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# Fuel Efficiency in Transportation Systems

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## Abstract

Transportation of people and of goods plays an important role in modern life. It is a major source of anthropogenic CO<sub>2</sub>. This chapter, after introducing some fundamentals of natural climate fluctuations as described by Milankovitch cycles,

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describes the causes and consequences of man-made climate change and the motivation for increased fuel efficiency in transportation systems. To this end, contemporary and future ground-based and air-based transportation technologies are discussed. It is shown that concepts that were already given up, such as turbine-driven cars, might be worthwhile for further studies. Alternative fuels such as hydrogen, ethanol and biofuels, and alternative power sources, e.g., compressed air engines and fuel cells, are presented from various perspectives. The chapter also addresses the contribution of CO<sub>2</sub> emissions of the supply chain and over the entire life cycle for different transportation technologies.

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## Introduction

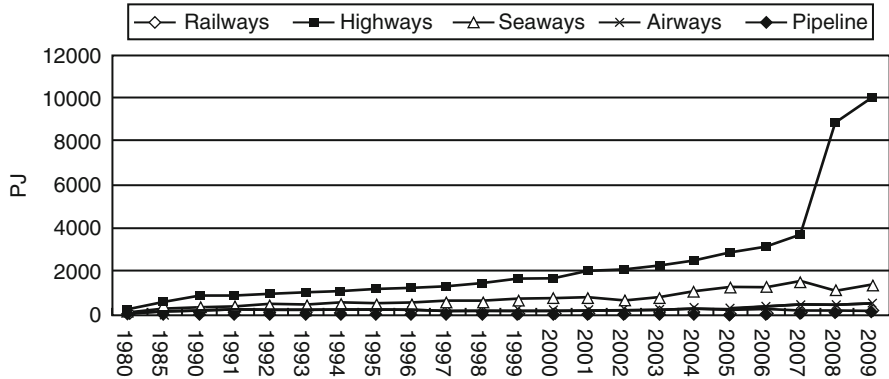
The purpose of this chapter is to introduce current concepts being examined to increase fuel efficiency in transportation systems in order to reduce their impact on unfavorable climate change. This is a daunting task that will take the cooperation and sacrifice of most of the entire human population to avoid a premature catastrophic event. Now, other chapters of this handbook reveal the salient scientific reasons for climate change, and the reader is encouraged to consult these chapters. However, here it is only necessary to establish that global warming or cooling has continually occurred by natural causes since Earth's formation. This can be deduced from examining the so-called Milankovitch cycles (Kukla and Gavin 2004).

Transportation of people (passengers) and goods (freight, cargo) can be done on the land, the sea, and the air. Approx. 50 % of all transportation emissions are from passenger transport (Lipsy and Schipper 2013). One can distinguish between individual transportation (e.g., cars, bikes) and mass transportation (e.g., trains, planes, buses). Land-based transportation is achieved on highways and on railroads. Travel intensity and choice of transportation mode depend on personal preference, income, and country (Lipsy and Schipper 2013). Trip distance, e.g., to work for commuters, is also an important driver (Muratori et al. 2013). Goods can also be moved in pipelines. With the globalization of the economy and shifts in lifestyle habits, transportation has become more and more important over the last 100 years, both in the industrial and the developing world. Figure 1 below, in an exemplary fashion, shows the increase in energy consumption for transportation in China.

According to Zhang et al. (2011a), highways have become the dominant mode of transportation in China. The energy consumption in this mode increased from 1980 to 2006 from 36.4 % to 61.5 %. Other economies have seen similar developments. As Fig. 1 shows, other transportation systems have seen more and more usage as well.

Transportation systems are mainly driven by fossil fuels, predominantly those made from crude oil. The reason is that liquid fuels such as gasoline and diesel have high energy content that are safe and convenient to handle at low costs.

Energy efficiency of transportation systems can be defined as the amount of energy needed for a certain task, e.g., the transportation of one passenger or one unit of cargo over a certain distance. Transportation and energy is reviewed in



**Fig. 1** Chinese transportation sectors and their energy consumption from 1980 to 2009 (Reproduced with permission from Zhang et al. 2011b)

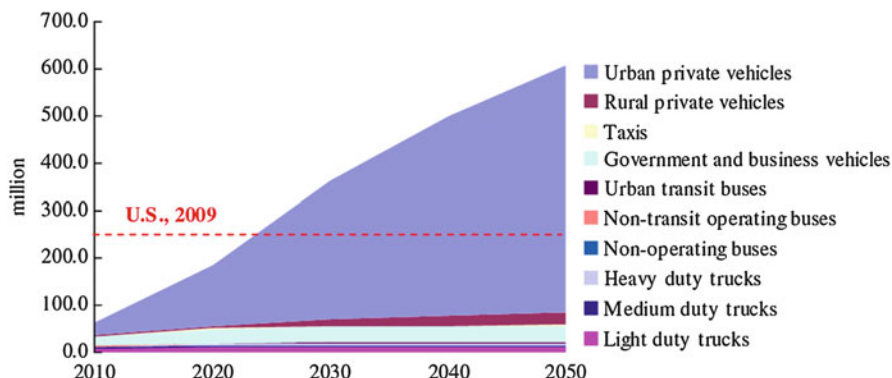
Greene (2004). Energy efficiency is the most economic way for climate change mitigation (Kamal 1997). Therefore, efforts need to be taken to improve energy efficiency of transportation systems.

Since the year 2000, the world production of gasoline (petrol) has matched consumption of this product. This has led to sporadic shortfalls of gasoline at the pumps along with elevated costs. Beyond the uncertainty of future fuel costs, the predictions for effects of global warming on the planet are very severe, and it is important that mankind addresses the issue of how transportation systems contribute to this problem. Today there are over one billion vehicles in the world, and within 20 years, the number will double (Sperling et al. 2010), largely a consequence of China's and India's explosive growth. Figure 2 takes a look at the projected number of cars in China. An impressive increase is expected over the next years (Hao et al. 2011).

Figures 1 and 2 depict the situation in China, which was chosen as a showcase example here, as China is currently one of the world's major emitters of anthropogenic CO<sub>2</sub>.

At the present time, as shown in this chapter, there are only partial solutions to reduce the impact of transportation systems on global warming. Energy conservation by avoiding travel is one option. Technical improvements to transportation systems are another approach.

Readers will note that the production of CO<sub>2</sub>, a by-product from the combustion of carbonaceous fuels such as gasoline with air, has been linked to a global increase in temperature. With an increase in the Earth's temperature comes melting of the ice caps and a rise of sea level on coastal cities. Of most concern is an accompanying change in composition of the Earth's fragile atmosphere. Millions of years ago the Earth had a very different atmosphere than it does today, where ice caps were melted and instead had lush forests. The percentage of O<sub>2</sub> was over 30 %, a level that would support large mammals, as it did, but not the present human population. Therefore, it is imperative that economical methods be found to reduce the emission of CO<sub>2</sub> if mankind is to have a sustainable future. Tim Flannery (2006) (<http://www>.



