LIFE CYCLE ENERGY DEMAND AND GREENHOUSE GAS EMISSIONS IN CHINA'S ROAD TRANSPORT SECTOR: FUTURE TRENDS AND POLICY IMPLICATIONS

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DECLARATION

This thesis entitled

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Was composed by me and is based on my own work. Where the work of the others has been used, it is fully acknowledged in the text and in captions to tables and illustrations. This thesis has not been submitted for any other qualification.

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Date 26/07/2008

Abstract

A critical evaluation of the national profile of energy supply and demand and the associated greenhouse gas (GHG) emissions in China has been conducted. The contribution of the transport sector in China, the road transport sector in particular, to China's overall energy demand and GHG emissions has been assessed and compared with values for other countries. Approaches for reducing energy demand and GHG emissions in the road transport sector worldwide have been reviewed.

A detailed bottom-up model has been developed using 'LEAP' software, to estimate future energy demand and GHG emissions in China's road transport sector, incorporating China's recent efforts in alternative fuel promotion. Modelling approach and historical data used have been tested and verified to ensure reliability. Two scenarios have been designed to describe the future strategies relating to the development of China's road transport sector between 2005 and 2030. The 'Business as Usual' scenario is used as a baseline reference scenario, in which the government is assumed to do nothing to influence the long-term trends of road transport energy demand. The 'Best Case' scenario is considered to be the most optimized case where a series of available reduction measures are assumed to be implemented. Energy demand and GHG emissions in China's road transport sector up to 2030 are estimated in these two scenarios. The reduction potential and the relative contribution of each measure have been estimated.

A 'life cycle assessment' model for the road transport sector has been developed. The life cycle energy demand and GHG emissions in China's road transport sector are estimated using the model. The reduction potential and the relative contribution of each measure have been re-assessed from a life cycle perspective. Potential impacts on global oil resources, availability and prices are discussed. The importance of life cycle assessment in evaluating the effects of different reduction measures is discussed. Policy implications are presented.

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Contents

Nomenclature

AAGR	average annual growth rate
ADB	Asian Development Bank
AECV	annual energy consumption per vehicle
AFV	alternative fuel vehicle
APEC	Asia-Pacific Economic Cooperation
AQSIQ	General Administration of Quality Supervision, Inspection and Quarantine of the PRC
B20	20% biodiesel and 80% CD blend by volume
BAU	business as usual
BC	best case
BFP	biofuel promotion
BP	British Petroleum
BTS	Bureau of Transportation Statistics
CAAM	Chinese Association of Automotive Manufacturers
CAFE	Corporate Average Fuel Economy
CATRC	China Automotive Technology and Research Center
CD	conventional diesel
CDIAC	Carbon Dioxide Information Analysis Center
CFE	a factor representing the decline in *FE* as a vehicle ages
CG	conventional gasoline
CGR	combustion GHG emission rate
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	CO_2 equivalents
CSPIN	China State Power Information Network
CVDT	a factor representing the change in *VDT* as a vehicle ages
DME	dimethyl ether
DfT	Department for Transport
DoT	Department of Transportation
E	energy demand

E-cassava	cassava-based ethanol
E-corn	corn-based ethanol
E10	10% bioethanol and 90% CG blend by volume
EIA	Energy Information Administration
EU	European Union
F	fossil energy demand
FAFE	fleet average on-road vehicle fuel economy
FAVDT	fleet average annual vehicle distance travelled
FE	vehicle fuel economy in the first year of use
FEC	final energy consumption
FER	fuel economy regulation
FR	fossil energy consumption rate
FShare	the share of fuel type in the newly-added vehicle fleet
FT	fuel tax
G	GHG emissions
GDP	Gross Domestic Product
GHG	greenhouse gas
GR	GHG emission rate
Gt	gigatonnes
GW	gigawatts
GWEC	Global Wind Energy Council
GWh	gigawatt-hours
HC	hydrocarbon
HDB	heavy-duty bus
HDT	heavy-duty truck
ICE	internal combustion engines
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LDB	light-duty bus
LDT	light-duty truck
LEAP	Long-range Energy Alternatives Planning System
LFE	labelled fuel economy

LNG	liquefied natural gas
LPG	liquefied petroleum gas
MC	motorcycle
MCC	Ministry of Commerce of the PRC
MDT	medium-duty truck
MPS	Ministry of Public Security of the PRC
MT	mini truck
Mtoe	million tonnes of oil equivalent
MV	minivan
MW	megawatts
NBS	National Bureau of Statistics of China
NDRC	National Development and Reform Commission
NG	natural gas
NO_x	nitrogen oxides
N_2O	nitrous oxide
NREL	National Renewable Energy Laboratory
P	petroleum demand
p-km	passenger-kilometres
PC	private car
PDG	promoting diesel and gas vehicles
PEC	primary energy consumption
PM	particulate matter
PR	petroleum consumption rate
PRC	The People's Republic of China
PVC	private vehicle control
R/P ratio	reserves divided by current annual production rate
RME	rapeseed methyl ether
SAC	Standardization Administration of the PRC
Sales	the number of new vehicles added
SCCTPI	Shanghai City Comprehensive Transportation Planning Institute
Scrapage	the number of vehicles scrapped
SEI	Stockholm Environment Institute
SEPA	State Environmental Protection Administration of China

SO_2	sulphur dioxide
Survival	the fraction of vehicles surviving after a number of years
SUV	sports utility vehicle
t	tonne
t-km	tonne-kilometres
TA	taxi
TfL	Transport for London
TtW	Tank-to-Wheel
TWC	three-way catalyst
TWh	terawatt-hours
UK	United Kingdom
US	United States
VDT	annual vehicle distance travelled
VM	vehicle mass
VP	vehicle population
WB	World Bank
WTO	World Trade Organization
WtT	Well-to-Tank
WtW	Well-to-Wheel

Subscripts

FC	fuel cycle
i	vehicle type
j	fuel type
LC	life cycle
TtW	Tank-to-Wheel
v	vintage
VC	vehicle cycle
VD	vehicle disposal
VP	vehicle production
WtT	Well-to-Tank
y	calendar year

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Chapter 1

Chapter 1 Introduction

1.1 Background

The rapid economic expansion in the last two decades has made China the second-largest energy-consuming nation, with growth in demand continuing. Its future energy demand is considered to be a major influence on global energy markets, affecting the availability and prices of energy resources widely.

Carbon dioxide (CO_2), a major greenhouse gas (GHG) responsible for the global warming effect, is mainly emitted from fossil fuel use. China is currently the second-largest CO_2 emitter because of the rapid growing fossil energy use and is expected to experience more and more pressure from other countries on global warming issues.

The transport sector is a crucial component of modern economy. The transport sector in China, the road transport sector in particular, has been growing at a tremendous rate. This has led to substantial growth in oil demand and an increasing dependence on imported oil for China. This continued growth will not only affect China's oil security and the international oil prices but will also contribute to China's GHG emission increase in the future.

It is therefore of critical importance to analyze future energy demand and GHG emissions in China's road transport sector and to assess possible reduction measures. There are a number of studies which have estimated energy demand and GHG emissions in China's transport sector in the next two to three decades, often from a macro economic perspective. To date however, little work has been done for China's road transport sector in particular. The present study aims to provide a reliable model to estimate energy demand and GHG emissions in China's road transport sector, and to use it to analyze the future trends under different policy scenarios. The present study distinguishes itself from earlier efforts by incorporating a wide range of reduction measures and by assessing the impacts of different measures from a life cycle perspective.

1.2 Layout of the Thesis

The thesis initially provides a comprehensive background search in Chapter 2. This starts with a critical evaluation of the national profile of energy supply and demand and the associated environmental issues in China, followed by an assessment of the contribution of the transport sector in China and the road transport sector in particular, to China's overall energy demand and GHG emissions.

In Chapter 3 there is the development of a detailed model to estimate future energy demand and GHG emissions in China's road transport sector, based on a review of the methodologies and available historical data employed in earlier studies.

In Chapter 4 the driving factors for future growth in energy demand and GHG emissions in China's road transport sector are analyzed, followed by a review of the available approaches for reducing energy demand and GHG emissions in the road transport sector worldwide.

Chapter 5 deals with the design of future development strategies and policies for China's road transport sector and the impact assessment of different options on energy demand and GHG emissions in China's road transport sector, leading from the review in Chapter 4.

The development of a 'life cycle assessment' model for China's road transport sector is discussed in Chapter 6 and a re-assessment is made of the impacts of different options from a life cycle perspective.

Chapter 7 provides a comprehensive discussion of the model results and their further implications and Chapter 8 draws conclusions from the present study and provides some recommendations for future study.

Chapter 2

Chapter 2 Energy and Transport Sector in China

2.1 Introduction

Before analyzing the future energy demand and GHG emissions in China's road transport sector, a critical evaluation of the national profile of energy demand and supply and associated GHG emissions is very important.

The contribution of the transport sector in China to the overall energy demand and GHG emissions has been evaluated and compared with those in other countries. The rapid development of China's road transport sector in recent years and problem caused has been analyzed in detail.

2.2 Energy Supply and Demand in China and Related Issues

The transformation into a market economy and participation in world trade has led China to sustained high rates of economic growth for more than two decades. The average annual growth rate (AAGR) for Gross Domestic Product (GDP) in China was 10.3% between 1980 and 1990, 10.6% between 1990 and 2000, and 9.4% between 2000 and 2004 (WB, 2005, 2006). China is currently the third largest economy in the world, after the United States (US) and the European Union (EU). This has made China one of the largest energy-consuming nations, with growth in demand continuing.

2.2.1 Primary Energy: Past, Present and Future

Figure 2.1 shows the historical trend of primary energy consumption (PEC) in China compared with those in developed economies during 1965-2006. PEC in China increased at an AAGR of 5.6% from 182.4 million tonnes of oil equivalent (Mtoe) in 1965 to 1698 Mtoe in 2006, with a rapidly growing trend after 2000. China is reported to have accounted for more than half of global PEC growth, 38.6% of world coal consumption, 9% of oil, 13.7% of hydroelectricity, 1.9% of nuclear energy and 1.9% of gas consumption in 2005 (BP, 2007). PEC in China is highly unbalanced between the rural and urban areas as well as between provinces. For example, PEC per capita in 2000 was 0.97 toe in urban areas and 0.58 toe in rural areas, while PEC per capita in 2002 was 2.64 toe in Shanghai and 0.43-0.82 Mtoe in some developing provinces (Crompton and Wu, 2005). Although China accounts for about 15% of the world's PEC, its per capita PEC is far lower than that of many developed economies and is below the world average (Table 2.1). As its level of per capita PEC approaches levels of developed economies, China's PEC will grow substantially in the future.

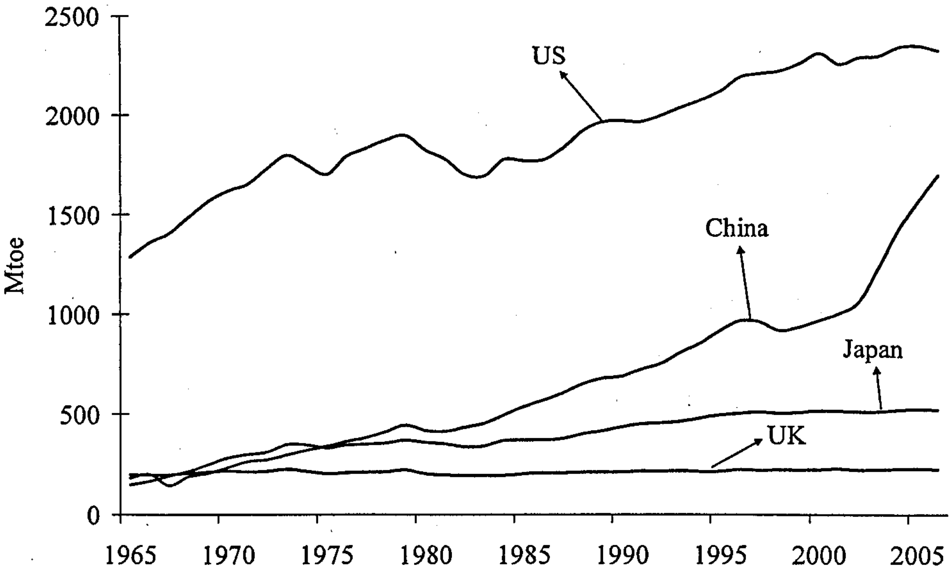

Figure 2.1 PEC in China compared with selected countries (data from BP (2007))

Table 2.1 PEC per capita in selected countries in 2005 (data from IEA (2007a))

China	US	Japan	UK	World
1.32	7.89	4.15	3.88	1.78

Figure 2.2 compares the prediction for PEC in China from a number of studies. Earlier studies appear to have underestimated PEC in China, while latest researches show that PEC in China is likely to reach 2600-2800 Mtoe in 2020 and 3400-3660 Mtoe in 2030, accounting for about 18% and 20% of world's total in 2020 and 2030, respectively. IEA and EIA both predicted that China will surpass the US and become the largest primary energy consumer between 2020 and 2025, and its influence on global energy markets will be enormous.

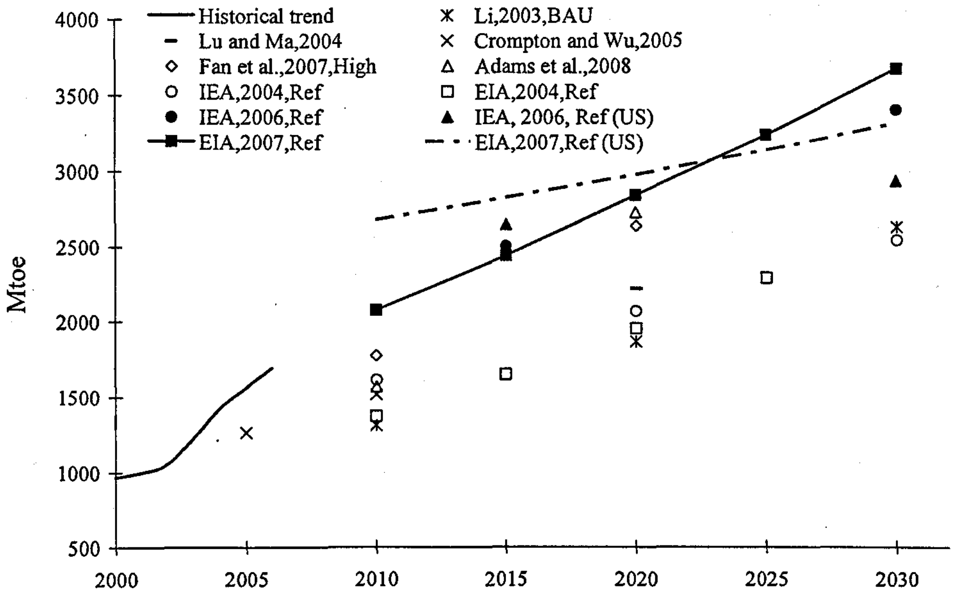

Figure 2.2 Comparison of China's PEC predictions from selected studies

a) Coal

China had reported coal reserves of 114.5 gigatonnes (Gt) at the end of 2006, about 12.6% of the world's proven recoverable reserves, with an R/P ratio (reserves divided by current annual production rate) of 48 (BP, 2007). Coal accounts for 95% of the proven reserves of fossil energy in China and, and accounts for 79% of China's power generation (IEA, 2007a). Most of China's coal reserves are located in the north and northwest, while coastal areas dominate the demand (Glomsrod and Wei, 2005).

China is the largest coal producer and consumer in the world. Coal production and consumption in China were 1212.3 and 1191.3 Mtoe in 2006, both accounting for nearly 40% of world's total (BP, 2007). There is a well established infrastructure for coal supply and utilization in China and, unlike oil and gas, coal has a relatively low and stable price, not influenced by international events. The rapid growth in electricity demand with increased manufacturing and residential use has been difficult to sustain as illustrated by power shortages in 75% of China's provinces in recent years, often prompted by lack of coal supplies (Feller, 2005). It is thus inevitable that this fuel will continue to play the major role in supplying China's energy needs in the future. Coal demand in China is estimated to be 2065 Mtoe in 2030, representing 46% of world total.

Heavy dependence on coal is responsible for China's serious air pollution problems. About 90% of sulphur dioxide (SO_2) and 73% of smoke dust in China came from coal combustion (Mao et al., 2005). The clean coal experience of the world suggests that the power generation sector is best developed for using coal cleanly, with clean coal technologies closely related to power generation. The percentages of coal used for power generation in the US, EU and Japan are 90%, 60% and 51% while this percentage in China is only 44% in 2005 (Liu et al., 2008). Given the major pollution from energy use in China is the direct result of the combustion of coal, it is reasonable that cleaner energy sources such as oil and natural gas will replace coal in residential use and transportation. This would leave most coal for power generation, where clean technology better permits easing the problem of heavy pollution. The share of coal used in total household energy has been dropping from 85% in 1980 to 23% in 2006, a significant shift in the structure of household fuel consumption (NBS, 1996, 2006).

b) Oil

China has very limited oil resource. China had proven oil reserves of 2.2 Gt at the end of 2006, about 1.3% of the world's proven recoverable reserves, with an R/P ratio of 12. Its per capita reserve is only about 7% of the world average.

Most of China's oil production is onshore, mainly at its largest production fields in the northeast at Daqing and Liaohe. Production from the east is starting to show a declining trend, but currently accounts for 65% of the total. Production from the west and offshore in recent years has increased rapidly. During 1990-2004, the contribution from these sources rose from 7.5% to 21.7% and 0.9% to 13%, respectively. So a likely trend will be an increase of production from the west and offshore making up for the decrease in supply from the east (Qiu and Fang, 2005).

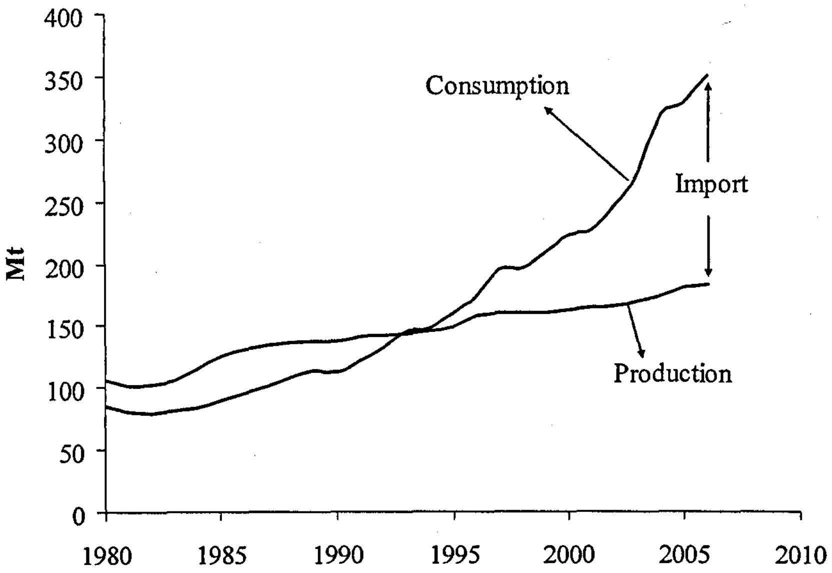

Figure 2.3 China's oil production, consumption and import in the last two decades (data from BP (2007))

China experienced an annual rate of increase of 4% in oil consumption over the past 20 years. By the end of 2002, it had overtaken Japan to become the second biggest oil consumer behind the US. It has accounted for 40% of the world's demand growth of crude oil since 2000. In 2006, oil consumption in China reached 350 Mt, accounting for 9% of world's total. However, China's oil production has been growing much slower (Figure 2.3). After a long period of being a net oil exporter, China became a net oil importer in 1993. Net import of crude oil and petroleum products in 2006 grew by about 16% over the previous year and reached approximately 169 Mt, accounting for almost 48% of China's total oil consumption. This level of dependence on imported oil increases the vulnerability for China's economic development. Latest estimates show that oil demand in China would reach 750-780 Mt in 2030 (IEA, 2006, EIA, 2007).

The Middle East is the principal source of China's oil imports, accounting for 40% in 2006. Another 21% came from the Asia Pacific region, about 23% from Africa, and 12% from Former Soviet Union (BP, 2007). The main way of importing oil is by ocean tankers, which accounts for 93% of the total. Nearly 80% of these oil imports pass through the Strait of Malacca, exposing China to the insecurities of over dependence on a congested passage (Yue, 2006). China must then start looking for new supplies for oil. It has been suggested that Russia and Central Asia would account for an increasing share of China's oil imports by means of a pipeline.

Domestic oil prices used to be fully state-controlled. With the dependence on foreign oil imports increasing, China had to adjust its domestic oil prices in accordance with the global oil price from 1998 (Hang and Tu, 2007). However, domestic oil prices are still not fully market-based and, while global oil prices rose 30% in the first 7 months of 2005, the retail price of gasoline in China rose by half that rate, causing a short-fall for the oil companies (ADB, 2005). Price controls have reduced gasoline availability in some cities, such as in the Pearl River Delta. This is partly because oil companies chose to export the fuel. Further reforms to the pricing system are being considered, and without more responsive pricing China may face increasing energy restrictions.

c) Natural Gas

China has very limited natural gas resource. China had proven gas reserves of 2.45 trillion cubic metres at the end of 2006, about 1.3% of the world's proven recoverable reserves, with an R/P ratio of 42. Its per capita reserve is only about 7% of the world average.

Gas production in China has been gradually rising since the mid-1990s, as new fields, particularly offshore, came on line, and new pipelines were built. Gas use is now being encouraged by the Chinese government because of the relatively low emissions of atmospheric pollutants and CO_2. The government has made investment in natural gas more attractive by adjusting domestic prices closer to internationally comparable levels (Sinton and Fridley, 2000). Despite recent growth, gas accounts for only about 3% of China's energy demand in 2006, much as it did in 1980. A target was set in China's 11th Five-year Plan (2006–2010) for the energy sector to increase the share of natural gas in the energy supply mix in the next five years and beyond. This would double the share of natural gas in the total primary energy supply by 2010.

The trans-China West-to-East gas pipeline, started in 2002, began full commercial operation at end of 2004. It was expected to bring 12 billion cubic metres of gas per year from the Tarim and Changqing gas fields in western Xinjiang and Shaanxi provinces, to Shanghai. The completion and operation of the gas pipeline, extending 4200 km through 10 provinces, should increase China's gas supply by almost 50 percent and increase the share of gas in the total energy consumption mix by up to two percent (Liu, 2005).

China will still need more gas than can be produced domestically. Imports from the Middle East are more likely to help meet future demand (Mao et al., 2005). A gas pipeline from the Irkutsk area of Siberia is another option (Economides, 2005). Sustained growth of supply will need investment in developing new sources and extending the infrastructure for importation.

d) Hydroelectricity

China has a large geographical area and a number of rivers, which give it one of the largest hydroelectricity resources in the world—a theoretical generation capacity of 694 gigawatts (GW) and an economically viable generation capacity of 402 GW (Zhu, 2005).

