Alternative Transportation FUELS

Utilisation in Combustion Engines

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Preface

During the past couple of decades, there has been a large expansion in the transport sector, which resulted in a significant increase in the consumption of petroleum-based fuels such as gasoline and diesel. This situation is likely to pave the way for the depletion of fossil fuel–based reserves and to deteriorate the quality of the environment. Hence, there exists a definite need to stem this problem to the maximum possible extent by exploring the feasibility of using alternative fuels that could pave the way for the sustained operation of the transport sector. In this direction, this book exposes the reader to the assessment of the potential avenues that could be contemplated for using different alternative fuels in the transport sector.

Chapter 1 briefly highlights several modes of transport and their effect on the environment, while Chapters 2 and 3 discuss conventional and alternative fuels for land transport. Fuels for the aviation sector are covered in Chapter 4. Experimental investigations relating to the utilisation of alternative fuels in internal combustion engines are reported in Chapter 5. Fuel quality characterisation and a modelling of alternative-fuelled engines are briefly highlighted in Chapters 6 and 7, respectively. Chapter 8 briefly describes alternative-powered vehicles. Potential alternative fuels for rail, marine and aviation applications are presented in Chapters 9, 10 and 11, respectively. Chapter 12 highlights potential global warming and climate change on account of utilising conventional and alternative fuels. Some of the material in this book is based on the authors' own experience at different laboratories around the globe.

We are indeed grateful to the College of Engineering, Guindy, Chennai; Indian Institute of Technology, Madras; Indian Institute of Technology, Delhi; Indian Institute of Petroleum, Dehradun; University of Tokyo; University of Melbourne; University of Manchester Institute of Science and Technology; and Hosei University for providing the necessary facilities for us to undertake some of the research activities indicated in this book.

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Finally, we wish to thank our family members for extending their support during the preparation of this book.

M.K. Gajendra Babu
K.A. Subramanian

Authors

M.K. Gajendra Babu is a senior professor at RMK Engineering College, Chennai after retiring from the Indian Institute of Technology (IIT), Delhi, where he had served as professor and head of the Centre for Energy Studies. He was also a Henry Ford Chair Professor at IIT Madras and a visiting faculty at the University of Tokyo, University of Melbourne, University of Manchester, and University of Hosei, Japan.

Dr. Babu has been working in the field of computer simulation, alternative fuels, instrumentation, and emission controls for internal combustion engines for the past 44 years.

Dr. Babu has published about 250 research papers in several national and international journals and conferences. He is a Fellow of the Society of Automotive Engineers (SAE) International. He has been awarded the Indian Automobile Engineer of the Year award, the Indian Society of Technical Education's Anna University Outstanding Academic Award, the Indian Society of Environment's honorary fellowships from A. P. J. Abdul Kalam and the SAE India Foundation's Automotive Education Award for his outstanding contribution to automotive education in India.

K.A. Subramanian is an associate professor in the Centre for Energy Studies, Indian Institute of Technology (IIT), Delhi. He is a former scientist in the Indian Institute of Petroleum.

Dr. Subramanian's research area includes utilisation of alternative fuels (biodiesel, compressed natural gas, hydrogen, etc.) in internal combustion engines, the development of the homogeneous charge compression ignition (HCCI) concept engine, greenhouse control in transport engines, sustainable power generation using a hybrid energy system, computer simulation, and computational fluid dynamics (CFD). He is involved in several R&D projects, including the development of a biodiesel–CNG-based dual-fuel diesel engine, the utilisation of enriched biogas in automotive vehicles, and hydrogen utilisation in a multicylinder spark ignition engine. A patent application has been filed in his name.

Dr. Subramanian has jointly supervised three doctoral scholars and supervised about 10 PhD scholars. He was nominated to participate in the project Study Mission on Energy Efficiency, sponsored by the Asian Productivity Organization, Japan in 2009.

Abbreviations

AC	Alternate current
AFVs	Alternate fuel vehicles
AK	Antiknock
Al_2O_3	Alumina
ASTM	American Standards Testing Material
ATR	Auto thermal reforming
B0 (or) D100	Diesel
B20	20% Biodiesel + 80% diesel
B40	40% Biodiesel + 60% diesel
B60	60% Biodiesel + 40% diesel
B80	80% Biodiesel + 20% diesel
BD	Biodiesel
BIS	Bureau of Indian Standards
BMEP	Brake mean effective pressure
BP	Brake power
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
BTL	Biomass to liquid
Btoe	Billion tonnes of oil equivalent
C_2H_5OH	Ethanol
$C_3H_6O_3$	Dimethyl carbonate
C_3H_7OH	Propanol
C_4H_9OH	Butanol
CAFE	Corporate average fuel economy
CAGR	Compound annual growth rate
CDM	Clean development mechanism
CFC	Chloro fluoro carbons
CFR	Cooperative Fuel Research
CH_3OH	Methanol
CH_4	Methane
CI	Compression ignition
CI engine	Compression ignition engine
CN	Cetane number
CNG	Compressed natural gas
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
CRC	Coordinating Research Council
CRDI	Common rail direct injection

CTL	Coal to liquid
Cu	Copper
CVS	Constant volume sample
°C	Degree Celsius
DC	Direct current
DC	Discounted cost
DEE	Diethyl ether
DICI	Direct injected compression ignition engine
DISI	Direct injection spark ignition engine
DME	Dimethyl ether or Di methyl ether
E10	Ethanol 10%
E15	15% Ethanol + 85% gasoline
E30	30% Ethanol + 70% gasoline
E70	70% Ethanol + 30% gasoline
E85	Ethanol 85%
E95	Ethanol 95%
EAMA	European Automobile Manufacturer's Association
EGR	Exhaust gas recirculation
EPEEE	European Program on Emissions, Fuels and Engine Technologies
EU	European Union
EU27	European Union of 27 member states
EV	Electrical vehicles
FBP	Final boiling point
FC	Fuel cell
FCC	Fluidised catalytic converter
FCV	Fuel cell vehicles
Fe	Iron
FFA	Free fatty acids
Fp	Finished product
Fpe	Finished products to the end user
FRJ	Fermentation renewable jet
FSU	Former Soviet Union
FT	Fischer–Tropsch
F–T Diesel	Fisher–Tropsch diesel
FTS	Fischer–Tropsch synthesis
g/km	Gram per kilometre
g/kWh	Gram per kilowatt hour
G-8	Group of eight
GDI	Gasoline direct ignition
GDP	Gross domestic product
GHGs	Green house gases
GTL	Gas to liquid
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water

HC	Hydrocarbons
HCV	Higher commercial vehicles
HDS	Hydro desulphurisation
HDT	Hydro treating
HEV	Hybrid electric vehicle
Hp	Horse power
HRJ	Hydro-treated renewable jet
HVAC	Heating ventilation and air conditioning
IATA	International Airline Industry Association
IBP	Initial boiling point
IC	Internal combustion
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IFO	Intermediate fuel oil
IMEP	Indicated mean effective pressure
IPCC	Intergovernmental Panel on Climate Change
IT	Injection timing
JASO	Japanese Automobile Standard Organization
K	Kelvin
kg	Kilogram
km	Kilometre
km/h	Kilometre per hour
KOH	Potassium hydroxide
kW	Kilowatt
Lb-ft	Pounds-foot
LCV	Light commercial vehicles
LH_2	Liquefied hydrogen
LNG	Liquefied natural gas
LOME	Line seed oil methyl ester
LPG	Liquefied petroleum gas
m^3	Cubic metre
M15	15% Methanol + 85% gasoline
M85	85% Methanol + 15% gasoline
MAP	Manifold absolute pressure
MEA	Mono-ethanol amine
MJ	Mega Joule
mm	Millimetre
MMT	Million metric tons
MON	Motor octane number
Mpg	Miles per gallon
Mph	Miles per hour
MT	Million ton
MTBE	Methyl tetra butyl ether
MTOE	Million ton oil equivalent
MUV	Multi-utility vehicle

