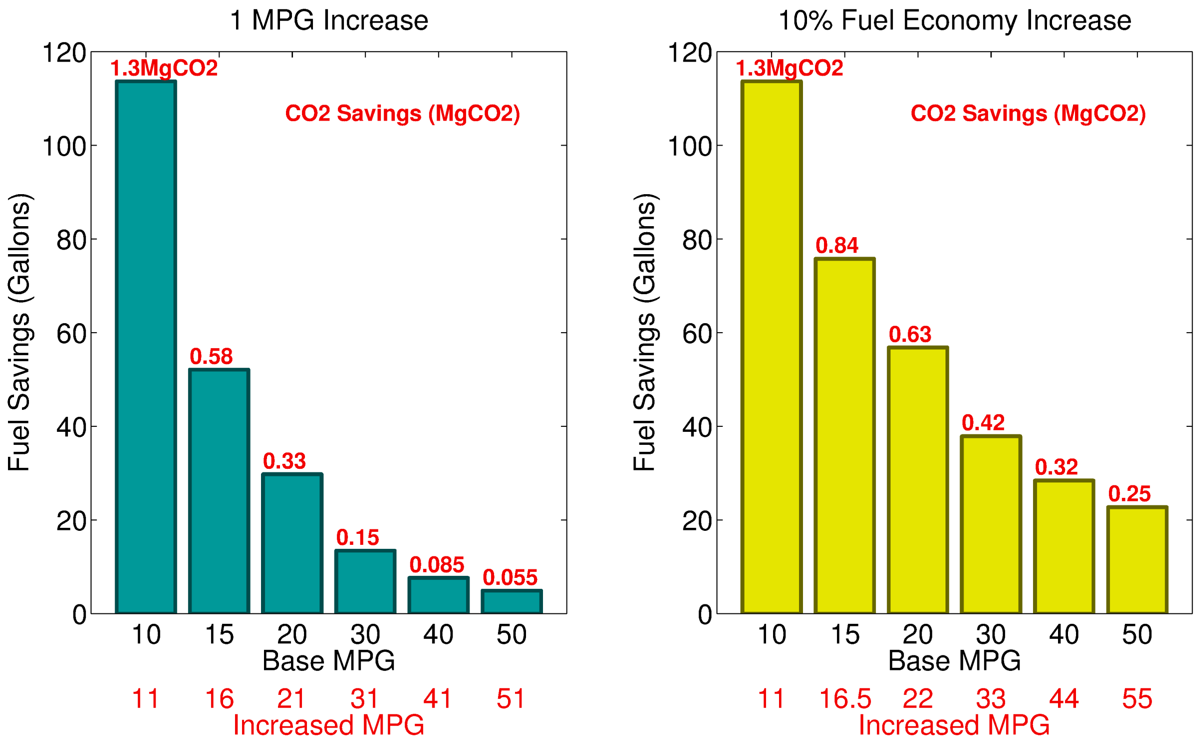

Figure 6.7: The left panel gives the yearly fuel (and CO_2e) savings for a 1 MPG increase for different base MPGs (assuming 12,500 miles per year), while the right panel gives fuel and CO_2e savings for 10% increases in fuel efficiency from the same base MPGs. In both cases the emissions savings are far more pronounced for improvements from low base MPGs, a consequence of the hyperbolic relationship between MPG and fuel consumption. The difference in GHG emissions between 10 and 11 MPG is 1.27 $MgCO_2e$. This difference alone is over 45% of the yearly emissions of 50 MPG vehicle.

Fuel–Cycle Only

	Miles (Thousands)							
MPG	5	7.5	10	12.5	15	17.5	20	22.5
12	4.6	7	9.3	12	14	16	19	21
15	3.7	5.6	7.4	9.3	11	13	15	17
18	3.1	4.6	6.2	7.7	9.3	11	12	14
21	2.7	4	5.3	6.6	8	9.3	11	12
24	2.3	3.5	4.6	5.8	7	8.1	9.3	10
27	2.1	3.1	4.1	5.2	6.2	7.2	8.3	9.3
30	1.9	2.8	3.7	4.6	5.6	6.5	7.4	8.4
33	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6
36	1.5	2.3	3.1	3.9	4.6	5.4	6.2	7
39	1.4	2.1	2.9	3.6	4.3	5	5.7	6.4
42	1.3	2	2.7	3.3	4	4.6	5.3	6
45	1.2	1.9	2.5	3.1	3.7	4.3	5	5.6
48	1.2	1.7	2.3	2.9	3.5	4.1	4.6	5.2
51	1.1	1.6	2.2	2.7	3.3	3.8	4.4	4.9