China is making an enormous effort to develop hydroelectric systems because they have several obvious advantages: they are relatively independent of price increases for fossil fuels, they tend to have longer lives than those using fuel-fired generation, and they have negligible emissions of atmospheric pollutants and CO_2. A series of large-scale hydroelectricity schemes, such as the Three Gorge project (Yao et al., 2007), has already been completed and is now in production. Hydroelectricity installed capacity and consumption in China has been increasing steadily in recent years, and reached 116 GW (APEC, 2007) and 90 Mtoe (BP, 2007) by 2005, both ranking the top in the world. However, this is currently developed to a degree that is around 29% of its potential.

According to the goal of the development of a modern society, hydroelectric installed capacity should reach 160 GW by 2010, representing 23% of the total installed electricity capacity; by 2020 this should reach 270 GW, representing 27% of the total (Zhu, 2005). If official plans are realised, the level of development of hydroelectricity will reach 67% of its potential. Nevertheless, the social and ecological impact of hydroelectric systems should be carefully evaluated.

e) Nuclear Energy

In comparison with fossil fuels, nuclear energy is considered a clean energy in terms of atmospheric environmental protection because it does not lead directly to the emissions of atmospheric pollutants and CO_2. There are however obvious problems of containment and long term radioactive product disposal.

The development of China's nuclear power started late. Six nuclear power plants with an installed capacity of 8.7 GW were built in China by 2004, accounting for 2.3% of China's total electricity capacity. Nuclear energy consumption in China is 12.3 Mtoe in 2006, much lower than those in developed countries (187.5 Mtoe in the US, 102.1 Mtoe in France, and 68.6 Mtoe in Japan). The Chinese government is planning to install 40 GW of nuclear power generation capacity by 2020 (Yao et al., 2007). At present, due to a limited technology reserve and a shortage of funds for construction, the growth rate of nuclear power capacity is likely to be low in the short term (Wang and Lu, 2002).

Nuclear energy is currently the only energy that can substitute fossil fuels in a centralized way and to a significant extent with commercial availability and economic competitiveness. It would be expected to play a prominent role in the future energy supply strategy of China and help solving pollution problems from coal use.

f) Primary Energy Structural Shift

The proportion of coal in the PEC fell from 90.8% in 1965 to 70.2% in 2006. The proportion of oil, gas and hydroelectricity increased from 6.0%, 0.4% and 2.7% respectively in 1980 to 20.6%, 2.9% and 5.6% in 2006, when there was also 0.7% of nuclear energy. This implies that China is developing a more 'environment-friendly' energy supply system. Compared with more developed economies, however, China's primary energy structure is still heavily reliant on coal (Table 2.2).

Table 2.2 Primary energy structure (percent mix) of world's big economies in 2006 (data from BP (2007))

	Oil	Natural Gas	Coal	Nuclear Energy	Hydro Electricity
US	40.4	24.4	24.4	8.1	2.8
Japan	45.2	14.6	22.9	13.2	4.1
Germany	37.6	23.9	25.1	11.5	1.9
UK	36.3	36.1	19.3	7.5	0.8
France	35.4	15.5	5.0	38.9	5.3
China	**20.6**	**2.9**	**70.2**	**0.7**	**5.6**
World	45.0	4.6	35.1	7.4	8.0

2.2.2 Renewable Energy Sources in China

Currently, renewable energy resources (except for hydroelectricity) account for only a small fraction of total energy consumption in China. The estimated growth in greenhouse gas emissions, as well as serious local and regional environmental pollution problems caused by fossil fuel consumption, however, provide strong arguments for the accelerated development of renewable energy resources.

a) Biomass

Biomass can be used as a combustible fuel for heating and to generate electricity or it can be transformed into liquid combustibles or motor fuel. As a big agricultural country, China has an abundant biomass energy resource, which is usually classified into four main categories: straw, firewood, agricultural and forestry residues and various kinds of organic wastes. Straw is the major part of the biomass energy resource, which accounts for 72% of the total in China. The total output of the crop straw was 622 Mt in 2002 (Zeng et al., 2007). Straw and residues suitable for energy production is estimated to represent a potential of

478 Mtoe, while wastes from processing of agricultural products and manure from livestock farms could, in theory, yield nearly 80 billion cubic metres of biogas (Yan and Crookes, 2007).

Biomass currently is a main source of energy for most of China's rural population and is used for home cooking and heating and for agriculture, but is not related to economic activity. Direct combustion of straw is the current main utilization of biomass energy in China, which leads to many problems. Currently the main fuel technologies developed and in use are for bioethanol and bio-oil. China has already established two large fuel ethanol production bases, with a total annual production capacity of over 1 Mt. Annual production of bio-oils has reached about 0.5 Mt. Power generation from biomass in China currently has an installed capacity of almost 2 GW (Yan and Crookes, 2007).

Biomass energy utilization has become more important in China following increased environmental pressure. The process of biomass production being developed for energy purposes in China is however, in the early stages and problems in exploitation include lack of readily available technology, low conversion efficiencies, high production costs and lack of competition. Development of policies and measures for development should allow biomass to play a far larger role in China's energy supply scenario.

b) Solar Energy

China has a large potential solar resource especially in the northwest, Tibet and Yunnan. The most common use of solar energy in China is in the supply of hot water. The total installed capacity of solar water heaters by the end of 2004 was 70 million square metres of collector area, with an AAGR of 27% over the last 10 years (Li et al., 2005).

Photovoltaic technology is the main technology used in China for the generation of electricity from solar energy. By the end of 2004, China's installed capacity of photovoltaic systems was over 60 megawatts (MW). About 50% was used to supply electricity to residents of remote rural areas, with an annual growth rate of

20%. The production capacity for urban photovoltaic lighting systems in China is over 10 MW, 70% of the world total (Li et al., 2005). Since solar photovoltaic could readily supplement present energy supplies with little associated pollution, it has the potential to become one of China's leading sustainable energy resources.

c) Wind Energy

China with a massive land territory and long coastline has great wind energy potential. The National Meteorology Institute has estimated a land based exploitable wind power resource of 253 GW. The installed capacity of wind power generation was 764 MW at the end of 2004. The high potential wind energy is mainly located in the remote areas, away from the current industrialised regions. This area has little by way of other energy resources, which should enable these remote rural populations to use the power for their own needs. These would include areas such as Inner Mongolia and the islands in the eastern coastal regions. A further 750 GW capacity could be derived from the ocean based wind resources. A total wind power capacity of 4 GW is predicted by the end of 2010, with a long term target of 20 GW for 2020 currently planned by the Chinese government (GWEC, 2005).

d) Future Prospect for Renewable Energy in China

Sources of renewable energy are abundant in China and, using known technology have the potential of being developed for application for energy purposes. The process however is in the early stages and problems in exploitation include lack of readily available technology, low conversion efficiencies, high production costs and lack of competition. Existing technology has yet to be formed into full scale production and the service system perfected. The potential for renewable energy use in China is much greater than that indicated by the current level of use. The most significant barriers are the lack of available advanced practical technology and the lack of development funds. Development of policies and measures for development should allow renewable energy to play a far larger role in China's energy supply scenario (Yan and Crookes, 2007).

2.2.3 Final Energy Consumption

Final energy consumption (FEC) in China increased from 318.2 Mtoe in 1980 to 904.6 Mtoe in 2005 (Figure 2.4). Industry is still the largest energy-consuming sector in China, with its share in the total slightly reduced from 68.3% in 1980 to 63.2% in 2005. Transport is the fastest-growing energy-consuming sector in China, and its share increased from 4.7% in 1980 to 11.9% in 2005. Energy consumption in the residential and commercial sector increased steadily, with its share reduced from 23.8% in 1980 to 17% in 2005.

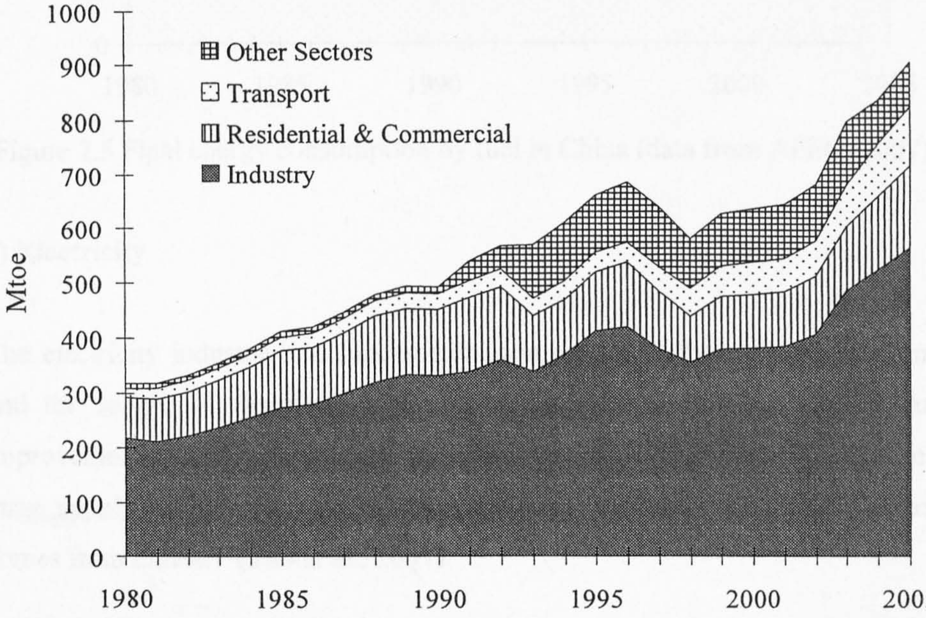

Figure 2.4 Final energy consumption by sector in China (data from APEC (2007))

Figure 2.5 shows the trend of fuel structure in China's FEC. Coal and coal products is still the most important fuel for end users, although its consumption did not grow much and its share in the total FEC reduced from 70.8% in 1980 to 38.4% in 2005. Crude oil and petroleum products, gas and electricity have been growing rapidly during the same period, with an AAGR of 7%, 6% and 8% respectively. Their shares in the total increased from 17%, 3.8% and 7.8% in 1980 to 31.4%, 6.2% and 18.8% respectively.

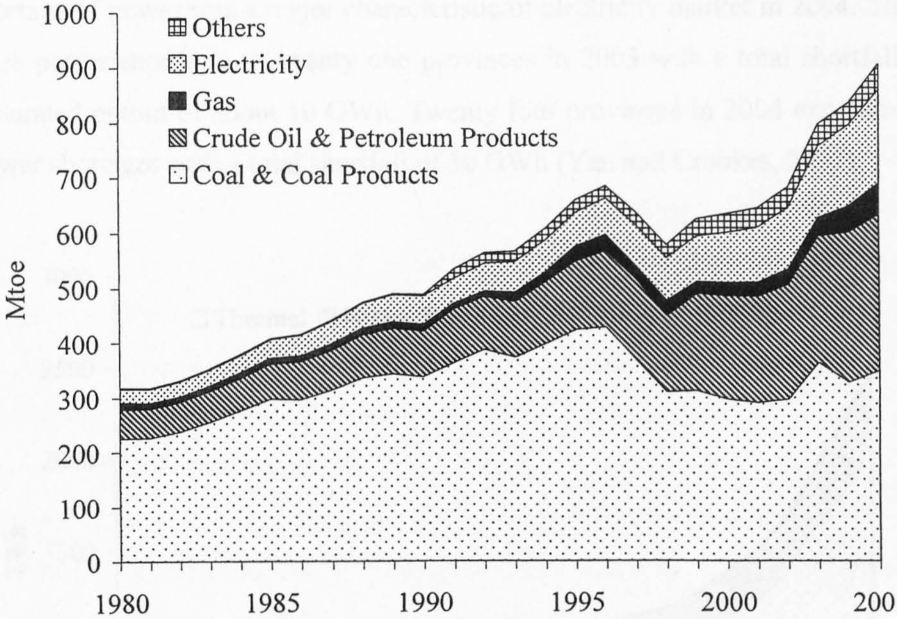

Figure 2.5 Final energy consumption by fuel in China (data from APEC (2007))

a) Electricity

The electricity industry is a fundamental component of the national economy, and the supply of electricity is crucial to socio-economic development and improvement of living standards. Rapid economic development will require a large supply of electricity in China, where nearly 80% of electricity demand comes from industry (Yao et al., 2007).

Figure 2.6 shows the rapid growing trend of China's electricity generation. China's total electricity generation was 2498 terawatt-hours (TWh) in 2005, 13% higher than in 2004. The commissioning of a series of large-scale hydroelectricity schemes brought hydroelectricity generation to 397 TWh in 2005, 12% higher than in 2004. Increase in thermal electricity generation was restricted to some degree by the supply of coal. A 14% growth however was achieved in 2005, with a total thermal electricity generation level of 2045 TWh. Generation from nuclear power stations grew 5% from 2004 to 53 TWh in 2005.

After 2003, 2004 had the second fastest growth in yearly electricity consumption (of 2173.5 TWh, 14.9% higher than in 2003) since the end of the 1970's, though shortage of power was a major characteristic of electricity market in 2004. There were power shortages in twenty one provinces in 2003 with a total shortfall of generated output of about 10 GWh. Twenty four provinces in 2004 experienced power shortages with a total shortfall of 30 GWh (Yan and Crookes, 2007).

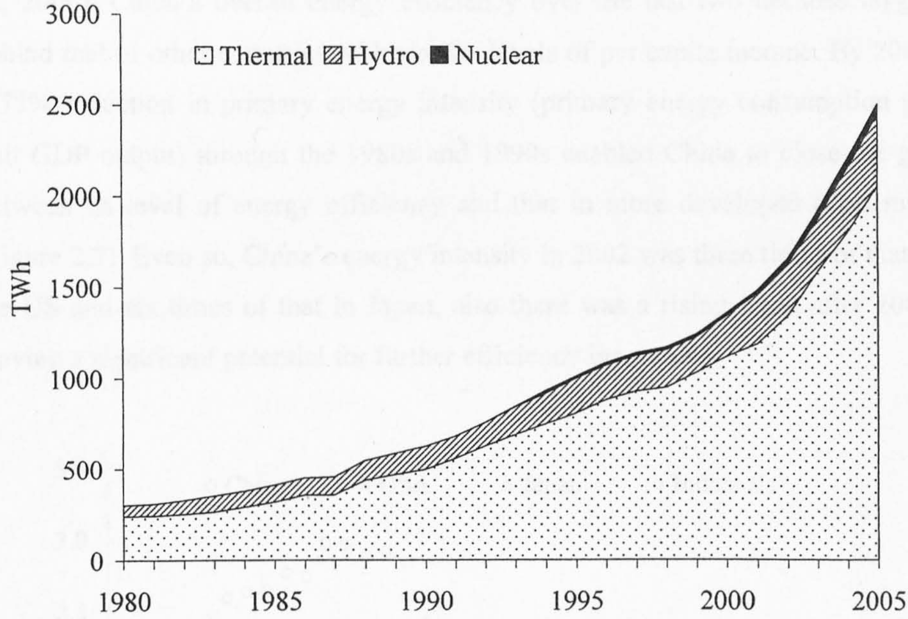

Figure 2.6 China's electricity generation by source (data from APEC (2007))

2.2.4 Energy Efficiency

Since the early 1980s, China has adopted a far-reaching series of policies and programs to promote greater energy efficiency in all sectors. In 1998, the national Energy Conservation Law came into force, codifying the country's approach to promoting energy efficiency under a more market-oriented economic system (Sinton and Fridley, 2000). China has witnessed an energy efficiency increase from 31% in 1998 to 33% in 2002 for coal-fired power generation, from 35% in the period 1990-1995 to 44% in 2003 for gas-fired power generation, and a constant of 34% in the period 1990-2003 for oil-fired power generation (Graus et al., 2007). However, the weighted average efficiency of fossil-fired power production in China still lagged behind those in developed economies.

Energy efficiency in most regions of China, especially for those located in the east and central areas, is improving, and more developed areas have higher energy efficiency (Hu and Wang, 2006).

Despite rising energy efficiency contributing to China's rising energy prices, changes in industrial composition and improved productivity (Fisher-Vanden et al., 2006), China's overall energy efficiency over the last two decades lagged behind that of other countries with similar levels of per capita income. By 2003, a 75% reduction in primary energy intensity (primary energy consumption per unit GDP output) through the 1980s and 1990s enabled China to close the gap between its level of energy efficiency and that in more developed economies (Figure 2.7). Even so, China's energy intensity in 2002 was three times of that in the US and six times of that in Japan, also there was a rising trend after 2002, leaving a significant potential for further efficiency increases.

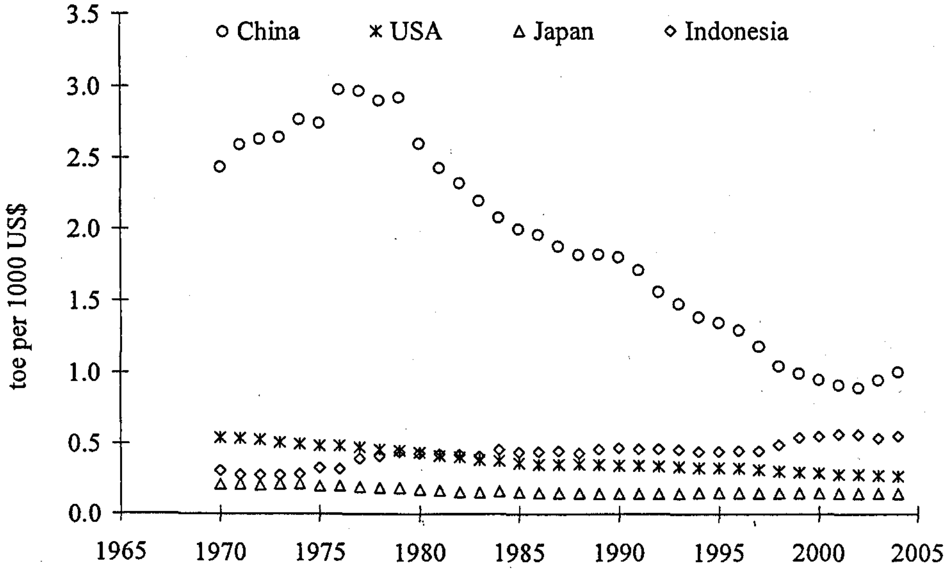

Figure 2.7 Primary energy intensity in selected countries (reproduced from Yan and Crookes (2007))

2.2.5 Fossil-fuel CO_2 Emissions and Air Pollution

China's fossil-fuel CO_2 emissions have grown steadily since 1950, when its annual emissions stood tenth in the world (Figure 2.8). After the recent two-year decline, it then rapidly rose to an all-time high of 5011 Mt in 2004 (17.3% of the world's total), making China the second largest CO_2 emitter just behind the US (6050 Mt in 2004). This growth has occurred largely from the use of coal. Solid fuels contribute 71.9% of total CO_2 emissions in China in 2004. Liquid fuels now contribute 17% of emissions and have grown appreciably over the past decade. Emissions from cement production account for 9.7% since China is the world's largest cement producer and produced roughly 44% of the world's supply in 2004. Per capita CO_2 emissions in China increased considerably over the past fifty years though the 2004 rate of 3.85 t is below the global average (4.51 t) and is only 18.7% of that of the US. According to latest estimates, China would be likely to surpass the US and become the biggest CO_2 emitter around 2010 (EIA, 2007).

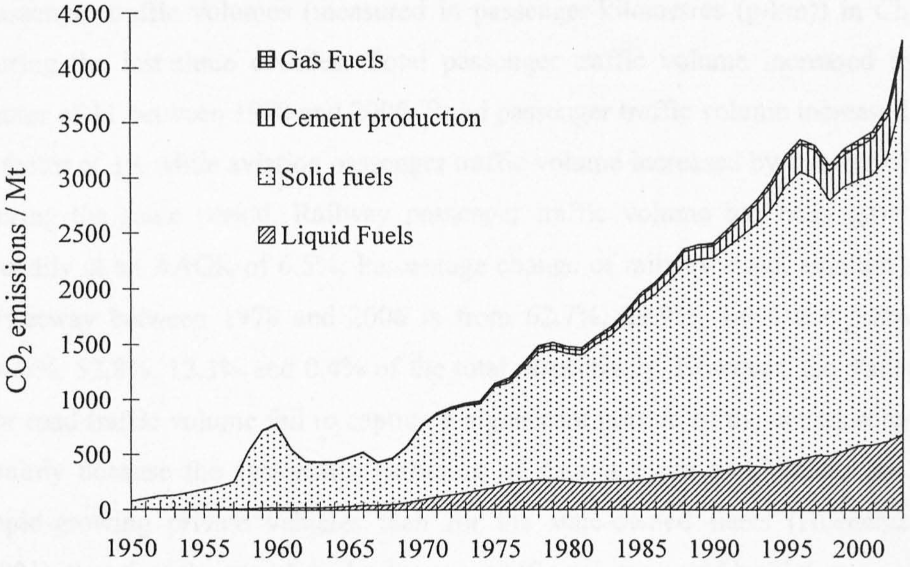

Figure 2.8 Fossil fuel CO_2 emissions in China by source 1950-2004 (data from CDIAC)

Air pollution in Chinese cities mainly originates from coal combustion, with an increase from mobile sources in recent years. Air quality appears to be deteriorating with the growing combined emissions of coal combustion and vehicle exhaust gas. According to SEPA (2006), of 522 cities monitored in 2005, the air quality in 207 did not meet Grade 2 (of the National Standards for Ambient Air Quality) in terms of total suspended particulate matter (PM), SO_2 and nitrogen oxides (NO_x), while 55 cities did not meet Grade 3 (the minimum level). SO_2 emissions in China reached 25.5 Mt in 2005, which was the highest in the world. About 30% of the area in China suffers from acid rain.

2.3 Transport Sector in China

2.3.1 Passenger Transport

With the fast growing economy, transport has become a crucial component of modern life in China. The development of towns and cities, increasing incomes, more social and leisure time and the diversity of activities have led to the requirement by people for ever-greater mobility and consequently a substantial increase in overall passenger travel in China. Figure 2.9 shows the trends of passenger traffic volumes (measured in passenger-kilometres (p-km)) in China during the last three decades. Total passenger traffic volume increased by a factor of 11 between 1978 and 2006. Road passenger traffic volume increased by a factor of 19, while aviation passenger traffic volume increased by a factor of 85 during the same period. Railway passenger traffic volume has been growing steadily at an AAGR of 6.5%. Percentage change of railway, road, aviation and waterway between 1978 and 2006 is from 62.7%, 29.9%, 1.6% and 5.8% to 34.5%, 52.8%, 12.3% and 0.4% of the total respectively. However, the statistics for road traffic volume fail to capture a significant portion of the actual volume, mainly because the systematic gathering of data is more problematic for the rapid-growing private vehicles than for the state-owned fleets (Huenemann, 2001), therefore the actual road passenger traffic volume could be higher.

2.3.2 Freight Transport

Increasing urban infrastructure construction and unbalanced distribution of raw materials and energy resources in a fast-growing economy has led to a significant increase in freight transport in China in recent years. Figure 2.10 shows the trends of freight traffic volumes (measured in tonne-kilometres (t-km)) in China during the last three decades. The mode share of freight traffic has not changed much. Waterway and railway are still the dominating modes, accounting for 62.4% and 24.7% of total volume in 2006, mainly because of their low cost.