N_2	Nitrogen
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NASA	National Aeronautical Space Association
NEDC	New European Driving Cycle
NGV	Natural gas vehicles
NH_3	Ammonia
NO_x	Oxides of nitrogen
O_3	Ozone
OC	Operating fuel cost
OECD	Organization for Economic Co-operation and Development
OEM	Original Engine Manufacturer
ON	Octane number
PAH	Poly aromatic hydrocarbon
PAHC	Polycyclic aromatic hydrocarbon
PISI	Port injected spark ignition engine
PJ	Pico Joule
PM	Particulate matter
POX	Partial oxidation
ppm	Parts per million
psi	Pounds square inch
PV	Photo voltaic
R&D	Research & Development
RFO	Refined fuel oil
Rm	Raw material
RON	Research octane number
RPK	revenue passenger kilometre
rpm	Revolutions per minute
s	Seconds
SCR	Selective catalytic reduction
SEC	Specific energy consumption
SI	Spark ignition
SI engine	Spark ignition engine
SiO_2	Silicon oxide
SIT	Self-ignition temperature
SMD	Sauter mean diameter
SMR	Steam methane reforming
SO_x	Sulphur oxides
SPK	Synthetic paraffinic kerosene
SRM	Steam reforming method
SUV	Sports utility vehicles
TAN	Total acid number
TBN	Total base number
TC	Transportation cost
T_{EG}	Exhaust temperature

TFp	Transportation cost of finished product from downstream of industries to retailer
TFpe	Transportation cost of finished product from retailer to end user
TRm	Transportation cost of raw material
TWe	Transportation cost of waste effluent
UBHC	Unburnt hydrocarbon
UC	Utility cost
UHC/UBHC	Unburnt hydrocarbons
UKCCC	United Kingdom Committee on Climate Change
US/USA	United States/United States of America
We	Waste effluent
Wh/kg	Watt-hour/kilogram
Wh/L	Watt-hour/litre
WOT	wide open throttle
WTW	Well to wheel
wt/wt	weight by weight
XTL	Anything to liquid (synthesis fuel)
ZEV	Zero emission vehicles
ZnO	Zinc oxide
ZnO_2	Zinc dioxide

1

Introduction: Land, Sea and Air Transportation

1.1 Transportation

Transportation can be defined as the movement of people, livestock and all types of goods from one place to another through the use of self-power, man-power, motor power or combinations of any two or all of the above. Nature is a good example of movement as planets rotate in their orbit around the sun. Six billion people in the world have to journey from their origin/home/house to other places for their education, office work, industry and other general purposes. The materials normally transported include commodities such as food items and industrial goods from the origin of production to the customer's destination for the survival of human life.

A raw material has to be moved from its source to end-users as depicted in Figure 1.1. Raw materials (Rm_1, Rm_2, Rm_3, …, Rm_n) have to be transported from their place of origin to upstream of an industry. The finished products (Fp_1, Fp_2, Fp_3, …, Fp_n) have to be transported from downstream of an industry to the retailer's end and then to the end-users (Fpe_1, Fpe_2, Fpe_3, …., Fpe_n). The waste effluent (We_1, We_2, We_3, …, We_n) from the industry needs to be disposed of to a safe place in view of its environmental concern. Thus, the transportation cycle of consumer goods is completed in this manner for most of the industries such as cement, paper, sugar and petrochemical. Total transportation cost could be written as a summation of all transportation costs such as raw materials, finished product to retailer, retailer to end-users and waste effluent disposal, as shown in Equation 1.1

$$\text{Total transport cost} \sum_{i}^{n} \mathrm{TRm}_i = \sum_{i}^{n} \mathrm{TFp}_i \sum_{i}^{n} \mathrm{TFpe}_i \sum_{i}^{n} \mathrm{TWe}_i \qquad (1.1)$$

where $i = 1,2,3,4,\ldots, n$.

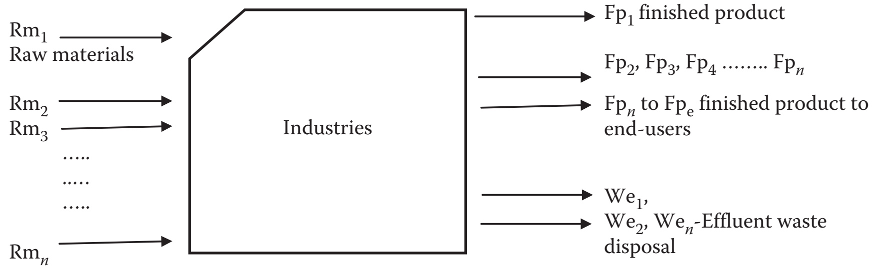

FIGURE 1.1
Schematic diagram of transportation of raw materials to end-users.

1.2 Modes of Different Transportation

A line diagram showing different modes of transportation is given in Figure 1.2. Two-, three- and four-wheelers are used for personal transportation for travelling short distances, whereas air mode transportation is used for longer distances. In case of mass transportation, heavy goods are transported using land mode transportation by internal combustion engine-powered vehicles and locomotives. Air mode is used for light goods and it is the fastest service that is preferred by all sectors. However, it is an expensive mode of transportation that is used in situations depending on the emergency or time-bound activities. Even though sea mode transportation is the cheapest as compared to other modes, it is only possible for ocean-bounded countries.

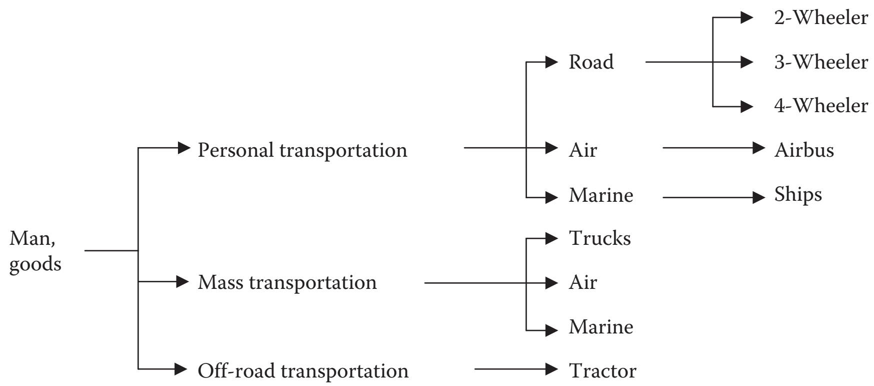

FIGURE 1.2
Line diagram of different modes of transportation.

1.3 Indigenous Production Levels of Crude Oil from Different Countries

The indigenous production of crude oil, shale oil, oil sands and NGLs (the liquid content of natural gas from where this is recovered separately) from different countries is given in Table 1.1. A comparison of the production of crude oil from different countries is shown in Figure 1.3.

1.4 Import and Export Levels in Different Countries

The production and import scenarios of the United States, China and India are shown in Figure 1.4a, b and c. The United States imports 68% of its crude oil requirement (Figure 1.4a), whereas India imports 79% of its crude oil requirement from other countries, as shown in Figure 1.4c. Trade movements of crude oil from different countries are shown in Table 1.2. Details of India's crude oil production and import from other countries are shown in Figure 1.5.