**Fig. 2** Projection of China's vehicle population through 2050 (Reproduced with permission from Hao et al. 2011)

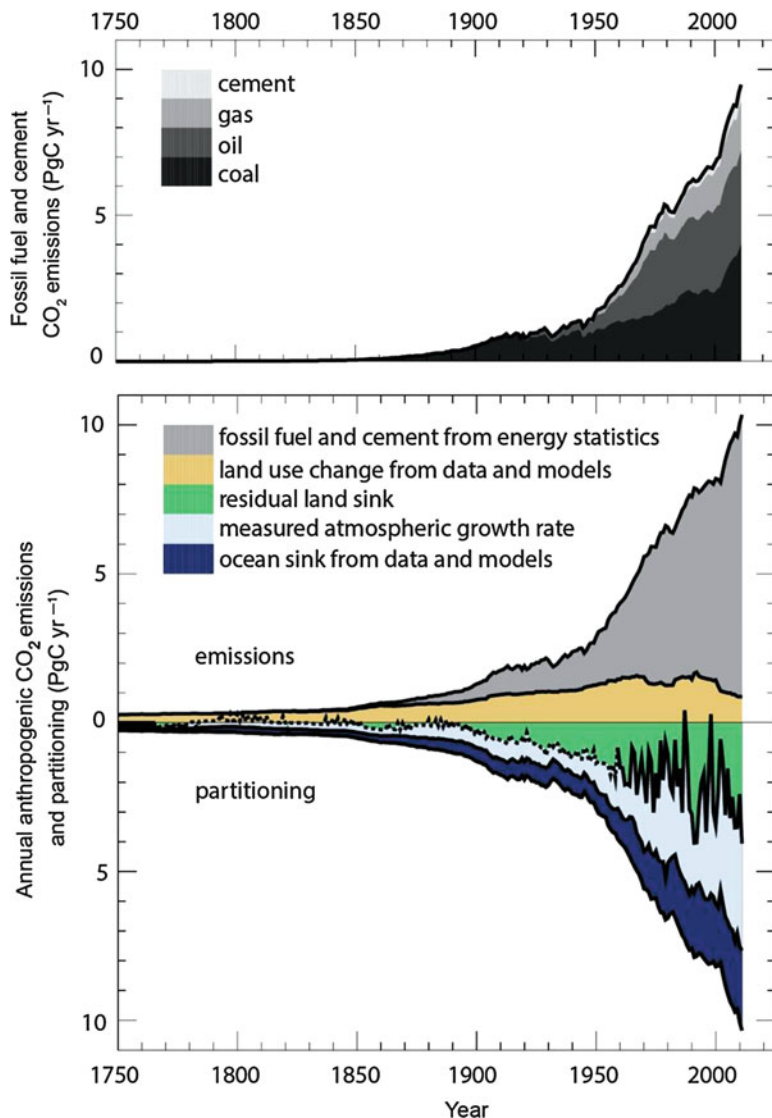
[theweathermakers.org/](http://theweathermakers.org/)) pointed out in his book that to stay below the threshold for melting of the ice sheets in Greenland and West Antarctica, it would be needed to reduce CO<sub>2</sub> emissions by 80 % from today's levels. This corresponds to no more than 30 lb of CO<sub>2</sub> per person per day. Further, Flannery predicts that if progress in reaching the above goal is not enough, only 20 % of the present world population will reach the year 2050. Professor Tim Flannery is an Australian mammalogist, paleontologist, environmentalist, and global warming activist.

In this chapter, the case for the reduction of CO<sub>2</sub> emissions from transportation systems is made. Solutions to efficient reductions are an evolutionary process where incremental change may represent mankind's only solution. With this viewpoint prior automotive designs that were introduced years ago and that failed to gain acceptance but may deserve another evaluation will be discussed. Present-day automotive engines utilize fuel injection systems instead of carburetors and represent the main reason for increased fuel mileage. Consequently, this chapter will also examine various engine cycles. Other measures such as lightweight construction materials, car pooling, and traffic management can also reduce fuel consumption. There is also a need to consider alternate fuels not only for emissions, but also reduction of the dependence on oil. Thus, the use of biofuels and hydrogen as substitutes for oil will be discussed. This is such a broad effort that this chapter will only be able to introduce a few concepts for automotive applications. Concepts for other landborne plus air- and seaborne transportation will be touched upon. The authors will also briefly discuss fuel cells, hybrid vehicles, and electric vehicles. Aircraft with respect to fuel efficiency will shortly be addressed. There is no question that aircraft play an important role in contemporary lifestyle, but they require significant energy to perform their mission. Thus it will be necessary to introduce radical designs that would substantially reduce the fuel burn rate.

## The Issue

Since Earth's formation, the atmosphere's composition and temperature has changed dramatically due to the Earth's cooling. However, there is another factor that affects the temperature of the atmosphere that is related to gravitational attraction between the planets and the sun. This gravitational attraction produces an eccentricity of the Earth's orbit, obliquity of the Earth's axis, and precession of the Earth's axis of rotation. These effects have various periods as was first noted by Milankovitch who observed the following periods of the Earth's axis: Wobble cycles of 19,000 and 23,000 years, tilt cycle of 41,000 years, and cycles of 100,000 and 400,000 years to the Earth orbit around the sun (Kukla and Gavin 2004). The Earth's orbit transitions periodically between a circular and an elliptical orbit. When on an elliptical orbit, the Earth's distance to the Sun has periods where it is the greatest, and the Earth's atmosphere is cold (i.e., ice age). Currently, the Earth is in a more circular orbit, and the Earth's temperature is warmer. These Milankovitch cycles are of course natural events that mankind cannot interfere with. During previous periods the ice caps were melted, and in the USA, alligators extended as far north as Denver. Data gathered from the Antarctica ice shelf allow researchers to infer the air temperature of the Earth at that location going back 400,000 years from analysis of cores drilled into the ice. Further analysis of these cores also permits one to estimate the percentage of CO<sub>2</sub> in the atmosphere during this period of time. One can also deduce that during nearly circular orbits, the Earth's temperature is the warmest, and during elliptical orbits, the Earth's temperature is the coldest. The temperature spikes around 320,000, 210,000 and 130,000 years before today's time and now have elevated contents of CO<sub>2</sub> in the atmosphere. The warming periods that occurred beyond present day were controlled by natural events. However, during the present cycle that includes the Industrial Revolution, there appears to be a large increase in the percentage of CO<sub>2</sub> that is significantly higher than recorded for previous cycles: the CO<sub>2</sub> concentration in the atmosphere is elevated by 100 ppm due to human action. During the warm periods where the Earth's orbit is nearly circular, the peak concentration of CO<sub>2</sub> has been in the order of 275 ppm CO<sub>2</sub>. Today (January 2015) it has spiked to just under 400 ppm (The Keeling Curve et al. 2015), about 40 % higher than in preindustrial times and higher than in any other period in at least 800,000 years. The level of atmospheric CO<sub>2</sub> is rising at a rate of approximately 2 ppm/year. This increase can be attributed to the presence of humans on Earth and their rapid consumption of energy, i.e., by the combustion of fossil fuels. A fair question to ask is what are the major contributors to CO<sub>2</sub> production and how the CO<sub>2</sub> concentration is related to Earth's average temperature. From Fig. 3, one can see that there are three main contributors to the production and emission of CO<sub>2</sub> in the atmosphere from burning fossil fuels, cement production, and land use change. The figure, reproduced from the 5th IPCC Assessment Report (2013), also shows the CO<sub>2</sub> sinks. These represent the areas where technology developments to reduce CO<sub>2</sub> are needed.

The question then is how this increase in concentration of CO<sub>2</sub> modifies the average temperature of the planet.



**Fig. 3** Leading contributors to production of CO<sub>2</sub> and sinks (Reproduced from IPCC 2013)

Note that CO<sub>2</sub> is not the only anthropogenic greenhouse gas, but also the most important one. Most of the natural greenhouse effect is caused by water vapor.

Other important greenhouse gases are CH<sub>4</sub>, N<sub>2</sub>O, and SF<sub>6</sub>. CH<sub>4</sub> emissions are also produced by the transportation sector, e.g., as losses from natural gas (and biogas) production and distribution and as unburnt hydrocarbon emission from the combustion process.

It is very surprising how small an increase in CO<sub>2</sub> concentration contributes to the average temperature around the globe. Now, the atmosphere has reached a level of said ~400 ppm. This means that the world has seen a nearly 2 °C increase in temperature over that of preindustrial times. Even with this small increase in average temperature, many today can recall changes that have occurred and are noteworthy (for more information on narrative research in climate change, see, e.g., (Paschen and Ison 2014)). In the early 1900s, people would drive their cars across Lake Ontario to Toronto, Canada, on the frozen ice sheet. This lake has not frozen over for more than 50 years. In Southern Virginia, James River used to freeze over as late as the 1950s, but no longer. Predictions by Flannery are that if an atmospheric CO<sub>2</sub> concentration between 900 and 1,000 ppm is reached, in the future only one in five people would survive. Now, aside from observations that have occurred with an increase in global temperature, one can observe that the ice sheets have already begun to melt. Figure 4 shows the extent of the Arctic sea ice averaged over the period 1979 to 2007 for the months May to September. Following Fig. 5, one can see that the ice shelf does not restore itself until September. In a typical year the ice sheet would begin to grow again in August, but now in August it is still melting. With melted ice sheets, the Earth's thermal energy balance is changed since more heat from the Sun is absorbed by the Earth rather than being reflected back into space. Thus, the cycle is intensified.

Figure 5 below shows the thickness of the ice sheet north of Greenland in the 1950s and the prediction by NOAA (National Oceanic and Atmospheric Administration) for the year 2050, which shows the ice sheet is predicted to be reduced to half its previous size.

