

Supporting Online Information for *Peak oil demand. The role of fuel efficiency and alternative fuels in a global oil production decline*

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S1. Supplementary methods

This supplementary information document contains additional methods discussion not included in the main paper. This includes additional Materials and Methods (Sections S1-S12) sections, additional figures (Figures S1-S19), and additional tables (Tables S1-S11). Also a *Microsoft Excel* worksheet for the Interactive petroleum Demand ESTimation (IDES) model is included. For an introduction to the IDES framework and the economic basis of IDES, please see Section 2 of the main text.

Because transport needs are the primary driver of current conventional oil demand, detailed modeling is performed on the land passenger transport (signified in equations as *lnd*, broken down into private and public land transport, or *prv* and *pub*), freight transport (signified by *fr*, broken down into road (*r*), railroad and domestic water (*rrw*) and international shipping (*ifr*)), passenger air transport (*air*), and military energy sectors (*mil*). Non-transport oil demand sectors are modeled using relationships between economic output and non-transport use of liquid fuels (*nt*) and other refinery outputs (e.g., asphalt, signified *ot*).

S2. Population and GDP

IDES requires wealth and population estimates over the modeled time period. IDES makes country-level projections. Country-level projections are summed in some instances to larger regional aggregations (e.g., UN regions). Because of the uncertainty of long-term socioeconomic predictions, we do not generate our own population and wealth scenarios, but instead use development pathways based on the Intergovernmental Panel on Climate Change (IPCC) SRES scenarios. The scenarios represent a diverse range of demographic and economic pathways, and thus capture a range of energy futures. While the SRES scenarios also characterize technology pathways that have implications for emissions and energy, our study uses only the SRES population and GDP projections [1].

For the years 1990-2010, the study uses observed GDP and population data from UN [2] and USDA [3] [4]. To project forward, data are gathered from the Center for International Earth Science Network, which downscales SRES scenarios for population and GDP to the country level to 2100 [5] [6]. We apply the current growth rates for these projections to the observed population and GDP data (see Table S1).

We measure GDP in 2005 US dollars at market exchange rates. In many developing countries, however, market exchange rates may not reflect the ability of people to purchase transport services and goods from other oil-consuming sectors. While measuring GDP at purchasing power parity (PPP) would overcome this problem, we are unable to project how PPP adjustments will evolve through 2100. Instead, we apply a GDP adjustment based on the following quadratic regression model:

$$g_{ry}^{PPP} = ag_{ry}^{mkt} + b(g_{ry}^{mkt})^2 \text{ if } g_{ry}^{mkt} < c$$

$$g_{ry}^{PPP} = g_{ry}^{mkt} \text{ otherwise}$$

The limit $c = \$24,820$ was determined iteratively based on the point where the PPP estimate is the same as market exchange rates. The coefficients $a = 1.878$ and $b = -0.000035$ were estimated via ordinary least squares using World Bank data for both GDP and PPP-adjusted GDP per capita for 182 countries between 1980 and 2010.

Table S1. Economic-population scenarios used in IDES.

Scenario name	Max. pop. (G persons)	GDP/cap in 2100 (2005\$/person)	Fraction wealth in OECD90 countries
A1	8.7	98897	14.5 %
A2	15.1	25320	20.4 %
B1	8.7	68609	16.5 %
B2	10.4	30917	13.7 %

S3. Land passenger sector

Since the early 1900s, land passenger transportation has been a main driver of demand for liquid fuels. As societies grow more affluent, there is a move first from non-motorized transportation to motorized public transportation, and then from public transportation to private vehicles. With each stage comes faster travel speeds and increased travel distances. While there is nothing deterministic about such a progression, and causal processes may flow in both directions, this broadly describes the experience of industrialized and middle-income countries to date [7].

Historically, passenger travel has grown almost linearly with GDP. While data are scarce, travel appears to continue to grow at this rate in the developing world. In industrialized countries, however, growth has halted, with passenger kilometers per capita by all land modes leveling out at a GDP of about USD \$25,000-\$35,000 per capita [8-10]. To the extent that per capita travel continues to grow in rich countries, it is likely to be by air travel [11]. There are sound theoretical reasons to expect land passenger travel to flatten out or even decline: infrastructure and congestion constraints; diminishing marginal utility to new destinations [10]; and historically stable travel time budgets, with about 1.1 hours per day per person in aggregate being devoted to travel in all societies [12, see also 13].

We divide the land passenger sector into two subsectors which have markedly different efficiencies in terms of energy per kilometer of passenger travel: (i) private vehicles, largely cars and light trucks; and (ii) public transportation, largely buses and trains. We ignore travel by non-motorized modes, as they do not require energy from liquid fuels.

S3.1. Data Sources

Unless otherwise stated, our data on passenger kilometers, modal shares and vehicle efficiencies are taken from a dataset compiled by Lee Schipper and collaborators [8]. We obtain fuel price data from GTZ [14, 15]. Urban densities are taken from the Gridded Population of the World (GPW) and Global Rural-Urban Mapping Project (GRUMP) datasets [16].

We calculate fuel taxes from fuel price data using EIA data [17] on the share of gasoline taxes, and assume that all non-tax components are constant across countries in a given year. (Note that since this procedure involves a simple linear transformation, our model specification and predictions would be identical if we used prices, rather than our estimates of taxes.)

Where fuel price data are missing for a country in a particular year, we impute them using linear regression from other years, or in the few cases where that was not possible, using urban density. Imputations are only used for prediction for individual countries, not to estimate model parameters.

To calculate public transportation efficiencies, we generally use official national statistics or similar authoritative sources as follows: U.S. – Oak Ridge National Laboratory’s *Transportation Energy Data Book* for 2011 [18] and previous years; Canada – Natural Resources Canada’s *Comprehensive Energy Use Database* [19]; Australia – Appelbaum Consulting’s *Australian Transport Facts* for 2009 [20] and previous years; U.K. – *Energy consumption in the UK* and *Transport Statistics Great Britain* for 2011 and previous years [21, 22]; Japan – the Schipper dataset discussed in [8].

S3.2. Calculation

The general form of the approach for land transport is illustrated by the equation for *private* land transport (sector *prv*):

$$E_{cy}^{prv} = P_{cy} t_{cy}^{lnd}(g_{cy}) m_{cy}^{prv}(g_{cy}) \left(f_{cy}^{prv}(g_{cy}) \right)^{-1} \eta_{cy}^{prv}(y, g_{cy}).$$

where $t(g)$ is the land travel demand [pkm/person] as a function of per capita GDP, $m(g)$ is the modal split for private transport [pkm private/pkm total] as a function of GDP, $f(g)$ is the vehicle load factor [pkm/vkm], and $\eta(g)$ is the efficiency of private land transport [MJ/vkm]. In this sector region r is defined by country.

Similarly, energy demand for public land transport (sector *pub*) is given by:

$$E_{cy}^{pub} = P_{cy} t_{cy}^{lnd}(g_{cy}) \left(1 - m_{cy}^{prv}(g_{cy}) \right) \eta_{cy}^{pub}(y, g_{cy}),$$

where in this case η is the efficiency of public transport [MJ/pkm], expressed directly in passenger rather than vehicle kilometers (load factors are implicit in the efficiency term).

With respect to regional specification, countries (c) are assigned to one of a series of illustrative pathways (p). This process is described below.

Land passenger travel pathways.

We model the relationship between land passenger travel $t(g)$ and GDP using four idealized pathways. The different pathways $p \in [1, 2, 3, 4]$ embody different policy choices with respect to road and public transportation infrastructure investment, fuel taxation and land development patterns; and different physical constraints such as national population density. The four pathways are fit by least squares to historical data for the U.S. (Pathway 1); Australia and Canada (Pathway 2); the U.K., Sweden, France, Italy, Germany and the Netherlands (Pathway 3); and Japan (Pathway 4). These country groupings are similar to those typically identified in the literature [23-25]. Figure S1 shows clear differences between the rates of growth in each group. We use a modified Gompertz functional form to capture the observed leveling out of per-capita travel at higher income levels, in line with previous studies of vehicle ownership rates which also use a Gompertz or similar functional form [26, 27]:

$$t_{cy}^{lnd} = \sum_{p=1}^4 \left[\left[a_p^{lnd} \exp \left[b_p^{lnd} \exp \left(c_p^{lnd} g_{cy} \right) \right] + d_p^{lnd} \right] \Pr[p_c = p] \right],$$

where t_{cy}^{lnd} is passenger kilometers per capita by land modes in country c in year y ; g_{cy} is GDP per capita in 2005 USD in country c and year y ; and a_p , b_p and c_p are parameters for countries in Pathway p that respectively control the saturation level,

x scaling (i.e., a horizontal shift) and growth rate. To reduce model degrees of freedom, the x scaling factor is constrained to be equal across pathways, i.e. $b_1 = b_2 = b_3 = b_4$. In a departure from the standard Gompertz function, we include a floor d_p which is the minimum level of land travel demand. This is set at 2,000 pkm/y for all pathways. $\Pr[p_c = p]$ is the probability that country c will follow pathway p , as discussed in Section 3.4.2.3.

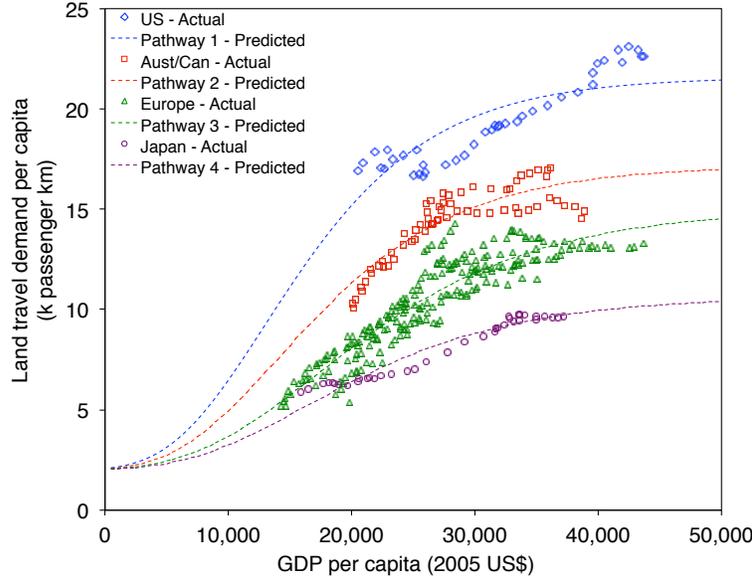


Figure S1. Actual and predicted distance traveled per person (passenger km) by all motorized land modes as a function of GDP

Modal share pathways.

We use a similar approach to model the modal shares of private vehicles and public transportation (m) as a function of GDP. We estimate four pathways based on the same country groupings as for land passenger travel. As before, we use a Gompertz functional form, which captures the historical pattern of a rapidly increasing private vehicle share followed by a leveling off. Again, the equation is slightly modified to incorporate a non-zero floor:

$$m_{cy}^{prv} = \sum_{p=1}^4 \left[\left[a_p^{m,prv} \exp \left[b_p^{m,prv} \exp \left(c_p^{m,prv} g_{cy} \right) \right] + d_p^{m,prv} \right] \Pr[p_c = p] \right],$$

The parameters are estimated via the following procedure: (1) For d_p , assume a minimum private vehicle mode share of 5% (an arbitrary floor); (2) Calculate the saturation level a_p based on the average private vehicle share from 2000-08/09 for countries in Pathway p ; (3) Estimate b_p and c_p separately for Pathways 3 (Europe) and 4 (Japan) by least squares; (4) Assume that the growth rate c_p is the same for Pathways 1 (U.S.) and 2 (Australia/Canada) as for Europe, since we do not have reliable data for this period (that is, $c_1 = c_2 = c_3$); (5) Estimate b_p separately for

Pathways 1 and 2 by least squares. As before, $\Pr[p_c = p]$ is the probability that country c will follow pathway p .

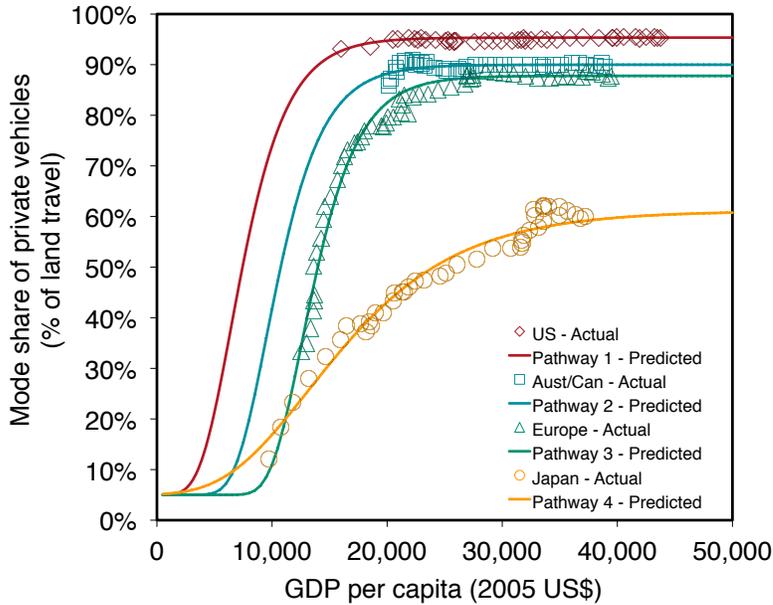


Figure S2. Actual and predicted mode share (pkm by private vehicles as a percentage of pkm by all motorized land modes) as a function of GDP.