- Europe's energy deficit remains roughly at today's levels for oil and coal but increases by 65% for natural gas (Figure 1.6). This is matched by gas production growth in the former Soviet Union (FSU) [4].
- Among energy-importing regions, North America is an exception, with growth in biofuel supplies and unconventional oil and gas turning today's energy deficit (mainly oil) into a small surplus by 2030.
- In aggregate, today's energy importers will need to import 40% more in 2030 than they do today, with deficits in Europe and Asia Pacific met by supply growth in the Middle East, the FSU, Africa and South and Central America.
- China's energy deficit increases by 0.8 Btoe (billion tonnes of oil equivalent, spread across all fuels) while India's import requirement grows by 0.4 Btoe (mainly oil and coal). The rest of Asia Pacific remains a big oil importer at similar levels to today.
- Asian energy requirements are partially met by increased Middle East and African production, but the rebalancing of global energy trade as a result of the improved net position in the Americas is also a key factor [4].
- Import dependency, measured as the share of demand met by net imports, increases for most major energy importers except the United States (Figure 1.7).

TABLE 1.1

Production of Crude Oil, Shale Oil, Oil Sands and NGLs (Excludes Liquid Fuels from Other Sources Such as Biomass and Coal Derivatives)

Production (Million Tonnes)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
United States	352.6	349.2	346.8	338.4	329.2	313.3	310.2	309.8	304.9	328.6	339.1
Canada	126.9	126.1	135.0	142.6	147.6	144.9	153.4	158.3	156.8	156.1	162.8
Mexico	171.2	176.6	178.4	188.8	190.7	187.1	183.1	172.7	157.7	147.5	146.3
Argentina	40.4	41.5	40.9	40.2	37.8	36.2	35.8	34.9	34.1	33.8	32.5
Brazil	63.2	66.3	74.4	77.0	76.5	84.6	89.2	90.4	93.9	100.4	105.7
Colombia	35.3	31.0	29.7	27.9	27.3	27.3	27.5	27.6	30.5	34.1	39.9
Ecuador	20.9	21.2	20.4	21.7	27.3	27.6	27.7	26.5	26.2	25.2	25.2
Peru	4.9	4.8	4.8	4.5	4.4	5.0	5.1	5.1	5.3	6.4	6.9
Trinidad and Tobago	6.8	6.5	7.5	7.9	7.3	8.3	8.3	7.2	6.9	6.8	6.5
Venezuela	167.3	161.6	148.8	131.4	150.0	151.0	144.2	133.9	131.5	124.8	126.6
Other South and Central America	6.6	6.9	7.8	7.8	7.3	7.2	7.0	7.1	7.0	6.7	6.6
Azerbaijan	14.1	15.0	15.4	15.5	15.6	22.4	32.5	42.8	44.7	50.6	50.9
Denmark	17.7	17.0	18.1	17.9	19.1	18.4	16.7	15.2	14.0	12.9	12.2
Italy	4.6	4.1	5.5	5.6	5.5	6.1	5.8	5.9	5.2	4.6	5.1
Kazakhstan	35.3	40.1	48.2	52.4	60.6	62.6	66.1	68.4	72.0	78.2	81.6
Norway	160.2	162.0	157.3	153.0	149.9	138.2	128.7	118.6	114.2	108.8	98.6
Romania	6.3	6.2	6.1	5.9	5.7	5.4	5.0	4.7	4.7	4.5	4.3
Russian Federation	323.3	348.1	379.6	421.4	458.8	470.0	480.5	491.3	488.5	494.2	505.1
Turkmenistan	7.2	8.0	9.0	10.0	9.6	9.5	9.2	9.8	10.3	10.4	10.7
United Kingdom	126.2	116.7	115.9	106.1	95.4	84.7	76.6	76.8	71.7	68.2	63.0
Uzbekistan	7.5	7.2	7.2	7.1	6.6	5.4	5.4	4.9	4.8	4.5	3.7
Other Europe and Eurasia	22.4	22.2	23.6	24.0	23.5	22.0	21.7	21.6	20.6	19.6	18.2
Iran	191.3	191.4	180.9	203.7	207.8	206.3	208.2	209.7	209.9	201.5	203.2

Iraq	128.8	123.9	104.0	66.1	100.0	90.0	98.1	105.2	119.5	119.8	120.4
Kuwait	109.1	105.8	98.2	114.8	122.3	129.3	132.7	129.9	137.2	121.7	122.5
Oman	46.4	46.1	43.4	39.6	38.1	37.4	35.7	34.5	35.9	38.7	41.0
Qatar	36.1	35.7	35.2	40.8	46.0	47.3	50.9	53.6	60.8	57.9	65.7
Saudi Arabia	456.3	440.6	425.3	485.1	506.0	526.8	514.3	494.2	515.3	464.7	467.8
Syria	27.3	28.9	27.2	26.2	24.7	22.4	21.6	20.6	19.8	18.6	19.1
United Arab Emirates	122.1	118.0	110.2	124.5	131.7	137.3	145.5	140.7	142.9	126.3	130.8
Yemen	21.3	21.5	21.5	21.1	19.9	19.6	17.9	16.3	14.4	13.5	12.5
Other Middle East	2.2	2.2	2.2	2.2	2.2	1.6	1.4	1.6	1.5	1.7	1.7
Algeria	66.8	65.8	70.9	79.0	83.6	86.4	86.2	86.5	85.6	77.9	77.7
Angola	36.9	36.6	44.6	42.8	54.5	69.0	69.6	82.5	92.2	87.4	90.7
Chad	—	—	—	1.2	8.8	9.1	8.0	7.5	6.7	6.2	6.4
Brazzaville	13.1	12.1	12.3	11.2	11.6	12.6	14.3	11.7	12.4	13.9	15.1
Egypt	38.8	37.3	37.0	36.8	35.4	33.9	33.7	34.1	34.6	35.3	35.0
Equatorial Guinea	4.5	8.8	11.4	13.2	17.4	17.7	16.9	17.3	17.2	15.2	13.6
Gabon	16.4	15.0	14.7	12.0	11.8	11.7	11.7	11.5	11.8	11.5	12.2
Libya	69.5	67.1	64.6	69.8	76.5	81.9	84.9	85.0	85.3	77.1	77.5
Nigeria	105.4	110.8	102.3	109.3	119.0	122.1	117.8	112.1	103.0	99.1	115.2
Sudan	8.6	10.7	11.9	13.1	14.9	15.0	16.3	23.1	23.7	23.6	23.9
Tunisia	3.7	3.4	3.5	3.2	3.4	3.4	3.3	4.6	4.2	4.0	3.8
Other Africa	7.2	6.6	6.7	6.8	8.1	7.7	7.6	8.3	8.1	7.7	7.1
Australia	35.3	31.8	31.5	26.6	24.8	24.5	23.2	23.5	23.7	21.9	23.8
Brunei	9.4	9.9	10.2	10.5	10.3	10.1	10.8	9.5	8.5	8.2	8.4
China	162.6	164.8	166.9	169.6	174.1	181.4	184.8	186.3	190.4	189.5	203.0
India	34.2	34.1	35.2	35.4	36.3	34.6	35.8	36.1	36.1	35.4	38.9
Indonesia	71.5	67.9	63.0	57.3	55.2	53.1	48.9	47.5	49.0	47.9	47.8
Malaysia	33.7	32.9	34.5	35.6	36.5	34.4	33.5	34.2	34.6	33.1	32.1
Thailand	7.0	7.5	8.2	9.6	9.1	10.8	118	12.5	13.3	13.7	13.8
Vietnam	16.2	17.1	17.3	17.7	20.8	19.4	17.8	16.4	15.4	16.8	18.0
Other Asia Pacific	9.4	9.1	9.0	9.1	10.5	12.5	13.2	13.9	14.7	14.3	13.6
Total world	3611.8	3601.6	3584.2	3701.1	3877.0	3906.6	3916.2	3904.3	3933.7	3831.0	3913.7