Figure 6.8: Annual CO_2e emissions ($MgCO_2e$) for various vehicle MPGs and annual mileages. Red text signifies annual emissions worse than average—6.45 $MgCO_2e$, based on 12,500 miles at 21.6 MPG—while green signifies emissions totals better than average. The greener (redder) the text, the better (the worse). The 21 MPG row and 12,500 mile column are highlighted as being typical of American cars and drivers.

of fuel consumed per gallon, and is mathematically the inverse of fuel economy. This is an important distinction, as highlighted by the discussion above, and carbon emissions are directly proportional to fuel consumption but not to fuel economy. Furthermore, as I discuss later, fuel consumption (and hence carbon emissions) increases linearly with vehicle size, whereas the relationship is hyperbolic with respect to MPG.

Finally, consider that "eco-driving" can decrease fuel consumption by about 10% on average (see Section 6.8). The effect of eco-driving on a vehicle getting 18 MPG at baseline would then be to increase mileage to 20 MPG and save 0.56 gallons of fuel per 100 miles, while eco-driving would shift a 36 MPG vehicle to 40 MPG and save 0.28 gallons per 100 miles. The MPG increase is twice as great for the higher mileage vehicle, yet the *actual fuel savings* are twice as high for the low-mileage vehicle; Figure 6.7 demonstrates how such relative changes in fuel economy translate into fuel savings. All this should highlight the fact that fuel consumption is a much "cleaner" metric than economy. Nevertheless, since MPG is so familiar and ubiquitous, I still present most results in terms of MPG (and fuel consumption as well where appropriate).

6.3 Petroleum fuels and tailpipe, well-to-pump, and total emissions

- Gasoline emits 8.887 kgCO_2/gallon at the point of combustion, while upstream emissions total 2.259 kgCO_2e/gallon, giving a fuel-cycle emissions factor of 11.146 kgCO_2e/gallon. Diesel is more emitting, at 12.504 kgCO_2e/gallon over the fuel-cycle, and one should discount the sticker MPG of a diesel vehicle by 11% to get the gasoline-equivalent MPG.
- Upstream processes generating emissions include oil extraction (about 40%), crude transport (5%), refining (50%), and final distribution (5%). Tar sand bitumen generates significantly more emissions at the extraction phase than does conventional oil.

At the point of combustion, petroleum fuels emit CO_2 and H_2O (along with other products of imperfect combustion), and it is straightforward to calculate the resulting direct, or "tailpipe," emissions from automobile use. This can be done using knowledge of the basic chemical composition of fuels, as discussed in Section 3.6, but I adopt standard EPA emissions factors (EFs), given as 8.887 kgCO_2/gallon gasoline and 10.180 kgCO_2/gallon diesel, assuming 100% of the carbon in fuel is oxidized to CO_2 [208]. Note that diesel, as the more carbon- and energy-dense fuel (on a volume-basis, on a mass-basis gasoline is actually slightly more energy-dense), has the higher combustion EF, and therefore, while diesel-powered vehicles typically have higher MPG ratings than comparable gasoline-powered cars, comparisons of such vehicles should adjust for this fact by reducing the diesel MPG by 11% to obtain gasoline-equivalent MPG (this factor includes the upstream fuel-cycle emissions discussed below). Thus, for example, the 2015 Volkswagen Jetta, which has a combined sticker rating of 35 MPG, adjusts downward to 31.2 MPG, lowered but still 8–20% better than the 26–29 MPG obtained by various gasoline models.

Upstream processes in gasoline production, including extraction, refinement, and distribution, are not at all negligible, and these are referred to as "well-to-pump" (WTP) emissions; they equal about 24–27% of gasoline tailpipe emissions, with fuel refining and oil extraction the major sources of WTP emissions. The basic process of conventional crude oil extraction and refining via distillation, whereby hydrocarbons of different density are separated, with gasoline representing a light distillation fraction, and diesel a heavy fraction, is outlined in Section 3.7.