Road is the fastest-growing mode and is gaining a rising share in the total, from 2.8% in 1978 to 11% in 2006. The main reason lies in the competitive advantage of trucks: they are generally faster and more flexible compared with other modes. Road freight traffic volume increased by a factor of 35 between 1978 and 2006, at an AAGR of 13.5%. Again, due to incomplete statistics, the actual volume should be higher.

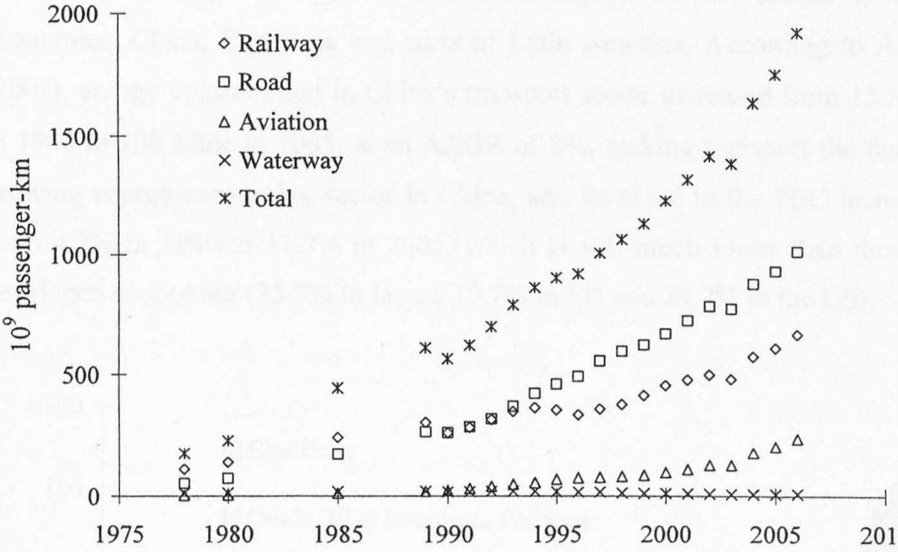

Figure 2.9 Trends of passenger traffic volumes in China (data from NBS (2007))

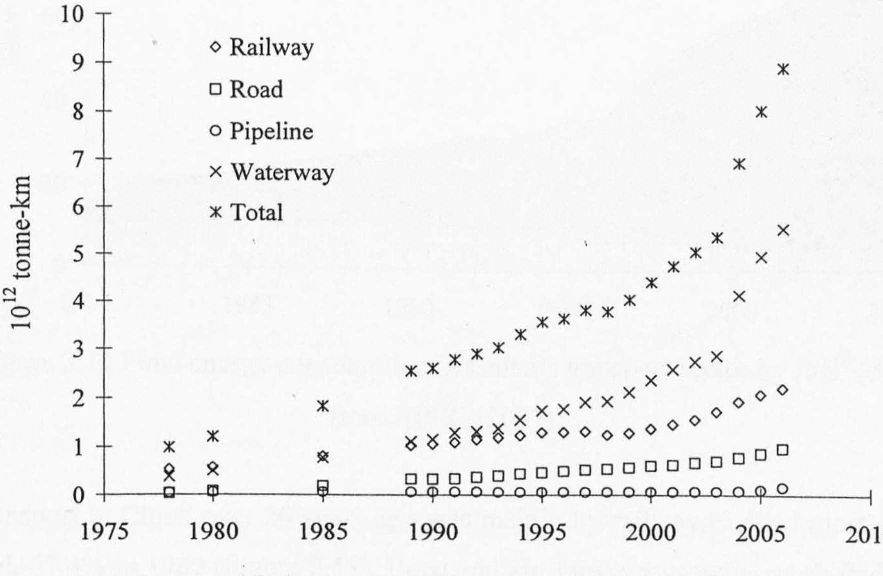

Figure 2.10 Trends of freight traffic volumes in China[1] (data from NBS (2007))

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[1] Aviation is too small to show on this graph

2.3.3 Energy Consumption in the Transport Sector

Globally the transportation sector is responsible for about 60% of the world oil consumption and about 28% of total FEC in 2005 (IEA, 2007a). It is also the most rapidly growing sector in terms of energy and particularly oil consumption. Over the past 30 years energy use worldwide in the transportation sector increased at an AAGR of 2.3%, more rapidly than any other sector (IEA, 2007a). Growth in transport energy use has been highest in the fastest growing economies: China, East Asia and parts of Latin America. According to APEC (2007), energy consumption in China's transport sector increased from 15 Mtoe in 1980 to 108 Mtoe in 2005, at an AAGR of 8%, making transport the fastest-growing energy-consuming sector in China, and its share in the FEC increased from 4.7% in 1980 to 11.9% in 2005, which is still much lower than those in developed economies (25.9% in Japan, 30.7% in EU and 39.7% in the US).

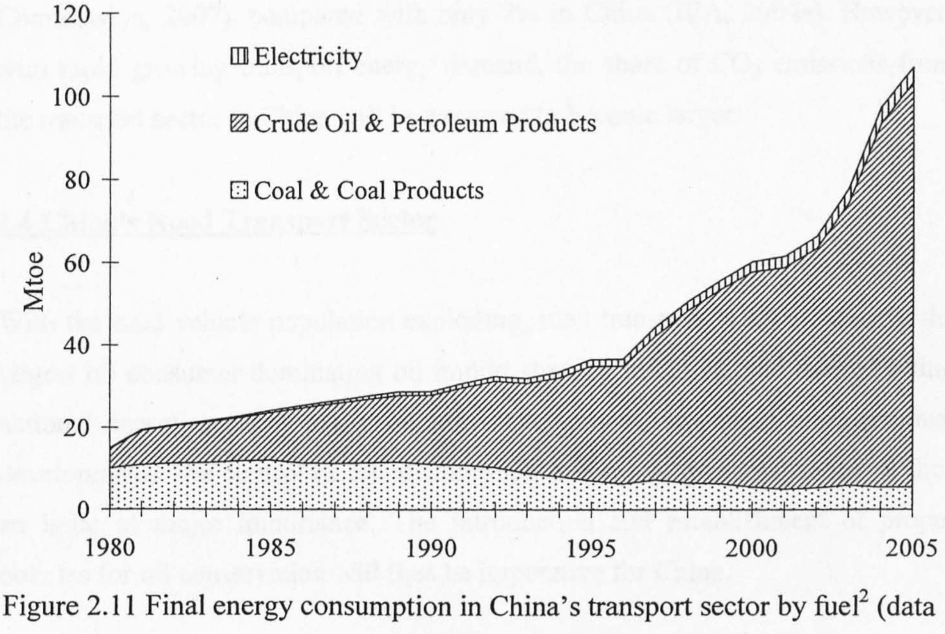

Figure 2.11 Final energy consumption in China's transport sector by fuel[2] (data from APEC (2007))

Transport in China over 20 years ago was mainly by railway, fuelled mostly by coal, 67.4% in 1980 (Figure 2.11). Road and air transport growth has shifted the total transport energy met by oil. It has now risen from 30.9% in 1980 to 90.7%

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[2] Proportions of gas and other minor forms of energy are too small to show

in 2005, with coal reduced to 5.1%. The transportation sector accounted for 36.4% of oil consumption in China in 2002 (Skeer and Wang, 2007), and is expected soon to rise to half of all oil use in China, in line with global patterns.

According to Tang (2007), petroleum products consumption in the transport sector increased at an AAGR of 13%, much higher than those in industry (2.7%) and agriculture (6.6%). Gasoline consumption in 2005 reached 48.5 Mt, which almost entirely came from road vehicle demand. Diesel consumption was 109.7 Mt in 2005, and the share for transport use increased from 38% in 2000 to 46% in 2005 (NBS, 2002, 2006).

2.3.4 CO_2 Emissions from the Transport Sector

Currently, 20% of all CO_2 emissions is from the transport sector worldwide (IEA, 2006), 32% in the US (Davis and Diegel, 2006) and 26% in the EU (European Commission, 2007), compared with only 7% in China (IEA, 2004a). However, with rapid growing transport energy demand, the share of CO_2 emissions from the transport sector in China will be expected to become larger.

2.4 China's Road Transport Sector

With the road vehicle population exploding, road transport is set to become the largest oil consumer dominating oil import strategy in China, and thus effecting national energy security and economic development, and threatening national development. The control of oil consumption in the road transport sector is thus an issue of major importance. The introduction and establishment of proper policies for oil conservation will thus be imperative for China.

2.4.1 Road Infrastructure

Road infrastructure conditions play a vital role in road transport conditions. Total highway length increased from 0.9 million km in 1978 to 3.5 million km in 2006. Total expressway length increased by a factor of 453, from 0.1 thousand km in 1988 to 45.3 thousand km in 2005 (NBS, 2007).

Urban road surface is important for public transport use, in terms of speed and safety. Road supply in Chinese cities was much lower than that in more developed countries (Table 2.3), and its development was much slower compared with vehicle population growth.

Table 2.3 Road area as a percentage of urbanized area in selected cities (data from Vasconcellos (2001))

Shanghai	New York	London	Tokyo	Paris
7.4	22	23	24	25

Road width is also important for capacity and safety purposes. Growth of area of surfaced roads was higher than that of length in Chinese urban area in recent years (Figure 2.12). This indicates the new built road is generally wider.

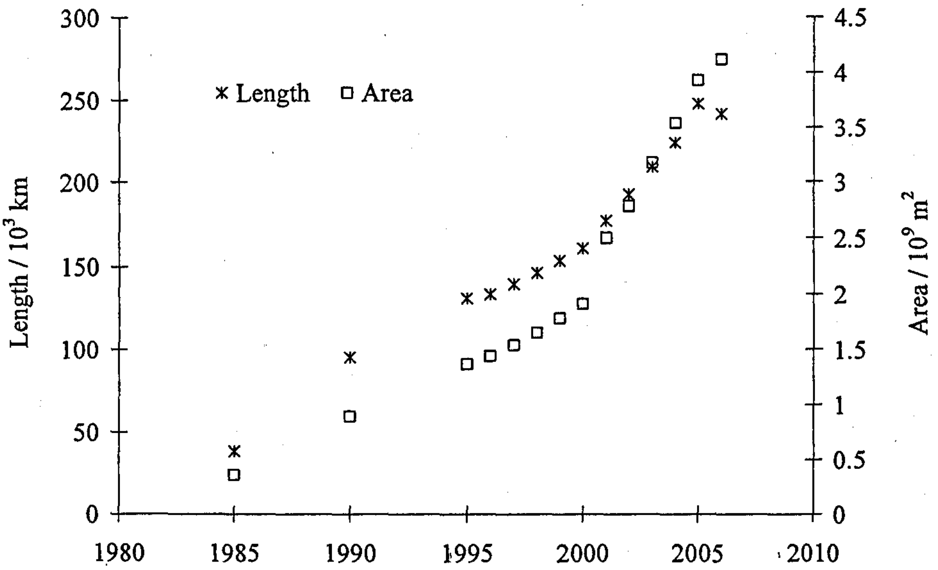

Figure 2.12 Development of surfaced roads in the Chinese urban area (data from NBS (2007))

2.4.2 Road Vehicles

Figure 2.13 shows the rapid-growing trends of motor vehicles in China in the last three decades. Motor vehicle population grew by a factor of 27 from 1.36 to 36.97 million between 1978 and 2006, among which the private-owned vehicle population grew by a factor of 80 from 0.29 to 23.18 million between 1985 and 2006, with the percentage of the total steadily increased from 9% to 63%.

In terms of vehicle type, trucks had been the dominant vehicle type until 1999, when passenger vehicle outnumbered trucks mainly because of the soaring private car market. China is now the third largest automobile producer and the second largest consumer in the world. Vehicle sales rose by 25% to a record of 7.2 million in 2006, and are expected to have increased at a similar rate in 2007 (IEA, 2007a). Motorcycle population also grew rapidly from 25.2 million in 1998 to 75.8 million in 2005.

Passenger car ownership in China is however much lower than that in developed economies and the world average, on a per capita basis (Table 2.4) and the potential for vehicle population growth is high.

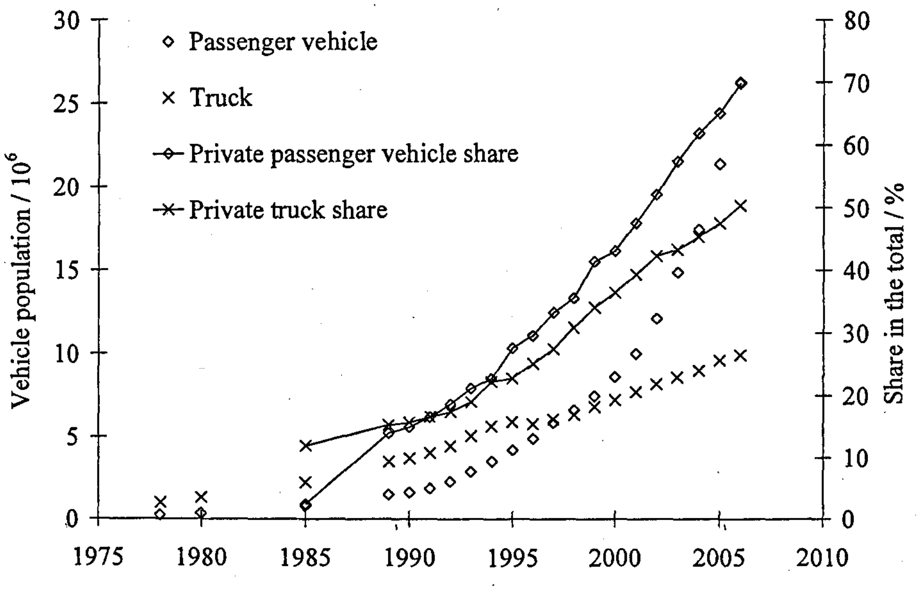

Figure 2.13 Motor vehicle population and the share of private-owned vehicles in China (data from NBS (2007))

Table 2.4 Number of cars per 10^3 persons in selected countries (calculated from WB (2006), Davis and Diegel (2006))

	China	US	Japan	UK	France	Germany	World
1990	1.4	535.7	282.8	391.1	405.8	386.6	82.8
2003	5.3	449.8	432.7	489.2	494.3	533.6	93.9

2.4.3 Urban Passenger Transport Situation

London was the first city in the world to have underground trains. There are currently 408 km of 'tube' and 27 km of light rail in London and 2.8 million journeys are made using them everyday. Although more than 40% of the total journeys are made by car, 76% are made on metro and 12% are made on bus during the morning peak (Table 2.5). This has significantly helped to release the traffic pressure on roads, reduce traffic jams and reduce fuel consumption and emissions.

The US is known as the "country on wheels", with the highest motor vehicle ownership in the world, and its passenger travel mode is predominantly by car, with more than 90% of journeys to work made by car on a national scale. However, in large metropolitan area like the New York City, public transit makes up 56.7% of passenger travel to work (Table 2.6).

The current passenger transport modal situation in the Chinese urban area is shown in Table 2.7 and Table 2.8. Its unique features include:

1. The proportion by walking is very high, mainly because travelled distance is comparatively short, especially in medium and small cities, where infrastructure such as residences, entertainment and work is concentrated.

2. Although bicycle's share in urban passenger transport decreased significantly since the mid 90s, it is still one of the dominant transport modes in China because it is economic and convenient, and the urban ownership level was 140 bicycles per 100 households in 2004. Bicycle use is under more and more restrictions in many Chinese cities, while in many developed countries, governments are trying to encourage people to use bicycles more (Fu et al., 2004).

3. The motorcycle proportion has been growing rapidly, especially in some developed medium and small cities. Having too many motorcycles on the road however can interfere with the performance of buses and cars, leading to traffic

jams, accidents, more fuel consumption and emission of pollutants (Zhao et al., 2005). Many cities have realised these problems, and as a result have started to restrict motorcycle use.

4. The Chinese government has been promoting metro systems in recent years because they tend to be faster and cleaner than road transport systems. However, metro development lags behind that in many more developed countries, with only a few lines existing in large metropolitan area like Shanghai and Beijing, mainly because metros have high cost and can only cover a limited share of travel demand, as experience in the most Metro-intensive cities (Paris, London, New York) suggests.

5. Buses are the main public transport mode in almost all Chinese cities, but the share of the total passenger travel is low (this does not reach 10% in some cities) and in most cases decreasing, mainly because of low speeds, poor reliability (service and management) and lack of infrastructure etc.

6. Taxi services grew significantly in recent years, to supplement bus services.

7. Private car use accounted for a small part of the total passenger travel, but it will grow substantially considering the rapid growth rate of the private car market in recent years. Rapid private motorization outpacing the expansion of road supply has directly led to traffic congestion in China's major cities.

China is undergoing rapid changes in its urban passenger transport systems: improved urban transport management, including the development of a broader public transport options such as express ways, metro systems, and increase in public buses (see Table 2.9), has increased the mobility of urban residents; non-motorized transport modes saw an decreasing share in the total passenger travel demand; rapid private motorization has caused a lot of problems such as soaring demand for petroleum products, severe traffic jams especially in large cities, rapidly deteriorating urban air quality and global warming effects.

Table 2.5 Daily average passenger transport modal split (%) in London in 2004 (data from TfL (2005))

	Metro	Bus	Taxi	Car	Motorcycle	Bicycle	Walking
All day	17.5	17.8	0.8	40.9	0.7	1.5	20.8
Morning peak	76.1	12	0.7	8.3	1.5	1.4	-

Table 2.6 Daily average modal split (%) of transport to work in the US (data from DoT and BTS (2006), US Census Bureau (2004))

	Year	Metro	Bus	Taxi	Car	Motorcycle	Bicycle	Walking	other
US	2003	4.6		0.1	90.9	0.6		2.8	1
New York	2004	41.4	15.3	1.2	32.4	0.1	0.4	7.9	1.3

Table 2.7 Urban passenger transport modal split (%) in selected Chinese cities (data from Jiang (2005), Ma (2004), SCCTPI (2005))

City	Year	Metro	Bus	Taxi	Private Car	Official Vehicle[3]	Motorcycle	Moped	Bicycle	Walking	Other
Chaohu	2004	0	11.58	2.79	1.18	4.46	7.02	2.68	27.81	40.32	2.15
Changshu	2004	0	6.53	0.68	4.5	2.19	21.76	9.82	32.7	20.92	0.9
Tongling	2004	0	10.75	3.68	0.62	8.18	3.65	2.72	10.76	58.95	0.69
Shanghai	2004	2.5	16	5.2	11.3		5.2	5.4	25.2	29.2	0
Guangzhou	2003	0.82	26.85	0.63	1.14	5.88	7.38	n/a	10.91	45.75	0.64

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[3] vehicles owned by government, institutions or companies etc

Table 2.8 Trend of passenger transport modal split (excluding walking) in Beijing between 1986 and 2000 (data from Liu et al. (2007))

	Bicycle	Mass transit	Private car	Taxi	Other
1986	58%	32%	5%	1%	4%
2000	38%	27%	23%	9%	3%

Table 2.9 Development of public transport in China (data from NBS (2007))

	Vehicle population (10^3)			Passenger-trips (10^9)	
	Bus	Metro	Taxi	Bus	Metro
1997	168.6	0.6	683.7	27.35	0.56
1998	188.4	0.6	754.2	28.57	0.59
1999	209.2	0.7	791.4	31.35	0.63
2000	225.1	0.9	825.7	33.50	0.61
2001	229.9	0.9	870.0	34.30	0.77
2002	245.0	1.0	884.2	37.53	0.83
2003	262.4	1.9	903.4	37.13	1.00
2004	279.6	1.9	903.7	41.40	1.33
2005	310.9	2.4	937.0	46.72	1.65
2006	312.8	2.8	928.6	44.78	1.82

2.4.4 Energy Consumption in the Road Transport Sector

More than 80% of transportation energy demand originates with road vehicles in the US (Davis and Diegel, 2006) and 83% in the EU (European Commission, 2007). The share of road transport in the total transport energy demand in China increased from 47.6% in 1990 to 68.1% in 2000 (Skeer and Wang, 2007), though it is still lower than those in the developed economies.

2.4.5 Air Pollution from the Road Transport Sector

Rapidly deteriorating air quality in many large cities is one of China's most pressing environmental problems. The rapid increase of vehicular emission is shifting the source of urban air pollution from a predominantly coal-burning type to a coal-vehicle mixed type or even to a vehicular pollution dominant type. Various studies showed that vehicular emission contributed 45-60% of the NO_x emissions and 80-90% of the carbon monoxide (CO) and hydrocarbon (HC) emissions in typical Chinese cities (Deng, 2006; Hao et al., 2006), and the estimated cost of air pollution caused by road transport in Beijing in 2000 was roughly 3.3 percent of GDP (Deng, 2006).

Less efficient technology makes the pollution level per vehicle much higher in China than in developed countries. Pollution control for motor vehicles in China has traditionally been relatively weak. The Euro II - emission standard currently adopted is equivalent to the control level in Europe in the mid-1990s. Gallagher (2006) found the joint ventures of Chinese and foreign auto manufacturers transferred relatively ineffective automotive emission-control technologies to China (compared with those used in developed economies) because there were little compelling policy incentives for the foreign firms to do so.

2.6 Summary and Conclusions

China has experienced remarkable economic growth over the last two decades, which has been accompanied by a corresponding growth in energy demand and associated GHG emissions. The magnitude of the Chinese energy demand and the rate of growth are on a scale that suggest future demand will have a major influence on world energy markets and resource supplies.

Coal has traditionally supplied a large proportion of China's energy needs and is expected to remain the most important fuel in the foreseeable future. The use of natural gas, hydroelectricity, nuclear energy and renewable energy has been raising steadily, yet still accounts for a relatively small proportion of the total energy mix. Development has been relatively slow because of obstacles such as shortage of funds for infrastructure development and a limited available technology expertise. The Chinese government is .making enormous efforts however, to develop the clean energy sources, to offset the shortage of fossil fuel and help to ease the growing pollution. Clean energy would be expected to play a more prominent role in the future energy supply for China.

Rapid development in the transport sector, road transport sector in particular, has made oil the second fast-growing energy source in China (after coal) and, by exceeding supply has led to an over dependence on imported oil. If oil demand in

China's road transport sector continues to increase without the development of viable reduction measures the security of oil supply (an essential factor of economic development) will be a major uncertainty in the economy.

Heavy reliance on coal and rapid growth of road vehicles has led to serious air pollutions in Chinese urban areas. This has also contributed significantly to the rise of GHG emissions in China. If the energy structure remains unchanged and growth of emissions from road vehicles are not controlled, China will not only suffer deteriorating local environment but soon become the largest GHG emitting nation overtaking the US and as a result start to experience more pressure from other countries on global warming issues.

There is an obvious need to establish appropriate strategies for the development of China's road transport sector to ensure its sustainability and minimize its environmental impacts in the future. It is therefore of critical importance to analyze future energy demand and GHG emissions in China's road transport sector and to assess possible reduction measures.