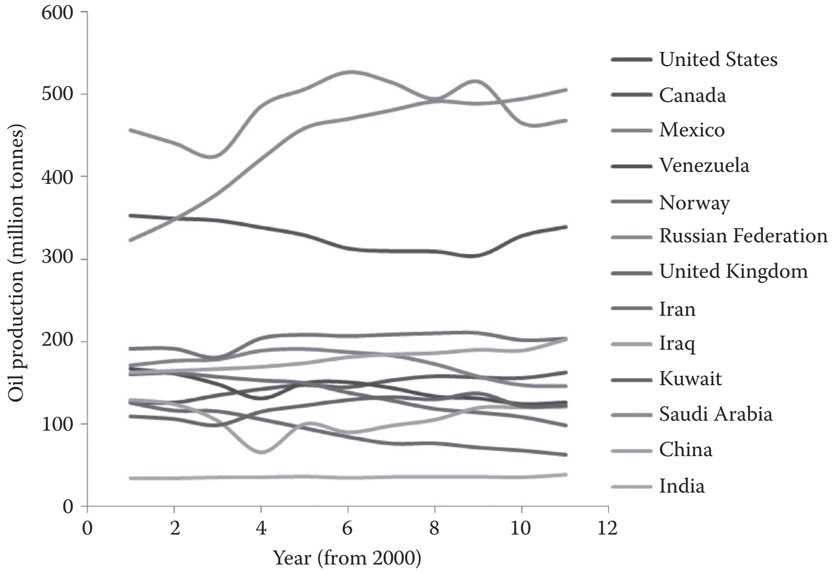

FIGURE 1.3
Comparison of production of crude oil from different countries.

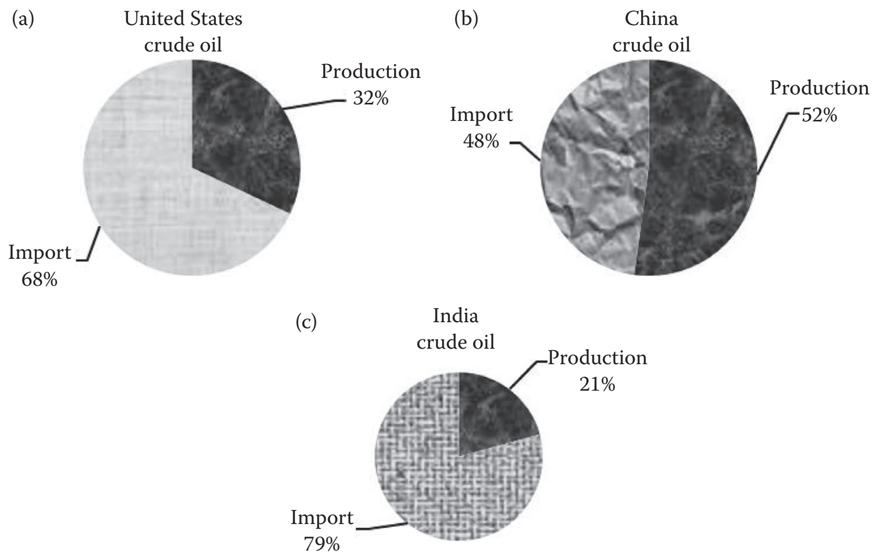

FIGURE 1.4
Production and import scenarios of crude oil in the (a) USA, (b) China and (c) India. (Adapted from IEA World Energy Outlook, www.iea.org, 2009; www.petroleum.nic.)

TABLE 1.2

Trade Movements of Crude Oil Worldwide

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Imports (Thousand Barrels Daily)											
United States	11,092	11,618	11,357	12,254	12,898	13,525	13,612	13,632	12,872	11,453	11,689
Europe	11,070	11,531	11,895	11,993	12,538	13,261	13,461	13,953	13,751	12,486	12,094
Japan	5329	5202	5070	5314	5203	5225	5201	5032	4925	4263	4567
Rest of the world	15,880	16,436	16,291	17,191	18,651	19,172	20,287	22,937	23,078	24,132	25,160
Total world	43,371	44,787	44,613	46,752	49,290	51,182	52,561	55,554	54,626	52,333	53,510
Exports (Thousand Barrels Daily)											
United States	890	910	904	921	991	1129	1317	1439	1967	1947	2154
Canada	1703	1804	1959	2096	2148	2201	2330	2457	2498	2518	2599
Mexico	1814	1882	1966	2115	2070	2065	2102	1975	1609	1449	1539
South and Central America	3079	3143	2965	2942	3233	3528	3681	3570	3616	3748	3568
Europe	1967	1947	2234	2066	1993	2149	2173	2273	2023	2034	1888
Former Soviet Union	4273	4679	5370	6003	6440	7076	7155	8334	8184	7972	8544
Middle East	18,944	19,098	18,062	18,943	19,630	19,821	20,204	19,680	20,128	18,409	18,883
North Africa	2732	2724	2620	2715	2917	3070	3225	3336	3260	2938	2871
West Africa	3293	3182	3134	3612	4048	4358	4704	4830	4587	4364	4601
Asia Pacific	3736	3914	3848	3978	4189	4243	4312	6004	5392	5631	6226
Rest of the world	940	1506	1551	1361	1631	1542	1359	1656	1363	1323	637
Total world	43,371	44,789	44,613	46,752	49,290	51,182	52,561	55,554	54,626	52,333	53,510

Source: Adapted from BP Statistical Review of World Energy, http://www.bp.com/statistical review, June 2011.

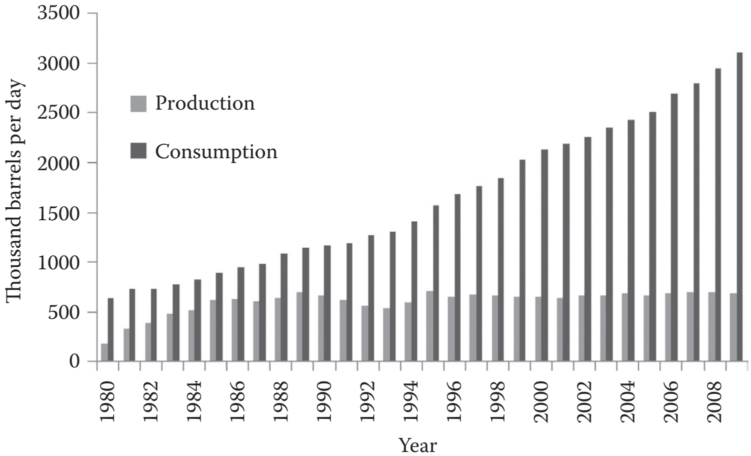

FIGURE 1.5
India's crude oil production and import from other countries. (Adapted from www.petroleum.nic.)

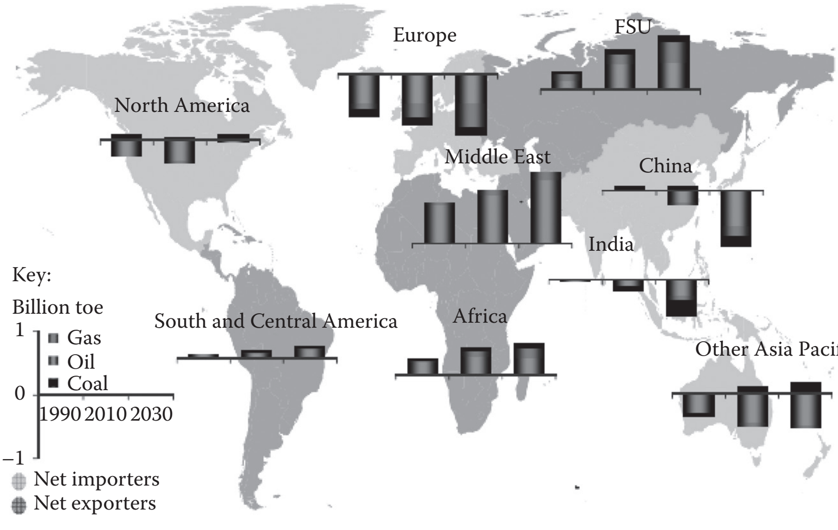

FIGURE 1.6
Net imports and exports of gas, oil and coal—world view. (Adapted from BP Energy Outlook 2030, London, January 2012.)