In terms of associated emissions, the Argonne National Laboratory has developed a comprehensive lifecycle model for various transportation fuels, termed the GREET model, and I draw directly from this work: the 2014 GREET 1 model estimates WTP emissions of 2.259 kgCO_2e/gallon of gasoline (25% of tailpipe emissions) and 2.324 kgCO_2e/gallon of diesel (23% of tailpipe emissions) (converted from 19.814 kgCO_2/mmBtu and 17.948 kgCO_2/mmBtu, assuming lower heating values of 0.114 mmBtu/gallon and 0.1295 mmBtu/gallon for gasoline and diesel, respectively[3]). Other estimates, many site-specific, of WTP emissions exist, but the GREET model is widely used and is representative of the national average.

Adding the tailpipe and WTP EFs gives the total well-to-wheels (WTW), or "fuel-cycle," EFs of 11.146 kgCO_2e/gallon gasoline and 12.504 kgCO_2e/gallon diesel. Emissions associated with the fuel-cycle are summarized in Figures 6.9 and 6.10. Oil extraction and refining are the two major processes that generate upstream WTP emissions, with extraction generating about 40% of emissions and refining about 50% (about 9–13% of oil energy is lost at the refining stage [209]); crude oil transportation and distribution are minor contributors, at around 5%

[3] I use GREET 1 estimates directly, but do note that using updated AR5 GWP values for CH_4 and N_2O suggest WTP emissions 5.0% and 4.4% higher for gasoline and diesel, respectively, but these respective differences translate into only 1% and 0.8% errors on an overall WTW basis.

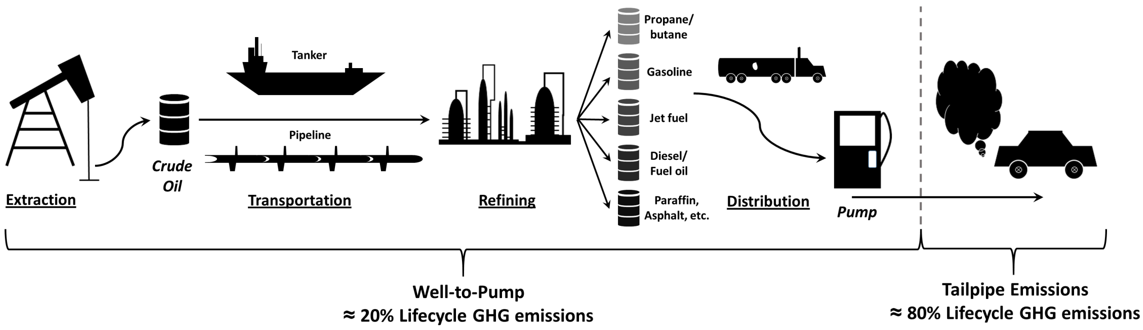

Figure 6.9: Schematic of the gasoline/diesel fuel cycle. The well-to-pump process proceeds from extraction at the well to yield crude oil, which is transported to refineries where it is refined into various fuels, which are it turn distributed to the customer. This whole process, along with the emissions embodied in developing the infrastructure for oil extraction, contributes about 20% of the fuel lifecycle emissions. Direct combustion of the fuel in automobiles generates tailpipe emissions, which account for roughly 80% of the fuel lifecycle emissions.

of emissions each [207]. The exact contribution of each of these processes varies significantly between oil sources. For example, extraction of conventional Kuwaiti crudes takes relatively little energy, while transport of this crude is more energy-intensive than average. Generally speaking, refining is consistently the most emissions-intensive process, with the major exception being tar sands bitumen, where extraction is dominant and highly emitting, as discussed next [207].

6.3.1 Tar sands vs. conventional crude and the Keystone XL

- Bitumen, found in the Alberta tar sands, is a form of extremely heavy oil or tar that may be found mixed with sand and clay. Hot water or steam is used to extract the bitumen, either from surface mined tar sands or via deep steam injection, and this extremely energy-intense process increases WTP emissions by 80–90%, and total lifecycle emissions by 15–25%, relative to typical crude oils.
- Surface mining of boreal forests is extremely locally destructive, and forest carbon losses may further increase tars sands WTP emissions by 15–25% and lifecycle emissions by 5–10%.