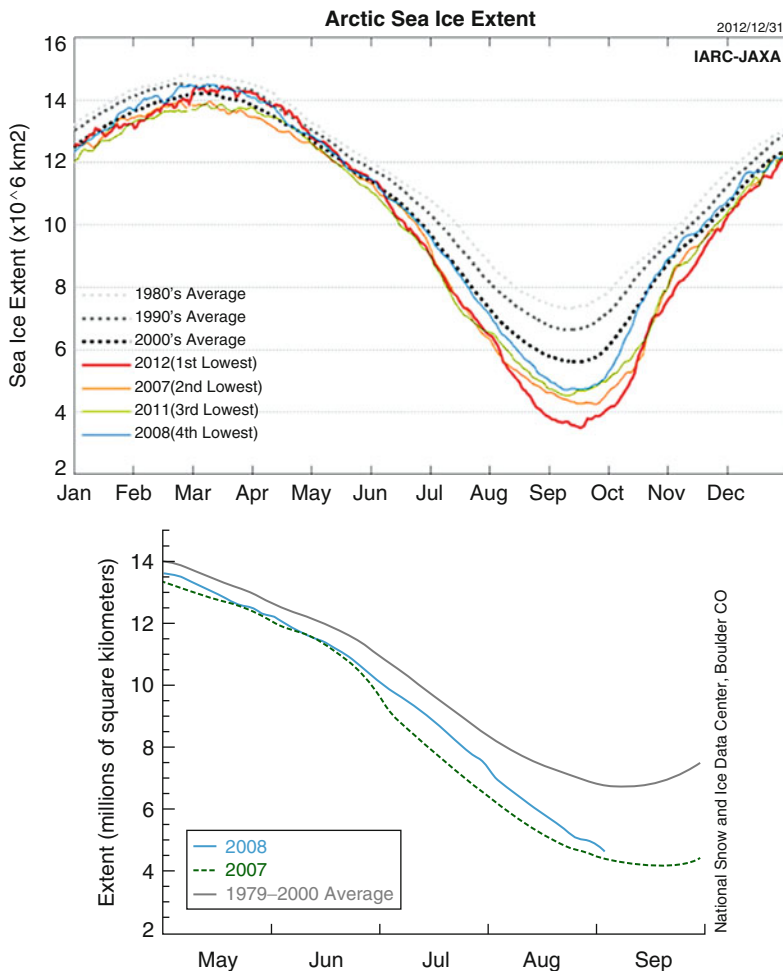
Therefore, there is a strong motivation to increase the fuel efficiency of transportation systems for people and freight to mitigate anthropogenic climate change. Several aspects will be discussed below.

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## Carbon Emissions by Light Duty Vehicles

It can be seen that since the beginning of the Industrial Revolution, the planet's atmosphere has increased in temperature by almost 2 °C. Not a large increase, but big enough to start significant melting of the ice caps. One can see that the temperature increase can be linked to a large increase in CO<sub>2</sub> in the atmosphere. Combustion of solid (coal), liquid (gasoline, diesel), or gaseous (natural gas) fuels, to a significant fraction for transportation purposes, is the major contributor to the production of anthropogenic CO<sub>2</sub>. Natural gas has a higher H/C ratio than diesel or gasoline. Therefore, it is more climatically benign when being burnt in engines (note that the greenhouse warming potential [GWP] of CH<sub>4</sub> is ~20 times that of CO<sub>2</sub>, so CH<sub>4</sub> emissions are to be avoided).

A natural question to ask at this point is what percentage of CO<sub>2</sub> production is due to transportation and which countries are the major contributors. DeCicco et al. provide a graphic illustration of each sector's contribution in Fig. 6. The estimates shown in this figure only include the use of fossil fuel. As can be seen,

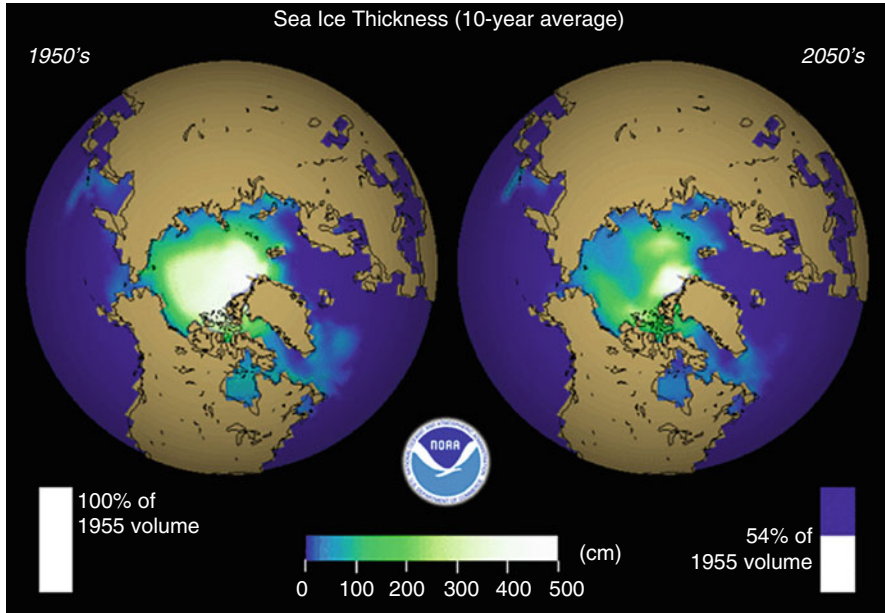


**Fig. 4** Annual cycle of the Arctic sea ice extent for 2012 (red), 2007 (orange), 2011 (green), and 2008 (blue). Dashed lines show decadal means for the 2000s (black dashes), 1990s (gray dashes), and 1980s (light-gray dashes) (Source: IARC/JAXA Sea Ice Monitor, [http://www.ijs.iarc.uaf.edu/en/home/seaiice\\_extent.htm](http://www.ijs.iarc.uaf.edu/en/home/seaiice_extent.htm)) (Walsh 2014)

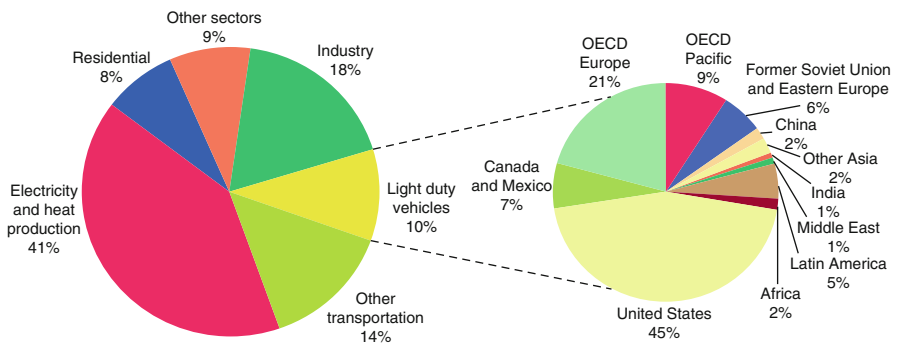
over 40 % of the CO<sub>2</sub> emissions are from the production of home electricity and heat. Light-duty vehicles only account for 10 % of the production, and almost half of that is produced in the USA with a significant nearly a quarter from Europe. One observes that only a little over 2 % occurs in China and India. In the next 20 years, China and India are expected to grow and consume an amount equal to the USA (compare also Figs. 1 and 2).