- The import share of oil demand and the volume of oil imports in the United States will fall below the 1990s levels, largely due to the rising production of domestic shale oil and ethanol, displacing crude imports. The United States also becomes a net exporter of natural gas.
- In China, imports of oil and natural gas rise sharply as the growth in demand outpaces domestic supply. Oil continues to dominate

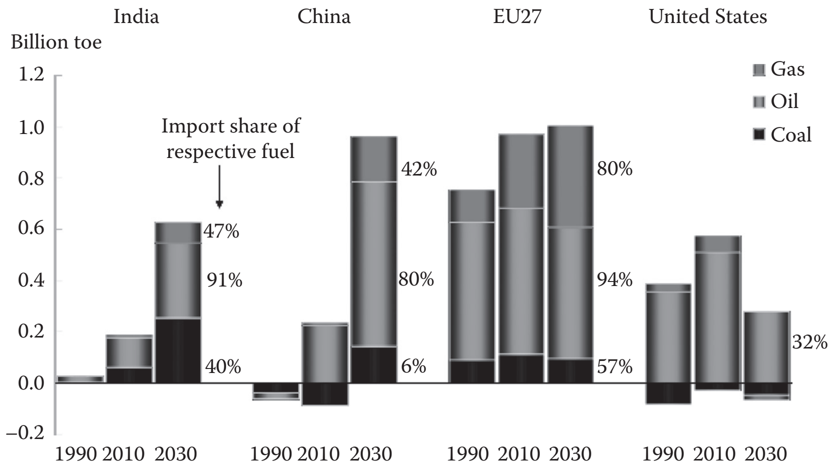

FIGURE 1.7
Import dependency rises in Asia and Europe. (Adapted from BP Energy Outlook 2030, London, January 2012.)

China's energy imports, although gas imports increase by a factor of 16. China also becomes a major importer of coal.

- India will increasingly have to rely on imports of all three—oil, coal and natural gas—to supply its growing energy needs.
- European net imports (and imports as a share of consumption) rise significantly due to the declining domestic oil and gas production and rising gas consumption. Virtually all of the growth in net imports is from natural gas [4].

1.5 Refining Capacities of Petrol and Diesel Worldwide

People have used naturally available crude oil for thousands of years. The ancient Chinese and Egyptians, for example, burned oil to produce light. Before the 1850s, Americans often used whale oil for light. When whale oil became scarce, people began looking for other oil sources. In some places, oil seeped naturally to the surface of ponds and streams. People skimmed this oil and made it into kerosene. Kerosene was commonly used to light America's homes before the arrival of the electric light bulb.

As demand for kerosene grew, a group of businessmen hired Edwin Drake to drill for oil in Titusville, PA. After much hard work and slow progress, he discovered oil in 1859. Drake's well was 21.18 metres deep, very shallow as compared to today's wells. Drake refined the oil from his well into kerosene for lighting. Gasoline and other products made during refining were simply thrown away because people had no use for them. In 1892, the horseless carriage, or automobile, solved this problem since it required gasoline. By 1920, there were nine million motor vehicles in the United States and gas stations were opening everywhere.

Although research has improved the odds since Edwin Drake's days, petroleum exploration today is still a risky business. Geologists study underground rock formations to find areas that might yield oil. Even with advanced methods, only 23% of exploratory wells found oil in 2009. Developmental wells fared slightly better as 38% of them found oil.

When the potential for oil production is found onshore, a petroleum company brings in a 15–30 m drilling rig and raises a derrick that houses the drilling tools. Today's oil wells average 1600 m deep and may sink below 6000 m. The average well produces about 10 barrels of oil a day.

Oil's first stop after being pumped from a well is an oil refinery. A refinery is a plant where crude oil is processed. Sometimes, refineries are located near oil wells, but usually the crude oil has to be delivered to the refinery by ship, barge, pipeline, truck or train. After the crude oil has reached the refinery, large cylinders store the oil until it is ready to be processed. Tank farms are sites with many storage tanks.

An oil refinery cleans and separates the crude oil into various fuels and by-products. The most important one is gasoline. Some other petroleum products are diesel fuel, heating oil and jet fuel.

Refineries use many different methods to make these products. One method is a heating process called distillation. Since oil products have different boiling points, the end products can be distilled, or separated. For example, asphalts have a higher boiling point than gasoline, allowing the two to be separated.

Refineries have another job. They remove contaminants from the oil. A refinery removes sulphur from gasoline, for example, to increase its efficiency and to reduce air pollution. Nine per cent of the energy in the crude oil is used to operate the refineries. The various products that are produced from one barrel of oil (1 barrel of oil = 159.11 L) are shown in Figure 1.8. The refining capacity of different countries is shown in Table 1.3.

1.6 Energy Consumption: World View

Crude oil is the world's largest total primary energy consumed as shown in Table 1.4. The crude oil-derived diesel and gasoline fuels are used as fuels in internal combustion engine-powered vehicles. However, some countries like Russia mostly use natural gas due to its abundant availability. It is clearly seen that crude oil usage influences the economic development of a country. If the crude oil cost fluctuates, there is an unstable economic development of a nation.

FIGURE 1.8
Products produced from a barrel of oil.

It can be observed from Figure 1.9 that economic growth is always associated with growth in energy consumption and associated emission. The growth rates of primary energy consumption, GDP and CO_2 emission were 4.9%, 4.7% and 4.7%, respectively. Passenger transportation by car is the highest for all countries as compared to other modes as shown in Table 1.5. The second largest transportation is by air for EU27 and the United States. The freight transportation for EU27, the United States, Japan, China and Russia is shown in Table 1.5. The rail transportation for freight is the highest in the United States, whereas sea transport is the highest in China. It is dependent on the geological structure and the country's political policy.

Based on the above discussion for different countries, it could be concluded that the passenger car, air and bus play a vital role for passenger transportation, whereas the rail and sea modes play a pivotal role for freight transportation.

It can be seen from the above discussion that the world economic development is primarily based on crude oil. However, the oil resources gradually deplete year after year as the demand increases steeply. The reserve-to-production ratio of fossil fuels such as oil, natural gas and coal is shown in Figure 1.10. If this ratio of oil reduces below a minimum value, it results in severe worldwide energy crisis. If the demand continues at the same rate and no new oilfield is explored, the oil resources may get depleted in about 50 years. Otherwise, it may not be possible to meet the required demand. As the crude oil price fluctuates, it affects the economic development of a country directly. The average crude oil price for the year 2008 peaked about 100 $/barrel as compared to the past couple of decades as shown in Figure 1.11. In countries that have a higher