Overview

As the reader is likely aware, there has been significant controversy over the Keystone XL pipeline (unapproved at the time of this writing, but this may change with the Trump presidency), with the increased energy and emissions associated with extraction of bitumen ("extra heavy oil" or "tar") from the Alberta tar sands as one of the major arguments for blocking its construction. Briefly, the tar sands (or "oil sands") are geologic formations composed of a mix of sand, clay, and bitumen. Bitumen is a form of extremely viscous heavy oil, and it is essentially identical to asphalt. While oil extraction is in general an energy-intensive process, extracting crude oil from the viscous bitumen of the tar sands is even more energy-intensive, with WTP emissions likely 80–90% greater than other typical North American crudes, and overall lifecycle emissions roughly 15–25% greater [211, 210, 212]. If carbon emissions resulting from boreal forest degradation related to oil sands exploitation are included in our accounting,

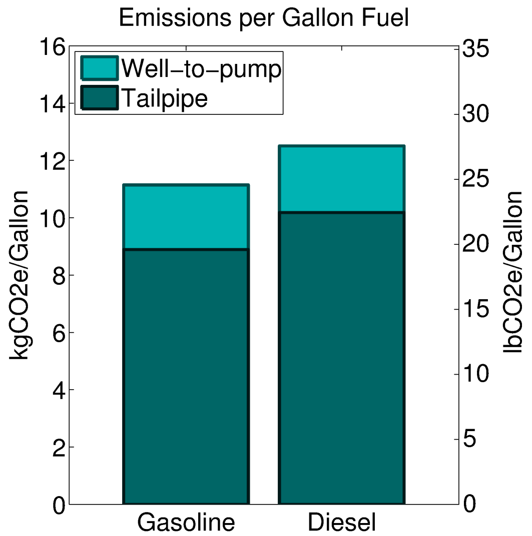

Figure 6.10: Upstream well-to-pump and direct tailpipe GHG emissions for gasoline and diesel, on a per-gallon basis.

lifecycle emissions may be 25–35% greater compared to conventional crude, and WTP emissions 2–2.5 times greater (see Section 6.3.1), but there is great uncertainty in this.

Bitumen is extracted from oil sands by either open-pit surface mining of shallow deposits, or via so-called *in situ* methods (Latin for "in place"), for deeper deposits. With surface mining, the oil sands are simply scooped up by heavy equipment, and the bitumen is extracted through a hot water process [210]. *In situ* methods involve injection of hot steam into the oil sands, which decreases the viscosity of bitumen, allowing it to be pumped out of the reservoir like conventional crude. That is, the basic difference between the methods is whether hot water is used to separate bitumen from sand that has already been mined in bulk (surface mining), or hot water is used to separate the bitumen from the sand while it is still in the geologic reservoir.

While historically most Canadian bitumen was extracted via surface mining, about 80% of oil sands reserves are only accessible via *in situ* methods, and in 2013, the *in situ* share reached 53% of total bitumen extraction in Alberta [4]. While surface mining is slightly less emissions-intensive than *in situ* extraction, it is far more locally destructive (and the destruction of forest could well tip the carbon balance in favor of *in situ* extraction). The two major *in situ* process are steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), with CSS, also known as the "huff-and-puff" method, the older technology.

Once extracted, bitumen is still much too viscous to flow in a pipeline, so it is diluted with a lighter material, such as synthetic crude oil (SCO), and then it is either sent to an upgrader facility, where the bitumen is processed into lighter SCO that is then sent on to a refinery, or delivered directly to a refinery that can accept raw bitumen; most bitumen is upgraded before refining.

Lifecycle analyses

The US State Department, in its final analysis, estimated that fuels derived from Canadian tar sands oil transported by the Keystone XL pipeline would ultimately have 17% higher WTW emissions than several reference crude oils [212], implying that the upstream WTP emissions

[4] Alberta Office of Statistics and Information, https://osi.alberta.ca/osi-content/Pages/OfficialStatistic.aspx?ipid=916, accessed 3/28/2015

are over 80% greater for this source.