A substantial growth in CO<sub>2</sub> production by light-duty vehicles would require additional refineries throughout the world, or extreme shortages at the pump would



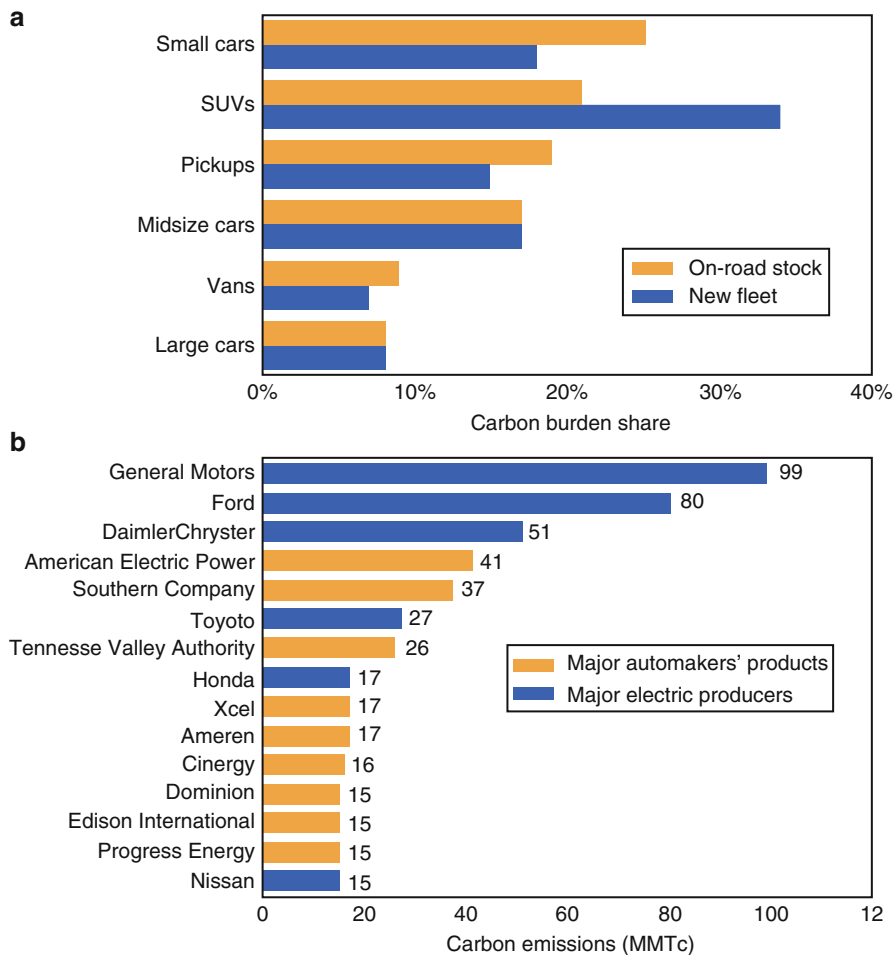


**Fig. 5** Melting of the polar ice cap (Reprinted with permission from the National Snow and Ice Data Center 2015)



**Fig. 6** Estimates for CO<sub>2</sub> production by sector and light-duty vehicles. *Left*: Global carbon emissions by sector ( $6,814 \cdot 10^6$  t). *Right*: Light-duty vehicle carbon emissions by region ( $680 \cdot 10^6$  t). (Reprinted with permission from DeCicco et al. 2015)

occur. Energy conservation will play a more realistic role in the future to avoid the problem of fuel shortage, but this cannot be expected to take effect until existing vehicles are replaced with ones using new technology. DeCicco also addressed this issue, and in Fig. 7a, one can see that old SUVs dominate the carbon burden share



**Fig. 7** Carbon emissions by new versus old vehicles and electric producers. (a) CO<sub>2</sub> pollution as % of new & old vehicles. (b) Carbon emissions: auto & electric producers DeCicco et al., *Global Warming on the Road* (DeCicco et al. 2015)

and that both new and old midsize cars contribute equally. Carbon emissions by cars dominate those associated with electric producers, see Fig. 7b. These statistics indicate that there is a need to adopt a policy to retire existing vehicles as soon as possible and, in particular, SUVs.

DeCicco et al. point out that there are three factors that govern the production of carbon dioxide in the transportation sector. The first is related to travel demand, the second to automotive efficiency, and the third to carbon content per gallon of fuel. Aside from reducing the distance travelled per year by car or light-duty truck, it is of interest to know how alternate means for ground transportation compare to decide which mode to emphasize. Table 1 shows a compilation of results by the US

**Table 1 Efficiency of various transportation systems** 1 gal (~3.7854 l) of gasoline contains approximately 114,000 BTU (120 MJ) of energy. MPGe = miles per gallon gasoline equivalent. This measure of the average distance travelled per unit of energy consumed compares the energy consumption of alternative fuel vehicles. 1 MPGe  $\approx$  0.0182 km/kW · h  $\approx$  0.005 km/MJ

Transport mode	Average passengers per vehicle	Efficiency per passenger	
		BTU/mi	l/100 km (MPGe)
Vanpool	6.1	1,322 BTU/mi	2.7 l/100 km (87 MPGe)
Motorcycles	1.2	1,855 BTU/mi	3.8 l/100 km (62 MPGe)
Rail (Amtrak)	20.5	2,650 BTU/mi	5.4 l/100 km (43 MPGe)
Rail (transit light and heavy)	22.5	2,784 BTU/mi	5.7 l/100 km (41 MPGe)
Rail (commuter)	31.3	2,996 BTU/mi	6.1 l/100 km (38 MPGe)
Air	96.2	3,261 BTU/mi	6.7 l/100 km (35 MPGe)
Cars	1.57	3,512 BTU/mi	7.2 l/100 km (33 MPGe)
Personal trucks	1.72	3,944 BTU/mi	8.1 l/100 km (29 MPGe)
Buses (transit)	8.8	4,235 BTU/mi	8.7 l/100 km (27 MPGe)

Department of Energy (DOE) for the efficiency of various transportation systems in terms of energy expended per passenger with an estimate of an equivalent number of liters per 100 km. The efficiency in Table 1 is estimated in terms of BTU/mile and also in miles per gallon.

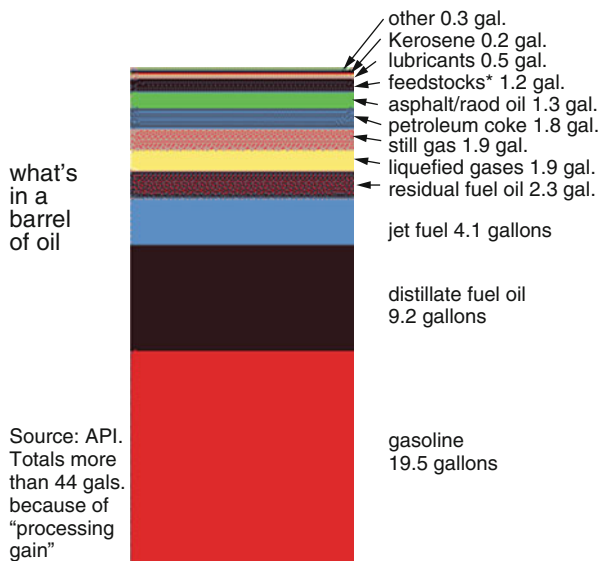
Table 1, from the US Department of Energy in 2008, clearly indicates the value of carpooling with a van that would carry six passengers. On a per passenger basis, the vanpool achieves 87 MPGe<sub>US</sub>, an efficiency that would be hard to match by an automobile with a single passenger. Only motorcycles nearly match the vanpool. Personnel trucks are listed as one of the most inefficient modes of transportation with cars, only slightly better. Transit buses are the worst form primarily due to the constant stopping and starting needed to pick-up and let off passengers.

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## Carbon Generated by Combustion with Air

Each barrel contains 42 gal (159 l) of crude oil and consists of various petroleum products as shown in Fig. 8. As one can observe, only about half a barrel of crude can be refined into gasoline (after fractionated distillation, several processes in a refinery such as cracking can shift the product mix).

**Fig. 8** Products obtained from refining a crude barrel of oil (Reproduced with permission from Gibson Consulting 2015). *API* American Petroleum Institute

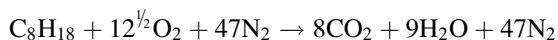


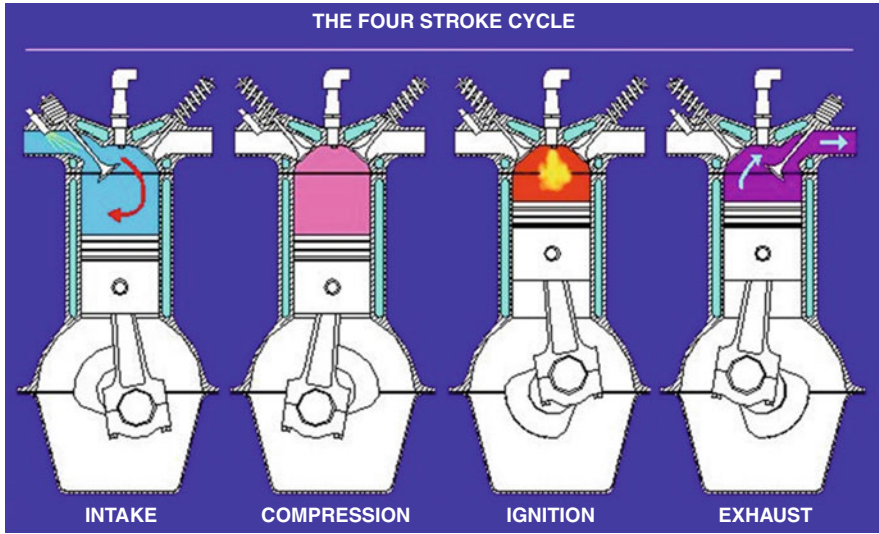
The amount of CO<sub>2</sub> emitted per gallon is governed by the Code of Federal Regulations (40CFR600.113) (Title 40 2015). The carbon content of gasoline per gallon is 2,421 g, whereas the carbon content of diesel fuel per gallon is 2,778 g.