Chapter 3

Chapter 3 Modelling Energy Demand and Greenhouse Gas Emissions for China's Road Transport Sector

3.1 Introduction

In order to analyze the future trends of energy demand and GHG emissions in China's road transport sector, a model taking into account all important driving factors and reliable historical trend of each factor are needed. In this chapter, a bottom-up model has been developed based on earlier efforts, in which all the driving factors are able to be modelled in more detail and China's recent efforts in alternative fuel promotion are incorporated. Energy demand and GHG emissions in China's road transport sector between 2000 and 2005 have been estimated using the model. Results are compared with those from earlier studies and with statistics data to analyze the reliability of the modelling approach and historical data used.

3.2 Earlier Work

Energy demand in the transport sector usually can be estimated based on transport activity volume for each transport mode and energy intensity (energy consumption to perform one unit of transport activity) for each mode (Wohlgemuth, 1997). There are typically two ways to project future energy demand in the transport sector—top-down and bottom-up. The top-down approach is generally based on the projections of total transport activity volume, the share in the total volume and energy intensity for each transport mode. The bottom-up approach is generally based on independent projections of transport activity volume and energy intensity for each transport mode. Each modal projection can be built on a different method, and the total transport activity volume becomes an aggregate of the independent estimates for all the modes (Schafer, 1998).

Schafer (1998) considered the top-down approach to be a better one in developing long-term scenarios since it can better model the competition between different modes given that the total transport activity volume can be modelled econometrically. Schafer (1998) estimated the passenger traffic volumes between 1960 and 1990 for the four major motorized modes of transport in the world—cars, buses, railways and aircraft—in eleven world regions. Based on these data, long-term trends in motorized traffic volume and modal split for each region were projected econometrically. Together with the projections for energy intensity of each mode, energy demand in world passenger transport sector up to 2020 was estimated.

Singh (2006) estimated energy demand and CO_2 emissions in India's land-based passenger transport sector based on the traffic volume and energy intensity data for five major motorized modes of transport in India—two-wheelers, cars, auto-rickshaws, buses and railways.

Huang et al. (2005) estimated the shares in the total passenger traffic volumes in Shanghai in 2000 for all major urban transport modes—mopeds, motorcycles, private cars, bicycles, light-duty buses, heavy-duty buses, taxies and metro trains. Total traffic volume in the future was projected based on a relation between total passenger traffic volume and GDP derived from past trends. Together with the projections of the share in the total volume, energy intensity and emission rate for each mode, energy demand and GHG and pollutant emissions in Shanghai up to 2030 were estimated.

Lu and Ma (2004) estimated the energy demand in China's transport sector in 2020 to be 222 Mtoe, simply based on assumptions of total traffic volume and over-all energy intensity for freight and passenger transport in 2020, respectively.

However, when only the road transport sector is considered, the top-down approach loses its advantage in modelling the competition between different transport modes. Furthermore, future vehicle efficiency improvements and the penetration of different fuels are difficult to model using the top-down approach, especially for China, where not only road vehicle population is growing at a tremendous speed but also the vehicle types and fuel types within the total fleet are changing rapidly. Therefore, the bottom-up approach is usually adopted to project future petroleum demand and/or associated GHG emissions in China's road transport sector (Zhang, 2004; He et al., 2005; Wang et al., 2007).

Zhang (2004) developed a simple model which uses two important factors—vehicle population (*VP*) and annual energy consumption per vehicle (*AECV*), to determine petroleum demand (*P*) in a given year, expressed as:

$$P = \sum_{\mathrm{i,j}} (VP_{\mathrm{i,j}} \times AECV_{\mathrm{i,j}}) \tag{3.1}$$

Where, i represents vehicle type, j represents fuel type (road vehicles were classified into trucks, buses, cars, minivans and motorcycles. Two types of fuel—gasoline and diesel were included). Future demand was projected based on individual projections of *VP* and *AECV* for each vehicle type and fuel type.

Historical data used were *VP* and *AECV* for each vehicle type and fuel type in 2003. Data of total *VP* in 2003 was taken from the China Statistical Yearbook (NBS, 2004). The share of each fuel type in each vehicle type and the share of each vehicle type in the total *VP* were estimated based on the production, import and export statistics in the China Automotive Industry Yearbooks (CATRC and CAAM, 1991-2003). Details of the methods for this estimation were not presented. Data of *AECV* for each vehicle type in 2003 was obtained from questionnaire in road transportation companies and other typical road users.

He et al. (2005) developed a detailed model which employed three important factors—*VP*, fleet average annual vehicle distance travelled (*FAVDT*) and fleet average on-road vehicle fuel economy (*FAFE*) to determine petroleum demand (*P*) in a given year, expressed as:

$$P = \sum_{\mathrm{i,j}} (VP_{\mathrm{i,j}} \times FAVDT_{\mathrm{i,j}} \times FAFE_{\mathrm{i,j}}^{-1}) \tag{3.2}$$

Where, i represents vehicle type, j represents fuel type (road vehicles were classified into trucks, buses, cars and motorcycles. Furthermore, trucks were classified into heavy-duty trucks, medium-duty trucks, light-duty trucks and mini trucks, and buses are classified into heavy-duty buses, medium-duty buses, light-duty buses and mini buses. Two types of fuel—gasoline and diesel were included). Future petroleum demand was projected based on individual projections of *VP*, *FAVDT* and *FAFE* for each vehicle type and fuel type. CO_2 emissions were calculated based on the assumption that all carbon in fuels was converted into CO_2.

Historical data used were *VP*, *FAVDT* and *FAFE* for each vehicle type and fuel type between 1997 and 2002. The *VP* of each fuel type and vehicle type between 1997 and 2002 was calculated based on the total *VP* and the share of each fuel type and vehicle type. Total *VP* data were taken from the China Statistical Yearbooks (NBS, 2002-2003). Fuel type and vehicle type shares in a given year were assumed to be the average value of sales share in the last 10 years, which were mainly obtained from the China Automotive Industry Yearbooks (CATRC and CAAM, 1991-2003). *FAVDT* of each fuel type in each vehicle type between 1997 and 2002 was calculated based on the total freight/passenger traffic volume, volume share, average load capacity, *VP* and actual load rate of each type. It was assumed that there would be no differences in *FAVDT* between the same types of vehicles with different fuel types. The relevant data were obtained from the China Statistical Yearbooks (NBS, 2002, 2003) and several other studies (Li et al., 1995; BMEPB et al., 1999). Results from other research efforts were also considered in determining *FAVDT* (DESE, 1999; Wang, 2000). The *FAFE* of each fuel type in each vehicle type between 1997 and 2002 was determined by the labelled fuel economy (*LFE*) multiplied by an adjustment factor. The *LFE* reflected the ideal fuel economy level of the vehicle model, while the adjustment factor represented the impact of other important factors such as vehicle age, driving habits and road quality etc. The *LFE* value of a given fuel type in a given vehicle type was assumed to be the population-weighted average *LFE* value of several dominant vehicle models for that particular fuel type and vehicle type. The average σ value of four vehicle types over their lifetime were investigated and used as the σ value for the whole vehicle fleet.

Wang et al. (2007) used the same modelling approach with He et al. (2005) to estimate petroleum demand and CO_2 emissions. Historical data used were *VP*, *FAVDT* and *FAFE* for each vehicle type and fuel type in 2000. The total *VP* data was taken from the China Statistical Yearbook (NBS, 2004). The share of each vehicle type in the total *VP* was taken from Huo (2002). The share of each fuel type in each vehicle type was taken from the China Automotive Industry Yearbook (CATRC and CAAM, 2001). *FAVDT* of each fuel type in each vehicle type was taken from Huo (2002). *FAFE* data were obtained using the same approach as did He et al. (2005).

3.3 The Present Model

Faced with incomplete statistics for the road traffic volume in China, an attempt is made here to calculate energy demand in China's road transport sector as a product of several important driving factors as did He et al. (2005). Such factors are: vehicle population, fleet average annual vehicle distance travelled, fleet average vehicle fuel economy and a changing mix of vehicle types and fuel types in the total fleet. Therefore, the present model can be seen as an improvement for the model developed by He et al. (2005).

3.3.1 Methodology

Motor vehicles have been classified into truck, bus, car and minivan (MV). According to the motor vehicle classification in the China Automotive Industry Yearbooks (CATRC and CAAM, 1991-2006), truck is classified into heavy-duty truck (HDT), medium-duty truck (MDT), light-duty truck (LDT) and mini truck (MT) based on gross vehicle weight[4], while bus is classified into heavy-duty bus (HDB), and light-duty bus (LDB) based on total vehicle length[5]. Car is classified into private car[6] (PC) and taxi (TA) in the present study according to utilization characteristics. Motorcycle is also included as a vehicle type. Therefore, the present study includes 10 vehicle types. HDT, MDT, LDT, MT, LDB and MV

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[4] HDT has a gross vehicle weight ≥14 t, MDT: 6 - 14 t, LDT: 1.8 - 6 t, and MT less than 1.8 t

[5] HDB has total vehicle length ≥7 m, LDB: 3.5 - 7 m

[6] Including those vehicles owned by the government or institutions because their shares in the total have been decreasing fast in recent years

are further classified into diesel and gasoline vehicles by different fuel types, while HDB, PC and TA are further classified into diesel, gasoline, liquefied petroleum gas (LPG) and compressed natural gas (CNG) vehicles, expressed as -G, -D, -LPG, -CNG, respectively. For instance, HDT-D represents heavy-duty diesel trucks. It has to be noted that bioethanol can be used in all gasoline vehicles (in the form of CG and blends with up to 10% bioethanol by volume) and biodiesel can be used in all diesel vehicles (in the form of any biodiesel and CD blends). Therefore, the present study includes 6 fuel types—CG, CD, LPG, CNG, bioethanol and biodiesel.

Long-range Energy Alternatives Planning System (LEAP) is a scenario-based energy-environment modelling tool, developed by Stockholm Environment Institute (SEI, 2007). With its flexible data structures, LEAP allows analysis in technological specification and end-use detail (see Appendix C). The present model is developed using LEAP's Transport Analysis methodology, where energy demand in road transport sector is calculated by the following expression.

$$E_{\mathrm{j},y} = \sum_{\mathrm{i}} \left(VP_{\mathrm{i,j},y} \times FAVDT_{\mathrm{i,j},y} \times FAFE_{\mathrm{i,j},y}^{-1} \right) \tag{3.3}$$

where, E (MJ) is the energy demand, y is the calendar year, j is the fuel type, i is the vehicle type, $VP_{\mathrm{i,j},y}$ is the vehicle population of the fuel type j for vehicle type i in the year y, $FAVDT_{\mathrm{i,j},y}$ (km) is the fleet average annual vehicle distance travelled of the fuel type j for vehicle type i in the year y, $FAFE_{\mathrm{i,j},y}$ (km/MJ) is the fleet average on-road fuel economy of the fuel type j for vehicle type i in the year y.

$VP_{\mathrm{i,j},y}$ is calculated by the following expression.

$$VP_{\mathrm{i,j},y} = \sum_{v} VP_{\mathrm{i,j},y,v} = \sum_{v} \left(Sales_{\mathrm{i},v} \times Survival_{\mathrm{i},y-v} \times FShare_{\mathrm{i,j},v} \right) \tag{3.4}$$

Where, v is the vintage (i.e. the year when a vehicle was put into use), $VP_{\mathrm{i,j},y,v}$ is the remaining stock in the year y for vehicles with fuel type j, vehicle type i and vintage v, $Sales_{i,v}$ is the number of new vehicles added for the vehicle type t in the year v, $Survival_{i,y-v}$ (%) is the fraction of vehicles surviving after y-v years for vehicle type t, $FShare_{i,j,v}$ (%) is the share of fuel type j within the *Sales* for vehicle type i in the year v. For example, the remaining stock in the calendar year 2015 for PC-G sold in 2005 will be the number of PC sold in 2005 times the fraction that survive 10 (2015-2005) years and times the share of gasoline vehicles within that sale.

$FAVDT_{i,j,y}$ is calculated by the following expression.

$$FAVDT_{i,j,y} = \frac{\sum_{v}\left(VP_{i,j,y,v} \times VDT_{i,j,v} \times CVDT_{i,j,y-v}\right)}{VP_{i,j,y}} \tag{3.5}$$

Where, $VDT_{i,j,v}$ is the annual vehicle distance travelled in the first year of use for vehicles with fuel type j, vehicle type i and vintage v, $CVDT$ is a factor representing the change in VDT as a vehicle ages (it equals 1 when y=v).

$FAFE_{i,j,y}$ is calculated by the following expression.

$$FAFE_{i,j,y} = \frac{\sum_{v}\left(VP_{i,j,y,v} \times FE_{i,j,v} \times CFE_{i,j,y-v}\right)}{VP_{i,j,y}} \tag{3.6}$$

Where, $FE_{i,j,v}$ is the vehicle fuel economy in the first year of use for vehicles with fuel type j, vehicle type i and vintage v, CFE is a factor representing the decline in FE as a vehicle ages (it equals 1 when y=v).

Since the proportions of gasoline vehicles using bioethanol blends and diesel vehicles using biodiesel blends were not available, bioethanol and biodiesel demand were estimated according to the government's target. Gasoline and diesel demand were calculated by assuming all the gasoline and diesel vehicles used only pure gasoline and diesel and then subtracting the amount substituted by bioethanol and biodiesel, respectively.

CO_2, methane (CH_4) and nitrous oxide (N_2O) are the three most important GHG. According to IPCC (2001), the global warming potentials of CH_4 and N_2O are 23 and 296 times those of CO_2, i.e. 1 g of CH_4 and N_2O are equal to 23 g and 296 g of CO_2 in terms of global warming potentials, respectively. Therefore, GHG emission can be measured in terms of CO_2 equivalents (CO_2-eq).

GHG emissions G (g CO_2-eq) are calculated using the following expression.

$$G_{j,y} = E_{j,y} \times CGR_j \tag{3.7}$$

Where, CGR (g CO_2-eq/MJ) is the combustion GHG emission rate (GHG emission per unit of fuel burned).

3.3.2 Data Sources

a) ***Sales***

Sales data between 1988 and 2005 for each vehicle type was obtained from the China Automotive Industry Yearbooks (CATRC and CAAM, 1991-2006). Production data between 1988 and 1993 was used because of the lack of sales statistics. Since the production volume and sales volume for each vehicle type was very close in China, use of production data is not expected to induce noticeable errors.

b) ***Survival***

China uniquely has for some time set a scrapping standard for motor vehicles. In the current Chinese vehicle scrapping standard, vehicle age and mileage are the two main criteria for deciding whether a vehicle should be scrapped or not: A vehicle has to be scrapped if it reaches the age or mileage limit for its vehicle type; if a vehicle reaches its age but not mileage limit, an extension of vehicle life with a maximum length can be granted subject to that it successfully pass all the technical standards (such as exhaust emissions standard). This is because the motor vehicle operating standard inspection network and its supervision mechanism have not been set up yet in China. Along with the rapid development of China's automotive industry, vehicle scrapping standards in China are becoming more scientific (Table 3.1).

Survival data for each vehicle type was estimated by the author according to the vehicle scrapping standard in China (Table 3.2). The estimated *Survival* data in the present study for PC, MV and LDB matched very well with those calculated using a probability distribution (Yang et al., 2005). However, *Survival* data for other vehicle types still need to be tested. Since it is possible to obtain the total number of trucks, passenger vehicles (including bus, MV and car) and TA in each year from China Statistical Yearbooks (NBS, 1996-2006), likely errors have been estimated for the *VP* calculations by comparing the results of *VP* for truck, passenger vehicle and TA in 2003, 2004 and 2005 with the statistics data, respectively (Table 3.3). The *Survival* data estimated by the author is thus considered to be fairly reliable since the differences between the results from the author's calculations and the statistics data are within a reasonable range.

Table 3.1 Changes in mileage and age limits according to the vehicle scrapping standards in China in recent years (data from Jiang and Yi (1997); MCC, NDRC, MPS and SEPA (2000); MCC (2006))

Year of adoption	Criteria	HDT+ MDT	LDT	MT	HDB	LDB+ PC+MV	TA	MC
1997	Mileage/10^3km	400	300	300	500	500	500	
	Age/year	10	8	8	10	10	8	
	Extension/year	5	0	0	5	5	0	
2000	Mileage/10^3km	400	400	300	500	500	500	
	Age/year	10	10	8	10	15	8	
	Extension/year	5	5	0	10	no limit	0	
2002	Mileage/10^3km							100
	Age/year							10
New 2008?	Mileage/10^3km	600	600	500	600	600	600	120
	Age/year	15	15	12	20	no limit	8	13

Table 3.2 Estimated survival rates of different vehicle types in China (%)

Age (years)	HDT	MDT+ LDT	MT+TA	HDB	PC+MV +LDB	MC
under 1	100	100	100	100	100	100
1	100	100	100	100	100	100
2	99	100	98	100	100	97
3	95	98	92	100	100	90
4	90	96	80	99	100	82
5	82	93	65	96	100	72
6	70	90	45	93	100	61
7	58	86	20	90	99	48
8	40	80		86	96	36
9	28	72		82	92	24
10	18	62		76	88	10
11	10	48		70	84	
12	6	32		60	79	
13	3	18		50	73	
14	1	5		40	66	
15				30	56	
16				20	44	
17				8	23	
Median lifetime	8 years	10.8 years	6 years	13 years	15 years	7.2 years

Table 3.3 Estimation of errors for the calculations of *VP*

		2003	2004	2005
Truck	Statistics / 10^6	8.54	8.93	9.56
	Author's calculation / 10^6	7.99	8.82	9.60
	Difference	-6.4%	-1.2%	+0.4%
Passenger vehicle	Statistics / 10^6	14.79	17.36	21.32
	Author's calculation / 10^6	13.90	17.15	21.03
	Difference	-6.0%	-1.2%	-1.4%
Taxi	Statistics / 10^6	0.90	0.90	0.94
	Author's calculation / 10^6	0.87	0.91	0.94
	Difference	-4.2%	+0.6%	0.0%

c) *FShare*

FShare data for gasoline and diesel vehicles between 1997 and 2005 is available from the China Automotive Industry Yearbooks (CATRC and CAAM, 1998-2006), while that before 1997 is estimated linearly by the author. *FShare* data for gas vehicles is authors' estimation based on the number of LPG vehicles and CNG vehicles 1999-2005 from Li and Gu (2006), the number of HDB-LPG, HDB-CNG, TA-LPG and TA-CNG in 2004 from Ren (2006) and the estimated survival rates for HDB and TA. *FShare* data for each fuel type in each vehicle type is listed in Table 3.4. It is assumed that *FShare* for HDT-G is 0 because it was less than 1% in recent years and continued to decrease.

Table 3.4 *FShare* data for different fuel types in each vehicle type in China (%)

		1997	2000	2002	2005
HDT	HDT-D	100	100	100	100
MDT	MDT-D	64.9	71.4	92.3	97
	MDT-G	35.1	28.6	7.7	3
LDT	LDT-D	55.3	80.6	88.2	90
	LDT-G	44.7	19.4	11.8	10
MT	MT-D	0.3	0.6	0.1	16
	MT-G	99.7	99.4	99.7	84
HDB	HDB-D	64.9	64.3	89	88
	HDB-G	35.1	24.2	1.9	3.1
	HDB-CNG	0	4.6	7.3	8.1
	HDB-LPG	0	6.9	1.8	0.8
LDB	LDB-D	29.6	27.6	27	30
	LDB-G	70.4	72.4	73	70
PC	PC-D	0	0	0	0
	PC-G	100	100	100	100
	PC-CNG	0	0	0	0
	PC-LPG	0	0	0	0
TA	TA-D	0	0	0	0
	TA-G	100	80.7	76.9	78.2
	TA-CNG	0	6.2	17	13.8
	TA-LPG	0	13.1	7.8	8
MV	MV-D	0	0	0	0
	MV-G	100	100	100	100
MC	MC-G	100	100	100	100

d) *CVDT*

Statistics on a national scale show there is usually a significant reduction for *VDT* with vehicle age (Kwon, 2006, Davis and Diegel, 2006). Guo et al. (2007) investigated approximately 3700 PC-G and 1300 LDT-G in 2004 in Hangzhou city and developed the mileage accumulation rates as a function of vehicle age for the two vehicle types during the first 14 years of use. The *VDT* as a function of vehicle age for the two vehicle types in Hangzhou is derived from this and compared with those in the UK and US in Figure 3.1, where similar decreasing trends are observed. However, when the trends derived from Guo et al. (2007) were used, the results showed that the gasoline demand in China's road transport sector in 2005 would be much higher than China's total gasoline demand. These trends are thus considered to be unreliable to describe the relation between *VDT* and vehicle age for all the vehicle types in China, probably because Hangzhou is only a medium city and only two vehicle types were studied. Therefore, an average value of *VDT* during a lifetime for each vehicle type has to be used in the present study, i.e. *CVDT* would equal 1 for all vehicle types.

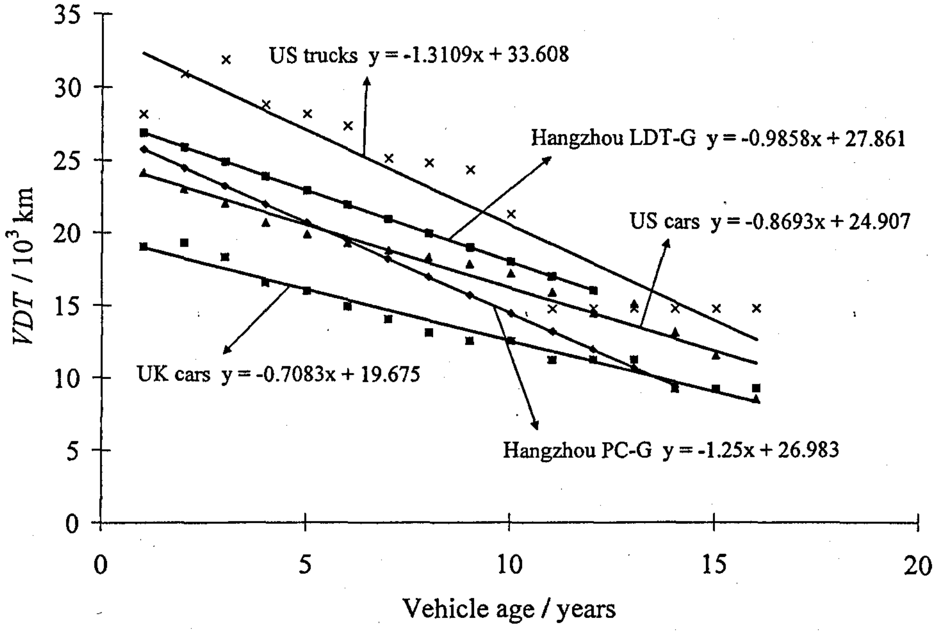

Figure 3.1 Comparison of *VDT* as a function of vehicle age in Hangzhou city with those in the UK and US

e) *VDT*

Since there are no official statistics for *VDT* in China, Equation 3.5 has not been able to be used to calculate *FAVDT* between 2000 and 2005. Therefore, *FAVDT* data in the present study has to be determined directly by taking several earlier studies into consideration (Chen and Lu, 2003; He et al., 2005; Chen et al., 2005; Meng et al., 2006; Wang et al., 2007) and selecting appropriate values. *FAVDT* for different fuel types in a given vehicle type are assumed to be the same. *FAVDT* data for each vehicle type in China between 2000 and 2005 is listed in Table 3.5. *VDT* data in 2005 are assumed to be the same with *FAVDT* data.