The income level at which the transition from public to private modes occurs is estimated from historical data, and reflects a period (e.g. the 1950s and 1960s in the UK) when private cars were much more expensive in real terms. Therefore, we make the following adjustments to the fitted model: (1) halve the horizontal shift parameter in Pathways 1 and 4; and (2) replace the horizontal shift parameter for Pathways 2 and 3 with that estimated for Pathways 1 and 2 respectively. This preserves the shape of the transition curve and the saturation level, but allows the transition to occur at a lower income level (e.g. for Europe, the transition would occur at the income level estimated for Australia/Canada, and in Australia/Canada, it would occur at the income level estimated for the U.S.).

Assignment to pathways.

We assign countries probabilistically to the four pathways using an ordered probit model [28], estimated by maximum likelihood with data for the ten countries whose pathway is known (the U.S., Canada, Australia, Japan and the six European countries named above). This approach posits a latent variable, $y_c^* = X'_c\beta + u_c$, where y_c^* might be interpreted as the travel intensity of country c 's economy, X is a vector of independent variables, β is the vector of coefficients to be estimated, and u_c is an error term with a standard normal distribution. This model also estimates the cut points τ_1, τ_2, τ_3 . A country's probability of following Pathway 1 is then $\Pr[y^* < \tau_1]$, its probability of following Pathway 2 is $\Pr[\tau_1 \leq y^* < \tau_2]$, and so on.

We employ two independent variables X to assign countries to one of the four pathways. First, the gasoline tax in each country both indicates a country’s current policy towards restraining passenger travel, and reduces travel directly through the price effect. Second, urban population density has both physical and land-use policy dimensions, and has an impact on travel through various channels including increasing the time cost of travel, bringing destinations closer together, and making public transportation more effective [24, 25, 29]. Adding national population density to the model in addition to urban population density yields almost identical results and a worse performing model as measured by AIC, a common model selection criterion. We do not attempt to estimate how each country’s fuel taxation and land-use planning will evolve, and assume that the pathway a country follows is fixed over time.

Table S2 shows the estimates of model coefficients and cut points. Figure S3 shows the model’s predictions for the ten countries with “known” pathways plus other major countries of interest. Pathway 1 consists mainly of OPEC countries that subsidize gasoline (i.e., have a negative tax). Pathway 3 is the modal pathway, and includes most European countries as well as China, India and Brazil. The ten countries used to estimate the model generally fall into the correct pathway, with the major exception being Japan. Here, the issue may be that vehicle ownership taxes and restrictions, which are relatively high in Japan, are not reflected in the model. Unfortunately, no consistent cross-national data are available for vehicle taxes.

The predictions are probabilistic. We then use these probabilities to construct a weighted average when predicting passenger travel and modal shares as shown in Eqs S5 and S6.

Table S2. Ordered Probit model used to assign countries to pathways

Variable	Coefficient	Standard error
Urban density	0.00341	0.00280
Gasoline tax	0.02465	0.01554
Cutpoint 1	1.41803	1.34561
Cutpoint 2	3.26136	1.76607
Cutpoint 3	7.02653	3.38229
N	10	
Pseudo R ²	0.427	

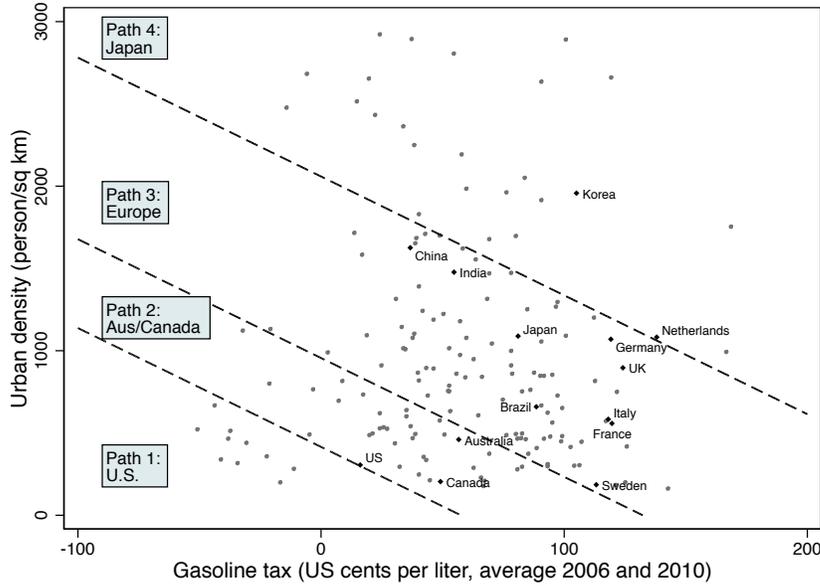


Figure S3. Point estimate predictions from ordered probit model. The area between each set of dotted lines represents a different pathway. Note that the model-generated probabilities, rather than the point estimates, are used when assigning countries to pathways. For example, the U.S. falls into Pathway 1 with probability 0.492, Pathway 2 with probability 0.474, Pathway 3 with probability 0.034 and Pathway 4 with probability 0.

Private vehicle efficiency.

Load factors in industrialized countries have converged over the past 30 years. In 2008, vehicle occupancy lay between 1.5 and 1.7 in all industrialized countries in the Schipper dataset discussed above, with the exception of Japan (1.41). At high GDP levels, we therefore assume a constant load factor f_{cy}^{prv} of 1.6 persons per vehicle (i.e., pkm/vkm = 1.6) for all regions and years.

For lower-income countries, there is limited data on vehicle occupancy. In line with [30], we assume that the occupancy level in the poorest countries is 2.5 persons per vehicle. We then allow occupancy to asymptotically decay to 1.6 using a negative exponential function, so that $f_{cy}^{prv} = 1.6 + (2.5 - 1.6) \exp(-0.0001g_{cy})$. This yields an occupancy level of 2.0 at a per capita GDP of \$8,500, and 1.65 at \$30,000.

Private vehicle efficiency η_{py}^{prv} is specified according to the four pathways discussed above. We assume that countries follow the same pathway for efficiency as for overall passenger travel, and that annual efficiency improvements occur exogenously at a constant rate that is independent of GDP.

For the three scenarios listed below we use the following figures:

Historical - 0.6% per year fuel economy improvement is the observed annual rate of change in the dataset, averaged across the 4 pathways. The U.S. achieved an annual 1.2% improvement during the 1970-2008 period (albeit in fits and starts), while other countries achieved lesser gains from a more efficient base, yielding an average of 0.6% (Table S3). While such a rate is far below estimates of the technical potential to improve energy efficiency, historically, technical progress has been used to increase vehicle power and weight more than to improve fuel economy [33].

High Technology - 2.4% per year fuel economy improvement, which is the annual rate of change mandated from 2005 to 2015, averaged across the 4 pathways, based on ICCT data [31]. The period analyzed is 2005-15 for the US, Japan and the EU; 2005-16 for Canada; and 2005-10 for Australia. For example, President Obama announced in July 2011 that fuel economy standards would rise to 54.5 mpg by 2025, while proposed European and Japanese standards would exceed 45mpg by 2015 [31]. Note, however, that these regulatory standards refer to test fuel economy for new vehicles. On-road efficiencies for the entire vehicle fleet will be lower [32], meaning that this scenario implies efficiency gains above and beyond existing mandates.

Efficiency Policy - 1.5% per year fuel economy improvement assumes that policy is lumpy, and so over a longer time period the annual rate of change will be between *Historical* scenario and near-term policy. This is typified by experience with the US CAFE standard (significant increase in efficiency from 1975-1985, long period of no policy change).

In all scenarios, we assume that the annual percentage improvement is constant across all countries. However, different countries have different initial levels of vehicle efficiency, according to the four pathways used to calculate land passenger travel and modal split. In the base year of 2005, we calculate vehicle efficiencies of 3.98 MJ per vehicle kilometer (U.S), 3.74 MJ/vkm (Australia/Canada), 2.90 MJ/vkm (Europe) and 3.74 MJ/vkm (Japan). Note that these vehicle efficiencies reflect not only the size and weight of the on-road fleet, but also traffic congestion and prevailing driving patterns, which explain the relative inefficiency of Japanese private vehicles.

In the poorest countries, we apply a fuel economy penalty, given that cars are unlikely to use the latest fuel saving technology. Indeed, they are often second-hand models that are imported from richer countries. Congestion and road maintenance are likely to adversely effect fuel economy in poor countries. Since there is almost no data on on-road, fleet fuel economy in developing countries, we use a technological delay factor. At a GDP of \$0 per capita, the delay factor is 15 years (i.e., the pathway-specific fuel economy is used, lagged 15 years). The delay factor then declines linearly with GDP until it reaches zero at a GDP of \$30,000 per capita.

Table S3. Historical and Projected Fuel Economy Improvements. Sources: See Section 3.4.1.

Country	MJ/vkm - Annual Change					MJ/vkm 2008	Annual Projected Change 2005-15*
	1970- 2008	1970- 80	1980- 90	1990- 2000	2000- 08		
U.S.	-1.2%	-1.4%	-2.3%	-0.6%	-0.3%	3.90	-2.9%
Canada	n/a	n/a	n/a	-0.6%	-0.4%	3.49	-2.8%
Australia	n/a	n/a	-0.7%	-0.5%	-1.0%	3.85	-2.4%
U.K.	-1.0%	-0.3%	-1.7%	-0.6%	-1.8%	2.71	-2.1%
Japan	0.3%	2.6%	-0.6%	0.6%	-1.9%	3.65	-1.9%

* Annual projected change refers to change in enacted fuel economy test standards for new cars and light trucks. Thus, this figure is not directly comparable to the annual change for 1970-2008, which refers to fleet-wide on-road efficiency. Data for annual projected changes are from [31]. Note that Australia data refer to the 1975-2007 period. U.K. data refer to the European Union.

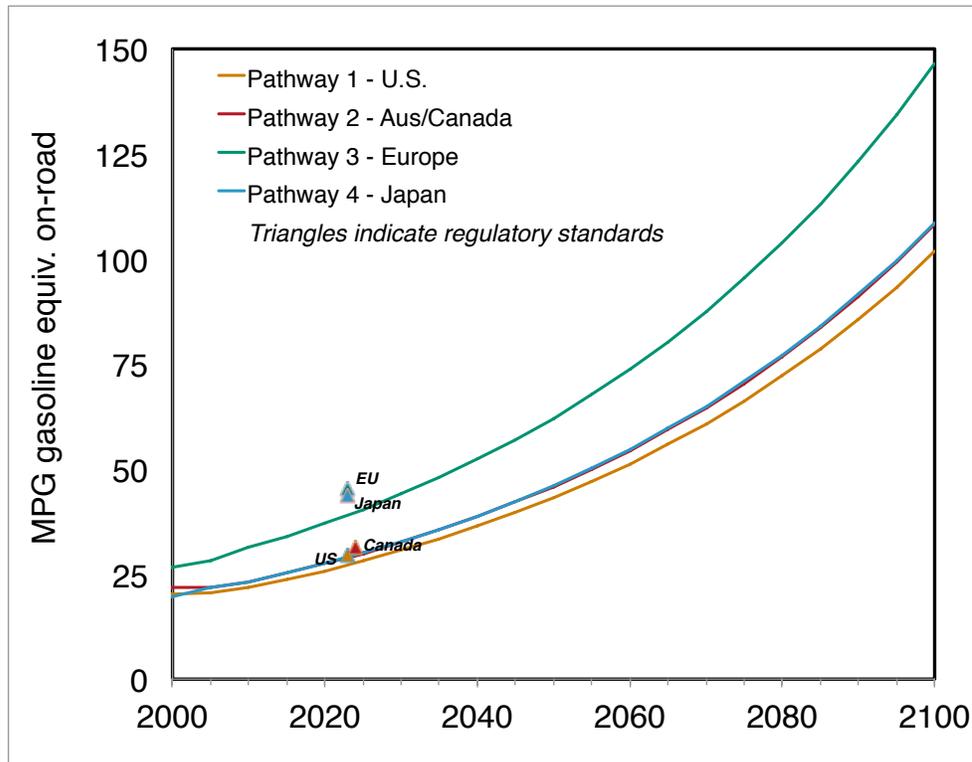


Figure S4. Estimated fuel economy of private vehicles, assuming an annual 1.7% efficiency improvement

Public transportation efficiency

We take a similar approach to public transportation efficiency as with private

vehicles, and assume an annual rate of improvement over the base year. Each pathway has a different efficiency η_{py}^{pub} , [MJ/pkm], which encompasses both vehicle efficiency [MJ/vkm] and load factors [pkm/vkm]. For example, high load factors and a larger share for (more efficient) rail over bus largely explain the efficiency of the Japanese public transportation system.