A 2012 analysis by Bergerson and colleagues [210] used confidential data (and hence their results cannot be replicated) from mining companies to estimate WTP emissions ranges of 122.04–186.84 gCO_2e/kWh and 93.24–154.44 gCO_2e/kWh of reformulated gasoline (RFG), for SAGD and surface mining, respectively, when bitumen was upgraded to SCO upstream of refining. The authors cite a range of 21.24–136.44 gCO_2e/kWh RFG for conventional crude, drawing upon multiple works of literature. Note that these ranges all overlap, and omitting upgrading from the bitumen pathway (shipping directly to refinery) results in lower overall emissions. However, since most bitumen is upgraded, I only compare SCO bitumen pathways to conventional crude. Furthermore, CSS is a commonly used *in situ* technology and appears to generate about 36 gCO_2e/kWh more than SAGD, largely because of increased extraction emissions.

The above ranges suggest average WTP emissions of 4.138 $kgCO_2e/gallon$, 5.160 $kgCO_2e/gallon$, 6.363 $kgCO_23e/gallon$, and 2.6341 $kgCO_2e/gallon$ for surface mined, SAGD, CSS, and conventional gasoline, respectively. Note that the latter figure is reasonably comparable to the GREET estimate of 2.259 $kgCO_2e/gallon$. Weighting *in situ* extraction 53% (in the absence of any concrete data, I make the crude assumption that SAGD and CSS each account for 50% of this total) and surface mining 47% suggests that WTP emissions and lifecycle emissions are 90% and 22% higher, respectively, for gasoline sourced from bitumen versus conventional crude.

An earlier review of studies by the same research group [211] suggested that total lifecycle emissions for surface mining and *in situ* techniques exceed, on average, those for conventional gasoline by 9% and 26%, respectively. Weighting the techniques by 47% and 53% as above suggests 18% higher lifecycle emissions overall. A 2009 Department of Energy/National Energy Technology Laboratory [207] study examined WTP emissions for diesel fuel for a variety of oil sources, and found Canadian oil sands to have the highest emissions of any source, at 4.403 $kgCO_2e/gallon$ (34.0 $kgCO_2e/mmBtu$). This is 85% higher than the US average in the study (2.383 $kgCO_2e/gallon$), and over 2.5 times the *domestic* oil average (1.748 $kgCO_2e/gallon$, 13.5 $kgCO_2e/mmBtu$).

Two reports examining lifecycle GHG emissions were commissioned by the Alberta government [214, 215]. One report [215] concluded that lifecycle emissions for the dilbit/synbit oil sands pathway (this is the pathway that excludes the emissions-intensive bitumen upgrade process) are about 10% higher than typical conventional crudes; the other [214] gives a range of results, but reports a lower gap between conventional crudes and bitumen than other studies, at 6 to 18% over the lifecycle (omitting questionable co-generation credits). Given that these are non-peer-reviewed reports and commissioned by a government with an active interest in promoting oil sands exploitation, skepticism is warranted. Other reports are fairly consistent in finding bitument to be 15–20% more emitting (over the lifecycle) than typical US crudes [213, 212, 207, 210, 211].

Emissions from forest degradation

While the analyses reviewed above indicate that *in situ* methods generate more emissions, largely due to the truly massive amounts of natural gas that must be combusted to generate steam in sufficient quantities, open pit surface mining is locally far more devastating, and requires the wholesale destruction of the boreal forest that overlies the oil sands. Boreal forests are a major global carbon sink, have been estimated to store 239 Mg carbon per hectare (876 $MgCO_2e/hectare$) [46], and continue to take up large amounts of carbon. Emissions from forest destruction is typically not accounted for by the analyses reviewed.

Data from Global Forest Watch[5] suggests that 775,500 hectares were cleared or degraded in the Canadian tar sands region from 2000–2012. There are 475,000 hectares of surface-minable area, and in this zone, forest loss is at 20%. If we assume that all carbon from the surface-mined areas has been oxidized to atmospheric CO_2, and that 40% [216] of the carbon from the other cleared and degraded areas is lost, we have roughly 322 million $MgCO_2$ from forest degradation, which is about 1.261 $kgCO_2e$/gallon bitumen[6]. Supposing that only half of forest degradation is attributable to tar sands exploration (the other half being due to logging and other industrial activity), we would have 0.794 $kgCO_2e$/gallon bitumen. In sum, forest degradation may increase upstream WTP emissions by an additional 15–25% and lifecycle emissions by 5–10%, although these figures are quite uncertain. An earlier report by Global Forest Watch also explores this issue in depth [216].