Table 3.5 *FAVDT* for each vehicle type in China 2000-2005 (10^3km)

	2000	2001	2002	2003	2004	2005
HDT	48.00	46.40	44.80	43.20	41.60	40.00
MDT	24.96	24.77	24.58	24.38	24.19	24.00
LDT	21.00	20.80	20.60	20.40	20.20	20.00
MT	21.00	20.80	20.60	20.40	20.20	20.00
HDB	48.00	46.40	44.80	43.20	41.60	40.00
LDB	31.50	31.20	30.90	30.60	30.30	30.00
PC	18.75	18.60	18.45	18.30	18.15	18.00
TA	90.00	92.00	94.00	96.00	98.00	100.00
MV	21.00	20.80	20.60	20.40	20.20	20.00
MC	8.00	8.00	8.00	8.00	8.00	8.00

f) *CFE*

Data concerning the rate of fuel economy worsen as a vehicle ages was not available from literature searching, therefore, an average value of *FE* during a lifetime for each vehicle type has to be used in the present study, i.e. *CFE* would equal 1 for all vehicle types.

g) *FE*

FAFE for each fuel type in each vehicle type as reported by He et al. (2005) was used as *FE* for vehicles sold before 2000, and *FE* for newly-added vehicles for each fuel type in each vehicle type as reported by Wang et al. (2007) was mainly used as *FE* for vehicles sold between 2000 and 2005. The exceptions were CNG/LPG vehicles and diesel cars as their *FE* was not available from literature, and gasoline cars sold between 2000 and 2005 as the number of cars has grown significantly over the last few years and *FE* for new gasoline cars is thus undergoing a rapid change. *FE* for these vehicle types was determined as follows (all converted to the same unit: km/MJ):

- The *FE* of HDB-CNG was found to be 21.7% (Silva et al., 2006) or 25-28% (Barnitt and Chandler, 2006) lower than the diesel ones, and newer technology made this value 16%-18% (Chandler et al., 2006). This value is assumed to be 25% in China.
- The *FE* of HDB-LPG was not available from literature therefore is assumed to be the same as that of HDB-CNG.
- The *FE* of CNG cars was found to be basically identical to that of the gasoline ones (NREL, 1999).
- The *FE* of LPG cars is assumed to be the average value of the *FE* of the two dominant LPG taxi models (available from Liu and Shao (2007))
- *FE* of diesel cars was found to be 34-41% higher than that of gasoline ones in UK, Germany and North America (Waters, 1992; Sullivan et al., 2004), and this value is assumed to be 34% in China due to limited light duty diesel vehicle technology.
- *FE* values for all the car models sold in the Chinese market between 2000 and 2005 are difficult to obtain. The population-weighted average *FE* value of the top 10 dominant car models in the Chinese market in 2005 for a given engine capacity range (Zhang, 2006) have been taken to be representative of the *FE* value of this particular range. These dominant models chosen accounted for 70% of the total cars sold in 2005. The *FE* value for each model was acquired from the actual on-road *FE* for 407 vehicle models released in 2006 (NDRC, 2006). The results show that in 2005, the sales-weighted *FE* for new gasoline cars in China (0.384 km/MJ) is nearly the same as that in the US (0.385 km/MJ according to Davis and Diegel (2006)).

FE data used in the present model are listed in Table 3.6.

Table 3.6 *FE* data for each fuel type in each vehicle type in China (km/MJ)

	Vehicles sold before 2000	Vehicles sold between 2000 and 2005
HDT-D	0.0881	0.1173
MDT-G	0.0902	0.1201
MDT-D	0.1135	0.1515
LDT-G	0.1780	0.2374
LDT-D	0.1732	0.2308
MT-G	0.3481	0.4639
MT-D	0.3581	0.4775
HDB-G	0.0796	0.0998
HDB-D	0.0963	0.1098
HDB-CNG	0.0824	0.0824
HDB-LPG	0.0824	0.0824
LDB-G	0.2383	0.3025
LDB-D	0.2340	0.3120
Car-G	0.3327	0.3840
Car-D	-	0.4525
Car-CNG	0.3840	0.3840
Car-LPG	0.3742	0.4116
MV-G	0.3590	0.4787
MV-D	-	0.5040
MC	1.1091	1.4786

h) Biofuel Substitution

Since the Chinese government has been promoting E10 (10% bioethanol and 90% CG blend by volume) since 2002, and annual E10 consumption reached 10 Mt in 2005, bioethanol demand in China's road transport sector is assumed to increase from 0 in 2001 to 0.68 Mtoe in 2005 linearly.

According to ACE (2005), *FE* for vehicles using E10 is 1.5% lower than CG when measured in km/l. The substitution ratio between E10 and CG was thus derived as 1:1.02 based on energy content (1 MJ of E10 would substitute 1.02 MJ of CG). When using E10, the effective substitution ratio between added bioethanol and CG was then derived as 1:1.33 based on energy content.

FE for vehicles using B20 (20% biodiesel and 80% CD blend by volume) was found to be reduced by an average of 1.4% when measured in km/l (McCormick et al., 2006). According to Holden et al. (2006), the reduction was 1.7%, and to Demirbas (2007), the reduction was 0.9-2.1%. The value was assumed to be 1.5% for the present study. The substitution ratio between B20 and CD was thus derived as 1:1.01 based on energy content. When using B20, the effective substitution ratio between added biodiesel and CD was then derived as 1:1.04 based on energy content.

i) *CGR*

Since the proportions of CH_4 and N_2O are very small compared to that of CO_2 in the fuel combustion process, the *CGR* in the present study is assumed to include CO_2 only and is calculated by assuming all the carbon in the fuel becomes CO_2 after combustion. Carbon content and *CGR* for each fuel is listed in Table 3.7.

Table 3.7 Carbon content and *CGR* for each fuel

	Carbon content by weight (%)	*CGR* (g CO_2-eq/MJ)
CG	84.6	69.2
CD	86.5	73.2
LPG	82	63.6
CNG	75	63.9
Bioethanol	52.2	70.9
Biodiesel	77.3	74.6

3.4 Results and Comparisons

3.4.1 Results for the Present Study

The results for energy demand and GHG emissions in China's road transport sector between 2000 and 2005 are listed in Table 3.8. Total energy demand is estimated to increase from 57 Mtoe in 2000 to 86 Mtoe in 2005. Private passenger vehicle fleet accounts for nearly half of the demand growth with its share in the total increase from 12% to 24% between 2000 and 2005. Energy demand of road vehicles in 2005 accounted 80% of the total transport sector (108 Mtoe according to APEC, 2007).

Petroleum (including CG, CD and LPG) demand in China's road transport sector is estimated to be 84.3 Mtoe in 2005, accounting for 86% of total petroleum demand in China's transport sector (98 Mtoe according to APEC, 2007), 30% of total petroleum demand in China (280.8 Mtoe according to APEC, 2007). Despite recent growth in alternative fuel use, petroleum still accounts for 98% of total energy demand in China's road transport sector in 2005.

GHG emissions are estimated to increase from 168.6 Mt CO_2-eq in 2000 to 254.9 Mt CO_2-eq in 2005.

Table 3.8 Estimated energy demand and GHG emissions in China's road transport sector 2000-2005

	2000	2001	2002	2003	2004	2005
Energy Demand / Mtoe						
CG	36.86	38.55	40.24	43.17	46.30	49.65
CD	19.72	21.68	24.71	27.49	31.32	33.92
CNG	0.12	0.20	0.44	0.62	0.79	0.97
LPG	0.40	0.56	0.63	0.74	0.74	0.74
Bioethanol	0	0	0.17	0.34	0.51	0.68
Total	57.10	60.99	66.18	72.35	79.66	85.96
GHG Emissions / Mt CO_2-eq						
	168.6	180.1	195.7	214.2	236.1	254.9

3.4.2 Comparisons of Results

Since there are no official statistics for energy demand or GHG emissions in China's road transport sector, it is difficult to analyze the reliability of these estimations. However, considering gasoline demand is almost entirely restricted to road vehicles, an attempt is made here to use statistical data of China's total gasoline demand (available from NBS) as China's road transport gasoline demand, with which the results for gasoline demand from the present and earlier studies are compared (Figure 3.2). Gasoline demand in 2003 estimated by Zhang (2004) is much higher than the statistical data. This could be because the *AECV* data obtained from the questionnaire was not very reliable or did not represent the national level due to lack of samples for private vehicle users. Gasoline demand between 1997 and 2002 estimated by He et al. (2005) is initially below the statistical data and then above. The reasons could be as follow: *FAFE* for each vehicle type was assumed to be constant between 1997 and 2002, while it actually should be improving; calculation for *FAVDT* was not very reliable because there were too many variables involved and might have decreased faster than in their calculation; the assumption that vehicle type share would be the average of sales share when calculating *VP* for each vehicle type was not very reliable. Gasoline demand between 2000 and 2005 estimated in the present study shows a good agreement with the statistical data.

Estimates for diesel demand in China's road transport sector in the present and earlier studies are compared in Figure 3.3. Estimates by Zhang (2004) agrees with the earlier trend estimated by CATRC (Zhang, 2004). However, there is a big difference between estimates by He et al. (2005) and Zhang (2004), while that by the author lies in between them.

Estimates for the current status of GHG emissions from China's road transport sector in the present and earlier studies are compared in Figure 3.4. Estimates by He et al. (2005) and Wang et al. (2007) are both higher than those by the author.

3.5 Summary

A detailed bottom-up model has been developed to estimate energy demand and GHG emissions in China's road transport sector. Fuel economy improvements, vehicle sales, vehicle survival rates, vehicle usage level and penetration of different fuels can be dealt with explicitly in this model.

A detailed and reliable data set has been provided concerning China's motor vehicle population, vehicle fuel economy and vehicle distance travelled by vehicle type and fuel type in recent years. Energy demand and GHG emissions in China's road transport sector between 2000 and 2005 are estimated using the present model. Total energy demand in China's road transport sector is estimated to increase from 57 Mtoe in 2000 to 86 Mtoe in 2005. Private passenger vehicle fleet contributes nearly half of the demand growth, with its share in the total demand increases from 12% to 24% between 2000 and 2005. Despite recent growth in alternative fuel use, petroleum still accounts for 98% of total energy demand in China's road transport sector in 2005. GHG emissions are estimated to increase from 168.6 Mt CO_2-eq in 2000 to 254.9 Mt CO_2-eq in 2005.

Comparison of the results from the present study with those from earlier studies and statistics data have suggested that the present model and historical data used is fairly reliable. Furthermore, if more data were available, especially data concerning *VDT*, *CVDT* and *CFE*, the results could have been more reliable.

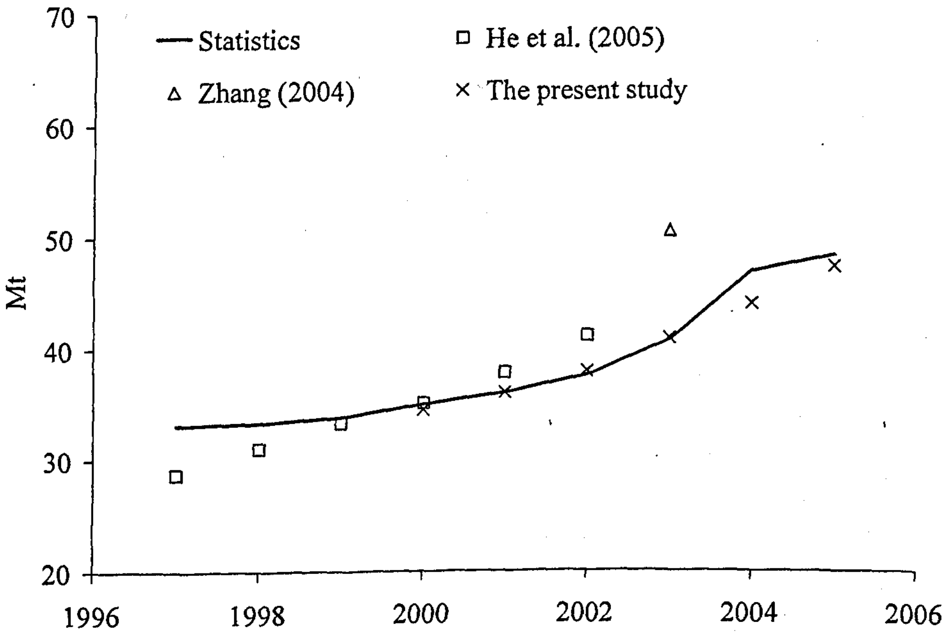

Figure 3.2 Current status of gasoline demand in China's road transport sector from selected studies and statistics

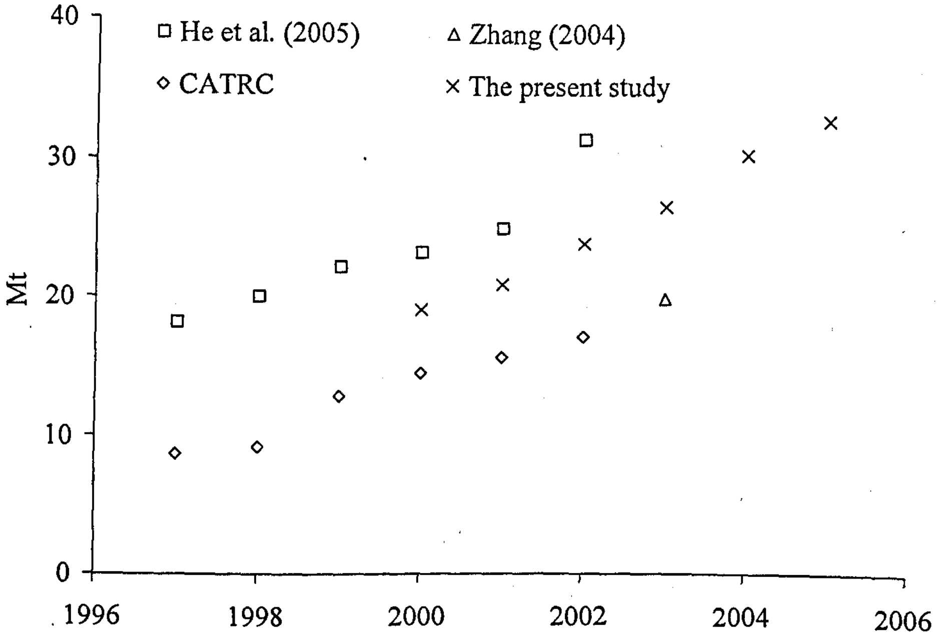

Figure 3.3 Current status of diesel demand in China's road transport sector from selected studies

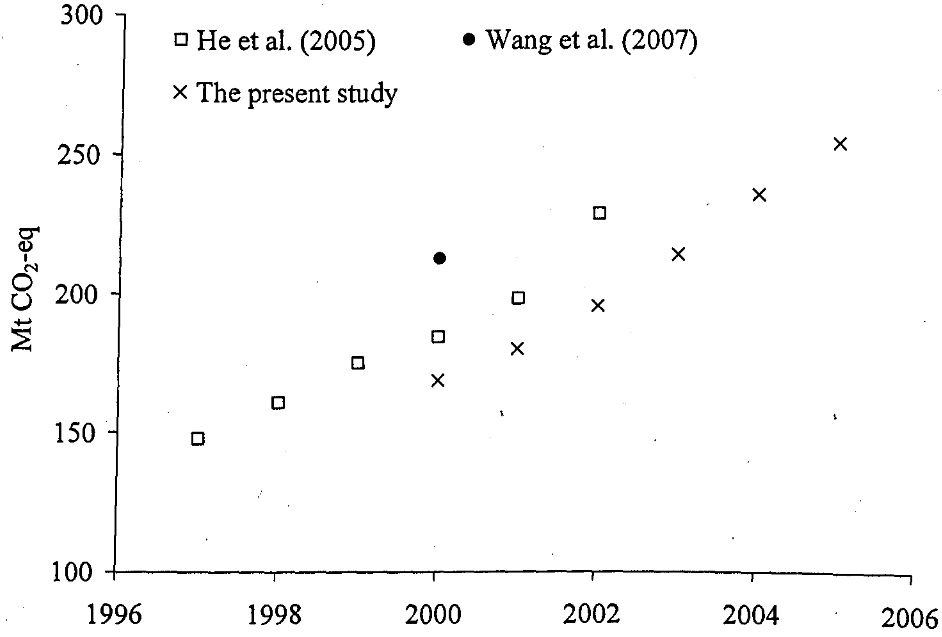

Figure 3.4 Current status of GHG emissions from China's road transport sector from selected studies

Chapter 4

Chapter 4 Approaches for Reducing Energy Demand and Greenhouse Gas Emissions in the Road Transport Sector

4.1 Introduction

In this section, the key driving factors for future growth in energy demand and GHG emissions in China's road transport sector, as identified in the modelling approach in Chapter 3, are analyzed. Available policy measures that could have potential impacts on these driving factors are reviewed.

4.2 Key Driving Factors

4.2.1 Vehicle Population and Vehicle Distance Travelled

The growing dependence on private motor vehicles for transport worldwide is currently a crucial component in the debate on sustainable development, considering the economic, social and environmental impact (Camagni et al., 2002). This should be treated with special care in China, where the income level of urban residents has started to make private vehicle use affordable. The growth of energy demand in China's private vehicle fleets in recent years as shown in Chapter 3 suggests that the control of private vehicle use could be an effective way to reduce future energy demand in the road transport sector.

4.2.2 Vehicle Fuel Economy

Vehicle on-road fuel economy is influenced by a number of factors including: the age of the vehicle; driving style; tyre characteristics; engine characteristics; physical design (e.g. mass, materials used) and specifications (e.g. air conditioning, extra safety features).

Vehicle fuel economy has improved remarkably over the recent decades. The majority of improvements are usually due to adoption of advanced technologies (Greene et al., 2005). The main reasons have been attributed to such factors as:

increasing compression ratios; reducing aerodynamic drag, tyre rolling resistance and car mass, and improvements in engine and powertrain efficiency (Kirby et al., 2000). Ramesohl and Merten (2006) believed it was possible that the fuel economy of gasoline and diesel cars would increase by 50% between 2000 and 2030. Currently, major Chinese automakers have joint ventures with major multi-national automakers, but vehicle technologies, even in these, are less advanced (He et al., 2005). The current fuel economy level of in-use vehicles in China is estimated to be at least 33% lower than that in Japan (Shen, 2006c), while that of new vehicles in China is 10-15% lower than in Europe, 5-20% lower than that in the US, and 20-25% lower than in Japan for an equivalent vehicle type (He et al., 2005). If gasoline cars in China could adopt advanced technologies such as Variable Valve Timing and Direct Injection, fuel economy could be improved largely (He, 2005). Fuel economy of buses also could be improved by engine optimization according to the operating behaviour (Mo and Yao, 2006). There is a great energy saving potential if the vehicle fuel economy level in China would catch up with those in Japan or other developed economies.

Higher efficiencies due to technological improvements, however, have partly been countered in vehicle fuel economy improvements by the trend toward larger engines and larger cars (Kaul and Edinger, 2004). Therefore, clear policy direction by the government encouraging people to choose vehicles with better fuel economy would be helpful in vehicle fuel economy improvements.

4.2.3 Vehicle/Fuel Switching

a) Gasoline and Diesel Vehicles

Internal combustion engines have been developed for over a century and have reached a high technological maturity. Two major types of internal combustion engines are gasoline engines and diesel engines. Relative to gasoline engines, diesel engines have higher compression ratios, more rapid combustion, lower throttling losses and operate leaner. As a result, diesel engines have greater thermodynamic efficiency and hence higher fuel efficiency, as well as lower CO_2 emissions than gasoline engines (Sullivan et al., 2004).

b) Gas and Gas Vehicles

Natural gas, which is primarily composed of methane, is regarded as one of the most promising alternative transport fuels due to its interesting chemical properties with high hydrogen to carbon ratio and high research octane number (about 130). Spark-ignition CNG engines using high compression ratio, lean burn mixture or high exhaust gas recirculation would be expected to outperform gasoline engines in torque and power and allow a reduction in pollutant emissions and an improvement in thermal efficiency. At present, CNG engines can achieve CO_2 emission levels below those of diesel and gasoline engines (Cho and He, 2007). Also HC, NO_x, and PM emissions of a spark-ignition heavy-duty CNG urban bus were significantly lower than those of one operated on diesel, with a reduction of 67%, 98% and 96%, respectively; no significant differences were observed for CO (Turrio-Baldassarri et al., 2006).

LPG, a petroleum-derived fuel mainly composed of propane, is regarded as one of the most promising alternative for gasoline. Higher thermal efficiency can be achieved from internal combustion engines running on LPG than gasoline. CO_2, CO, HC, NO_x, and PM emissions from LPG vehicles are significantly lower than gasoline and diesel vehicles (Karamangil, 2007; Ning and Chan, 2007).

c) Bioethanol and Biodiesel

Bioethanol is one of the most prevalent biofuels in the world, currently produced from many raw materials such as sugar cane, starch crops, waste biomass, etc. by using already improved and demonstrated technologies. Most gasoline vehicles can burn E10 without any modifications to the engines.

Biodiesel, as one of the most promising and available CD substitutes, is mainly being produced from soybean and rapeseed oils currently. However, any vegetable oil—peanut, sunflower, coconut or palm—could be used to produce biodiesel. Biodiesel can be easily used in existing diesel engines with no or minor modifications in any blend ratio with CD. The most common blend B20 has been subject widely to recent scientific investigation. Biodiesel has a higher oxygen content than CD and much lower sulphur content, thus higher combustion efficiency and lower emissions than CD can be achieved. Significant reductions of PM, CO and HC emissions and a slight increase of NO_x emissions have been observed when B20 was compared with CD (McCormick et al., 2006; Holden et al., 2006).

d) Other Alternative Fuels and Vehicles

Dimethyl ether (DME), as a viable alternative to diesel with reduced NO_x, HC, CO and PM emissions, is gaining more attention worldwide in recent years (Semelsberger et al., 2006; Arcoumanis et al., 2008). In China, DME is also expected to substitute diesel to some extents in the future, mainly because it can be produced from China's abundant coal and biomass resources (Zhang et al., 2006; Song et al., 2004; Wu, 2006). However, considering the development of DME technology in China is still at its early stages, DME is not included in the scope of the present study.

Other advanced alternative fuels such as hydrogen, gas-to-liquids and coal-to-liquids are not likely to make a significant contribution in the transportation fuel market over the next few decades except on a regional basis (Dorian et al., 2006). Therefore they are not included in the present study.

Other alternative vehicles such as fuel-cell and hybrid vehicles are also excluded because it will be difficult for China to skip to fuel-cell vehicles in the next two to three decades due to serious challenges and difficulties (Wang et al., 2005), and the current producers of hybrid-electric vehicles (Toyota and Honda) have so far been unwilling to transfer hybrid-vehicle technologies for production inside China (Gallagher, 2006).