Future public transportation efficiency is difficult to predict. During the 2000-08 period, U.S. and Japanese public transportation efficiency improved by more than 1% per year, while Australian efficiency became markedly worse and the U.K. remained flat. Our base case, which is adjustable by the user, assumes an annual 0.2% decrease in MJ/pkm in all four pathways. This conservative assumption reflects the range of experiences in different countries. Between 2000 and 2008, public transport efficiency improved by 1.7% annually in the U.S., 1.2% in Japan and 0.6% in Canada; stayed the same in the U.K. and declined by 3.6% annually in Australia.

Public transport efficiencies are likely to be considerably higher in the poorest countries due to very high load factors. As with private transport, however, there is little data on efficiency in countries at the lowest income levels. We therefore assume an efficiency of 0.6 MJ/pkm at a per capita GDP of \$0 (based on [34]), and a linear transition to the pathway-specific efficiency at a per capita GDP of \$5,000.

S4. Freight transport

Wealth has historically been coupled to freight activity and thus freight energy demand. Although the coupling between GDP and freight activity differs widely across countries, there does not appear to be a strong trend towards dematerialized economies. A 2009 study by Kamakate and Schipper [35] of five OECD countries noted a weak decoupling between the ratio of freight to GDP in four of the countries, and a 2011 study by Eom et al [36] of ten IEA countries reported freight activity still coupled with GDP growth. Even with a weak decoupling, growing populations and wealth may continue to increase total demand for freight activity.

Freight demand is met with a combination of road, rail, and water modes. According to the IEA, most road and rail freight moves within continents, whereas most intercontinental freight moves via international shipping [37]. Within continents, historical trends suggest that the modal split will favor both a growing share and volume of road transport. This shift has become the focus of recent studies. Schipper et al [38] reported increases in domestic freight volumes in a study of ten industrialized countries, with trucks transporting most of this increased activity. Kamakate and Schipper [35] highlighted trucking's growing importance because of its speed and flexibility versus other modes. The significance of a growing share of trucking relates to its energy intensity. Trucks have higher energy intensities than rail or water modes, and therefore a disproportionate energy impact [36]. Even with improvements in trucking energy intensity, a growing shift towards trucking activity leads to higher aggregate freight energy intensity and total energy use.

The freight module is composed of two separate components. The first component calculates energy demand from both international and domestic road and rail modes, and domestic coastal and inland water modes. The second component calculates freight energy strictly from international water shipping.

In the first component, we calculate aggregate freight activity as a function of GDP, divide the activity into (1) road and (2) railroad and water modes as a function of GDP, and apply an energy intensity term as a function of time. Railroad and domestic water are treated together, as they have similar energy intensities and are used for similar purposes – primarily low-value or bulky commodities where speed is not critical. In a similar manner to land passenger transport, we identify two different pathways for activity, modal shares and energy intensity, and assign countries to a pathway based on geographical area. This distinction stems from differences in modal split and energy intensity amongst large countries versus small. Specifically, large countries have larger modal shares of water and rail than smaller countries. Furthermore, modal energy intensities tend to be lower due to differences in congestion, distance, and loading [35-37]. We account for the fraction of freight energy supplied by electricity to power rail freight, and assume that liquid fuel supplies the remaining fraction.

In the second component, we calculate global international shipping activity as a function of global GDP, and apply an energy intensity term that reflects the historical energy intensity of shipping.

S4.1. Data Sources

For road, rail, and water (coastal and inland) modes, we use activity data from an OECD freight dataset that includes historical tonne-km values from 1970-2008 for 43 countries [39]. We did not include Russia because of data confidence issues. The data includes both domestic and international values – even if it were desirable, it would be extremely difficult to disaggregate road and rail into domestic and international activity. We use the underlying energy intensity data from Eom et al [36] to build energy intensity values for the two pathways. The data includes detailed breakdowns of activity and energy intensity by mode for ten countries from 1970-2008, although we base our trends on data from 1990 onwards for consistency between the two pathways. Importantly, the data also includes an estimated percentage of rail energy that is provided by electricity.

For international shipping, we use global historical shipping activity data for 1983-2008 from Fernley's *Review*, cited in [40, 41]. We calculate energy intensity based on a 2009 UN International Maritime Organization (IMO) study which provided historical marine fuel consumption from 1990-2007 [42]. We assume a constant mix of residual and distillate fuel as given by IMO for 2007 [42]. We converted the volumes into energetic quantities with higher heating values (HHV).

S4.2. Calculation – Road, Rail (International and Domestic) and Water (Domestic)

Freight energy demand is modeled using population, activity, and modal split:

$$E_{cy}^{fr} = P_{cy} t_{cy}^{fr} (g_{cy}) \left[m_{cy}^r (g_{cy}) \eta_{cy}^r + \left(m_{cy}^{rrw} (g_{cy}) \right) \eta_{cy}^{rrw} \right]$$

E_{cy}^{fr} describes the amount of energy necessary to satisfy freight energy demand by road (r) and railroad/water (rrw) modes for each country and year. A variety of terms affect freight energy demand: freight activity t_{cy}^{fr} [tkm/capita], modal share of road freight m_{cy}^r (and hence railroad/water), and modal freight energy intensity η_{cy} [M]/tkm] for road and railroad/water.

To forecast t_{cy}^{fr} [tkm/capita] for a given country and year, we use a linear equation that calculates the total freight activity for road, rail, and water modes:

$$t_{cy}^{fr} = b_p^{t,fr} g_{cy} + a_p^{t,fr}$$

Where $b_p^{t,fr}$ corresponds to a slope [tkm/GDP] according to pathway p , g_{cy} represents the GDP per capita [year 2005 \$/person, market exchange rates] for each country and year, and $a_p^{t,fr}$ represents the freight activity intercept for pathway p .

We assigned countries to one of two pathways p in order to distinguish freight activity pathways between large and small countries. Pathway 1 includes continental-scale countries: USA, Canada, Australia, China, Brazil, and Russia. Pathway 2 includes all other countries.

To calculate $a_p^{t,fr}$ and $b_p^{t,fr}$ for each pathway, we apply a least-squares linear regression between historical freight activity per capita and GDP per capita for each freight activity pathway p . The historical data for each pathway are weighted by population and activity. The activity represents all three major modes of transport. Although the regressions for each pathway accurately represent historical freight activity at high income levels, they poorly represent low-income countries. Therefore, we separated low-income countries from the Pathway 2 OECD dataset and built a third linear activity curve to describe freight activity at income levels (<\$4000/cap). Essentially, this led to a piecewise linear regression, where both Pathway 1 and 2 countries have activity curves that share the low income curve until the trends intersect, as shown in Figure S5.

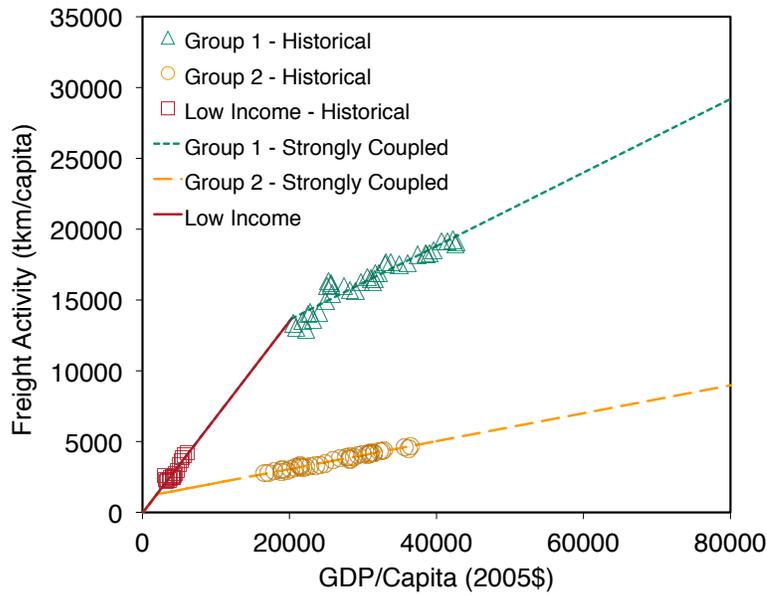


Figure S5. Freight activity per capita, based on 42 countries' historical data [39].

To forecast the modal share for a given country and year, we use a linear function for the fraction of total freight provided by road m_{cy}^r and railroad/water m_{cy}^{rrw} modes.

$$m_{cy}^r = b_p^{m,fr} g_{cy} + a_p^{m,fr}$$

$$m_{cy}^{rrw} = 1 - m_{cy}^r$$

Where $b_p^{m,fr}$ corresponds to a slope [cap/GDP] according to pathway assignment p , g_{cy} represents the GDP per capita [year 2005 \$/person, market exchange rates] for each country and year, and $a_p^{m,fr}$ represents the road fraction intercept for pathway p . As seen above, the modal fraction dedicated to railroad/water modes is simply a function of the fraction dedicated to road. To calculate $a_p^{m,fr}$ and $b_p^{m,fr}$ for each pathway, we apply a linear regression between the historical fraction of total activity provided by road and GDP per capita for each freight pathway p . The historical data for each pathway are weighted by population and activity. The fraction of freight activity provided by (1) road and (2) railroad and water as a function of GDP per capita is shown in Figure S6 for freight pathway 1.

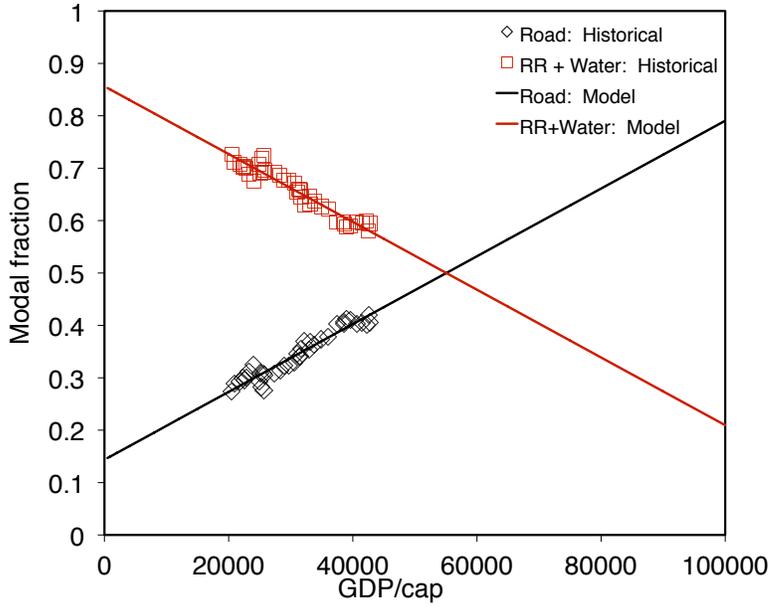


Figure S6. Modal fraction provided by (1) road and (2) rail and water modes for Pathway 1 countries.

To forecast the energy intensity for a given pathway and year, we use a nonlinear equation that calculates the energy intensity for (1) road η_{py}^r and (2) rail and water (coastal and inland) η_{py}^{rrw} modes:

$$\eta_{py}^r = a_p^{\eta_r, fr} (1 - b_p^{\eta_r, fr})^{y-1990}$$

$$\eta_{py}^{rrw} = a_p^{\eta_{rrw}, fr} (1 - b_p^{\eta_{rrw}, fr})^{y-1990}$$

Here $b_p^{\eta_r, fr}$ and $a_p^{\eta_r, fr}$ correspond to a rate and intercept according to a pathway p for each mode, and each are a function of the year y . We apply the same pathway assignments as with freight activity. To calculate the constants for each mode and pathway, we apply a least-squares exponential regression between historical freight energy intensity and year for each mode for each pathway, where the energy intensity data is weighted by activity. The resulting energy intensity curves are shown in Figure S7 for Pathway 1.

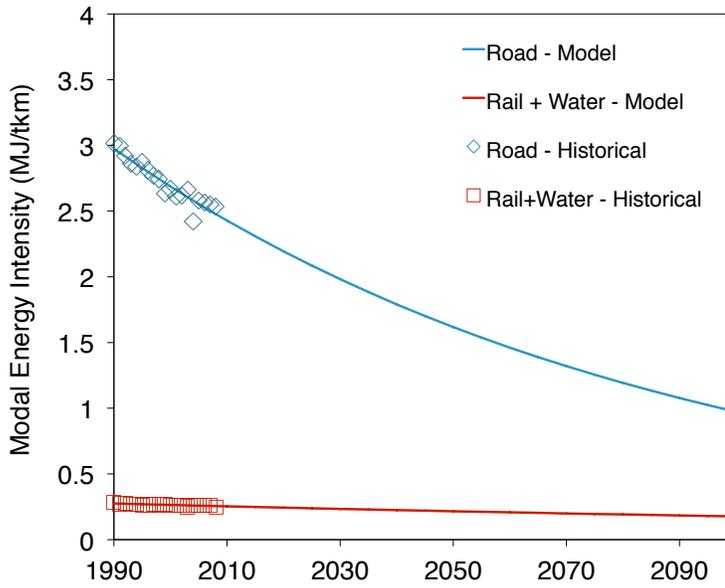


Figure S7. Modal energy intensity for (1) road and (2) rail and water modes for Pathway 1.