TABLE 1.3

Refinery Capacities from Various Countries

Capacity (Thousand Barrels Daily)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
United States	16,595	16,785	16,757	16,894	17,125	17,339	17,443	17,594	17,672	17,688	17,594
Canada	1861	1917	1923	1959	1915	1896	1914	1907	1951	1976	1914
Mexico	1481	1481	1463	1463	1463	1463	1463	1463	1463	1463	1463
Argentina	626	619	619	620	623	627	623	634	634	635	638
Brazil	1849	1849	1854	1915	1915	1916	1916	1935	2045	2095	2095
Netherlands Antilles	320	320	320	320	320	320	320	320	320	320	320
Venezuela	1269	1269	1269	1269	1284	1291	1294	1303	1303	1303	1303
Other South and Central America	2207	2189	2234	2229	2235	2251	2260	2310	2356	2335	2351
Belgium	770	785	803	805	782	778	774	745	745	823	823
France	1984	1961	1987	1967	1982	1978	1959	1962	1971	1873	1703
Germany	2262	2274	2286	2304	2320	2322	2390	2390	2366	2362	2091
Greece	403	412	412	412	412	418	425	425	425	425	440
Italy	2485	2485	2485	2485	2497	2515	2526	2497	2396	2396	2396
Netherlands	1277	1278	1282	1282	1284	1274	1274	1236	1280	1280	1274
Norway	318	307	310	310	310	310	310	310	310	310	310
Russian Federation	5655	5628	5590	5454	5457	5522	5599	5596	5549	5527	5555
Spain	1330	1330	1330	1347	1372	1377	1377	1377	1377	1377	1427
Sweden	422	422	422	422	422	422	422	422	422	422	422
Turkey	713	713	713	713	693	613	613	613	613	613	613

United Kingdom	1778	1769	1785	1813	1848	1819	1836	1819	1827	1757	1757
Other Europe and Eurasia	6002	5912	5754	5691	5687	5650	5537	5573	5559	5596	5705
Iran	1597	1597	1597	1607	1642	1642	1727	1772	1805	1860	1860
Iraq	740	740	740	740	740	743	748	755	744	763	856
Kuwait	740	759	809	909	931	931	931	931	931	931	931
Saudi Arabia	1806	1806	1810	1890	2075	2100	2100	2100	2100	2100	2100
United Arab Emirates	440	674	711	645	620	620	620	625	673	673	673
Other Middle East	1168	1170	1248	1248	1248	1248	1283	1339	1345	1491	1491
Total Africa	2897	3164	3228	3177	3116	3224	3049	3037	3171	3022	3292
Australia	828	815	829	756	763	711	694	733	734	734	740
China	5407	5643	5933	6295	6603	7165	7865	8399	8722	9479	10,121
India	2219	2261	2303	2293	2558	2558	2872	2983	2992	3574	3703
Indonesia	1127	1127	1092	1057	1057	1057	1133	1157	1068	1106	1158
Japan	5010	4705	4721	4683	4567	4529	4542	4598	4650	4621	4463
Singapore	1255	1255	1255	1255	1255	1255	1255	1255	1385	1385	1385
South Korea	2598	2598	2598	2598	2598	2598	2633	2671	2712	2712	2712
Taiwan	732	874	1159	1159	1159	1159	1140	1197	1197	1197	1197
Thailand	899	1064	1068	1068	1068	1078	1125	1125	1175	1240	1253
Other Asia Pacific	1403	1512	1487	1416	1410	1428	1435	1443	1459	1605	1662
Total world	82,473	83,469	84,183	84,468	85,355	86,147	87,427	88,552	89,446	91,068	91,791

TABLE 1.4
World Energy Consumption by Different Fuel Type (Year: 2009)

S. No.	Region	Oil (MT)	Natural Gas (MTOE)	Coal (MTOE)	Nuclear Energy (MTOE)	Hydroelectricity (MTOE)	Total (MTOE)
1	Total North America	1025.5	736.6	531.3	212.7	158.3	2664.4
2	Total South and Central America	256	121.2	22.5	4.7	158.4	562.9
3	Total Europe and Eurasia	913.9	952.8	456.4	265	182	2770
4	Total Middle East	336.3	311	9.2	—	2.4	659
5	Total Africa	144.2	84.6	107.3	2.7	22	360.8
6	Total Asia Pacific	1206.2	446.9	2151.6	125.3	217.1	4147.2
	Total world	3882.1	2653.1	3278.3	610.5	740.3	11,164.3

Source: Adapted from BP Statistical Review of World Energy, http://www.bp.com/statistical review S, June 2010.

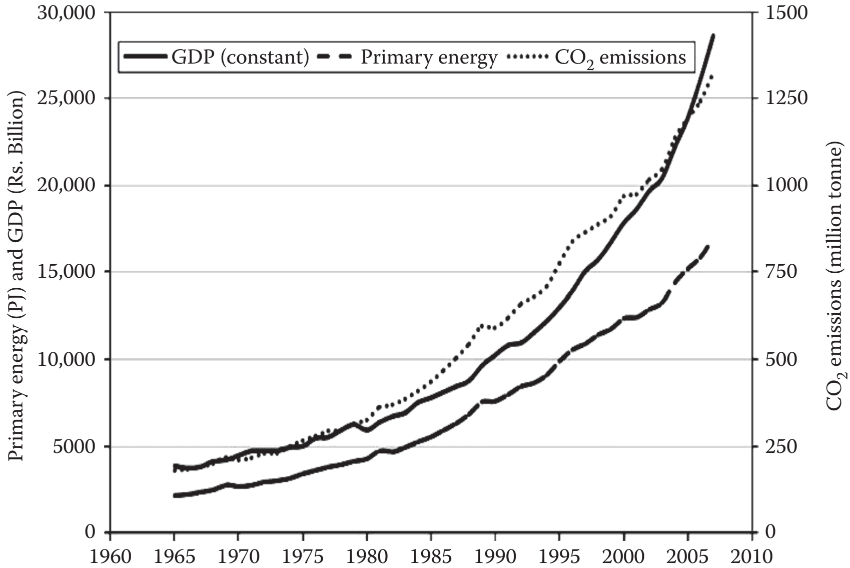

FIGURE 1.9
Trends in GDP, primary energy consumption and CO_2 emission in India. 1 U.S. dollar = INR 54.020 (on September 2012). (Adapted from D. R. Balachandra and N. H. Ravindranath, *Journal of Policy*, 38, 6428–6438, 2010.)

GDP growth rate, the high dependency on crude oil import from other countries leads to unstabilised economic growth. The solution to this problem lies in the exploration of alternative fuels for sustainable transportation.

1.7 Transportation Sector: Current Scenario

The primary modes of transportation are land, air and water. The land mode plays a pivotal role in personal, mass and off-road transportation as already depicted in Figure 1.2. The personal transport over a short distance is normally done by two-, three- and four-wheelers.

Man—personal transportation: Two-wheeler (motorbike, mopeds and scooters), three-wheeler (auto), four-wheeler (car, MUV), bus (six-wheeler)

Mass transportation: Three- (LCV), four- (LCV and HCV), six- and more wheelers (HCV)

Off-road transportation: Tractors and farm equipments such as tillers and grinders

TABLE 1.5
Passenger and Freight Transport from Different Countries

S. No.	Mode of Transport	Passenger Transport (Billon Passenger Kilometre)				
		EU27	USA	Japan	China	Russia
1	Passenger car	4725	7201.8[a]	769.1[b]	1263.6[c]	—
2	Bus + trolley bus + coach	546.7	243	89.9	—	124.8
3	Railway	409.2	37.1	404.6	777.9	175.9
4	Tram + metro	89.0	21.1			51.6
5	Waterborne	40.9	0.6	5.5[d]	7.5	0.9
6	Air (domestic/intra-EU-27)	561	977.8	81	288.3	122.6
		Freight Transport (Billon Tonnes Kilometre)				
1	Road	1877.7	1922.9	346.4	1135.5	216.3
2	Rail	442.7	2656.6	22.3	2379.7	2116.2
3	Inland waterways	145.3	472.3	—	1559.9	64
4	Oil pipeline	124.1	814.2	—	186.6[e]	2464.0
5	Sea (domestic/intra-EU-27)	1498.0	333.0	187.5	4868.6	85.0

Source: Adapted from Eurostat, Japan Statistics Bureau, US Bureau of Transportation Statistics, Goskom STAT (Russia), National Bureau of Statistics of China, International Transport Forum. EU and transport in figures, Statistical pocket book 2010, European Union 2010.