Recall the words of Tim Flannery who said that to prevent the ice sheets from melting, every human had to be on a diet of 30 lb or less of carbon a day. So each person could only use about a gallon and a half of gasoline each day. The ability to use only a gallon and a half each day strongly suggests an elusive goal. While one may not be able to meet this goal, earnest conservation steps can ease the way into the inevitable. One of the first conservation steps one can take is to consider engine thermodynamic cycles to see if there is any advantage. Toward this purpose, the bare essentials associated with the spark and compression ignition engines are discussed.

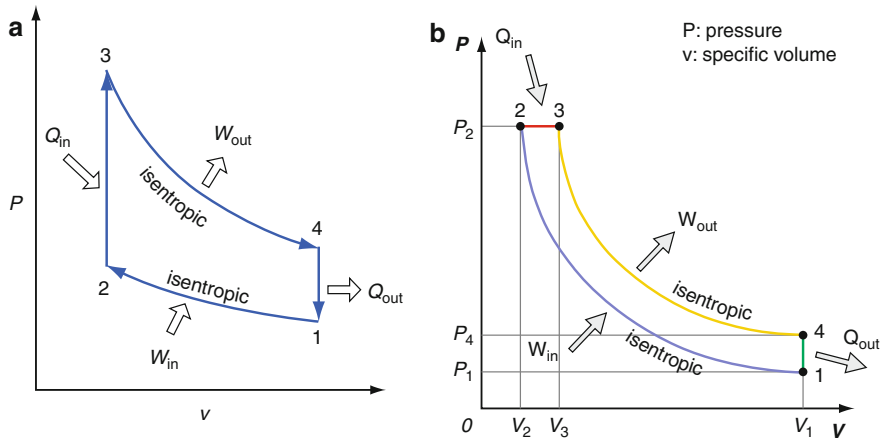
The four-stroke engine cycle was first patented by Eugenio Barsanti and Felice Matteucci in 1854. An illustration of the four-stroke cycle, reproduced from Obert (1973), is shown in Fig. 9. There, one sees the position of the cylinder head, intake valve, exhaust valve, and spark ignition for one entire cycle. Figure 10a, b show that the thermodynamic model for either SI (spark ignition) or CI (compression ignition) during intake and exhaust is considered to be an isentropic process (=constant entropy). During cycles of heat in or out, the thermodynamic model is far from isentropic. Note that for compression ignition engines, during combustion, the process takes place at constant pressure.

For the ideal combustion, the efficiencies associated with the stoichiometric combustion of these fuels with air are illustrated in Fig. 10. For gasoline, this is given by





**Fig. 9** Graphic illustration of four-stroke compression ignition engine (Reproduced from Obert 1973)



**Fig. 10** Idealized four stroke for SI and CI combustion models. (a) Otto cycle Pv Diagram. (b) Diesel cycle Pv Diagram(Reproduced from Obert 1973). *P*, pressure; *v*, volume; *W*, work; *Q*, heat; *SI*, spark ignition; and *CI*, compression ignition

where following Fig. 10a one can note

$$Q_{Arev} = c_v(T_3 - T_2) \quad \eta_t = \frac{Q_A + Q_R}{Q_A} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{\gamma-1}}$$

$$Q_{Rrev} = c_v(T_1 - T_4)$$

where  $r_v$  is the engine compression ratio. As an example, consider the following: engine compression ratio,  $r_v = 8$ ; ambient temperature,  $T_a = 540 \text{ }^\circ\text{R}$  (300 K); ambient pressure,  $P_a = 14.7 \text{ psia}$  (101.3 kPa = 1.014 bar); and then one has that

$$\eta_t = 1 - \frac{1}{r_v^{\gamma-1}} = 1 - \frac{1}{8^{0.4}} = 0.565 = 56.5\%$$

Factoring in transmission and drive train, the overall gasoline-powered automobile efficiency is approx. 17 % (Obert 1973). Quite remarkable, about 83 % of the available energy is wasted on the gasoline-powered internal combustion engine. Even the thermal efficiency of the four-stroke ideal diesel engine cycle appears more attractive. Consider the Pv diagram shown in Fig. 10b, which shows air coming into the system at constant pressure and air being discharged from the system at constant pressure. Based on this cycle one can derive that the reversible heat added and discharged is given by

$$\begin{aligned} Q_{A\text{rev}} &= c_v(T_3 - T_2), \text{ and since } \left(\frac{T_3}{T_2}\right)^\gamma = \left(\frac{T_4}{T_1}\right), \text{ the thermal efficiency is given by} \\ Q_{R\text{rev}} &= c_v(T_1 - T_4) \end{aligned}$$

$$\eta_t = \frac{Q_A + Q_R}{Q_A} = 1 - \left(\frac{1}{\gamma}\right) \left(\frac{T_4 - T_1}{T_3 - T_2}\right) = 1 - \frac{1}{r_v^{\gamma-1}} \left[\frac{r^\gamma - 1}{\gamma(r - 1)}\right]$$

Typical values for the diesel cycle are compression ratios near 25 to ensure auto ignition. A diesel engine takes in just air, compresses it, and then injects fuel into the compressed air. The heat of the compressed air lights the fuel spontaneously. A typical thermal efficiency computed from the above equation using a compression ratio of 25 is a value  $\eta_t = 0.264$ . Note: Diesel engines are in general 30–35 % more efficient than gasoline-powered vehicles; however, efficiency strongly depends on the vehicle load.

The energy efficiency of alternative power trains in vehicles is discussed in Åhman (2001).

Otto and diesel engines are most commonly used in transportation. The Wankel engine is another concept with less proliferation. It operates without pistons. The Mazda RX-8 is one example of a car that deploys a Wankel engine. Table 2 shows some aspects of Wankel engines.

Experiments with turbine-powered cars were carried out in the USA around 1960. The following pros and cons were identified (Table 3).

Gas turbines are very efficient at high speeds and constant load. They need time to reach optimum operating conditions, and they produce thrust rather than torque. The problem with vehicles is that they are operated in several load conditions and often only for short distances.

Although the concept of turbine cars was abandoned soon after their appearance, they might still offer an interesting route to future efficient cars, so new research is carried out in this area, for instance, on micro-gas turbines (MGT) to recharge battery packs, in particular, for electric vehicles (EVs) (Sim et al. 2013).

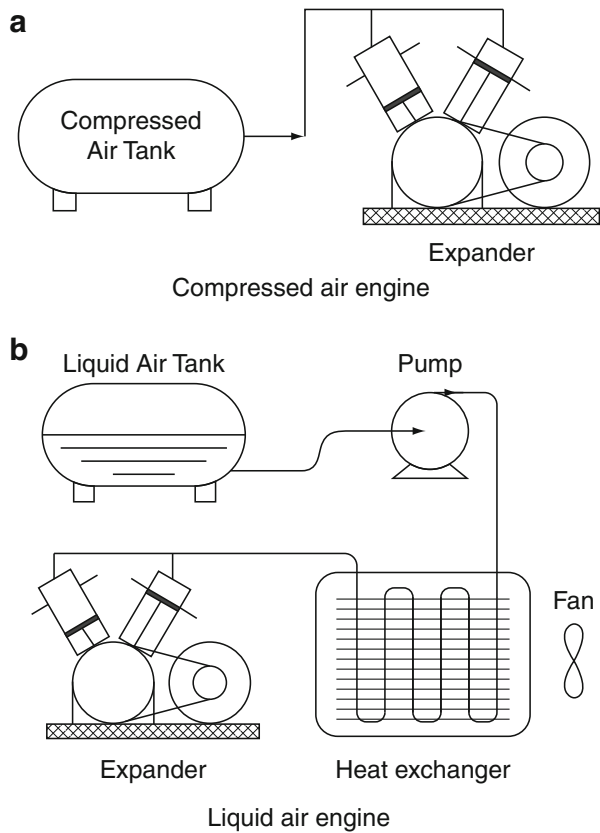
**Table 2** Assessment of the Wankel engine (Reproduced with permission from Hege 2006)

Pros	Cons
High power output/unit weight	Rotating seals reduce engine compression ratio
Good fuel/air mixing	Large fraction of unburned fuel lowers the efficiency
Even combustion	Excessive noise due to rotating seals

**Table 3** Assessment of turbine-powered automobiles (Reproduced from Hege 2006)

Pros	Cons
Low maintenance	High fuel consumption at idle due to high rpm throttle lag from idle as the engine spools up. High temperature of exhaust gases, low efficiency High noise emissions Expensive
Long engine life expectancy	
Reduction of number of parts by 80 %	
No warm-up period, easy low-temperature start	
No stall at sudden overload	
Hot but clean exhaust gases	
Low oil consumption	
Operation on wide fuel variety	

**Fig. 11** Air-fuelled engines (Reproduced with permission from Chen et al. 2011)



Another technology is the “air fuelled engine.” It can be operated by compressed air (Miller et al. 2010) or by liquid air, yielding zero tailpipe emissions (Chen et al. 2011), compare Fig. 11.