The above figures represent technological pathways as a function of time based on ten developed countries. However, due to issues with congestion, older vehicle technology, and inefficient transportation infrastructure, it is likely that developing countries will not experience the same energy intensity as rich countries in a given year. Hence, we apply a scalar to developing countries to simulate a delay in reaching a given energy intensity, where the delay diminishes with increasing wealth. This delay function is applied to every country, but only has an effect for countries below a threshold GDP/cap:

$$d_{cy}^{fr} = \left(\frac{d^{fr} (g_d - g_{cy})}{g_d} \right)$$

Where d^{fr} represents the maximum delay (set at 15 years), and g_d represents the threshold GDP/cap at which the delay no longer applies, set at \$25,000/cap. This is calculated for each country in each 5-year increment. The technological delay was included because evidence suggests that various factors in developing countries lead to less favorable energy intensity. However, little research has explored the subject in depth, and certainly not to the point where we could confidently parameterize the findings.

$$\eta_{py}^r = a_p^{\eta r, fr} (1 - b_p^{\eta r, fr})^{y-1990-d_{cy}^{fr}}$$

$$\eta_{py}^{rrw} = a_p^{\eta rrw, fr} (1 - b_p^{\eta rrw, fr})^{y-1990-d_{cy}^{fr}}$$

S4.3. Calculation – International Shipping

The calculation for international freight energy demand is as follows:

$$E_y^{ifr} = T_y^{ifr} \eta_y^{ifr}$$

The E_y^{ifr} term describes the amount of energy necessary to satisfy global international shipping freight energy demand for a given year. The equation accounts for freight activity T_y^{ifr} (tkm) and freight energy intensity η_y^{ifr} [MJ/tkm] for a given year.

To forecast T_y^{ifr} for a given year, we use a linear equation that calculates the global international freight activity:

$$T_y^{ifr} = b^{t,ifr} \sum_c P_{cy} g_{cy} + a^{t,ifr}$$

Where b^{ifr} and a^{ifr} represent the slope and intercept of a least squares linear regression of the historical worldwide international shipping freight and world GDP, as shown in Figure S8. For the default case, we include a saturating effect, where b^{ifr} reduces to half of its historical value for global economic growth above 100 T\$/y (approximately twice 2010 global GDP).

To forecast η_y^{ifr} for a given year, we use a power function that calculates the international shipping energy intensity:

$$\eta_y^{ifr} = \eta_{1990}^{ifr} \left(1 - b^{\eta,ifr}\right)^{\Delta y}$$

Where η_{1990}^{ifr} represents international energy intensity in 1990, and $b_{\eta,ifr}$ represents the average annual improvement over the years 1990-2008. This equation was fit to historical energy intensity data [40].

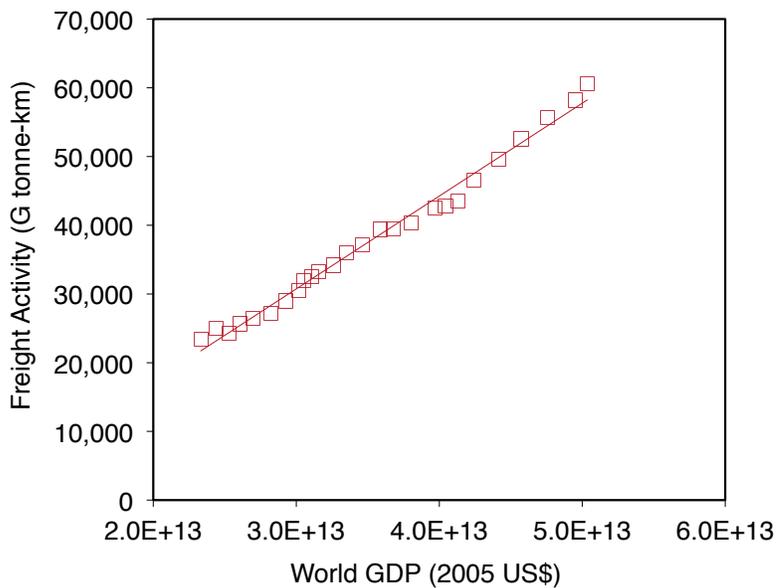


Figure S8. World international shipping freight activity versus world GDP from 1983-2008 [43].

S5. Passenger air transport

Aviation travel demand has increased in proportion with GDP, and comprised approximately 10 percent of world pkm in 2005 [44]. Some have argued that high-speed transport modes such as aviation are necessary to cover greater distances within a constrained time travel budget [45]. Such concepts may explain aviation's fast growth compared to other modes of transit. Industry forecasts expect continued passenger growth not only in established markets, but also in markets with high economic growth rates such as Asia. Boeing's 2011 Market Outlook predicts about two-thirds of large airplane deliveries scheduled for the next twenty years will be to Asia and the Middle East [46]. Since airplanes primarily burn kerosene for propulsion, rising passenger aviation may have a strong impact on oil demand over the long term.

The global fleet energy intensity of aviation has decreased rapidly compared to other modes of travel over the past forty years. The introduction of high bypass ratio engines, combined with increased combustion temperature and pressure, has led to more efficient engines and reduced energy use. Likewise, aerodynamic improvements including higher lift-to-drag ratios and better wing design have also reduced energy use. Operational changes such as reduced air and ground delays, deregulation and the use of hub-and-spoke systems, and increased seating per airplane have impacted both the energy use and load factor [47].

Commercial aviation's energy intensity now compares favorably to single passenger car use in terms of energy per passenger-km [48]. But the future rate of

improvement remains unclear. Some research notes that energy efficiency has not been the primary goal for commercial airplane design, because factors such as passenger comfort, speed, and range play into the decision [49]. Indeed, the largest contributors to improved energy efficiency have not been recent; high bypass ratio engines were introduced prior to 1970, deregulation in the US occurred in 1978, and ground and air efficiency measures have remained mostly unchanged from 1968 [47]. In fact, more than eighty percent of the reduction in average jet fleet energy use occurred prior to 1990. In the near term, shifts from aluminum to light weight composites as planned for the Boeing 787 and Airbus A350 will likely have the largest impacts [47] [50] [51]. Conversely, public policy concerns about emissions may actually hamper efforts to increase fuel efficiency from traditional engines; for example, higher temperature combustion leads to improved energy use, but higher NO_x emissions [47]. Furthermore, speculative alternatives such as hydrogen might reduce traditional pollutants but lead to more vapor contrails, an issue that has come under scrutiny due to their effects on radiative forcing. Future improvements will require balancing efficiency versus emissions.

Available evidence suggests that increased worldwide passenger aviation activity will likely outpace improvements in energy intensity, leading to higher airline fuel consumption. To combat concerns about oil supply, price uncertainty and emission concerns, industry and academia are both pursuing alternatives to oil in air transport. Biofuels, hydrogen, methanol, ethanol, and Fischer-Tropsch synthetic fuels offer the clearest alternatives to kerosene at the moment. However, any kerosene replacement needs to display similar attributes to kerosene such as specific energy, energy density, thermal stability, and cost. According to the IPCC, no such alternative will likely replace kerosene in the coming decades. [52]

S5.1. Data Sources

Historical passenger travel data from two sources are used to build relationships between GDP and travel behavior. Air travel data [pkm] are collected from 1980-2007 in OPEC-defined regional groups [53], including both domestic and international activity. Due to data quality issues, we use China data only from 1992-2007 and Russia data from 1993-2007. To assist in formulating activity projections, we used year 2000 data from the International Civil Aviation Organization [54] to provide country-level passenger travel data.

Passenger load factor data are obtained for 1950-2009 [55], and are used as a basis for projecting future load factors.

To estimate aviation energy use, we generated a historical relationship between available seat-miles and aviation fuel consumption for both domestic and international US flights from 1960-2009 [56]. Note that these data represent the US airplane fleet and not individual airplanes; this is a more appropriate measure because it incorporates the lag between the performance of new aircraft and the overall fleet average.

S5.2. Calculation

Projecting energy use for air travel requires estimating passenger activity (pkm), and energy consumption on a passenger basis (MJ/pkm). The energy necessary to transport a passenger a given distance is a product of the amount of energy required to transport an airplane seat a given distance (MJ/skm) and the airplane load factor (pkm/skm). The formula for passenger air travel energy demand e_{cy}^{air} in a given country and year is:

$$E_{cy}^{air} = T_{cy}^{air} f_y^{air} \eta_y^{air}$$

Where T_{cy}^{air} represents the passenger activity [pkm] for each country for each year, f_y^{air} represents the load factor [skm/pkm] for each year, and η_y^{air} represents the energy use [MJ/skm] for each year. As discussed, both f_y^{air} and η_y^{air} are global values and apply to each country.

To forecast T_{cy}^{air} for a given country and year, we use a linear relationship between wealth and travel:

$$T_{cy}^{air} = b_r^{air} (P_{cy} g_{cy} - P_{c,2000} g_{c,2000}) + T_{c,2000}^{air}$$

Where b_r^{air} corresponds to a regional slope [pkm/\$] for one of eleven regions r . To calculate b_r^{air} , we apply a linear regression between historical passenger activity and GDP in eleven OPEC-defined regions: Middle East and Africa, Latin America, North America, Southeast Asia, South Asia, China, Western Europe, OECD Pacific, Russia, Transition Economies, and OPEC (shown in Figure S9 for selected regions). The slope determined from this regression is applied to all of the countries within the defined region. $T_{c,2000}^{air}$ represents the year 2000 pkm value for country c .

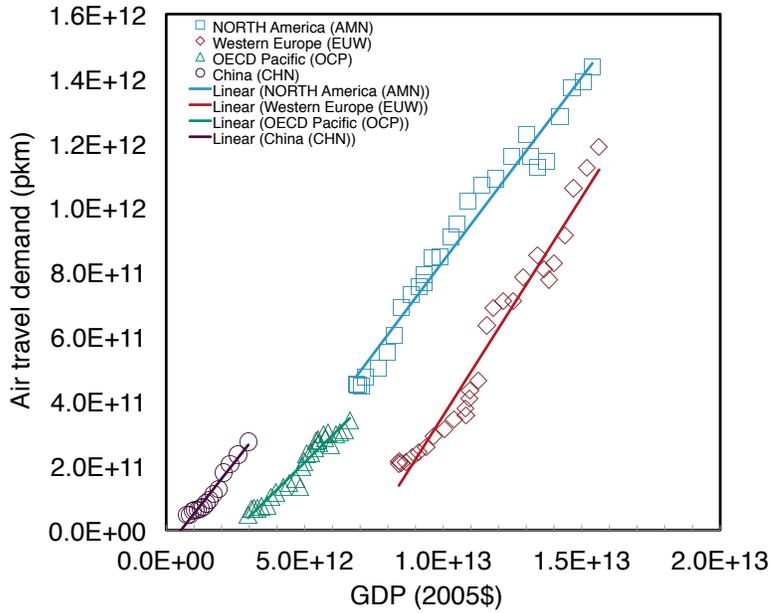


Figure S9. Historical relationship between GDP and air travel passenger activity for North America, Western Europe, OECD Pacific, and China.

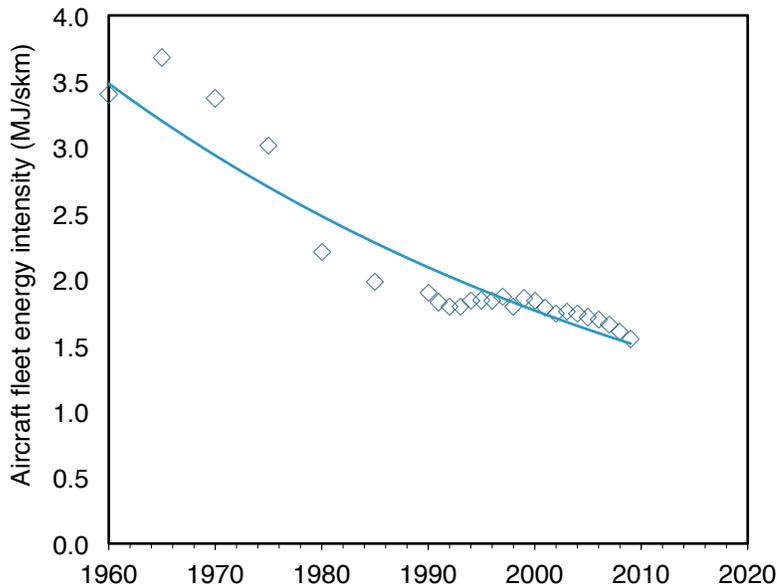


Figure S10. US fleet energy intensity [MJ/skm] as a function of time.

To forecast the worldwide fleet energy intensity η_y^{air} for a given year, we estimate a least squares exponential equation using the historical US fleet energy intensity (as shown in **Figure S10**):

$$\eta_y^{air} = a^{\eta,air} \exp(-b^{\eta,air} y)$$

where $a^{\eta,air}$ and $b^{\eta,air}$ are fitting constants.

We assume that the annual worldwide fleet energy intensity trend continues until 2100. This is a reasonable assumption given that the model forecasts values that reflect predictions from other sources [44, 57]¹. Because of a lack of international energy intensity data, we apply the US energy intensity calculation to every country. In doing so, we acknowledge that this may not represent the energy intensity of every country. However, given the range of stage lengths, fleet diversity and age, and inclusion of both domestic and international flights, we believe that US data acts as a representative proxy to other countries' flights. We did not build a module to predict energy intensity based on fleet turnover and average stage length because such a model would be difficult to parameterize.