6.3.2 WTP emissions vary widely by crude oil source

From the above analysis, it should be clear that Canadian oil sands crude is markedly more emissions-intensive than the national US average. However, it is also important to note that both domestic and international sources of crude vary markedly in WTP emissions intensity. A DOE/NETL report [207] concluded that domestically produced conventional oil has low WTP emissions, by global standards, while, as noted above, Canadian tars sands and Venezuelan "extra heavy oil" have the highest WTP emissions, as summarized in Figure 6.11.

[5] see http://www.wri.org/blog/2014/07/tar-sands-threaten-world%E2%80%99s-largest-boreal-forest, accessed 3/28/2015

[6] Determined from bitumen extraction statistics for 2003–2012 from the Alberta Office of Statistics and Information. Yearly extraction from 2000–2002 was assumed to be equal to that in 2003, a likely overestimate.

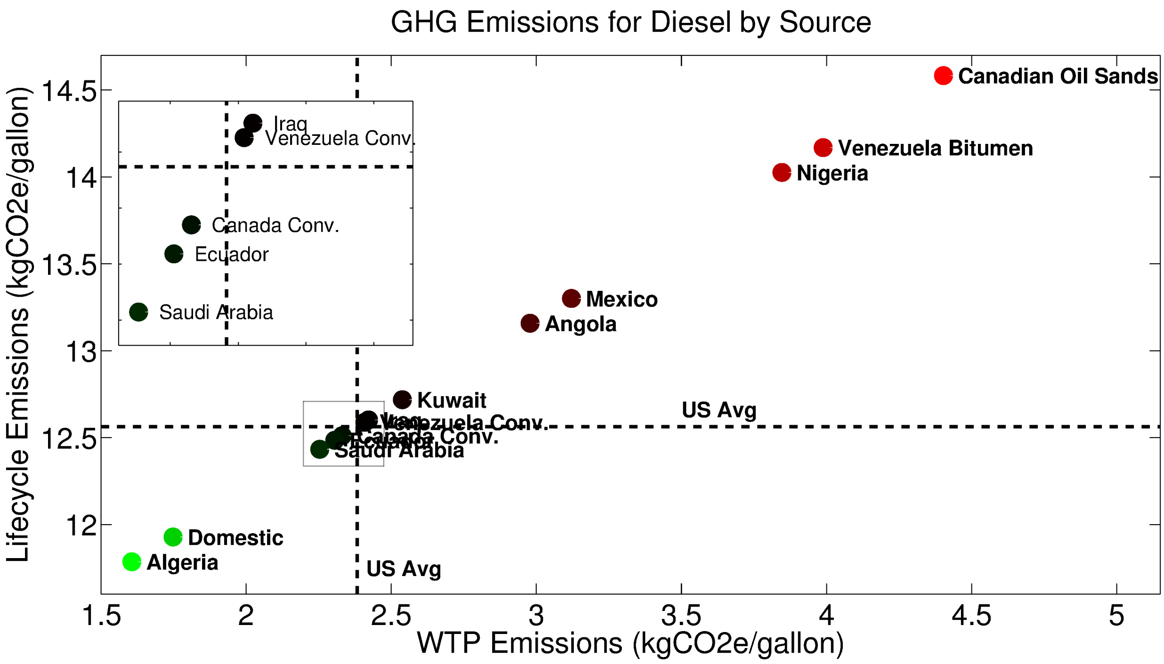

Figure 6.11: The WTP and lifecycle emissions for diesel fuel for various sources of crude oil, based on 2005 data. Pump-to-wheel emissions are identical, regardless of oil source, and so all variation is due to differences at the WTP level. Note that this data largely pre-dates the increase in shale/tight oil exploitation in the US (domestic), and so may be slightly out-of-date. However, the conclusion that bitumen from Venezuela and the Canadian oil sands has the highest associated emissions is expected to be robust.