Due to the high energy consumption of air liquefaction plants, the compressed air-powered engines have a better energy efficiency than the liquid air ones (28.3 % to 36.0 % vs. 12.8 % to 17.0 % for the setups studied in Chen et al. 2011). Compared to liquid hydrocarbon fuels, compressed air has a lower energy density.

A novel concept for internal combustion engines is HCCI (homogeneous charge compression ignition) (Zhao 2007). It is a kind of hybrid between a compression ignition and a spark ignition engine, in that a homogeneous fuel/air mixture is brought to autoignition. This combustion mode resembles the typical “knocking” in gasoline engines. It is fast and hard to control. However, HCCI offers the potential of low-pollution and high-efficiency automotive engines.

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## Alternative Fuels

With depleting fossil fuel resources, costs go up and supply shortages might occur, apart from the emission of CO<sub>2</sub> into the atmosphere from the burning of these fuels. Alternative fuels can be unconventional fossil fuels (such as those derived from shale gas (Mallapragada et al. 2014), methane hydrate, fracking, etc.) and “renewable” fuels. This section focuses on renewable fuels, which are produced directly or indirectly from sunlight, without the need to turn to fossil fuels. The following energy carriers have been envisaged as fuels for combustion engines and/or fuel cells:

- Hydrogen
- Ethanol
- Ammonia (Zamfirescu and Dincer 2009)
- Methane
- Methanol

These fuels can be produced via various routes, both from fossil and renewable resources. Methane is also the main constituent of biogas. There are so-called flexible-fuel (flex fuel) vehicles that can run on several fuels, e.g., ethanol. A blend of gasoline and 85 % ethanol is called E85. Flex-fuel vehicles (FFV) have been produced since the 1980s. Ethanol (von Blottnitz and Ann Curran 2007) and biodiesel (Ticker 2003) are two common “biofuels.” Fischer Tropsch synthesis and biomass gasification are important processes to obtain fuels from biomass, apart from anaerobic digestion and fermentation. Fuels from waste are also considered biofuels. Oil crops yield fuels from extraction and pressing of suitable plants (Tickell 2000). Also, aquatic biomass such as certain algae can be used, e.g., for biodiesel production.

There is also some controversy around biofuels. Two issues associated with biofuels are



- Potential competition over farmland with food crops
- Water consumption associated with their production (see concept of virtual water, Allan 2011)

One can distinguish between 1st, 2nd, and 3rd generation of biofuels.

First-generation biofuels are made from foodstuff (ethanol from corn, biodiesel from soybean, or rapeseed via transesterification). They are mature and available on the market.

Second-generation biofuels are produced from lignocellulose. There are thermal and enzymatic processes to break of the biopolymers into smaller units.

There are also “1.5 G” biofuels, which utilize the full plant of 1G fuels.

The first 1.5G and 2G biofuel commercial production plants are on stream. Their advantage is that no competition over arable land with food crops exists. Also, 2G biofuels can be grown on marginal land.

Third-generation biofuels target algae for “green” fuel production, as they are expected to yield more biomass per area than land-based fuels. They could use sewage as nutrient, and avoid land usage (land use change, e.g., through deforestation to produce cropland), which also contributes to climate change.

Energy produced from biomass was initially considered carbon neutral because biomass is renewable through photosynthesis. Controversies, however, have emerged about the various impacts of promoting the use of first-generation biofuels. Major concerns about using bioethanol as fuel include the following issues:

- Corn is a food source, and corn ethanol production will reduce food availability. Developing countries that depend on the corn donation from the west have already experienced food shortages.
- Fertilizer is required in corn production; both cost and energy consumption are incurred during fertilizer production. Moreover, unprecedentedly large scale use of fertilizer alters the natural nitrogen cycle and induces other ecological/environmental problems that have already been identified as threats.
- About 5 gal of water are needed in the production of each gallon of ethanol in a plant; this does not consider the amount of water it takes to grow the corn. So potable water shortages might result from excessive bioethanol production.
- Bioethanol production requires energy input. Ethanol purification by distillation is energy intensive and usually involves consumption of natural gas, which, in turn, produces CO<sub>2</sub> from fossil fuel. As a result, while bioethanol utilization reduces fossil fuel dependence, it is not a completely carbon neutral process.

Widespread adoption of bioethanol will cause redistribution of the world’s natural resources and wealth. The actual environmental and societal costs of bioethanol are likely to be much higher. A good starting point for a healthy debate on this issue can be found at (Schulz 2007).

The transportation of energy carriers also consumes, naturally, energy. In Hamelinck et al. (2003), the energy consumption of biofuel transportation from production site to point of use is discussed, so that biofuels are not entirely carbon

**Table 4** Energy density of various fuels

Fuel	Volumetric (Wh/l)	Gravimetric (Wh/kg)
Diesel	10,942	13,762
Gasoline	9,700	12,200
LPG (liquefied petroleum gas)	7,216	12,100
Propane	6,600	13,900
Ethanol	6,100	7,850
Methanol	4,600	6,400
Liquid hydrogen	2,600	39,000
Hydrogen (150 bar)	405	39,000
Nickel-metal hydride	100	60
Lead acid battery	40	25
Compressed air	17	34

neutral or even carbon negative. The carbon balance of several biofuels is even worse than that of gasoline or diesel. A detailed life cycle assessment is necessary.

When assessing biofuels, next to climate change, abiotic depletion, acidification, eutrophication, and human toxicity (Petersen et al. 2015) need to be considered.

Second- and third-generation biofuels hold promise for CO<sub>2</sub> emission savings.

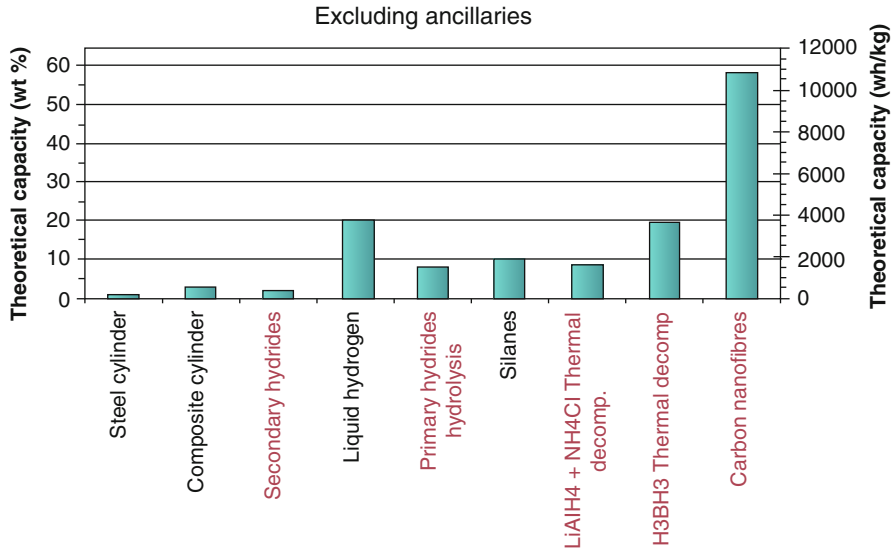
The share of biofuels is expected to increase significantly over the next decade. An important aspect of alternative fuels, apart from their specific costs, is the energy density (see Table 4).