[a] United States: including light trucks/vans.
[b] Japan: including light motor vehicles and taxis.
[c] China: including buses and coaches.
[d] Japan: included in railway passenger kilometre (pkm).
[e] China: oil and gas pipelines.

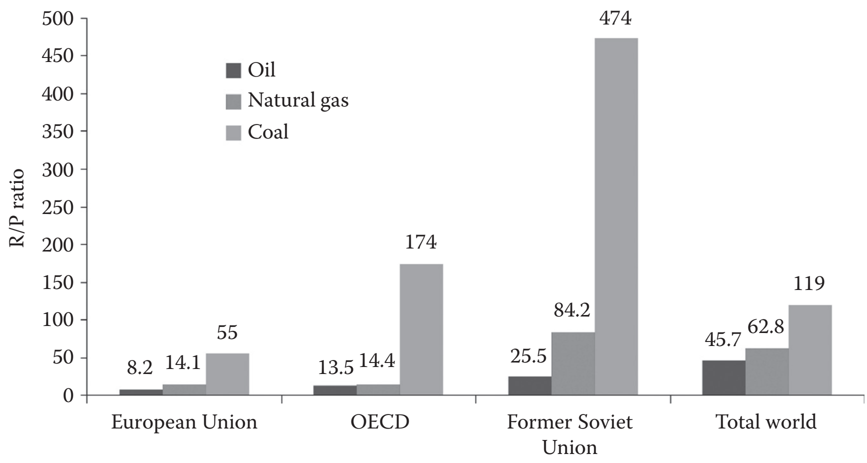

FIGURE 1.10
Fossil fuel reserves to production (R/P) ratio. (Adapted from Repowering Transport—A Cross-Industry Report, World Economic Forum, Geneva, February 2011.)

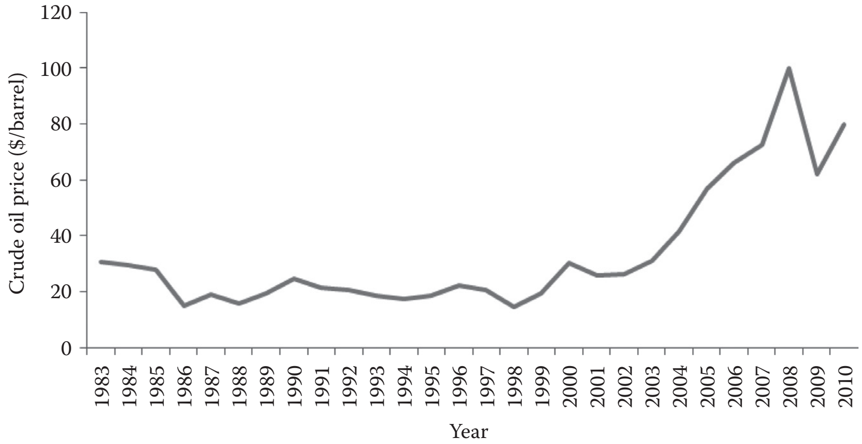

FIGURE 1.11
Crude oil price from the year 1983 to 2010. (Adapted from IEA World Energy Outlook, www.iea.org, 2009.)

The statistical data of vehicles in India and around the globe are given in Table 1.6. The engine power of a passenger car normally lies in the range of 15–300 kW.

1.7.1 Mass Transportation: Diesel Buses and Trucks

The medium distance is generally covered by public transportation such as buses. The mass transportation for goods and raw material is also undertaken by trucks, lorries and light commercial vehicles. Goods from industries to retailers are transported by trucks. The local distribution is undertaken by a three- or four-wheeled LCV.

1.7.2 High-Power Rail Transportation

The larger-distance transportation is usually done by using rail transportation. The advantages of rail transportation are lower travel cost and fast services due to a free traffic. However, it cannot provide services like road transport.

1.7.3 Aviation Sector: Gas Turbines

Air transportation is the second largest sector for passenger transportation in several developed countries. Gas turbines are used in airbuses. The growth in this sector has been significant due to an enhanced increase in economic growth. The fuels used for the airbus are aviation kerosene and jet fuels. NO_x and CO_2 are major pollutants in the aviation sector. In addition to this, noise pollution is another irritant to the public.

TABLE 1.6
Statistical Data of Vehicles (2008)

Mode of Transport	Range of Engine Power (in kW)	Type of Engine	Number of Vehicles in India	Number of Vehicles in the World
Road Transport				
Mopeds, scooters and motorcycles	0.75–7	SI, 2/4 stroke	71,025,312	117,264,312
Small passenger cars	15–75	SI, 4 stroke	12,546,841	165,641,327
Large passenger cars	75–200	SI, 4 stroke	1,120,369	196,565,887
Light commercial	35–150	SI/CI, 4 stroke,	3,368,923	268,794,513
Heavy commercial	120–300	CI, 4 stroke	2,125,676	255,615,515
Agricultural	3–150	SI/CI, 2/4 stroke	2,748,686	25,680,124
Rail Transport				
Railway locomotives	400–3000	CI, 2/4 stroke	5022	26,415
Air Transport				
Helicopters	45–1500	SI, 4 stroke	298	56,200
Aeroplanes	45–2700	SI, 4 stroke	1151	418,899
Marine Transport				
Ships	3500–22,000	CI, 2/4 stroke	735	43,457

Source: Adapted from www.data.worldbank.org.

1.7.4 Global Vehicle Fleet

The global vehicle fleet (commercial vehicles and passenger cars) will grow rapidly—by 60% from around 1 billion today to 1.6 billion by 2030 (Figure 1.13). Most of the growth will be in the developing world with some mature markets at saturation levels. More than three quarters of the total fleet growth will occur in the non-OECD countries, where the vehicle population will rise from 340 million to 840 million over the next 20 years—a 2½-fold inscrease (Figure 1.12). From 2010 to 2030, the vehicle density per 1000 population will grow from approximately 50 to 140 in China (5.7% p.a.) and from 20 to 65 in India (6.7% p.a.) as shown in Figure 1.13. China is expected to follow a slower path to vehicle ownership than is seen historically in other countries. This reflects the impact of current and assumed future policies, designed to limit oil import dependency and congestion, including rising fuel taxation, widespread mass transportation options and relatively uneven income distribution [4].

- Transport fuel in 2030 is expected to be dominated by oil (87%) and biofuels (7%). Other fuels gain share, such as natural gas and electricity (4% and 1%, respectively, in 2030), are constrained by limited policy support combined with a general lack of infrastructure in all but a handful of markets.

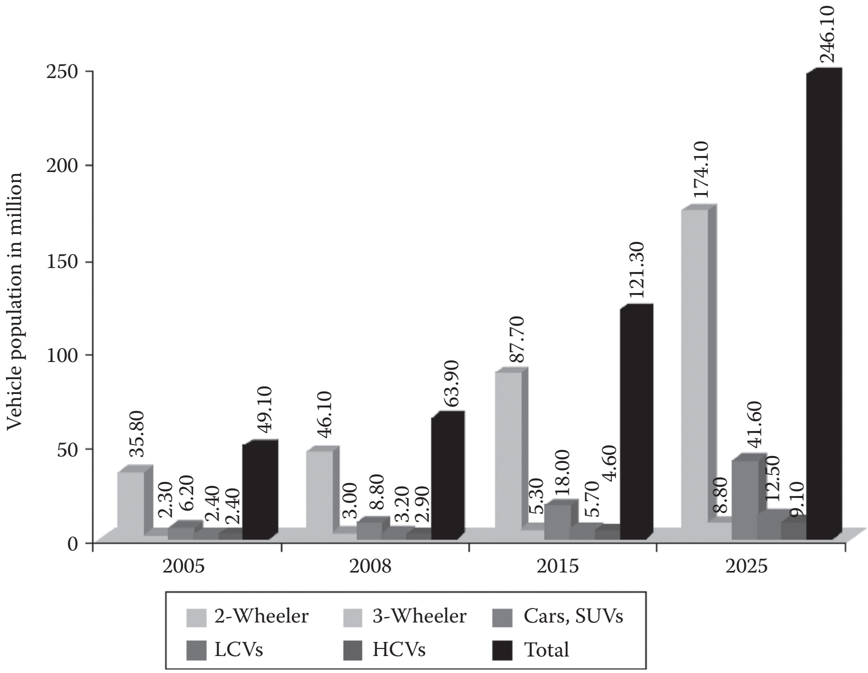

FIGURE 1.12
Projections of vehicle fleet. (Adapted from Asian Development Bank (ADB), Energy efficiency and climate change considerations for on-road transport in Asia, Asian Development Bank, Philippines, 2006.)