To forecast the load factor f_y^{air} [skm/pkm] for a given year, we estimate a least squares natural log equation using historical world ICAO data (see **Figure S11**):

$$f_y^{air} = \left(a^{f,air} \ln \left(\sum_c P_{cy} g_{cy} \right) - b^{f,air} \right)^{-1}$$

Where $a_{f,air}$ and $b_{f,air}$ are constants, and $\sum_c P_{cy} g_{cy}$ represents total global GDP.

¹ We do not include energy use data prior to 1960 because piston powered airplanes and avgas were the primary engine designs and fuel; airplanes design shifted to jet engines and kerosene in the 1960s.

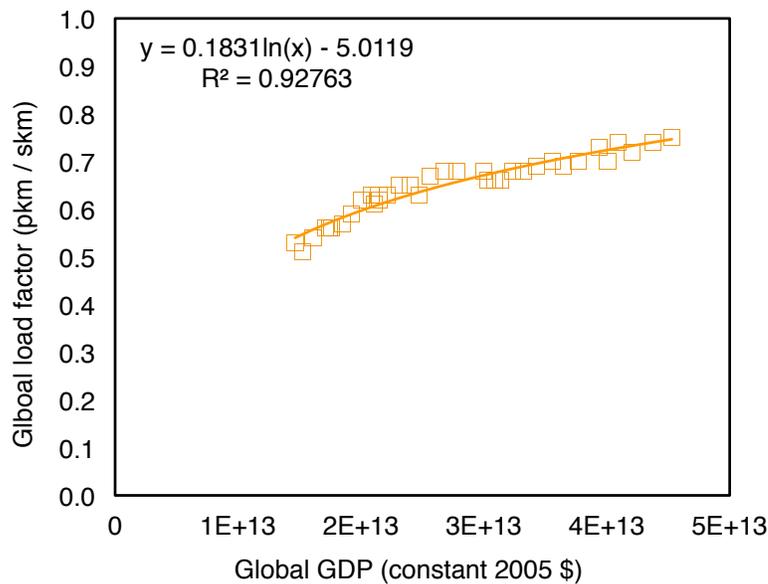


Figure S11. Annual world load factor, from 1970-2009, as a function of GDP.

S6. Military oil use

Historically, warfare utilized humans and animals to move soldiers and equipment. This trend changed in the 20th century with the expansion of oil supply and a shift towards mechanized armies.

A 2009 Deloitte study chronicled the historic use of oil per US soldier from World War II to the recent Iraq and Afghanistan wars and found a linear growth rate of approximately 1.5% per year [58]. Although efficiency improvements and alternative energy strategies are being investigated, the expeditionary nature of US warfare and the high reliance on vehicles continues to drive consumption. Today, the US military is the single largest consumer of oil in the United States.

We model worldwide military demand for oil by using the historic relationship between military oil consumption and military spending. The US military is used as a benchmark (supplemented with limited years of UK military data). While the US military may not reflect the behavior of other militaries, a lack of data from other countries necessitates using US trends.

S6.1. Data Sources

For military spending, historic military spending data were collected for 170 countries from 1988 to 2010 [59].

US military oil consumption is derived from the US Defense Energy Support Center annual yearbooks from 1997-2009 [60] [61]. Some years of military oil

consumption behavior for the United Kingdom were collected as well from the UK Ministry of Defense by converting 2007-2009 emissions data into fuel estimates using a constant emissions factor [62].

S6.2. Calculation

The calculation for world military energy demand for a given year is:

$$E_{wy}^{mil} = fr_w^{mil} \eta_w^{mil}$$

where fr_w^{mil} represents the fraction of GDP dedicated to military spending [\$ military spending/\$ GDP]. From 1988 to 2009, the weighted average of GDP spent on the military of the top 15 countries ranged from 2.3 to 4.2 percent, with an average of 2.9%. We assume a baseline value of 2.9% across all model years.

The cut-off of the top 15 countries was chosen because it represents the bulk of military spending (~ 80-92 percent) of the worldwide spending between 1988 and 2009. The top 15 countries are mostly of the same economic status and technological standing, implying their militaries may have the same proportional energy needs.

η_w^{mil} represents military energy demand per unit of military spending [M] energy / \$ military spending]. We use the historical US military average from 1997 to 2009 (0.0003 bbl / \$ military spending). The limited years of data overlap between the US and UK show a similar correlation between military oil consumption and spending.

S7. Other petroleum uses

Petroleum demand for non-transport (*nt*) sectors is modeled simply because these uses are not major drivers of oil demand. The use of petroleum products in non-transport sectors as a function of economic output has declined over all historical data. This is because of the high value of liquid fuel products in the transport market, which has supplanted non-transport demand. This trend will likely continue due to increasing demand for transportation fuels and ready availability of substitutes (e.g., natural gas) in home heating, power generation, and industrial uses [63].

S7.1. Data sources

Non-transport use of petroleum products is modeled using IEA data for petroleum product consumption from 1971-2008 [64]. Non-transport oil use is computed by subtracting the world consumption of oil in transport from the world production of petroleum products. Transport fuels include all fuels used for transport, including marine bunkers and international aviation. Although the total consumption of petroleum products in non-transport applications has increased moderately during

the past few decades, total refinery outputs have grown more quickly and the fraction of refinery products destined for non-transport consumption has decreased significantly. Likewise, this has resulted in significant reductions in non-transport products use per unit of GDP.

S7.2. Calculation

Overall use of oil for non-transport sectors is given by:

$$E_y^{nt} = \left[\sum_c P_{cy} g_{cy} \right] e_y^{nt}$$

Where e_y^{nt} represents the non-transport energy demand per unit GDP in a given year. This is related to economic output using an exponential function:

$$e^{nt} = a^{nt} e^{(r^{nt}y)}$$

Where a and r are fitting constants. These constants are fit by least-squares fitting at $a = 4.0658$ and $r = -0.027$. Thus, non-transport use of oil per unit of GDP has declined by 2.7% per year.

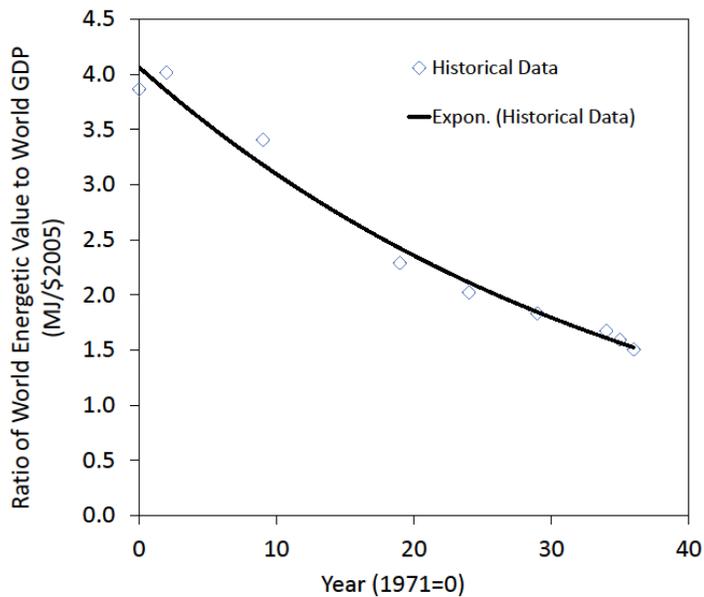


Figure S12. Demand for non-transport refinery products [64].

S8. Projecting alternative fuel supply

In addition to demand for energy, supply of oil alternatives is modeled.

S8.1. Supply of non-liquid energy carriers

Conventional oil demand can decrease as the fraction of energy supplied by liquid energy carriers declines due to introduction of non-liquid oil alternatives. We model this factor with the term l_{ly}^s [M] liquid fuels/M] total energy demand]. This term is applied in multiple sectors, and the rate of substitution can vary across sectors. We consider the introduction of numerous non-liquid energy carriers, including natural gas (CNG+LNG), electricity, and hydrogen.

Non-liquid energy carriers face barriers to entry in the transport market due to the generally superior volumetric and gravimetric energy densities of liquid hydrocarbons (see especially the air travel sector). Given these difficulties, previous efforts to introduce these non-liquid carriers have repeatedly failed [65].

Because non-liquid energy carriers rely on alternative vehicle and infrastructure technologies, the rate of change of the vehicle fleet is the key driver of adoption. Both the speed of fleet turnover and the willingness of investors to adopt new technologies are slowed by increased capital intensity (e.g. power plants both turnover more slowly and are more conservative in their technological evolution than energy-consuming home appliances).

A variety of technology penetration rates have been calculated for the transportation sector. For example, the transition from early transport modes (horses and sailing ships) to modern transport types (automobiles and fossil-fueled steam ships) [66] was illustrated by Grubler, (see Figure S13) as was the diffusion of automobile technologies [66] (as shown in Figure S14).

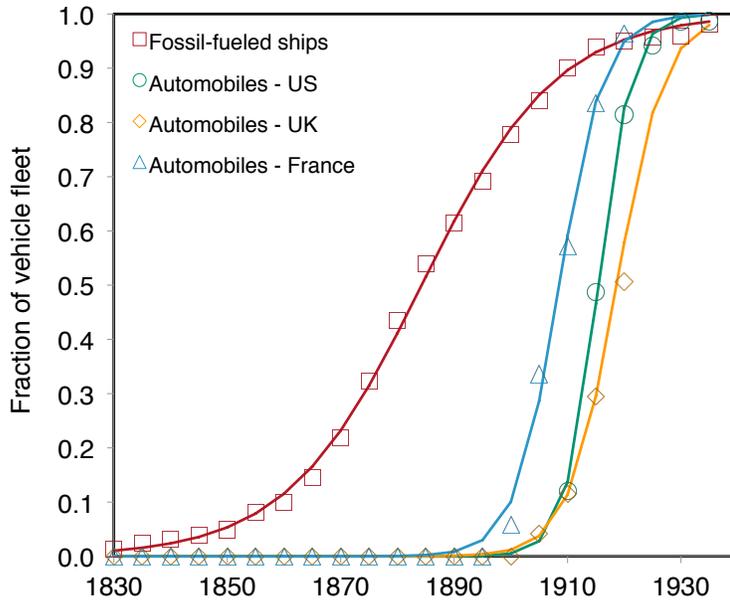


Figure S13. Introduction of fossil fueled ships and automobiles in preference to sailboats and horses in the 19th century. Data replotted from Grubler [66].

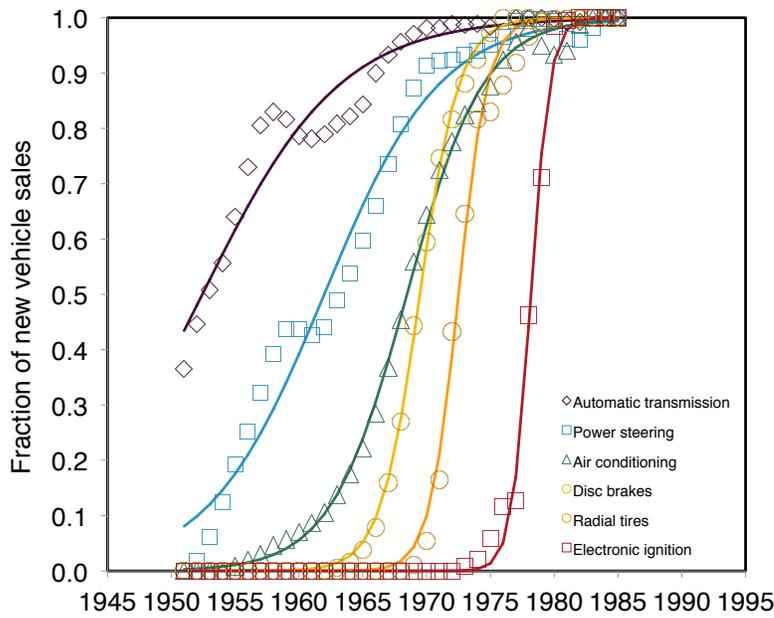


Figure S14. Introduction of new vehicle technologies. Data replotted from Grubler [66].

In these figures (and the model below) we model these transitions with logistic market penetration functions (sometimes called the Fisher-Pry model). A difficulty of these logistic market penetration models is that they are most usefully used in a post-hoc fashion: they cannot be used to predict whether a technology will succeed or fail until the diffusion process is well underway. Also, fitting of these curves is unstable in early years of a technology so we adopt wide uncertainty ranges for these curves.

S8.2. Data sources

Vehicle penetration data are collected from a variety of sources. Comprehensive fleet makeup data were collected for the UK, US, and Japan [67-70]. R.L. Polk vehicle registrations by vehicle fuel type were collected for Argentina, France and South Korea for the years 1999-2000 [71]. These fleet data have significant numbers of vehicles listed as “unspecified” fuel type (2-15%), resulting in some fuel mix uncertainty. Non-liquid fueled vehicles are assumed to include CNG, gas/LPG vehicles, hydrogen vehicles, and electric vehicles.