From the above Table 4, one can see that compressed air has a low energy density both in terms of volume and weight. The energy density is important for the range of a vehicle. Gases can be stored in compressed form, as hydrides or as a liquid in cryogenic conditions. Liquefaction can consume a considerable amount of energy. For hydrogen, one can define the gravimetric storage density. It is the weight of hydrogen being stored divided by the weight of the storage and delivery system. A typical value is 2–4 %. Storage has to be achieved in a safe, cost-effective, and efficient way. Alkanates are a promising material class for hydrogen storage (Gross et al. 2002). Hydrides, this is chemically bond hydrogen in a solid material. This storage approach should have the highest hydrogen-packing density. However, storage media have to meet several requirements:

- Reversible hydrogen uptake/release
- Lightweight with high capacity for hydrogen
- Rapid kinetic properties
- Equilibrium properties (p, T) consistent with near-ambient conditions

There are two solid-state approaches:

- Hydrogen absorption (bulk hydrogen)
- Hydrogen adsorption (surface hydrogen)



**Fig. 12** Graphic illustration of hydrogen storage methods. *Red color* indicates that the technologies have not reached maturity yet (Reproduced from Obert 1973)

For details on hydride storage, see Agresti (2010).

Figure 12 compares several storage methods for hydrogen. Hydrogen can be produced, e.g., by electrolysis (solar power) or gasification.

Renewable energies for sustainable development are discussed in Lund (2007).

## Alternative Power Sources

Electric cars come as battery-powered and fuel-cell-powered models. For a comparison on “well-to-wheel” energy pathways, see, e.g., (Eaves and Eaves 2004). So-called hybrid vehicles use a combination of an internal combustion engine (ICE) plus an electric motor (van Vliet et al. 2010).

## Air Transportation

According to Chèze et al. (2011), world air traffic should increase by about 100 % between 2008 and 2025. The world jet fuel demand is expected to increase by about 38 % during the same period (Chèze et al. 2011). Aircraft manufacturers have reduced the specific fuel consumption of their equipment over the last decades, e. g., by using more efficient turbines, lightweight construction materials, and improved design. More radical concepts might help lower specific fuel consumptions further. Blended-wing-body (BWB) aircraft are promising constructions currently being studied. Their benefits are 10–15 % less weight and 20–25 % less fuel

consumption. Challenges today are the integration of the propulsion system into the airframe, aerodynamics, and control. An important aspect for the fuel efficiency of aircraft is the so-called aerodynamic efficiency. It determines its range with all other parameters kept constant. For details, see Qin et al. (2004).

CO<sub>2</sub> emissions and energy efficiency of aircraft are treated in Lee (2010), Babikian et al. (2002), Lee et al. (2004), and Morrell (2009).

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## Cargo

Freight transportation is a huge industry. Goods are moved by sea, air, and land, where seaborne transportation has the highest share with over 30,000 billion tonne-miles per year. Sea transportation aboard large container ships has a particularly advantageous energy efficiency compared to other modes. Because of concerns for the air quality in harbors and port cities, the emissions from ships have recently received more attention. For details on CO<sub>2</sub> emissions from shipping activities and their mitigation, see Fitzgerald et al. (2011), Villalba and Gemechu (2011), Cadarso et al. (2010), Geerlings and van Duin (2011), Heitmann and Khalilian (2011), Schrooten et al. (2009).

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## Means of Energy Efficiency

Energy efficiency improvements can be achieved in various ways.

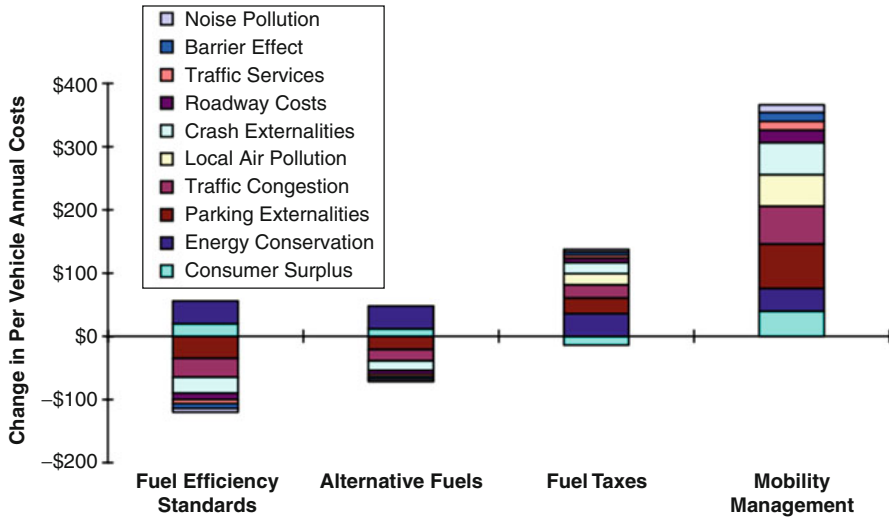
By training staff, an “energy saving mindset” can be created. It can yield fuel savings directly, without the need for significant investment costs. However, the impact will not be as long lasting as technical improvements. Building upon the above idea of different means to achieve energy efficiency gains, the following Fig. 13 below highlights four energy conservation strategies for road transportation and their monetary impact, reproduced with permission from Litman (2005).

In Parry et al. (2014), an analytical framework for comparing the welfare effects of energy efficiency standards and pricing policies for reducing gasoline, electricity, and carbon emissions is discussed.

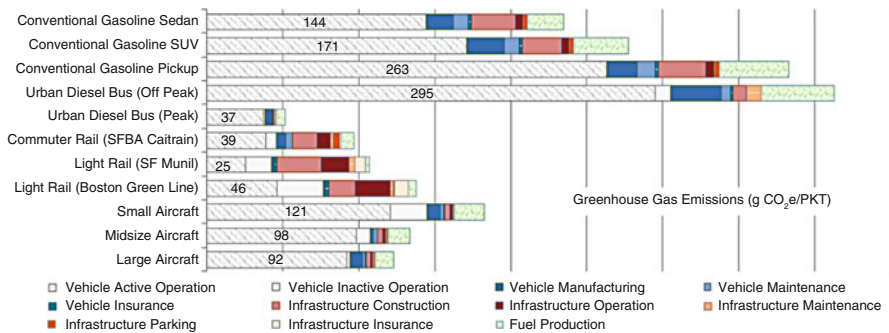
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## Comparison of Different Transportation Technologies

A key question related to energy efficiency in transportation is how various modes compare to each other. This is shown in an exemplary way for the greenhouse gas emissions (g CO<sub>2</sub> equivalents) per PKT (PKT = passenger kilometer travelled). In that paper (Chester and Horvath 2009), it is concluded that the total life cycle energy inputs and greenhouse gas emissions for road, rail, and aircraft transportation on top of the tailpipe emissions are 63 %, 155 %, and 31 %, respectively. This means that in the case of rail transportation, the major part of CO<sub>2</sub> emissions does not occur during the use of the vessel for a journey, but rather in related areas such as infrastructure



**Fig. 13** Cost impact of four different strategies for energy conservation. Above the 0 line, benefits are shown, and below costs. The barrier effect refers to delays that motorized traffic causes to other modes of transportation. In Litman (2005), it is valued at 0.7 cent per vehicle kilometer. For more details, the reader is referred to Litman (2005)



**Fig. 14** Total GHG (greenhouse gas) emissions per PKT (passenger kilometer travelled). The components of vehicle operation are depicted in grey, while other vehicle components are shown in blue shades. Infrastructure components are shown in red and orange. Fuel production components carry green color. All components appear in the order of the legend (Reproduced with permission from Chester and Horvath 2009)

construction and infrastructure operation. The infrastructure for railways is more complex than that of large aircraft, for instance.

As can be seen from Fig. 14 above, it is important to consider infrastructure and supply chain aspects when comparing different transportation modes for their energy efficiency. The (assumed) passenger occupancy is one parameter that strongly affects the results of such studies.

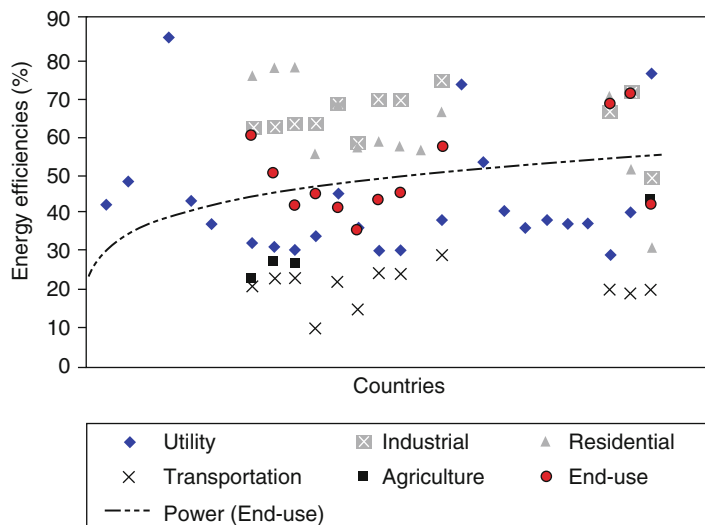
Energy efficiency of rail transportation is detailed in Miller (2009); of buses in Ally and Pryor (2007); and of aircraft in Lee (2010), Babikian et al. (2002), Lee et al. (2004) and Morrell (2009).