In the long run, hydrogen fuel cell, as the transition goal of a new generation of auto energy powertrain system, has been favoured globally. It is particularly suitable for China to develop a hydrogen energy transportation powertrain system given the situation of China's energy sources (hydrogen can be obtained from coal, nuclear and hydroelectric energy and various other renewable resources) and urban/rural layout (transition is easier to be realized because of concentrated infrastructure). It is estimated that the commercialization of cars with fuel cell will happen around the year of 2020, and the ultimate hydrogen economy will be realized between 2040 and 2050 (Wang and Ouyang, 2007).

e) Summary

Since engines running on diesel or LPG have higher thermal efficiency than gasoline, switching from gasoline vehicles to diesel or LPG vehicles could result in an improvement of fuel economy and thus less energy demand. Switching from gasoline and diesel to CNG, bioethanol and biodiesel could offer a reduction of fossil energy demand, petroleum demand in particular, because CNG is produced from natural gas and bioethanol and biodiesel are produced from renewable sources.

4.3 Available Policy Measures

A series of policy measures aiming to reduce energy demand and GHG emissions in the road transport sector are reviewed here. These measures include those already implemented in China in recent years, those going to be implemented according to government's plan and those might reasonably be expected to adopt because of successful implementation elsewhere.

4.3.1 Private Vehicle Control

Many factors influence whether or not a person owns a vehicle, how intensively this vehicle is used and whether other transport modes play a significant role in the total travel demand. In addition to income, other factors like prices of motor vehicles, the cost of driving, availability and fare prices for public transport, quality of the transport infrastructure, social patterns and climatic, physical and geographical conditions can play an important role (Wohlgemuth, 1997).

Singapore and Hong Kong both have shown how motorisation can be curbed in the context of rapidly rising incomes by private vehicle control (PVC) measures.

These measures usually are economic constraints on private vehicle ownership and use in parallel of significant investments in public transport, especially a mass rapid transit system (Cameron et al., 2004).

Most motor vehicles in China, especially private-owned ones, are concentrated in major cities. Beijing, for example, accounted for 6.6% of total *VP* and 8.1% of private-owned *VP* in China in 2005, while its population accounted for only 1.2% of the total (NBS, 2006). Therefore, it would be effective to control private vehicle ownership and use in China by PVC measures. In fact, the effectiveness of controlling private vehicle ownership in China by economic constraints has already been shown through quite conflicting official attitudes in different regions. For instance, the Beijing Municipal Government has adopted a few policies to stimulate the purchase of private vehicles, such as the provision of vehicle mortgages and the deduction of relevant fees for vehicle use (Liu et al., 2007), while the Shanghai Municipal Government has adopted policies to restrict the purchase of private vehicles such as high registration fees for private vehicles. The result of these different policies is that, although GDP per capita in Beijing is lower than it is in Shanghai, private vehicle ownership is much higher (Figure 4.1).

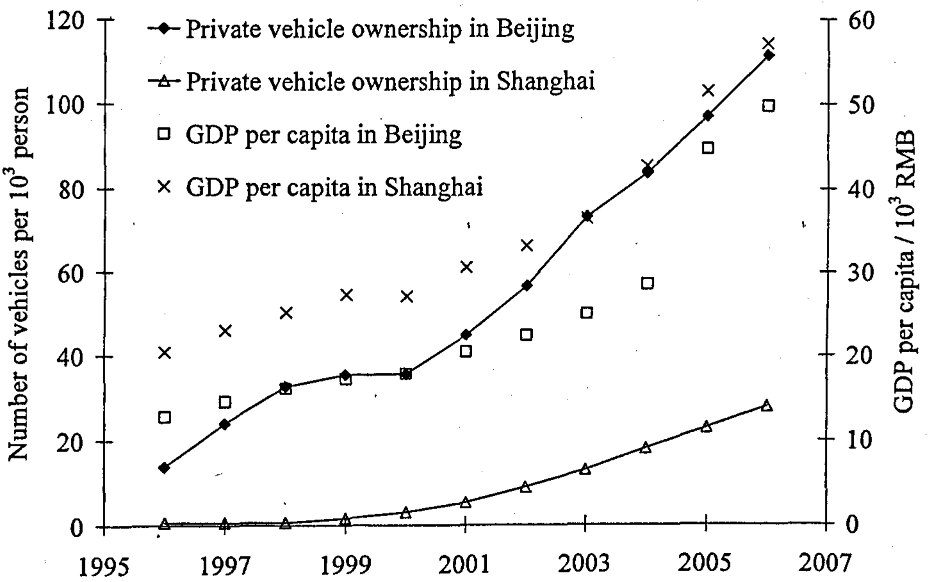

Figure 4.1 GDP per capita and private vehicle ownership in Beijing and Shanghai (Calculated from NBS (1996-2007))

4.3.2 Fuel Economy Regulation

Fuel economy regulation (FER) is considered to be an effective measure to improve vehicle fuel economy by forcing or encouraging automobile manufacturers to produce more fuel efficient vehicles, as illustrated by the Corporate Average Fuel Economy (CAFE) standards in the US, the Weight-class-based fuel economy standards in Japan and the voluntary agreement in motor vehicle CO_2 emissions between the EU and the European Automobile Manufacturers Association (He et al., 2005).

China recently implemented mandatory regulations for its first fuel economy standard for the passenger vehicle fleet: *Limits of fuel consumption for passenger cars* (AQSIQ and SAC, 2004). The standard will be implemented in two phases: Phase 1 took effect on July 1, 2005, for new vehicle models and on July 1, 2006, for existing vehicle models. Phase 2 should have taken effect on January 1, 2008, for new models and on January 1, 2009, for existing models. Maximum allowable fuel consumption limits by weight category were set up in the standard (Table 4.1), and every individual vehicle model sold in China will be required to meet the standard for its weight class. The standard covers all passenger vehicles weighing no more than 3500 kg, but exclude vehicles that use gas, ethanol or other alternative fuels. Standards for passenger cars with manual and automatic transmissions are separate. Sports utility vehicles (SUV) and multi-purpose vans, regardless of their transmission types, share the same standards as passenger cars with automatic transmissions. Another standard targeting light duty commercial vehicles (LDB, LDT and MT)—*Limits of fuel consumption for light duty commercial vehicles* (AQSIQ and SAC, 2006) will be implemented in 2008 or the year after.

The current Chinese standard is more stringent than those in Australia, Canada and the US, but less stringent than those in the EU and Japan (Figure 4.2). The fuel economy limit for Chinese new passenger vehicles is about 15% and 25% lower than that in the EU and Japan, respectively. Further strengthening fuel economy regulations are therefore likely to be introduced in the near future.

Table 4.1 Maximum limits for fuel consumption (l/100 km) for passenger vehicles in China

	Phase 1 [2005]		Phase 2 [2008]	
Mass / kg	Manual	Auto/SUV	Manual	Auto/SUV
≤750	7.2	7.6	6.2	6.6
≤865	7.2	7.6	6.5	6.9
≤980	7.7	8.2	7.0	7.4
≤1090	8.3	8.8	7.5	8.0
≤1205	8.9	9.4	8.1	8.6
≤1320	9.5	10.1	8.6	9.1
≤1430	10.1	10.7	9.2	9.8
≤1540	10.7	11.3	9.7	10.3
≤1660	11.3	12.0	10.2	10.8
≤1770	11.9	12.6	10.7	11.3
≤1880	12.4	13.1	11.1	11.8
≤2000	12.8	13.6	11.5	12.2
≤2110	13.2	14.0	11.9	12.6
≤2280	13.7	14.5	12.3	13.0
≤2510	14.6	15.5	13.1	13.9
≤3500	15.5	16.4	13.9	14.7

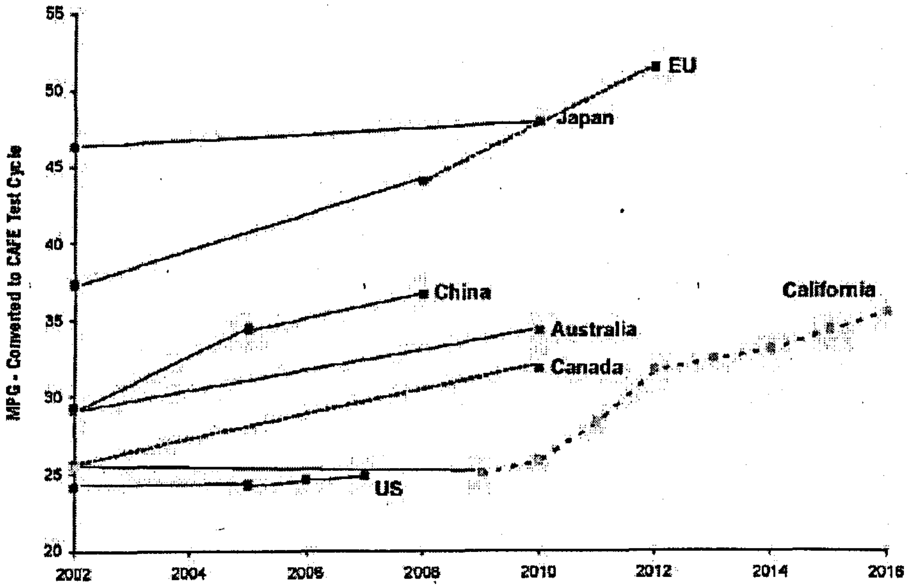

Figure 4.2 Comparison of fuel economy standards for passenger vehicles in selected countries (reproduced from An and Sauer (2004))

4.3.3 Promotion of Diesel and Gas Vehicles

European countries saw an increasing share of diesel cars in recent years, especially France, where the share of diesel cars exceeds 40% in the total passenger car fleet, mainly because diesel vehicles have higher efficiency than gasoline ones. However, development for diesel cars in China lagged far behind mainly because of severe government constrains, lack of awareness and public acceptance, and limited diesel engine technology. Diesel cars only accounted for less than 0.6% in the total car sales in 2004, and the existing diesel car population accounted for less than 0.2% of the total vehicle population (Luo and Xiong, 2007).

Currently, management systems and policy regulations for promoting gas vehicles have already been established in 19 'alternative fuel vehicles (AFV) demonstration' regions/cities in China. The industry chain from development and production of critical components for gas vehicle, for whole vehicle and refuelling equipment production, to the operation, maintenance and inspection of gas vehicles has also been set up in these areas (CATRC and CAAM, 2006). The scale of gas vehicle utilization is increasing steadily, and construction of infrastructure such as refuelling stations is speeding up (Table 4.2 and Table 4.3). There were 240 thousand gas vehicles in these cities in 2005 and more than half of them were CNG vehicles. Approximately 1.4 Mt of oil was saved in the same year and the air quality in those cities was improved. Currently there are more than 300 thousand gas vehicles in China and more cities have joined the program (CATRC and CAAM, 2006).

Table 4.2 Number of CNG/LPG vehicles and refuelling stations in China (data from Li and Gu (2006))

	1999	2000	2001	2002	2003	2004
LPG vehicles	39000	61000	85000	96000	114000	114000
CNG vehicles	4000	15000	25000	57000	79000	101000
LPG refuelling stations	85	140	206	255	299	355
CNG refuelling stations	45	85	120	233	295	357

Table 4.3 Number of CNG/LPG buses and taxis in China in 2004 (data from Ren (2006))

LPG bus	CNG bus	LPG taxi	CNG taxi
12519	27479	101481	73521

CNG and LPG vehicles account for a large amount of urban buses and taxis in some regions, for example, more than 74% of taxis in Shanghai and 85% of buses in Sichuan province have changed to CNG/LPG fuelled vehicles. However, the majority of China's CNG/LPG fuelled vehicles are retrofitted, with about 16% being newly manufactured vehicles. And AFV programs in China have tended to focus more on the acquisition of AFV rather than on the use of alternative fuels. The number of vehicles that were converted to be capable of using LPG or CNG increased, but the number of vehicles actually using these fuels remained low (Zhao and Melaina, 2006).

4.3.4 Fuel Tax

Fuel tax (FT) is considered to be an important instrument for climate policy. Currently, most countries are using FT as an instrument for controlling vehicle fuel consumption (Table 4.4). Michaelis and Davidson (1996) believed that a 30% fuel price increase due to tax increase would reduce driving by 5% and improve fuel economy by 9%. Litman (2005) believed that a 10% fuel price increase due to tax increase would reduce driving by 3.2% and improve fuel economy by 6%. Turrentine and Kurani (2007) found that US consumers generally did not analyse their fuel costs in a systematic way and ignored fuel economy in their automobile or fuel purchases, and cited the low fuel prices compared with income as a possible reason for this. Sterner (2007) believed that oil demand and CO_2 emissions in Europe could be much higher if there was not the high taxation on fuels. When high fuel prices due partly to FT levels are combined with a well developed public transport system, like in case of the UK, people tend to use their own vehicles less and use public transport more (see Table 4.5).

Table 4.4 Gasoline taxes and retail prices in selected countries in 2005

	Tax[a]	Retail Prices[b]
Western Europe		
Italy	90	148.6
UK	97	151.4
France	89	140.6
Germany	90	146.5
Portugal	103	135.1
Spain	72	113.5
Switzerland	50	117.0
Eastern Europe		
Hungary	125	128.5
Poland	118	118.9
Czech Republic	117	108.2
Non European		
Japan	46	111.6
Australia	35	78.4
Canada	26	68.0
US	10	51.3

a, *Source*: Sterner (2007). Leaded/unleaded weighted by consumption shares. Figures in purchasing power parity constant (2000) US cents per litre
b, *Source*: IEA (2005). Unleaded premium gasoline prices for 1st quarter 2005. Figures in current US cents per litre

Table 4.5 Shares of transport mode to work and car *FAVDT* in the US and UK in 2004 (data from DoT and BTS (2007), DfT (2006))

	Shares of transport mode to work (%)			Car *FAVDT*
	Private car	Public transport	Other	10^3 km
US	88.4	4.4	7.2	20.12
UK	71.2	14.6	14.2	14.68

FT also plays a significant role in switching fuels from conventional to alternative types, and the rate of switching is faster when the incentive is higher, as reflected in the Hong Kong experience (Hung, 2006).

China is among countries that have the lowest fuel price with no FT employed. The FT has been endlessly debated and postponed over the past few years, since it would lead to a politically sensitive increase in gasoline and diesel prices. According to a report from the Ministry of Finance, China intended to finally introduce a FT in 2007 though the measure would be counterbalanced by the cancellation of highway tolls and other administrative fees (IEA, 2007b).

4.3.5 Biofuel Promotion

a) Bioethanol

The Chinese government has been promoting E10 as an alternative transport fuel in some of the major grain producing regions since 2002. There are 9 E10 promoting provinces currently. China is the third biggest producer of fuel ethanol after Brazil and the US. As at end of 2005, annual E10 consumption in China reached 10 Mt, about 20% of the total gasoline consumption. The Chinese government is planning to increase the current annual fuel ethanol production capacity of 1 Mt to 3 Mt by 2010 and 10 Mt by 2020, and two-thirds of production should be from non-food sources. This is clearly stated in the *Mid and Long-term Development Strategies for Renewable Energy* (Liu, 2006).

b) Biodiesel

Biodiesel cost is 1.5-3 times higher than CD currently cost in developed countries, which is in large part due to the high price of the feedstock (Demirbas, 2007). Therefore, the competitiveness of biodiesel to CD will depend on the fuel tax approaches. Boosted by the tax reductions for biofuels that are currently granted by most of the EU member states, biodiesel production has increased substantially. EU – Germany in particular – currently dominates world biodiesel production and use (Frondel and Peters, 2007)

Biodiesel research in China started in 1985, but it did not get enough attention from the government until 2000. The current production capacity for biodiesel in China is about 60 thousand tonnes, and the feedstock is mainly from waste oil mainly because of the high costs of oil crops (Shen, 2006b). However, biodiesel technology development is still in its early stages in China, and biodiesel produced by the current technique in China can only be used in agricultural vehicles or power generation machines because of its poor quality. The Chinese government is planning to establish a vehicular biodiesel production capacity of 0.2 Mt by 2010 and 2 Mt by 2020 (Liu, 2006).

4.4 Summary

The key driving factors for future growth in energy demand and GHG emissions in China's road transport sector, as identified in the modelling approach in Chapter 3, have been analyzed. These driving factors include vehicle population, vehicle distance travelled, vehicle fuel economy and vehicle/fuel switching. Available policy measures that could have potential impacts on these driving factors have been reviewed. These measures include private vehicle control, fuel economy regulation, promoting diesel and gas vehicles, fuel tax, and biofuel promotion. However, the effects of these measures on the future energy demand and GHG emissions in China's road transport sector need to be carefully assessed to support decision-making.

Chapter 5

Chapter 5 Future Energy Demand and Greenhouse Gas Emissions in China's Road Transport Sector and Policy Implications

5.1 Introduction

In this Chapter, two scenarios has been designed to represent the worst and best case of the development strategies for China's road transport sector in terms of energy demand and GHG emissions. A business as usual (BAU) scenario is established assuming no policy measures will be used, and then used as a reference scenario with which a best case (BC) scenario will be compared. In the BC scenario, a series of policy measures are expected to be implemented by the government and lead to a reduction of energy demand and GHG emissions in China's road transport sector. The model developed in Chapter 3 has been used to analyze the future trends of energy demand and GHG emissions in China's road transport sector in these two scenarios.

Policy-making is not easy if the impacts of various measures are not quantified, and if the interaction between different options is not considered. However, it is very difficult to quantify the impacts of different measures or to evaluate the interaction between different options in China because it is such a large and populated country with various levels of economic development. Quantification has been made for the potential impacts of various measures on the driving factors in the model through the author's best estimates based on the extensive review of earlier studies in Chapter 4. Reduction potentials due to each kind of measure for energy demand and GHG emissions in China's road transport sector have been estimated and analyzed.

5.2 Earlier Work

A few Chinese researchers have analyzed the future trends of petroleum demand and/or associated GHG emissions in China's road transport sector according to the government's plan or policy directions. Zhang (2004) predicted the petroleum demand in China's road transport sector up to 2020, based on historical trends. To explore the importance of policy options in curbing the rapid growth in China's road transport petroleum demand, He et al. (2005) designed three scenarios regarding vehicle fuel economy improvements in predicting future petroleum demand and CO_2 emissions up to 2030. Wang et al. (2007) took He et al.'s research as a starting point, and reviewed all recent environmental policies relating to the road transport sector, and developed three scenarios to estimate different emissions reduction potentials in 2020 for different road transport development strategies.

5.2.1 Scenarios design

Zhang (2004) first predicted the future production for each vehicle type based on their historical trends and future economic growth and then predicted future vehicle import and export, composition of total vehicle fleet and vehicle scrapage rate. *VP* for each vehicle type was derived from the above predictions. The share of diesel vehicles for each vehicle type was also predicted. The share of alternative-fuel vehicle population in the total fleet was assumed to be 2%, 4% and 7% in 2010, 2015 and 2020, respectively. *AECV* for each vehicle type in the future was projected to be 5%, 15%, 20% and 25% less in 2005, 2010, 2015 and 2020, respectively than in 2003.

He et al. (2005) designed three different scenarios for future fuel economy improvement, based on the assumption that the Chinese government would implement in phases some measures to regulate fuel economy of the targeted fleets (cars, minibuses and light duty buses). The measures would be carried out in three phases—2008, 2013 and 2018. In the non-improvement scenario, the fuel economy level of new vehicles would remain at the current level, while in the low-improvement scenario, fuel economy improving measures would result in 20%, 10% and 10% improvements in fuel economy of new vehicles in the three phases over the previous period. This improvement would be 30%, 20% and 20%, respectively, in the high-improvement scenario. Together with the prediction of total population and number of new vehicles sold in each year for each vehicle type, *FAFE* for each vehicle type can be determined. The estimation of future *VP* was based on an economic elasticity method relating per-capita vehicle ownership to per-capita GDP, urban population density, conditions of urban public transport systems and the direction of governmental policies. The Japanese growth trend for passenger vehicle population was used to determine the elasticity for China. The future trend of vehicle type composition was projected according to government policies and the development plan of the Chinese automobile industry. In particular, the following factors were taken into account: passenger car population would experience increasing growth rate; the share of trucks in China's vehicle fleet would gradually decrease; the share of diesel vehicles would increase. The number of new vehicles sold by vehicle type was also estimated for each year, which was essential for calculating fuel economy improvement benefits. The share of alternative-fuel vehicles was conservatively assumed to be no more than 1% in the next 30 years. Therefore, alternative-fuel vehicles were not considered. The projections of future *FAVDT* were based on some research results of total traffic volume projections (Wang, 2000). The projected *VP* and *FAVDT* would be the same in the three scenarios.

The three scenarios designed by Wang et al. (2007) were based on the existing literature and on analysis of past environmental policies related to the road transport sector. The Reference Baseline Scenario was a conservative projection of the future of China's road transport sector, assuming that the future fuel economy level of new vehicles would remain at the level in 2000. In the Recent Policy Scenario, a combination of measures and policies in place before the end of 2005, especially the implementation of fuel economy limits for the targeted fleets, was incorporated. In the New Policy Scenario, sustainable development and climate change issues were emphasized, where it was assumed that China would invest heavily to adopt more advanced technologies to reduce energy demand and GHG emissions. Future *VP* was projected using a similar method with He et al. (2005). Future *FAVDT* was projected based on the following assumptions: the *FAVDT* in China generally would have a tendency to decrease because the growth rate of vehicle population outpaced those of passenger and freight transport volume; the decline of *FAVDT* for medium and heavy vehicles would be comparatively slow while that for light duty vehicles would be faster. The projected *VP* and *FAVDT* would be the same in the three scenarios.

5.2.2 Results

Zhang's results showed that population of diesel vehicles, gasoline vehicles and motorcycles in 2020 would reach 36, 83 and 128 million, respectively, while gasoline and diesel demand in 2020would reach 126 and 95 Mt, respectively.

He et al.'s results showed that petroleum demand in 2030 would reach 363, 308 and 278 Mt in the non, low and high *FE* improvement scenarios, and the associated CO_2 emissions would be 1146, 972 and 879 Mt, respectively.

Wang et al.'s results showed that CO_2 emissions in 2020 would reach 785, 727 and 430 Mt in the Reference Baseline Scenario, Recent Policy Scenario and New Policy Scenario, respectively.

5.3 Scenarios Design in the Present Study

2005 was chosen to be the base year and 2006-2030 was the selected scenario period. It is firstly assumed that: China's economy growth will sustain a high level during the scenario period as it did in the past two decades; fuel prices will remain fairly stable in spite of the fluctuations of international crude oil price because of the tight state control; vehicle scrapping standards remain the same with the base year, i.e. *Survival* data would remain unchanged through the scenario period. The detailed description of assumptions made for the two scenarios and each kind of measure are as follows.

5.3.1 Reference Scenario: Business as Usual

The key assumption in the BAU scenario is that no measures will be implemented during the scenario period to reduce the energy demand and GHG emissions in China's road transport sector. Some measures already implemented by 2005 are also disregarded. Therefore, the BAU scenario should not be considered as forecasts, but rather a reference vision of how energy demand and GHG emissions in China's road transport sector would evolve if the Chinese government does nothing to influence long-term trends.