Additional data were collected on natural gas and electric vehicle penetration. Natural gas vehicle penetration data from the International Association of Natural Gas Vehicles (IANGV) [72]. IANGV data are sometimes in misalignment with Polk data, with Polk data typically showing lower rates of NGV penetration. We assume that some NGVs are included in the significant “unspecified” category of Polk vehicle data. These data show that CNG vehicle penetration has reached above 10% in Bolivia and Columbia, and above 20% in Argentina, Armenia, Bangladesh, Iran, and Pakistan [72].

Electric two-wheeled vehicle data from China are also collected from a variety of sources [73-75]. Electric two-wheeled vehicles represent some 50% of sales in 2010 (~20 M vehicles), a rapid increase from very small numbers in the late 1990s. Sales data are converted to fleet data assuming a uniform fleet lifetime of 5 years [75]. These data are likely quite uncertain (at least +/- 10%).

Figure S15 plots these data as the sum of electric, hydrogen, and CNG vehicles as a fraction of the reference light-duty vehicle fleet. Note that the diffusion rate of non-liquid fueled vehicles into the light-duty transportation sector varies significantly across countries. In most regions, the rate of penetration of non-liquid fueled vehicles is very slow (particularly in developed nations). Fitted logistic penetration function values are presented in Table S4 for these data and also other historical data.

Table S4. Best fitting market penetration functions to historical data and recent non-liquid fuel vehicle data.

	<i>a</i>	<i>b</i>	Market penetration time (10% to 90%) [yrs]
<i>Historical vehicle shifts</i>			
US Autos	0.34	-5.3	12.9
UK Autos	0.24	-3.2	18.5
France Autos	0.26	-4.8	17.1
Steam + motor ships	0.08	-4.6	52.4
<i>Automobile technologies</i>			
Automatic transmission	0.18	-0.4	23.8
Power steering	0.22	-2.4	19.8
Air conditioning	0.33	-4.8	13.1
Disc brakes	0.65	-4.9	6.8
Radial tires	0.88	-4.0	5.0
Electronic ignition	1.35	-8.3	3.3
<i>Non-liquid fueled vehicles</i>			
Argentina - LDVs	0.14	-2.4	31.0
Brazil - LDVs	0.18	-4.3	24.5
France - LDVs	0.17	-8.8	25.5
South Korea - LDVs	0.21	-4.9	20.5
UK - LDVs	0.18	-8.1	24.0
Japan - LDVs	0.17	-8.6	25.0
China - Two-wheeled EVs	0.30	-5.2	14.8
USA - LDVs	0.15	-7.6	29.0

S8.3. Calculations

We represent the fraction of fuels consumed as liquid fuels using the logistic market penetration function [66]:

$$l_y^s = 1 - f_{max}^{l,s} \frac{\exp(a^{l,s}y + b^{l,s})}{1 + \exp(a^{l,s}y + b^{l,s})},$$

where *a* and *b* represent fitting terms for the relative rate of increase and delay in market penetration, respectively. Note that the fitting terms *a* and *b* can vary by sector (e.g., longer delay and slower transition for the air sector than the land travel sector). Because not all transport needs are likely to be met by non-liquid fuels in the timeframe of the study, the parameter f_{max} represents the maximum fraction that can be met with non-liquid fuels for a given sector *s*. Fitting our data described above, we find parameters outlined in Table S4. From these parameters, we set default values as in Table S5, illustrated in Figure S16. The gray range in Figure S16 is given by two extreme cases: high rate is the rate of adoption of ethanol in Brazil

from 1975-1985, while the low rate is the shift from coal and oil to natural gas from 1850-1950 (USA).

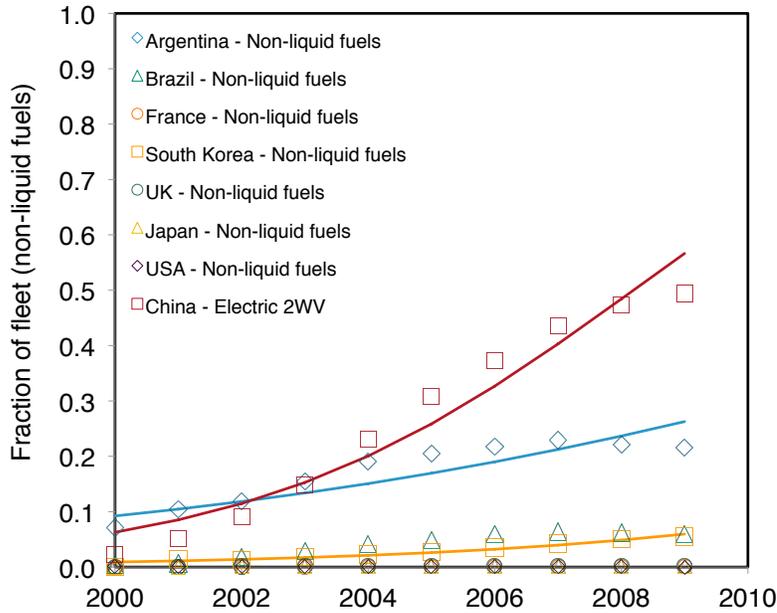


Figure S15. Fractional share of vehicle fleet powered by non-liquid fuels in a variety of countries. See text for data sources.

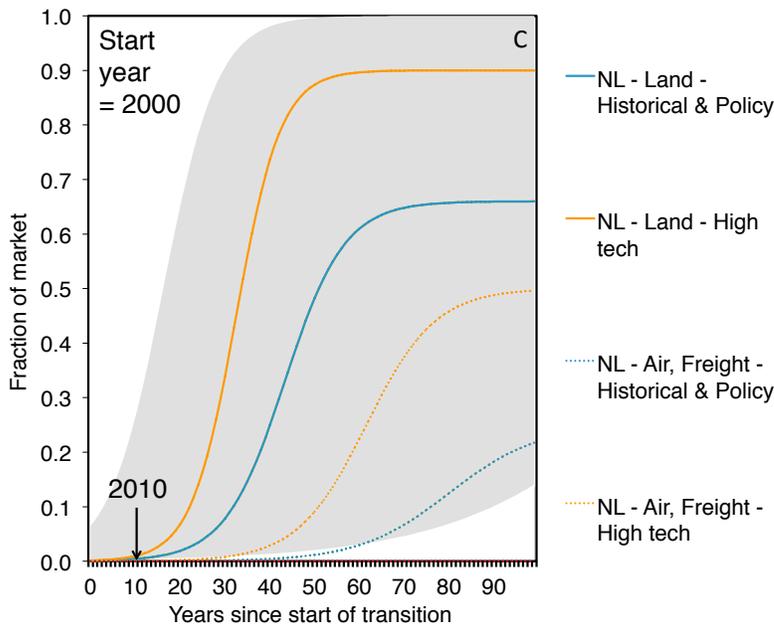


Figure S16. Model assumptions for non-liquid fuels module. Numerical inputs shown in Table S5.

Due to lack of any historical data, conservative values for air, freight, and international shipping are chosen. Possible fleet substitution with natural gas (in the case of LNG-powered trucking) represents one possible counter example to this assumption.

Table S5. Default values for non-liquid fuel vehicle diffusion for model sectors

	Historical scenario			Low sensitivity			High sensitivity		
	<i>a</i>	<i>b</i>	<i>f_{max}</i>	<i>a</i>	<i>b</i>	<i>f_{max}</i>	<i>a</i>	<i>b</i>	<i>f_{max}</i>
<i>lnd</i>	0.15	-6.5	0.66	0.1	-6.5	0.25	0.33	-6.5	0.9
<i>air, fr int</i>	0.1	-8	0.25	0.08	-8	0.15	0.2	-8	0.66
<i>mil, nt</i>	-	-	-	-	-	-	-	-	-

S9. Supply of alternative liquid fuels

In contrast to non-liquid energy carriers for transport, alternative liquid fuels are readily usable substitutes for conventional oil. Alternative liquid fuels can often be utilized in the existing capital stock with no or little modification (e.g., blend-in fuels such as oil sands derived gasoline and ethanol are already consumed in significant quantities). Adoption of alternative liquid fuels is not currently limited by vehicle penetration rates, but by the rate of expansion of supply.

Supply of alternative liquid fuels has increased significantly since the 1960s, and now amounts to over 5% of total liquid fuel supply on an energy-equivalent basis (see Figure S17). Significant capacity expansions are planned for these alternative liquid fuels. For example, oil sands production capacity that is announced, planned, in the permitting process, or under construction is ~ 7 Mbbbl/d, compared to current capacity of 1.5 Mbbbl/d [76].

In our model, alternative liquid fuels include: natural gas liquids, enhanced oil recovery, oil shale, oil sands, coal-to-liquid synthetic fuels, gas-to-liquid synthetic fuels, biodiesel, and all forms of bio-ethanol. We assume that the supply of alternative liquid fuels will not be limited by underlying resource constraints during the time frame of this modeling effort. This assumption is supported by widespread deposits of low quality hydrocarbons, coal, and natural gas for producing alternative liquid fuels at prices in line with recent oil prices.

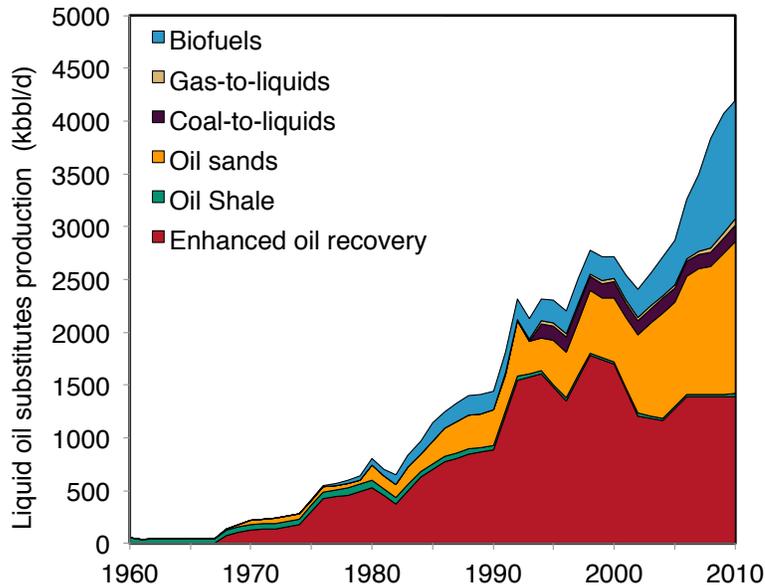


Figure S17. Production of substitutes for conventional petroleum from 1960 to 2010. See text for data sources. All data converted to kbbl of oil equivalent using energy densities of biofuels and conventional crude oil (assumed nominal 6.1 GJ/bbl oil equivalence).

S9.1. Data

Production data for the liquid substitutes for conventional oil are collected from historical studies as follows:

Enhanced oil recovery: Data from Oil & Gas Journal Biennial EOR survey, from even years 1974 forward [77]. Data interpolated for odd years. Data from before first OGJ EOR survey from California Department of Oil, Gas and Geothermal Resources, for Wilmington field and all other EOR by district, from Summary of Operations years 1966-1974 (even years) [78]. Data are interpolated between sampled years.

Oil shale: Historical data from 1880-2000 taken from Dyni [79]. More recent data from China are available from Li [80], and are added to assumed constant output from other world oil shale projects.

Oil sands: Data for 1968-1979 from Chastko [81], from 1980-2004 from Stringham [82], and from 2005 to the present from Energy Resources Conservation Board [83, 84]. Data collected for crude bitumen production (m^3) and synthetic crude oil production (m^3) and converted to kbbl/d of total output. Initial bitumen volumes that are later converted to SCO are not double counted.

Coal-to-liquids and gas-to-liquids: Data for South Africa CTL and GTL production

from South Africa Department of Minerals and Energy [85, 86] and Sasol annual reports [87]. GTL in Malaysia and Qatar is less well reported, but approximate estimates are made given existing capacity (Bintulu Malaysia assumed operating at 80% of capacity, Oryx Qatar assumed operating 50% of capacity in first year, 75% in next year).

Ethanol and other biofuels: Historical US fuel ethanol production from Renewable Fuels Association [88] and EIA [89]. Historical Brazilian ethanol production from Martines-Filho [90]. Other global biofuel production from 2000 to present from EIA [89].

The total production volume to which the fraction of unconventional fuels is compared is given by EIA.

S9.2. Calculations

To model the substitution of alternative liquid fuels for conventional fuels, the logistic market penetration function is used:

$$o_y = 1 - f_{max}^{o,s} \frac{\exp(a^{o,s}y + b^{o,s})}{1 + \exp(a^{o,s}y + b^{o,s})},$$

where o is the fraction of liquid fuels supplied by conventional oil, a and b are fitting constants that can vary by sector (that is, $a = a(s)$) and y is the elapsed time since the outset year.

Fractional substitution values as a function of time are plotted in Figure S18 for the historical data, the best fitting case and the user bounds in IDES. These bounds are shown in the context of the range of historical emissions in Figure S19. The fitting parameters for the best-fitting, low, and high cases are included in Table S6. The gray range in Figure S19 is given by two extreme cases: high rate is the rate of adoption of ethanol in Brazil from 1975-1985, while the low rate is the shift from coal and oil to natural gas from 1850-1950 (USA).