- Despite the projected 60% increase in vehicles over the next 20 years, energy consumption in total transport is forecast to grow only 26% (1.2% p.a.—down from 1.9% p.a. between 1990 and 2010).
- The growth rate of energy (Figure 1.13) used for transport declines due to accelerating improvements in fuel economy and the impact of high oil prices on driving behaviour. Vehicle saturation in the OECD countries and a likely increase in taxation (or subsidy reduction) and the development of mass transportation in the non-OECD countries are other factors.
- Vehicle fuel economy improvements are driven by a tightening policy (CO_2 emission limits in Europe and corporate average fuel economy (CAFE) standards in the United States), which is enabled by improving technology. Prices also play a role, since high fuel costs provide an additional incentive to improve vehicle efficiency [4].
- Assuming no changes to vehicle usage, efficiency and the use of alternatives, oil demand in road transport would increase by a massive 23 Mb/d over the next 20 years, more than the total projected

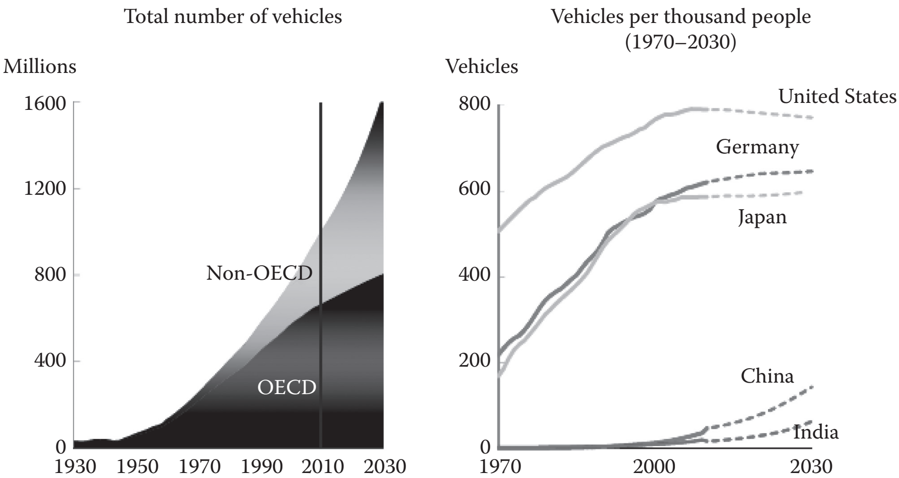

FIGURE 1.13
Growth of global vehicle fleet. (Adapted from BP Energy Outlook 2030, London, January 2012.)

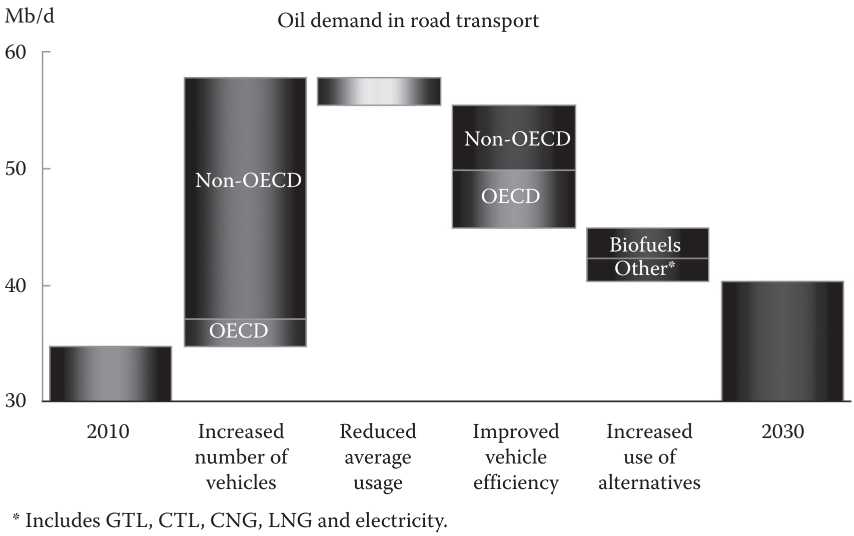

FIGURE 1.14
Oil demand in road transport.

oil demand growth (16 Mb/d), mostly due to more vehicles in the non-OECD countries. Instead, we project oil demand growth for road transport to be 6 Mb/d. Vehicle fuel economy is forecast to improve by 1.1% p.a. in both the OECD and non-OECD countries as shown in Figure 1.14. These efficiency gains are equivalent to 11 Mb/d by

2030—saving approximately half of the incremental oil demand that would otherwise be required under the above 'no change' case.

- Average miles driven per vehicle is expected to fall (saving 2.4 Mb/d) as high fuel prices (partly due to rising taxes or reduced subsidies), congestion and mass transit outweigh the impact of rising incomes.
- Biofuels make up more than half of the incremental demand for alternative fuels in transport. The use of electric vehicles and compressed natural gas/liquefied natural gas (CNG/LNG) is growing, but there are still barriers delaying the scale-up. Alternative fuels, therefore, are not expected to have a material impact until 2030 [4].

1.8 Fossil Fuel Consumption in the Transport Sector

Transportation and fossil fuels are currently inextricably linked; more than 60% of the 84 million barrels of oil consumed every day powers the world's cars, trucks, planes and other modes of transportation [2,5] and more than 96% of current energy supply to the transport sector is from liquid fossil fuels. Many studies of energy usage in the transport sector show a significant growth in demand in the years ahead. The ramifications of this dependency are becoming more transparent every year. The increasing concentration of conventional oil production in fewer geographies and the increasing cost of new liquid fuels have combined to generate significant unease at the global and national levels regarding the security of supply (Figure 1.15a and b). Indeed, many countries rely on imported crude oil and refined oil products to fuel their transport sectors, and that dependence will only become more severe in the coming decade. U.S. crude oil imports are projected by the International Energy Agency (IEA) to account for 80% of the total consumed by 2020, up from 65% in 2008; China's reliance on imports will increase to 68% from 49% over this same time period.

Recent increases in the price of oil and persistent volatility in energy prices have exacerbated these concerns, and most forecasts point to even higher energy costs in the years to come (Figure 1.16).

The global transport sector consumes about 2200 million tonnes of oil equivalent (MTOE) of energy each year. Of this, more than 96% comes from oil, comprising over 60% of the world's total oil production (Figure 1.17). Road transport accounts for the majority of this energy consumption, with light-duty vehicles (LDVs) accounting for about 52% of the total, while buses and trucks combined represent a 21% share. While air and marine transport each account for roughly 10% of global transport energy consumption, aviation is by far the fastest-growing sector, with a forecast increase in revenue-tonne-kilometres of ~5.1% per year to 2030. The rail sector accounts for roughly 3% of total transport-related energy consumption.