Private passenger vehicle ownership in China has entered a rapid-growing stage as indicated by the high sales growth rates for PC and MV and low ones for the commercial passenger vehicle fleets (HDB and LDB) in recent years, especially after China joined the World Trade Organization (WTO) in 2001 (Figure 5.1). Besides rising incomes, a greatly reduced price of motor vehicles due to the entry to the WTO is the main reason for the rapidly rising private vehicle ownership. Therefore, in the BAU case, annual sales growth rates for PC and MV are assumed to stay at a high level while those for HDB and LDB are at a low level. In medium and small cities, the share of TA in the total travel volume is generally low, and the occupation rate of TA is also low mainly due to the supply of TA surpassing the demand (Jiang, 2005). It is assumed that the development of the TA industry will focus on better management rather than putting more TA onto the market, therefore annual sales growth rates for TA is medium in the BAU case. MC will maintain a stable growth rate due to the increasing demand from rural areas.

Increasing urban infrastructure construction, energy transportation needs (mainly coal and oil) and logistics needs are the main factors driving the future demand of trucks in China. Figure 5.1 has shown that the annual sales growth rates for HDT were very high between 1998 and 2004 and then became very low in 2005 and 2006; annual sales growth rates for MDT has been low in recent years while those for LDT and MT have been high (Figure 5.2). The main reasons for these trends could be: heavier vehicles are more fuel efficient than lighter ones; the government has been promoting more fuel efficient transport modes (railway and waterway) to replace highway in long-distance freight transport; strengthening emission standards hit heavy polluters like HDT most; rapidly changing logistic and supply-chain pressures, such as just-in-time deliveries will lead to increasing numbers of trucks running below capacity or empty thus increasing demand of light trucks (Si, 2006). In the BAU case, sales growth rates for HDT and MDT are assumed to be low, while those for LDT and MT are high.

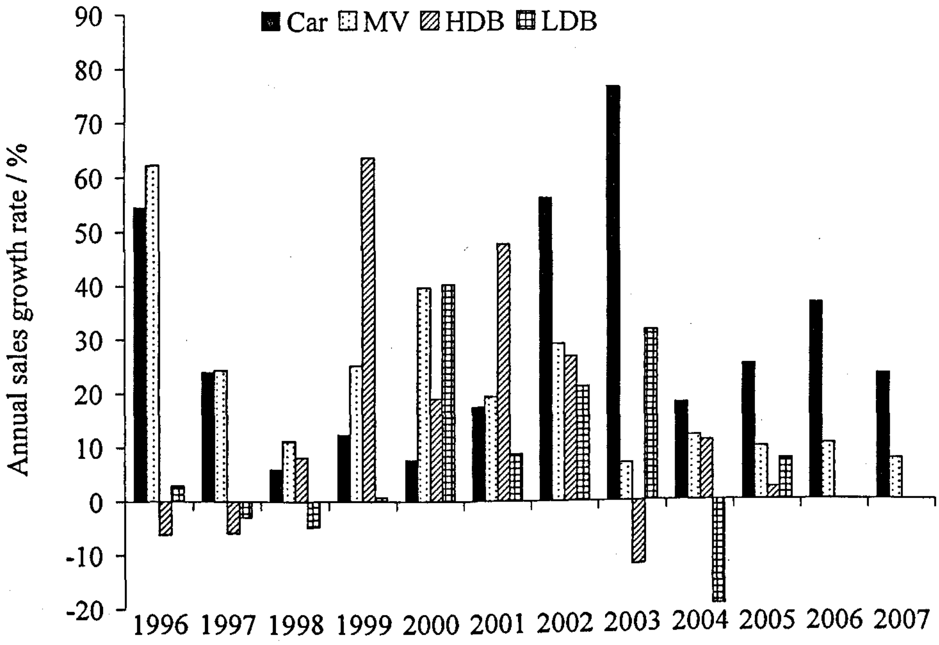

Figure 5.1 Annual sales growth rates for passenger vehicle fleets in China in recent years (data from CATRC and CAAM (1997-2006), CAAM (2007-2008))

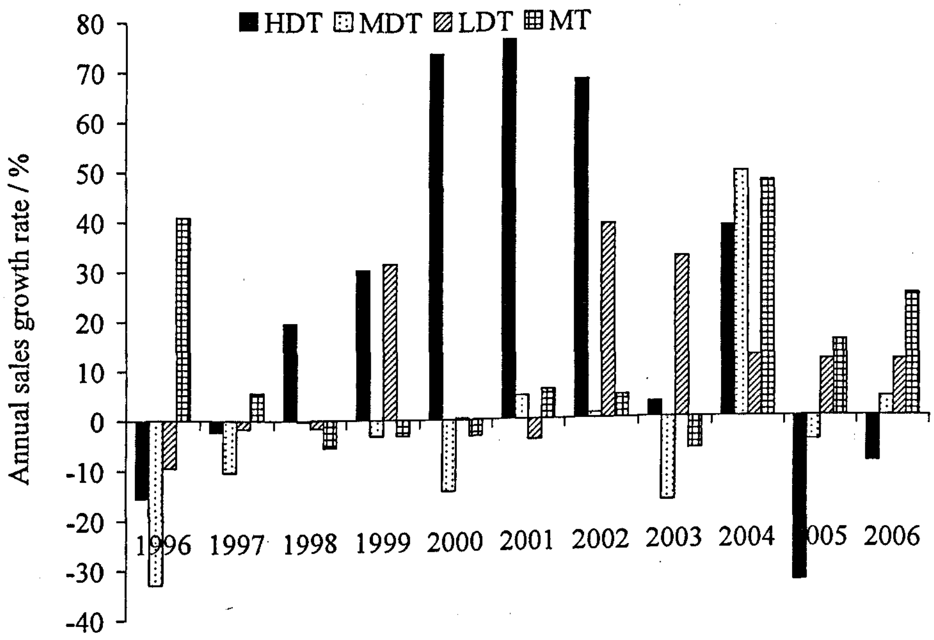

Figure 5.2 Annual sales growth rates for truck fleets in China in recent years (data from CATRC and CAAM (1997-2006), CAAM (2007))

Table 5.1 Average annual sales growth rates for each vehicle type in the past and future estimates in the BAU scenario (%)

	Historical data*	Future estimates in the BAU scenario			
	1996-2005	2006-2010	2011-2015	2016-2020	2021-2030
HDT	20.3	8	4	2	1
MDT	-4.7	0	-2	-4	-8
LDT	9.8	9	6	3	1.5
MT	8.8	8	4	2	1
HDB	13.3	10	6	3	1.5
LDB	7.3	6	4	2	1
PC	28	20	12	6	3
TA	15	8	6	3	1.5
MV	23.1	10	6	3	1.5
MC	3.1	3	3	2	2

* calculated from CATRC and CAAM (1997-2006)

Average annual sales growth rates for each vehicle type in the past and future estimates in the BAU scenario are listed in Table 5.1. It should be noted that the growth trend of *VP* in developed economies has followed a similar path through which a rapid growth trend lasts for 30-40 years, and then *VP* tends to be stabilized into a saturation period. During this process, growth rates of new vehicle sales gradually decrease with the growth of the existing vehicle stock (Davis and Diegel, 2006). Therefore, it is assumed that this will also be the case in China.

FShare and *FE* for each fuel type in each vehicle type and biofuel demand are assumed to be the same level as in the base year through the scenario period since there would be no incentive to change or improve.

FAVDT for private vehicles tends to decrease with increasing levels of vehicle ownership (Schafer, 1998). The *FAVDT* for PC and MV fleets in China would be expected to gradually reduce as the *VP* grows and the proportion of private vehicles becomes bigger. It is assumed that the *FAVDT* for PC and MV fleets in China will reduce by 20% by 2030 linearly. *FAVDT* for other vehicle types is assumed to stay the same as in the base year level through the scenario period.

5.3.2 Best Case Scenario

In the BC scenario, all policy measures as reviewed in Chapter 4 will be implemented. Details of the assumptions for each kind of measure are described as follows.

a) Private Vehicle Control

PVC measures in the present study are assumed to include economic incentives to restrict private vehicle purchase and utilization such as high vehicle taxes, registration fees, parking fees or even congestion charges (as experienced in London), in parallel of efforts to promote public transport such as establishing special lanes, better network design and improving service quality for transit buses. These measures will greatly increase the cost for private vehicle purchase and use and thus result in less demand. On the other hand, a higher demand for buses will be needed to fulfil the total passenger transportation needs.

b) Fuel Economy Regulation

FER measures in the present study are assumed to include: China's recently implemented mandatory fuel economy regulation—*Limits of fuel consumption for passenger cars* (AQSIQ and SAC, 2004); another standard to be implemented in 2008 or the year after—*Limits of fuel consumption for light duty commercial vehicles* (AQSIQ and SAC, 2006); further strengthening regulations. These measures would result in fuel economy improvements in the new vehicle fleets for the targeted vehicle types.

c) Promotion of Diesel and Gas Vehicles

PDG measures in the present study are assumed to include such as R&D programs for diesel and gas vehicle technologies, low vehicle tax and road tax for diesel and gas vehicles, government subsidy for gas vehicles in urban transit vehicles and taxies, and investing in gas infrastructures (mainly refuelling stations) etc. will be implemented to encourage automobile manufacturers to develop and people to buy diesel and gas vehicles.

The price difference between CNG/LPG and conventional fuels such as gasoline and diesel has often been cited as the most important factor in attracting consumers to switch to CNG/LPG vehicles. A natural gas pump price of at least 40-60% below the gasoline price is common in most countries that have had successful CNG/LPG vehicle penetration (Yeh, 2007). Due to lower income levels, consumers in China are more sensitive to fuel price than are consumers in developed economies. The price for LPG and CNG is slightly lower than the price of gasoline in China, but the price gap is not a large enough for private consumers to switch to LPG or CNG vehicles (Zhao and Melaina, 2006).

The impacts of PDG measures are assumed to include: heavy gasoline vehicle sales will be expected to be reducing fast while light diesel vehicle sales will be increasing steadily. Shares of gas vehicles in urban transit vehicles and taxies will be increasing steadily while those in private vehicles will remain zero due to lack of incentives for private use of gas vehicles.

d) Fuel Tax

It is assumed that in the FT measure, a 30% fuel tax on gasoline and diesel will be implemented in 2006, and a lower tax rate on LPG and CNG. This will increase the operational cost for all the vehicle types (except for HDT) especially light duty vehicles (Meng et al., 2006), and provide direct incentives for private consumers to switch from gasoline vehicles to diesel and gas vehicles, to choose vehicles with better fuel economy and to reduce vehicle use.

According to Dargay (2007), private vehicle ownership is less sensitive to fuel prices than to purchase costs in developed countries like UK, and this is also assumed to be the case in China.

China has experienced an AAGR of more than 20% in LPG consumption since the 1990s. China's LPG consumption in 2004 exceeded 20 Mt with 1/3 of it depending on imports, making China the second largest LPG importer, just after Japan (Wu, 2006). China's natural gas supply is also limited considering the strong growth in residential use. It is therefore unlikely that gas powered vehicles will take a significant proportion of the private vehicle market, due to the limitation on CNG/LPG availability in the long run.

The impacts of FT implementation are assumed to include: *FE* improvements for all vehicle types; *Sales* reduction for light duty commercial vehicles; *Sales* increase for heavy duty commercial vehicles; utilization reduction for private vehicles; a trend to switch from gasoline vehicles to diesel and gas vehicles for both private and commercial users.

e) Biofuel Promotion

In the BFP measures, it is assumed that the government will make efforts to realize its target set for the promotion of bioethanol and biodiesel for vehicle use.

The development of China's major bioethanol feedstock is shown in Table 5.2. Currently, most fuel ethanol production in China is from corn, with a small part from wheat, mainly because of the high storage cost of the over-produced grain in the late 1990s. However, wheat production decreased in recent years and China had to import 3.3 Mt of wheat to meet the demand in 2005 (MAPRC, 2006). Food security has always been the priority for China. Therefore, fuel ethanol production from wheat is just temporary. Since production and cultivation area for sugar beet in China have both been decreasing in recent years, the potential of fuel ethanol production from sugar beet is considered to be very limited. Production, cultivation area and yield rate for corn in China have all been increasing steadily. China exported more than 8 Mt of corn in 2005 (MAPRC, 2006). 3.2 tonnes of corn is needed to produce 1 tonne of ethanol. If cultivation area and yield rate for corn in China continue to increase as in the past two decades, there will be more than enough corn available for fuel ethanol to meet the government's target. Non-food sources such as cassava, sugarcane and forest residue are currently under research and development for long term bioethanol production.

Table 5.2 Development of China's major bioethanol feedstock (data from NBS (2006) and MAPRC (2006))

		Wheat	Corn	Sugarcane	Sugar beet
Production Mt	1980	55.2	62.6	22.8	6.3
	1985	85.8	63.8	51.5	8.9
	1990	98.2	96.8	57.6	14.5
	1995	102.2	112	65.4	14
	2000	99.6	106	68.3	8.1
	2005	97.4	139.4	86.6	7.9
Cultivation area Million ha	1980	28.8	20.1	0.48	0.44
	1985	29.2	17.7	0.97	0.56
	1990	30.8	21.4	1.01	0.67
	1995	28.9	22.8	1.13	0.7
	2000	26.7	23.1	1.19	0.33
	2005	22.8	26.4	1.35	0.21
Yield rate t / ha	1980	1.92	3.11	47.50	14.32
	1985	2.94	3.60	53.09	15.89
	1990	3.19	4.52	57.03	21.64
	1995	3.54	4.91	57.88	20.00
	2000	3.73	4.59	57.39	24.55
	2005	4.27	5.28	64.15	37.62
	US(2005)	2.82	9.32	66.63	49.30
	Germany(2005)	7.40	8.60	n/a	59.40
	Brazil(2005)	2.19	3.04	72.85	n/a

Cassava as another major potential feedstock for fuel ethanol in China has two advantages: it thrives better in poor soils than any other major food plant, and use of fertilizer is thus rarely necessary. 2.7 tonnes of cassava dry chips are needed to produce 1 tonne of ethanol (Leng et al., 2008). Guangxi province is the main cassava-producing region in China, with its planted area and annual production of cassava accounting for 60% of that of the whole country (Dai et al., 2006). The local government of Guangxi is launching an ambitious program of production of fuel ethanol from cassava. A 100 thousand litre demonstration plant was set up, as well as a target of 1 Mt annual fuel ethanol production capacity by 2010 (Liu, 2006). It is expected that cassava-based ethanol will become more and more poplar because it is economically viable while corn-based ethanol is not without government subsidy (Yu and Tao, 2008), and it is more ethically acceptable for a populated country since it does not effect food supply and demand.

Sugarcane as a feedstock for fuel ethanol in China has a major advantage: it requires much less land to produce the same amount of ethanol than all the other feedstock mentioned above because it is one of the most efficient plants for converting solar energy (Fan, 2006). With its production, cultivation area and yield rate increasing, sugarcane could play a promising role in the future.

The development of China's major biodiesel feedstock is shown in Table 5.3. Production, cultivation area and yield rate for rapeseed and soybean in China have been increasing steadily in recent years. The potential of future production increase is large considering the low yield rate for rapeseed (compared to Germany) and soybean (compared to the USA) in China. However, China has to import a great amount of soybean to meet the demand (26 Mt in 2005) according to MAPRC (2006). The potential for soybean as a biodiesel feedstock in China is thus very limited considering the supply constrains. While for rapeseed, a relatively small amount of demand depends on import (0.5 Mt in 2005). Therefore, rapeseed is the most likely feedstock for China's biodiesel production in the future.

Table 5.3 Development of China's potential biodiesel feedstock (data from NBS (2006), MAPRC (2006))

		Rapeseed	Soybean
Production Mt	1980	2.4	n/a
	1985	5.6	10.5
	1990	7	11
	1995	9.8	13.5
	2000	11.4	15.4
	2005	13.1	16.4
Cultivation Area Million ha	1980	2.8	n/a
	1985	4.5	7.7
	1990	5.5	7.6
	1995	6.9	8.1
	2000	7.5	9.3
	2005	7.3	9.6
Yield Rate t / ha	1980	0.86	n/a
	1985	1.24	1.36
	1990	1.27	1.45
	1995	1.42	1.67
	2000	1.52	1.66
	2005	1.79	1.71
	US(2005)	1.49	2.87
	Germany(2005)	3.46	1
	Brazil(2005)	1.7	2.19

The impacts of BFP measures are assumed to include: bioethanol demand in China's road transport sector would increase linearly from 0.68 Mtoe in 2005 to 1.94 Mtoe in 2010, 6.45 Mtoe in 2020 and 12.9 Mtoe in 2030. One third of the bioethanol would be produced from corn and the rest two thirds from cassava; biodiesel demand in China's road transport sector would increase from 0 in 2008 to 0.18 Mtoe in 2010, 1.82 Mtoe in 2020 and 3.63 Mtoe in 2030 linearly. All of the biodiesel would be produced from rapeseed.

f) Impacts Quantification for Each Kind of Measure

Impacts quantification for each kind of measure on the driving factors in the present model is based on the earlier analysis and listed in Table 5.4.

Advocates of energy efficiency acknowledge that some of the savings from efficiency improvements will be taken in the form of higher energy consumption—the so-called 'rebound' effect. This is not surprising since the effect of increased efficiency is to lower the implicit price of an energy supply, and hence make its use more affordable, thus leading to greater use (Herring, 2006). As for the road transport sector, improving vehicle *FE* reduces per-km operation costs, causing vehicles to be used more (*VDT* to increase). This rebound effect in transport sector is typically estimated to be 20-40% (Litman, 2005), i.e. a 10% increase in *FE* leads to a 2-4% increase in *VDT*. It is assumed that in the present study the rebound effect is 30% for PC and MV and this effect will not have a significant impact on the use of MC and commercial vehicles such as trucks and buses.

Note that the effects of each kind of measure are progressive when these measures are combined together in the BC case, and therefore may differ from those when each kind of measure is implemented individually.

Table 5.4 Quantification of impacts for each kind of measure

Measure	Quantification of impacts on each driving factor			
	Vehicle population	Vehicle distance travelled	Vehicle fuel economy	Fuel switching
PVC	*Sales* for PC and MV will reduce by 20% while *Sales* for HDB and LDB increase by 10%	*FAVDT* for PC and MV will reduce by 10% by 2030		
FER			*FE* for PC, TA, MV, LDB, LDT and MT will increase by 40% by 2030 (gas vehicle not included)	
PDG				*FShare* for MDT-G and HDB-G will reduce to 0 by 2010 while that for LDT-D will increase to 100% by 2015; *FShare* for PC-D, TA-D and MV-D will increase from 0 to 20% by 2030; *FShare* for HDB-LPG/CNG, TA-LPG/CNG, LDB-D and MT-D will increase by 50% by 2030
FT	*Sales* for LDT, MT and LDB will reduce by 20% while *Sales* for HDT and HDB increase by 10%	*FAVDT* for PC and MV will reduce by 10% by 2030	*FE* for all vehicle types will increase by 20% by 2030	*FShare* for MDT-G and HDB-G will reduce to 0 by 2010 while that for LDT-D will increase to 100% by 2015; *FShare* for PC-D, TA-D and MV-D will increase from 0 to 20% by 2030; *FShare* for HDB-LPG/CNG, TA-LPG/CNG, LDB-D and MT-D will increase by 50% by 2030; *FShare* for PC-CNG and PC-LPG will increase from 0 to 5% and 3% by 2030, respectively
BFP				Bioethanol and biodiesel demand will increase from 0.68 and 0 Mtoe in 2005 to 1.94 and 0.2 Mtoe in 2010, 6.45 and 1.82 Mtoe in 2020, and 12.9 and 3.63 Mtoe in 2030, respectively

5.4 Results

5.4.1 Vehicle Population

Motor vehicle population in China is estimated to be 205.4 million in 2020 and 342.3 million in 2030 in the BAU scenario, while in the BC scenario, it is estimated to be 169.3 million in 2020 and 278.7 million in 2030. The share of private passenger vehicles (PC and MV) in the total vehicle stock would increase from 52% in 2005 to 86% and 84% in 2030 in the BAU and BC scenario, respectively.

Figure 5.3 shows the predictions of China's motor vehicle population in the present study and earlier studies for comparison purpose. Dargay and Gately (1999) projected China's vehicle population to be 79.3 million in 2015 using an econometrically estimated model based on annual data for 26 countries. Walsh (2003) estimated vehicle population in 2020 to be 110.2 million in the high economy growth case and 54.5 million in the low economy growth case by assuming that vehicle growth rates are the same as income growth rates. Wei and Ba (2004) projected that vehicle population in 2020 would be 188.8 million in the high growth case and 101.5 million in the low growth case, using a model based on GDP per capita and urbanization rate. Zhang (2004) estimated vehicle population in 2020 to be 118.4 million by first predicting the future production for each vehicle type based on historical trend and future economic growth, and then predicting future vehicle import and export, composition of total vehicle fleet and vehicle scrapage rate. Compared with the historical trend it can be observed that most of the earlier studies have underestimated the strong growth of China's vehicle population.