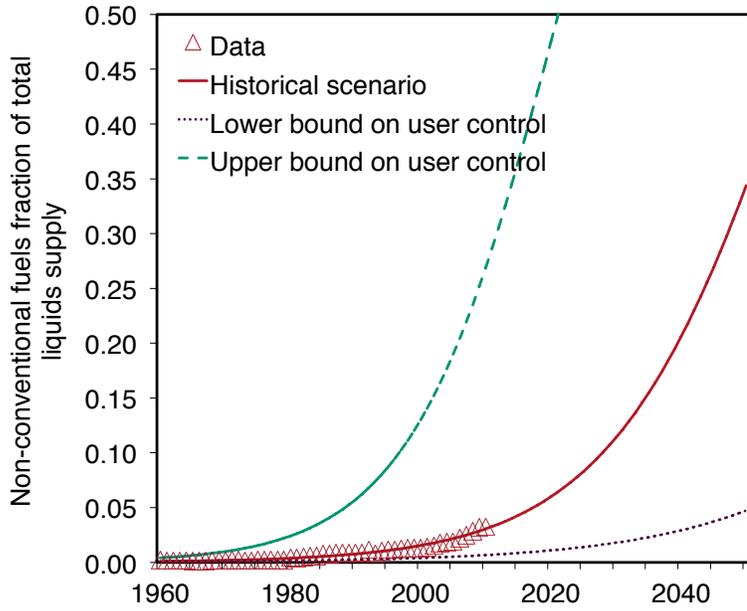


Figure S18. Fraction of liquid fuels supplied by resources other than conventional oil. Best fitting logistic model is least-squares fit to fractional supply of unconventional fuels.

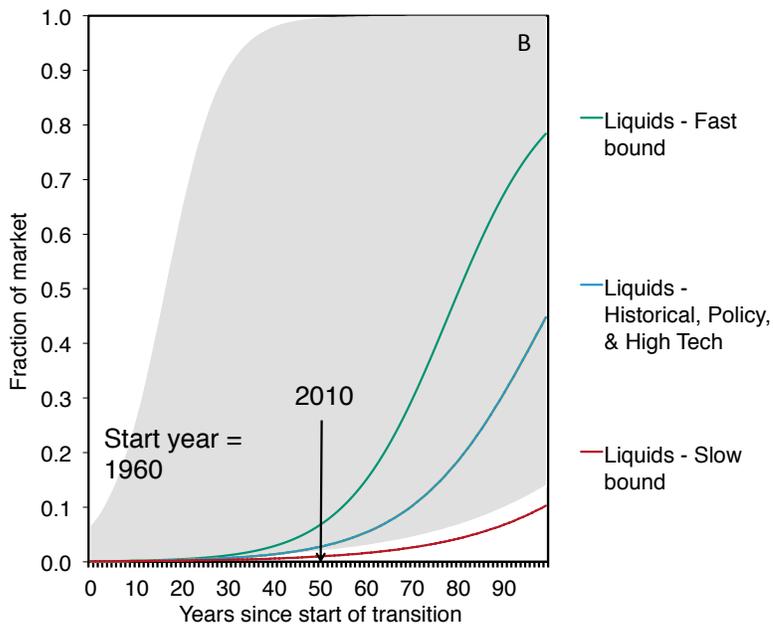


Figure S19. Model bounds and indicative scenario settings for liquids transitions.

Table S6. Fitting parameters for logistic market penetration model for alternatives to conventional crude oil.

	Historical scenario	Low user bound	High user bound
<i>a</i>	0.07	0.05	0.09
<i>b</i>	-7	-7	-7

S10. Energy input to refining

Refineries satisfy liquid fuel demand using a combination of crude oil, unconventional liquids, and natural gas liquid (NGL) inputs. The inputs are then transformed into a variety of products depending on economic demand.

The refinery module integrates demand from transport and non-transport output sectors into a total refinery energy demand. It accounts for the mitigated need for refinery liquid fuel outputs due to non-liquid oil substitutes (see section S8.1), as well as the substitution of unconventional liquid supplies for conventional crude (see section S9). We assume no limitations on refining capacity, and assume that future refineries are capable of handling conventional fuels, unconventional fuels, and NGLs in any quantity or combination.

S10.1. Data

EIA datasets provide historical global refinery inputs [91]. Mass of refinery inputs and all refinery outputs are converted to higher heating values [92-94]. Energetic yield of refinery output products as a fraction of refinery inputs² is approximately equal to 0.945 from 1990-2008, and is assumed to remain unchanged in future projections.

S10.2. Calculations

Total demand for refinery products, e_y^{ref} [MJ] is a summation of the transport and non-transport sectors for a given year:

$$e_y^{ref} = \sum_s E_y^s J_y^s + E_y^{nt}$$

² Crude refinery inputs are assumed to come from EIA categories crude petroleum, “feedstocks”, natural gas liquids, plant condensate, and other liquids. These inputs do not include natural gas and other forms of supplemental energy consumed by refineries, so this throughput ratio is higher than an overall refinery efficiency (e.g., 95% compared to 88-90%).

Total refinery input energy supply e_y^{sup} [MJ] in a given year, and its constituents, is a function of refinery energy demand and refinery losses:

$$e_y^{sup} = e_y^{ref} \left[\frac{1}{\eta_{ref}} \right]$$

where η_{ref} is the effective throughput efficiency of the refinery. Refinery energy supply can be broken down into two constituents: liquids input (l) and natural gas liquids input (ngl). Furthermore, refinery liquids inputs are made up of conventional (c) and nonconventional liquids (uc), where conventional refers to conventional crude oil. Fractional input ratios f can be defined for each constituent:

$$f_y^{ngl} = 1 - f_y^l,$$

$$f_y^c = f_y^l o_y,$$

$$f_y^{uc} = f_y^l (1 - o_y)$$

Finally, to calculate crude oil demand C , we apply the fraction of conventional crude oil inputs to refineries to the total demand for refinery supply:

$$C = f_y^c e_y^{sup}$$

We use a linear relationship to forecast the fraction of refinery inputs from liquid fuel sources (namely crude production and unconventional feedstocks) f_y^l for a given year:

$$f_y^l = a^l y + b^l$$

Where a_l and b_l are fitting constants found by performing a least squares linear regression of the historical fraction of refinery inputs from liquid fuel. The fraction of liquid has declined slightly over the dataset, reflecting the increasing importance of NGLs in the refinery input mix.

S11. Greenhouse gas emissions

Greenhouse gas (GHG) emissions impacts from oil substitution are computed simply due to two key reasons:

1. GHG emissions are not the primary focus of this study;
2. GHG emissions are highly uncertain and depend on which substitutes for conventional oil are deployed, which we do not attempt to model.

The central estimate for GHG impacts from oil substitution assumes 50% high carbon liquids (oil shale) and 50% low-carbon liquids (cellulosic ethanol). [95, 96] Similarly, the non-liquid fuels are represented by equal shares of low-carbon (offshore wind used in EVs) [97] and high-carbon (CNG) energy sources[98]. Bounding cases are 75%/25% splits between low- and high-carbon substitutes. Emissions are given as life cycle emissions, not direct combustion emissions. See Table S7.

Table S7. GHG intensity of selected oil substitutes

Substitute	Type	Emissions (gCO ₂ /MJ)	Source
Offshore wind	Non-liquid, low carbon intensity	16.5	Schleiser (2000)
Compressed natural gas	Non-liquid, high carbon intensity	68	CARB (2012)
Cellulosic ethanol	Liquid, low carbon intensity	11	Farrell (2006)
Oil shale	Liquid, high carbon intensity	140	Brandt (2009)

S12. Case definitions

In IDES, three cases are defined as pre-set scenarios. These scenarios are called “Historical”, “Efficiency Policy” and “High technology”

S12.1. Historical scenario

The *Historical* scenario attempts to model (as much as is possible) the continuation of historical trends, with no allowance made for policy changes or technology developments that are more rapid than those seen in previous decades. Therefore, in the *Historical* scenario, model assumptions are derived exclusively from above figures and tables. Where various data sources are cited above in text, [var.] is listed as source.

The settings for important model parameters in the *Historical* scenario are shown in Table S8

Table S8. Parameter settings for *Historical* scenario

Sector	Parameter	Value	Unit	Source
<i>all</i>	IPCC population & GDP scenario	A1	Pop	[5]
	Increase/Decrease from historical		\$/pop	
<i>air</i>	passenger travel	100	pkm/\$	[53]
<i>air</i>	Max load factor (% of seats filled)	80	pkm/skm	[55]
<i>air</i>	Annual energy intensity improvement	170	%/y	[56]
	Land travel saturation (% of estimated ceiling)	100	%	var.
<i>lnd</i>	Annual efficiency improvement - private vehicles	0.6	%/y	[8]
<i>lnd</i>	Annual efficiency improvement - public transport	0.35	%/y	[8]
<i>fr</i>	Max fraction of trucking	85	%	-
<i>fr</i>	Annual efficiency improvement - trucking	1.01	%/y	[36]
<i>ifr</i>	Annual efficiency improvement - int. freight	0.16	%/y	[42]
<i>mil</i>	Military spending (% of GDP)	2.9	%	[59]
<i>all</i>	Refinery loss rate	5.5	%	[91]
<i>all</i>	Liquid substitution slope (<i>a</i> param)	0.0702	1/y	var.
<i>all</i>	Liquid substitution delay (<i>b</i> param)	-6.97	-	var.
<i>lnd</i>	Land Passenger non-liquid substitution (<i>a, b, max penetration</i>)	0.15, -6.5, 66%	-	var.
<i>air, fr, ifr</i>	Other sector non-liquid substitution (<i>a, b, max penetration</i>)	0.1, -8, 25%	-	var.
<i>all</i>	Fraction clean liquid fuel alternatives	50%	-	Assum.
<i>all</i>	Fraction clean non-liquid fuel alt.	50%	-	Assum.

S12.2. Efficiency Policy scenario

The *Efficiency Policy* scenario is similar to the *Historical* scenario, except it assumes that recent policies that have been proposed or passed are successfully implemented and that these policies continue indefinitely into the future. These regulations include: fuel economy regulations for passenger vehicles [31], fuel economy regulations for heavy vehicles such as freight trucks [99], and for international shipping [42].

The settings for important model parameters in the *Efficiency Policy* scenario, if they differ from the *Historical* scenario, are shown in Table S9 below.

Table S9. Parameter values for *Efficiency Policy* scenario

Sector	Parameter	Value	Unit	Source
<i>lnd</i>	Annual efficiency improvement - private vehicles	1.5	%/y	[31]
<i>fr</i>	Annual efficiency improvement - trucking	1.10	%/y	[99]
<i>ifr</i>	Annual efficiency improvement – int. freight	0.81	%/y	[42]

S12.3. High Technology scenario

The *High Technology* scenario, in contrast, adds more rapid technology development to the policy case. In this scenario, technology penetration rates for alternative liquid fuels and non-liquid fuels are set to more rapid values than their Historical and Efficiency Policy scenario settings (see Table S5 and Table S6). Also, fuel efficiency improvements are increased above those in the policy case.

The settings for important model parameters in the *High Technology* scenario, if they differ from the *Historical* scenario, are shown in Table S9 below.

Table S10. Parameter values for *High Technology* scenario

Sector	Parameter	Value	Unit	Source
<i>lnd</i>	Annual efficiency improvement - private vehicles	2.4	%/y	[31]
<i>fr</i>	Annual efficiency improvement - trucking	3.45	%/y	[99]
<i>ifr</i>	Annual efficiency improvement – int. freight	2	%/y	[42]
<i>all</i>	Refinery loss rate	3.2	%	[91]
<i>lnd</i>	Land Passenger non-liquid substitution (<i>a, b, max penetration</i>)	0.2, -6.5, 90%	-	var.
<i>air, fr, ifr</i>	Other sector non-liquid substitution (<i>a, b, max penetration</i>)	0.13, -8, 50%	-	var.

Works Cited

1. IPCC, *IPCC Special Report on Emissions Scenarios - Summary for Policymakers*. 2000, Cambridge, UK: Cambridge University Press.
2. UN, *GDP and its breakdown at constant 2005 prices in US Dollars*, in *National Accounts Main Aggregates Database* 2010, United Nations.