## Future Directions

Over the last years, a “green” development has emerged, and sustainability has become a buzzword also among consumers and in the transportation industries. In Utlu and Hepbasli (2007), the energy efficiencies of different sectors in several countries are compared (see Fig. 15 below). One can spot that they range from 35 % to 70 %. There is a big potential for savings in all sectors, and it is largest in the transportation area, followed by utilities, residential/commercial, and industrial sectors.

The efficiency of vehicles on US roads from 1923 to 2006 is discussed in Sivak and Tsimhoni (2009). In Romm (2006), Joseph Romm ponders on the car and fuel of the future, and in Azar et al. (2003), global energy scenarios in transportation until 2100 are developed. By looking at Fig. 15, one can assume that the transportation sector offers plenty of potential for energy efficiency improvements. An interesting study (Åkerman and Höjer 2006), which is partly reproduced below, has attempted to quantify these potentials, see Tables 5 and 6.

For cargo transportation, airships might be an energy-efficient means of transportation in future (Liao and Pasternak 2009).



**Fig. 15** Energy efficiencies of different countries by sector. In transportation, the potential for improvement seems biggest (Reproduced with permission from Utlu and Hepbasli (2007))

**Table 5** Potential to reduce the energy use per passenger-km in Sweden from 2000 to 2050. The occupancy and speed are kept constant (Reproduced with permission from Åkerman and Höjer 2006) (see there for details)

	kWh/ passenger-km, 2000	Potential change by 2050 (%)	kWh/ passenger-km, 2050
Car, combustion mode, 1,2 pass/car (<100 km)	0.75	-75	0.20
Car, electric mode (<100 km)			0.10
Small electric city vehicle			0.07
Car, combustion mode, 2 pass/car (>100 km)	0.32	-65	0.12
Bus (<100 km)	0.22	-60	0.09
Bus (>100 km)	0.13	-40	0.07
Ferry (20 knots)	0.60	-30	0.42
High-speed ferry (40 knots)	1.80	-30	1.30
Rail (<100 km)	0.16	-50	0.08
Rail, 200 km/h (<100 km)	0.11	-50	0.05
Air	0.57	-44	0.32

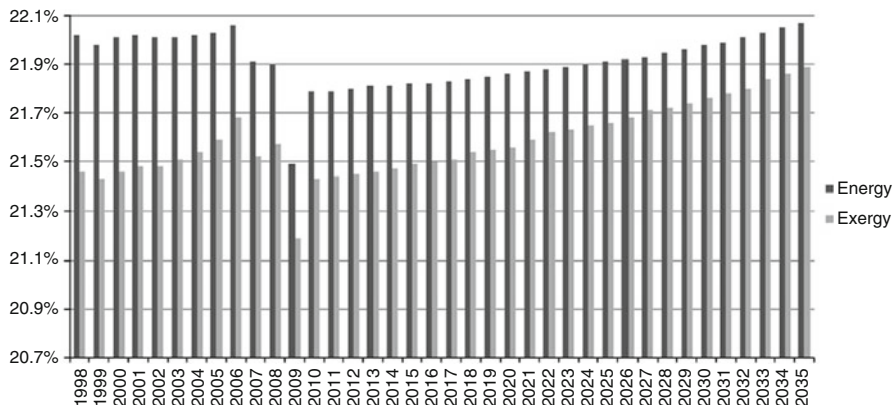
**Table 6** Potential to reduce the energy use per tonne-km in Sweden from 2000 to 2050. The load factor and speed are kept constant (Reproduced with permission from Åkerman and Höjer 2006) (see there for details)

	kWh/tonne-km, 2000	Potential change by 2050 (%)	kWh/tonne-km, 2050
Lorry (<100 km)	0.70	-40	0.42
Lorry (>100 km)	0.25	-30	0.17
Light lorry (<3.5 t)	-	-45	-
Rail	0.05	-30	0.20
Ferry (20 knots)	0.20	-30	0.14
Cargo ship	0.05	-30	0.04
Air	3.00	-44	1.68

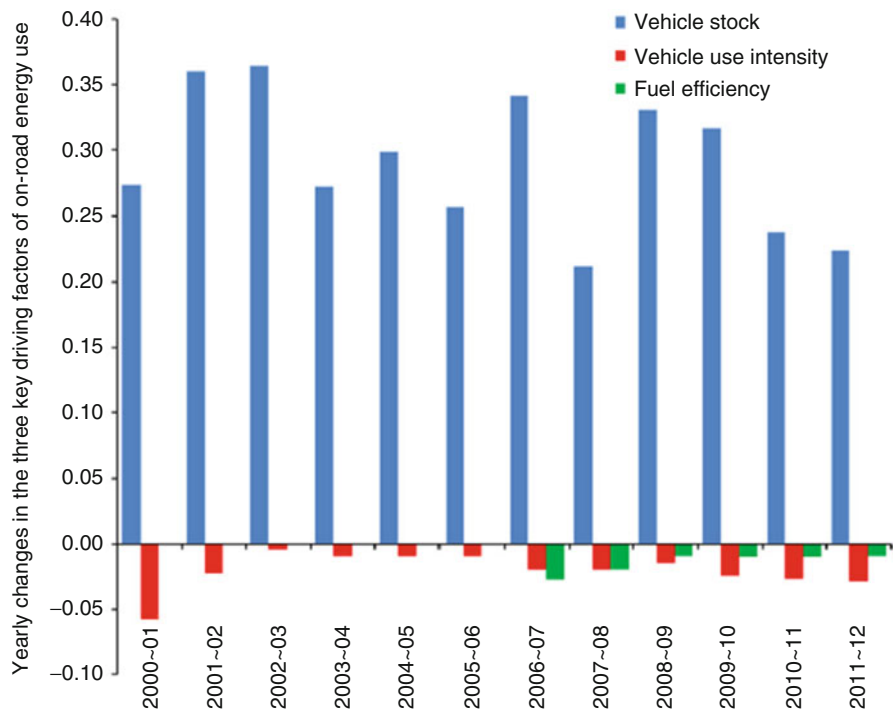
Future energy-efficient transportation systems can be developed based on new radical approaches such as blended-wing-body aircraft or by revisiting “old” ideas such as turbine cars.

It is expected that energy efficiency in the transportation sector will increase in the coming years, also driven by cost-saving attempts, see Fig. 16 as an example (Iran).

One can see that there was a fluctuation in both the energy and exergy efficiencies in the period between 1998 and 2009, and the minimum value of energy and exergy efficiencies occurred in the previous year. Some socioeconomic and political reasons, such as the increase and decrease in the export of petroleum and import of petroleum products, the establishment of new refineries, national subsidies, international sanctions, and war are considered as the main reasons for changes in the



**Fig. 16** Overall energy and exergy efficiencies in Iran between 1998 and 2035 (Source: Zarifi et al. 2013)



**Fig. 17** Relative changes in the three driving factors behind energy use in the road transport sector in China (Source: Wu and Huo 2014)



contribution of each fuel and, consequently, change in the overall energy and exergy efficiencies during the previous years (Zarifi et al. 2013).

It has to be borne in mind that efficiency improvements in transportation can be offset by increased mobility, see Fig. 17 (example of China).

In this chapter, several aspects of energy and fuel efficiency on the transportation industries were touched upon. For comparisons, well-to-wheel (WTW) efficiencies need to be considered (Mallapragada et al. 2014). For further reading, see the cited references and also the chapter “Energy Efficiency” in this handbook. For an in-depth discussion of alternate fuels, see the following chapters in this handbook: Biochemical Conversion of Biomass to Fuels, Hydrogen Production, Conversion of Syngas to Fuels, and Integrated Gasification Combined Cycle (IGCC). Another interesting, promising approach is onboard reforming of fuels (Martin and Wörner 2011).

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