3. Shane, M., *Historical population and growth rates in population for baseline countries/regions 1969-2010*, 2011, United States Department of Agriculture Economic Research Service.
4. Shane, M., *Real historical GDP and growth rates of GDP for baseline countries/regions 1969-2010*, United States Department of Agriculture Economic Research Service.
5. CIESIN, *Country-level Population and Downscaled Projections based on the B2 Scenario, 1990-2100*, 2002, Center for International Earth Science Information Network, Columbia University: Palisades, NY.
6. CIESIN, *Country-level GDP and Downscaled Projections based on the A1, A2, B1, and B2 Marker Scenarios, 1990-2100*, 2002, Center for International Earth Science Information Network, Columbia University: New York.
7. Ingram, G. and Z. Liu, *Motorization and the Provision of Roads in Countries and Cities*, in *World Bank Policy Research Working Paper No. 1842* 1997, World Bank: Washington, DC.
8. Millard-Ball, A. and L. Schipper, *Are We Reaching Peak Travel? Trends in Passenger Transport in Eight Industrialized Countries*. *Transport Reviews*, 2011. **31**(3): p. 357-378.
9. Puentes, R. and A. Tomer, *The Road...Less Traveled: An Analysis of Vehicle Miles Traveled Trends in the U.S.* , 2008, Brookings Institution: Washington, DC.
10. Metz, D., *Saturation of Demand for Daily Travel*. *Transport Reviews*, 2010. **30**(5): p. 659-674.
11. Schäfer, A., et al., *Transportation in a Climate-Constrained World*. 2009, Cambridge: MIT Press.
12. Schafer, A. and D.G. Victor, *The future mobility of the world population*. *Transportation Research Part a-Policy and Practice*, 2000. **34**(3): p. 171-205.
13. Mokhtarian, P.L. and C. Chen, *TTB or not TTB, that is the question: a review and analysis of the empirical literature on travel time (and money) budgets*. *Transportation Research Part A: Policy and Practice*. **38**(9-10): p. 643-675.
14. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, *International Fuel Prices 2007. 5th Edition*, 2007, GTZ: Eschborn.
15. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, *International Fuel Prices 2010 / 2011. Data Preview*, 2011, GTZ: Eschborn.
16. CIESIN, IPFRI, and CIAT, *Global Rural-Urban Mapping Project (GRUMP) alpha and Gridded Population of the World (GPW) Version 3*, 2004, CIESIN, Columbia University: Palisades, NY.
17. Energy Information Administration, *Gasoline and Diesel Fuel Update*, 2011.
18. Davis, S.C., S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 30* 2011, Oak Ridge National Laboratory: Oak Ridge, TN.
19. NRC, *Comprehensive Energy Use Database*, 2011, Natural Resources Canada, Office of Energy Efficiency: Ottawa.
20. Apelbaum Consulting Group, *Australian Transport Facts 2009*, 2009, Apelbaum Consulting Group: Clayton, Victoria.
21. Department of Energy and Climate Change, *Energy Consumption in the UK: Transport Data Tables*, 2011, DECC: London.

22. DFT, *Transport Statistics Great Britain*, 2010, Department for Transport: London.
23. Pucher, J., *Urban Travel Behavior as the Outcome of Public Policy: The Example of Modal-Split in Western Europe and North America*. Journal of the American Planning Association, 1988. **54**(4): p. 509-509.
24. van de Coevering, P. and T. Schwanen, *Re-evaluating the impact of urban form on travel patterns in Europe and North America*. Transport Policy, 2006. **13**(3): p. 229-239.
25. Cameron, I., T.J. Lyons, and J.R. Kenworthy, *Trends in vehicle kilometres of travel in world cities, 1960-1990: underlying drivers and policy responses*. Transport Policy, 2004. **11**(3): p. 287-298.
26. Dargay, J., D. Gately, and M. Sommer, *Vehicle Ownership and Income Growth, Worldwide: 1960-2030*. Energy Journal, 2007. **28**(4): p. 163-190.
27. De Jong, G., et al., *Comparison of Car Ownership Models*. Transport Reviews, 2004. **24**(4): p. 375-408.
28. Long, J.S., *Regression Models for Categorical and Limited Dependent Variables*. 1997, Thousand Oaks: Sage.
29. Stead, D. and S. Marshall, *The Relationships between Urban Form and Travel Patterns. An International Review and Evaluation*. European Journal of Transportation and Infrastructure Research, 2001. **1**(2): p. 113-141.
30. Schafer, A., *The global demand for motorized mobility*. Transportation Research Part A: Policy and Practice, 1998. **32**(6): p. 455-477.
31. International Council for Clean Transportation, *Global Comparison of Light-Duty Vehicle Fuel Economy/GHG Emissions Standards. Update June 2011*, 2011.
32. Schipper, L. and W. Tax, *New car test and actual fuel economy: yet another gap?* Transport Policy, 1994. **1**(4): p. 257-265.
33. Knittel, C.R., *Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector*. American Economic Review, 2011. **101**(7): p. 3368-3399.
34. Schafer, A. and D.G. Victor, *Global passenger travel: implications for carbon dioxide emissions*. Energy, 1999. **24**(8): p. 657-679.
35. Kamakate, F. and L. Schipper, *Trends in truck freight energy use and carbon emissions in selected OECD countries from 1973 to 2005*. Energy Policy, 2009. **37**(10): p. 3743-3751.
36. Eom, J., L. Schipper, and L. Thompson, *We keep on truckin': Trends in freight energy use and carbon emissions in 11 IEA countries*. Energy Policy, 2012. **45**(0): p. 327-341.
37. IEA, *Transport, Energy, and CO₂*, 2009, International Energy Agency: Paris, France.
38. Schipper, L., L. Scholl, and L. Price, *Energy use and carbon emissions from freight in 10 industrialized countries: An analysis of trends from 1973 to 1992* Transportation Research, 1997. **2**(1): p. 57-76.
39. ITF, *Trends in the transport sector*, 2009, International Transport Forum.
40. United Nations Conference on Trade and Development (UNCTAD), *Review of Maritime Transport 2009*. 2009, New York: UN Publications.
41. Shipbuilders' Association of Japan, *Shipbuilding Statistics*, 2010.

42. UNIMO, *Prevention of air pollution from ships; Second IMO GHG study*, 2009, United Nations International Maritime Organization: London.
43. UNCTAD, *Review of Maritime Transport*, 2009, United Nations Conference on Trade and Development: New York and Geneva.
44. Lee, J.J., *Can we accelerate the improvement of energy efficiency in aircraft systems?* *Energy Conversion and Management*, 2010. **51**: p. 189-196.
45. Schafer, A. and D.G. Victor, *The future mobility of the world population*. *Transportation Research*, 2000. **34**: p. 171-205.
46. Boeing, *Current market outlook 2011-2030*, 2011, The Boeing Company: Seattle.
47. Joosung J. Lee, S.P.L., and Ian A. Waitz, *Aircraft and energy use*, in *Encyclopedia of energy* 2004. p. 29-38.
48. Small, K.A. and K. van Dender, *Long run trends in transport demand, fuel price elasticities and implications of the oil outlook for transport policy*, 2007, Joint Transport Research Centre.
49. Peeters, P.M., Middel J., and H. A., *Fuel efficiency of commercial aircraft: An overview of historical and future trends*, 2005, National Aerospace Laboratory NLR: Germany. p. 37.
50. Boeing, *787 Dreamliner*, 2011, Boeing.
51. Airbus, *A350 XWB*, 2011, Airbus.
52. Chevron, *Alternative jet fuels*, 2006, Chevron Corporation.
53. Mazraati, M., *World aviation fuel demand outlook*. *OPEC Energy Review*, 2010. **34**(1): p. 42-72.
54. ICAO, *Traffic by State of Air Carrier Registration*, 2006, International Civilian Aviation Organization.
55. ICAO, *International Traffic Services 1970-2005*, 2006, International Civil Aviation Organization.
56. NTS, *Energy Intensity of Certified Air Carriers, All Services*, 2010, National Transportation Statistics.
57. NASA, *Beauty of Future Airplanes is More than Skin Deep*, 2009.
58. Deloitte LLP, *Energy security: America's best defense*, 2009. p. 34.
59. SIPRI, *SIPRI Military expenditure database*, 2011, Stockholm International Peace Research Institute: Solna, Sweden.
60. DESC, *Fact Book FY 2002*, 2002, Department of Defense, Defense Energy Support Center.
61. DESC, *Fact Book FY 2009*, 2009, Department of Defense, Defense Energy Support Center.
62. UK Defence Statistics, *Ministry of Defence Carbon Dioxide Emissions*, 2010.
63. Dargay, J.M. and D. Gatley, *World Oil Demand's Shift toward Faster Growing and Less Price-Responsive Products and Regions*. *Energy Policy*, 2010. **38**(10): p. 6261-6277.
64. IEA, *Energy balances of non-OECD countries*, 2009, International Energy Agency: Paris.
65. Smil, V., *Energy at the crossroads: Global perspectives and uncertainties*. 2003, Cambridge, MA: MIT Press.

66. Grubler, A., *The rise and fall of infrastructures: Dynamics of evolution and technological change in transport*. 1990, Heidelberg: Physica-Verlag.
67. DFT, *Vehicle licensing statistics - Table VEH0203: Cars licensed by propulsion/fuel type, Great Britain, annually: 2000-2010*, 2011, Department for Transport Statistics.
68. EIA, *Alternatives to traditional transportation fuels 2008*, 2010, U.S. Energy Information Administration - Office of coal, nuclear, electric, and alternate fuels: Washington, DC. p. 69.
69. JAMA, *Motor Vehicle Statistics of Japan - 2010*, 2011, Japan Automobile Manufacturers Association, Inc.: Tokyo.
70. JAMA, *Achieving greater safety and environmental protection in road transport - On the road to sustainable mobility*, 2011, Japan Automobile Manufacturers Association, Inc.: Tokyo. p. 8.
71. Polk, *Light duty vehicle fuel type by country (custom dataset incl. Argentina, Brazil, France, South Korea)*, 2011, R.L. Polk & Co.: Southfield, MI.
72. IANGV, *Natural gas vehicle statistics*, 2011, International Association for Natural Gas Vehicles: Auckland, NZ.
73. EBWR, *Electric bikes worldwide reports, 2004-2010*, 2011, Electric Bikes Worldwide Reports.
74. Freedonia, *Motorcycle demand in China by engine type: 1999-2019*, 2011, The Freedonia Group, Inc.
75. Weinert, J., et al., *The future of electric two-wheelers and electric vehicles in China*. Energy Policy, 2008. **36**: p. 2544-2555.
76. Dunbar, R.B., *Existing and proposed Canadian commercial oil sands projects*, 2011, Strategy West Inc.: Calgary, AB.
77. OGJ, *Oil & gas journal biennial EOR survey (1974-2010)*. Oil & Gas Journal, 2011. **Various**.
78. CDC-DOGGR, *Summary of operations: California oil fields, 1966-1974*, California Department of Conservation, Division of Oil and Gas: Sacramento, CA.
79. Dyni, J.R., *Geology and resources of some world oil-shale deposits*, 2006, US Geological Survey: Reston, Virginia. p. 42.
80. Li, S. and J. Qian. *New development of Chinese oil shale activities*. in *30th Oil Shale Symposium*. 2010. Colorado School of Mines, Golden CO.
81. Chastko, P., *Developing Alberta's oil sands: From Karl Clark to Kyoto*. 2004, Calgary, AB: University of Calgary Press.
82. Stringham, G., *The Canadian oil sands: Opportunities and challenges*, 2006, Canadian Association of Petroleum Producers.
83. ERCB, *ST53: Alberta Crude Bitumen In Situ Production Monthly Statistics, 2010 Monthly Data*, 2011, Energy Resources Conservation Board: Calgary.
84. ERCB, *ST39: Alberta Mineable Oil Sands Plant Statistics Monthly Supplement, 2010 monthly data*, 2011, Energy Resources Conservation Board: Calgary.
85. Cooper, C., *Digest of South African Energy Statistics -2005*, 2005, Department of Minerals and Energy - Republic of South Africa: Pretoria. p. 61.
86. Van Wyk, J., *Aggregate energy balances, 1992-2004*, Department of Minerals and Energy - Republic of South Africa: Pretoria.

87. Sasol, *Sasol Annual Review and Summarised Financial Information*, 2003-2010, Sasol Incorporated.
88. RFA, *Growing innovation: America's energy future starts at home*, in *Ethanol Industry Outlook 2009*, Renewable Fuels Association: Washington, D.C.
89. EIA, *Renewable Energy Annual 2008: Biofuels overview*, 2010, Energy Information Administration.
90. Martines-Filho, J., H.L. Brunquist, and C.E.F. Vian, *Bioenergy and the rise of sugarcane-based ethanol in Brazil*. *Choices: The magazine of food, farm, and resource issues*, 2006. **21**(2): p. 91-96.
91. EIA, *World Total Oil Supply 1980-2010*, 2011, Energy Information Administration.
92. Prakash, S., *Petroleum fuels manufacturing handbook*. 2004, New York: McGraw-Hill.
93. Boundy, B., et al., *Biomass energy databook: Edition 3*, 2010, Oak Ridge National Laboratory, TN: Oak Ridge, TN.
94. EIA, *Annual energy review 2005*, 2006, Energy Information Administration: Washington, D.C. p. 435.
95. Brandt, A.R., *Converting Oil Shale to Liquid Fuels with the Alberta Taciuk Processor: Energy Inputs and Greenhouse Gas Emissions*. *Energy & Fuels*, 2009. **23**(12): p. 6253-6258.
96. Farrell, A., et al., *Ethanol can contribute to energy and environmental goals*. *Science*, 2006. **311**(27 January): p. 506-508.
97. Schleisner, L., *Life cycle assessment of a wind farm and related externalities*. *Renewable Energy*, 2000. **20**(3): p. 279-288.
98. CARB, *California Low Carbon Fuel Standard - Carbon Intensity Lookup Table*, 2012, California Air Resources Board: Sacramento, CA.
99. Kodjak, D., B. Sharpe, and M. Campestrini, *Evolution of HDV GHG / fuel economy standards: The importance of US HDV rule*, in *Asilomar Conference On Transportation and Energy 2011*, UC Davis and International Council on Clean Transportation: Pacific Grove, CA.