5.4.2 Demand for Each Fuel

a) Conventional Gasoline

Future trends for CG demand are shown in Figure 5.4. CG demand would reach 328.1 Mtoe in 2030 in the BAU case. Increasing private passenger vehicles (PC and MV) is the main factor driving future CG demand. The share of CG demand for PC and MV fleets in the total demand is 40.7% in 2005 and will be 83.2% in 2030 under the BAU scenario. CG demand in 2030 would reduce by 22.8% to 253.3 Mtoe if PVC measures were introduced, because CG demand mainly comes from private vehicles and PVC measures would reduce annual private vehicle sales by 20% and private vehicle utilization by 10% linearly by 2030. It would reduce further by 14.6% to 216.4 Mtoe if FER measures were introduced, mainly because the FER measures would improve the *FE* of newly-added light duty vehicles by 40% linearly by 2030, and it would take longer for the *FE* level for the whole fleet to improve as the new vehicles gradually replaced the old vehicles, and part of the reduction potential from efficiency gains was offset by higher utilization. It would further reduce by 15.6% to 182.6 Mtoe if the PDG measures were introduced, mainly because the trend of switching from gasoline vehicles to diesel and gas vehicles. It would further reduce by 32.4% to 123.5 Mtoe if the FT measures were introduced, mainly because the FT measures would improve the *FE* of newly-added vehicles for all vehicle types by 20% linearly by 2030, and reduce the private vehicle utilization by 10% linearly by 2030, and result in a trend of switching from gasoline vehicles to diesel and gas vehicles. It would further reduce by 13.2% to 107.2 Mtoe if BFP measures were introduced, mainly because the substitution of CG by bioethanol.

b) Conventional Diesel

Future trends for CD demand are shown in Figure 5.5. CD demand would reach 109 Mtoe in 2030 in the BAU case. Increase of commercial vehicles (trucks and buses) population is the main factor driving future CD demand. CD demand in 2030 would increase 2.6% to 111.8 Mtoe if the PVC measures were introduced, because PVC measures would increase annual HDB sales by 20%. It would reduce 10.4% to 100.2 Mtoe if FER measures were introduced, mainly because the FER measures would improve the *FE* of newly-added LDT-D, MT-D and LDB-D by 40% linearly by 2030. It would increase 25.5% to 125.8 Mtoe if the PDG measures were introduced, mainly because the trend of switching from gasoline to diesel for all vehicle types. It would reduce 2.2% to 123 Mtoe if the FT measures were introduced, mainly because the FT measures would improve the *FE* of newly-added vehicles for all vehicle types by 20% linearly by 2030 and result in a trend of switching from gasoline vehicles to diesel vehicles. It would reduce 3.1% to 119.2 Mtoe if BFP measures were introduced, mainly because the substitution of CD by biodiesel.

c) Liquefied Petroleum Gas

Future trends for LPG demand are shown in Figure 5.6. LPG demand would reach 1.46 Mtoe in 2030 in the BAU case. It would increase by 2.1% to 1.49 Mtoe if the PVC measures were introduced, because PVC measures would increase annual HDB sales by 20% and thus increase annual HDB-LPG sales by 20%. It would further increase by 43% if the PDG measures were introduced, mainly because the trend of switching from gasoline to gas for public transport vehicles (HDB and TA). It would further increase by 128.6% to 4.87 Mtoe if the FT measures were introduced, mainly because the FT measures would provide an incentive for private vehicles to switch from gasoline to gas.

d) Compressed Natural Gas

Future trends for CNG demand are shown in Figure 5.7. CNG demand would reach 4.81 Mtoe in 2030 in the BAU case. It would increase by 5.6% to 5.08 Mtoe if the PVC measures were introduced, because PVC measures would increase annual HDB sales by 20% and thus increase annual HDB-CNG sales by 20%. It would further increase by 40.9% if the PDG measures were introduced, mainly because the trend of switching from gasoline to gas for public transport vehicles (HDB and TA). It would further increase by 78.6% to 12.79 Mtoe if the FT measures were introduced, mainly because the FT measures would provide an incentive for private vehicles to switch from gasoline to gas.

e) Bioethanol

Future trends for bioethanol demand are shown in Figure 5.8. Bioethanol demand would still be at the level of 0.68 Mtoe in 2030 in the BAU case. It would reach 12.9 Mtoe if the BFP measures were introduced.

f) Biodiesel

Future trends for biodiesel demand are shown in Figure 5.9. Biodiesel demand would still be at the level of 0 in 2030 in the BAU case. It would reach 3.63 Mtoe if the BFP measures were introduced.

5.4.3 Total Energy, Fossil Energy and Petroleum Demand

Future trends of total energy demand in China's road transport sector and reduction potentials of each kind of measure are shown in Figure 5.10. Total energy demand would reach 444 Mtoe in 2030 in the BAU case, more than 5 times that in 2005. It would be reduced by 16.1% to 372.4 Mtoe if PVC measures were introduced mainly because of the 22.8% reduction for CG demand. It would be further reduced by 13.1% to 323.8 Mtoe if FER measures were introduced mainly because of the 14.6% and 10.4% reduction for CG and CD demand, respectively. It would be further reduced by 1.7% to 318.4 Mtoe if PDG measures were introduced mainly because of the 15.6% reduction for CG demand and the 25.5%, 43% and 40.9% increase for CD, LPG and CNG demand. It would be further reduced by 16.8% to 264.8 Mtoe if FT measures were introduced mainly because of the 32.4% and 2.2% reduction for CG and CD demand and the 128.6% and 78.6% increase for LPG and CNG demand, respectively. It would be further reduced by 1.6% to 260.6 Mtoe if BFP measures were introduced mainly because of the reduction for CG and CD demand and the increase for bioethanol and biodiesel demand. Therefore, total energy demand would reach 260.6 Mtoe in 2030 in the BC case, only 3 times that in 2005.

Future trends of fossil energy demand in China's road transport sector and reduction potentials of each kind of measure are shown in Figure 5.11. Fossil fuel demand would reach 443.3 Mtoe in 2030 in the BAU case, more than 5 times that in 2005. It would be reduced by 16.2% to 371.7 Mtoe if PVC measures were introduced mainly because of the reduction for CG demand. It would be further reduced by 13.1% to 323.1 Mtoe if FER measures were introduced mainly because of the reduction for CG and CD demand. It would be further reduced by 1.7% to 317.7 Mtoe if PDG measures were introduced mainly because of the reduction for CG demand and the increase for CD, CNG and LPG demand. It would be further reduced by 16.9% to 264.2 Mtoe if FT measures were introduced mainly because of the reduction for CG and CD demand and the increase for gas demand. It would be further reduced by 7.6% to 244.1 Mtoe if BFP measures were introduced mainly because of the reduction for CG and CD demand. Therefore, fossil energy demand would reach 244.1 Mtoe in 2030 in the BC case, only 2.9 times that in 2005.

Future trends of petroleum demand in China's road transport sector and reduction potentials of each kind of measure are shown in Figure 5.12. Petroleum demand would reach 438.5 Mtoe in 2030 in the BAU case, again more than 5 times that in 2005. It would be reduced by 16.4% to 366.6 Mtoe if PVC measures were introduced mainly because of the reduction for CG demand. It would be further reduced by 13.3% to 318 Mtoe if FER measures were introduced mainly because of the reduction for CG and CD demand. It would be further reduced by 2.4% to 310.5 Mtoe if PDG measures were introduced mainly because of the reduction for CG demand and the increase for CD, CNG and LPG demand. It would be further reduced by 19.1% to 251.4 Mtoe if FT measures were introduced mainly because of the reduction for CG and CD demand and the increase for LPG demand. It would be further reduced by 8% to 231.3 Mtoe if BFP measures were introduced mainly because of the reduction for CG and CD demand. Therefore, petroleum demand would reach 231.3 Mtoe in 2030 in the BC case, only 2.7 times that in 2005.

5.4.4 Greenhouse Gas Emissions

Future trends of GHG emissions from China's road transport sector and reduction potentials of each kind of measure are shown in Figure 5.13. GHG emissions would reach 1303.7 Mt CO_2-eq in 2030 in the BAU case, as expected more than 5 times that in 2005. It would be reduced by 15.9% to 1096.4 Mt CO_2-eq if PVC measures were introduced mainly because of the reduction for CG demand. It would be further reduced by 13.0% to 953.5 Mt CO_2-eq if FER measures were introduced mainly because of the reduction for CG and CD demand. It would be further reduced by 1.3% to 941.3 Mt CO_2-eq if PDG measures were introduced mainly because of the reduction for CG demand and the increase for CD and gas demand. It would be further reduced by 16.7% to 783.6 Mt CO_2-eq if FT measures were introduced mainly because of the reduction for CG and CD demand and the increase for gas demand. It would be further reduced by 1.4% to 772.5 Mt CO_2-eq if BFP measures were introduced mainly because of the reduction for CG and CD demand. Therefore, GHG emissions would reach 772.5 Mt CO_2-eq in 2030 in the BC case, only 3 times that in 2005.

5.4.5 Comparisons with Earlier Studies

A summary of results for the year 2030 in the present study is listed in Table 5.5. In 2030, all the measures combined together could achieve a reduction of 183.4 Mtoe in total energy demand, 199.2 Mtoe in fossil energy demand, 207.2 Mtoe in petroleum demand and 531.2 Mt CO_2-eq in GHG emissions.

Because of the different modelling approaches and assumptions made, results from the present study can not be compared directly with those from earlier studies. Therefore, results are only compared generally, and no firm conclusions are drawn from this.

Zhang (2004) projected that gasoline and diesel demand in 2020 would reach 126 and 95 Mt, respectively, while in the present study these were estimated to be 106-202 Mt and 87-92 Mt, respectively.

He et al. (2005) showed that the GHG emissions reduction potential for FER measures in 2030 was 15.2-23.3%, while in the present study this was estimated to be 13%. Since He et al. (2005) did not take into account the fact that consumer preference towards larger engines and larger vehicles, their estimates could be very optimistic.

Wang et al. (2007) showed that the GHG emissions reduction potential for FER measures in 2020 was 7.4%, while in the present study this was estimated to be

6.4%. Their estimates were also considered to be optimistic for the same reason as He et al. (2005).

5.4.6 Policy Implications

The results in the present study suggest that PVC, FER and FT would be the most effective measures to reduce demand of total energy, fossil energy and petroleum, and GHG emissions.

The PDG measure would not be very effective in reducing total energy demand and GHG emissions. It would have a larger effect of reducing demand of petroleum than that of total energy and fossil energy, because of the substitution of petroleum-based fuels by CNG. It would have a smaller effect of reducing GHG emissions than total energy demand, mainly because CD has a slightly higher GHG emission rate per unit of delivered fuel than CG.

BFP measure would not be very effective in reducing total energy demand. However, it would have a much larger effect in reducing fossil energy and petroleum demand, because of the substitution of fossil fuels by biofuels. It would have a smaller effect of reducing GHG emissions than total energy demand, mainly because bioethanol and biodiesel have slightly higher GHG emission rates per unit of delivered fuel than CG and CD, respectively.

5.4.7 Limitations

The present model and scenario design has its limitations because of the complexity of the transport energy system:

Simplifications have to be made for the quantification of technological and behavioural aspects in each kind of measure. Interactions between different measures are also simplified.

Considering *VDT* for diesel vehicles is much higher than for gasoline vehicles in some cases (40-110% higher in five major European countries according to

Sterner, 2007), the assumption that all fuel types having a same *VDT* for a given vehicle type may not reflect the reality.

The US Department of Transportation estimates that fuel wasted in traffic congestion accounted for more than 4% of the US's total gasoline consumption in 1984 (Riley, 1994). A more recent study shows various transport-pricing schemes can yield appreciable reductions in traffic congestion delays, and corresponding increase in average travel speeds (Palma et al., 2006). However, this effect can not be taken into account in the present model.

5.5 Summary and Conclusions

Two scenarios has been designed to represent the worst and best case of the development strategies for China's road transport sector in terms of energy demand and GHG emissions. A BAU scenario is established assuming no policy measures will be used, and then used as a reference scenario with which a BC scenario will be compared. In the BC scenario, a series of policy measures are expected to be implemented by the government and lead to a reduction of energy demand and GHG emissions in China's road transport sector. The model developed in Chapter 3 has been used to analyze the future trends of energy demand and GHG emissions in China's road transport sector in these two scenarios. Quantification has been made for the potential impacts of various measures on the driving factors in the model through the author's best estimates based on the extensive review of earlier studies in Chapter 4. Reduction potentials due to each kind of measure for energy demand and GHG emissions in China's road transport sector have been estimated.

The results suggest that in the BAU scenario, total energy demand, fossil energy demand, petroleum demand and GHG emissions in China's road transport sector in 2030 would reach 444 Mtoe, 443.3 Mtoe, 438.5 Mtoe and 1303.7 Mt CO_2-eq, respectively. While in the BC scenario these would be 260.6 Mtoe, 244.1 Mtoe, 231.3 Mtoe and 772.5 Mt CO_2-eq, with reduction potentials as large as 41.3%, 44.9%, 47.2% and 40.7% achieved, respectively.

The present investigation also suggests that PVC, FER and FT would be the most effective measures to reduce the demand of total energy, fossil energy and petroleum, and GHG emissions. PDG measure would not be very effective in reducing total energy demand and GHG emissions. It would have a larger effect in reducing the demand of petroleum than that of total energy and fossil energy and a smaller effect in reducing GHG emissions than energy demand. BFP measure would not be very effective in reducing total energy demand. However, it would have a much larger effect in reducing fossil energy and petroleum demand and a smaller effect in reducing GHG emissions than total energy demand.

Due to the limitations of the present model and scenario design, the results would be subject to the assumptions made. For the sensitivity analysis to the assumptions made, see Chapter 7 and Appendix D.

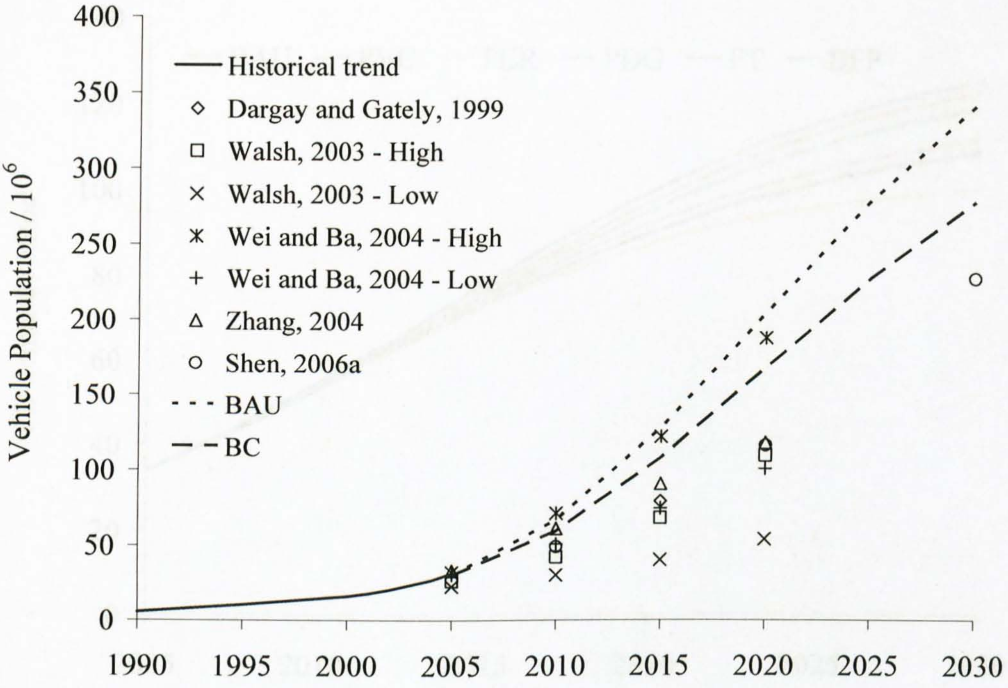

Figure 5.3 Historical trend and future predictions for China's motor vehicle population

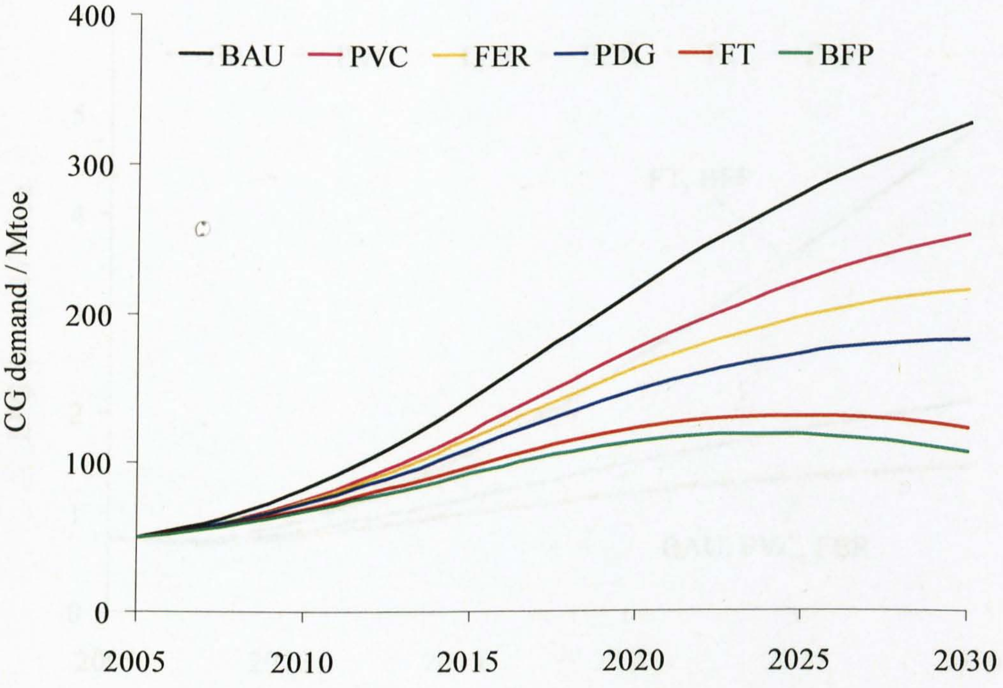

Figure 5.4 CG demand in China's road transport sector after each kind of measures were implemented 2005-2030

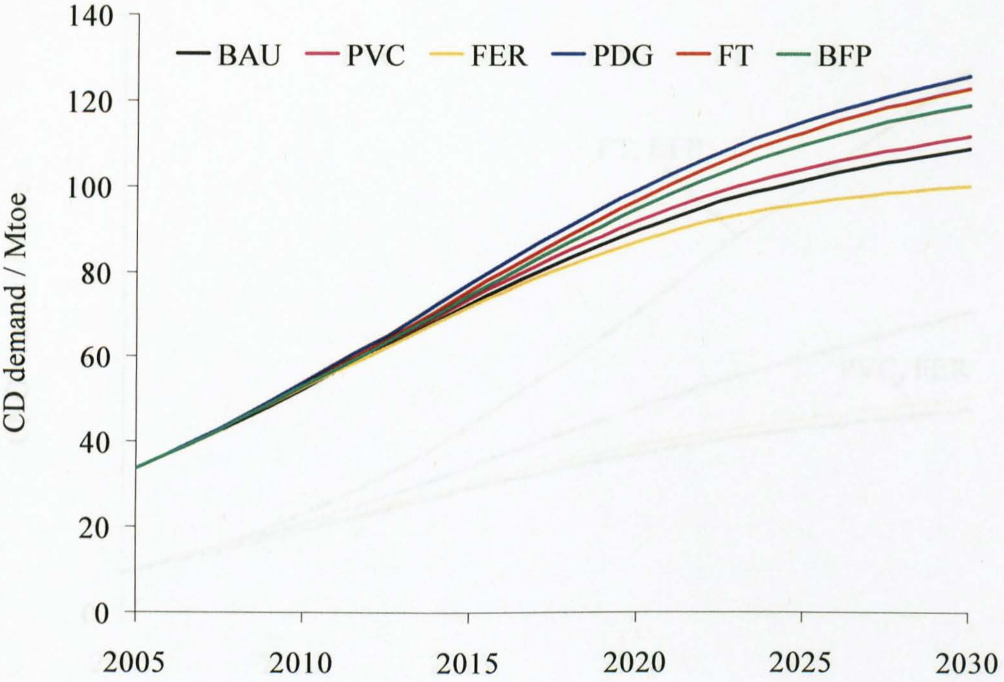

Figure 5.5 CD demand in China's road transport sector after each kind of measures were implemented 2005-2030

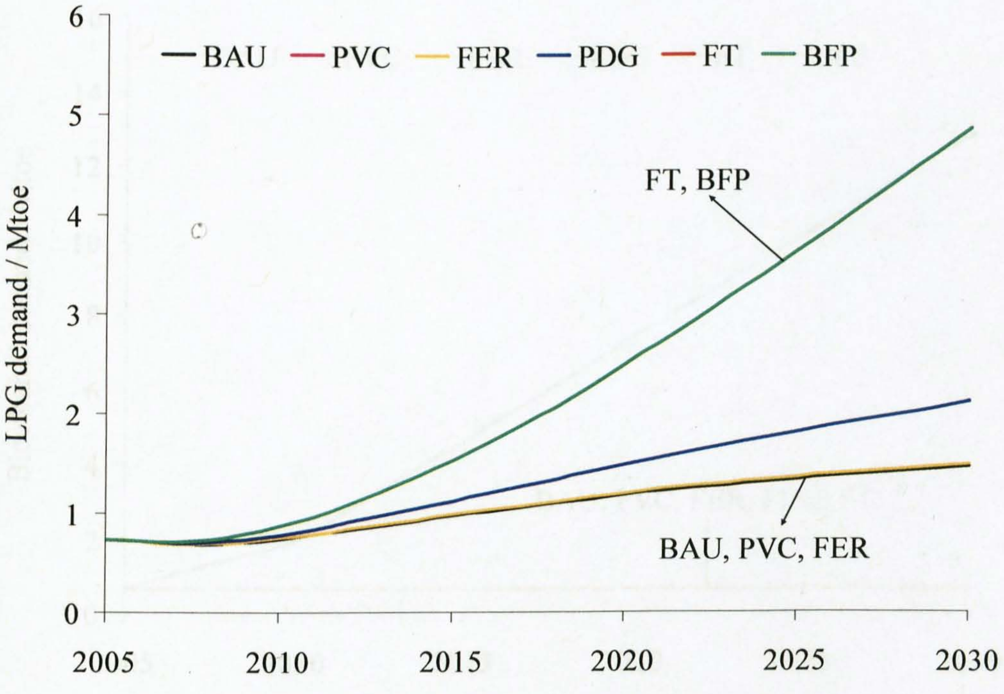

Figure 5.6 LPG demand in China's road transport sector after each kind of measures were implemented 2005-2030

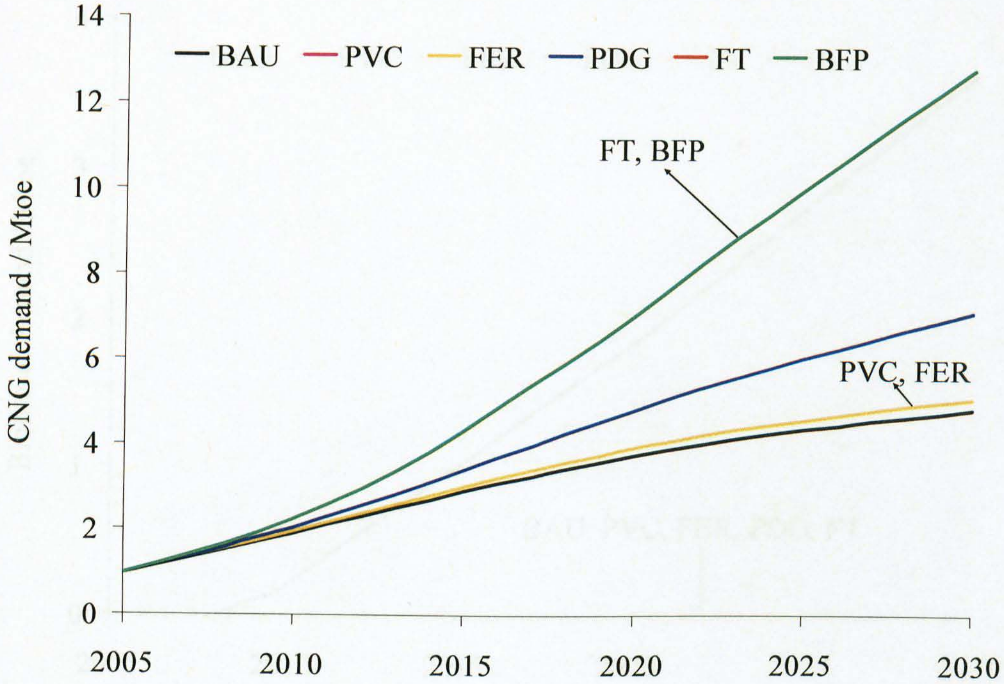

Figure 5.7 CNG demand in China's road transport sector after each kind of measures were implemented 2005-2030

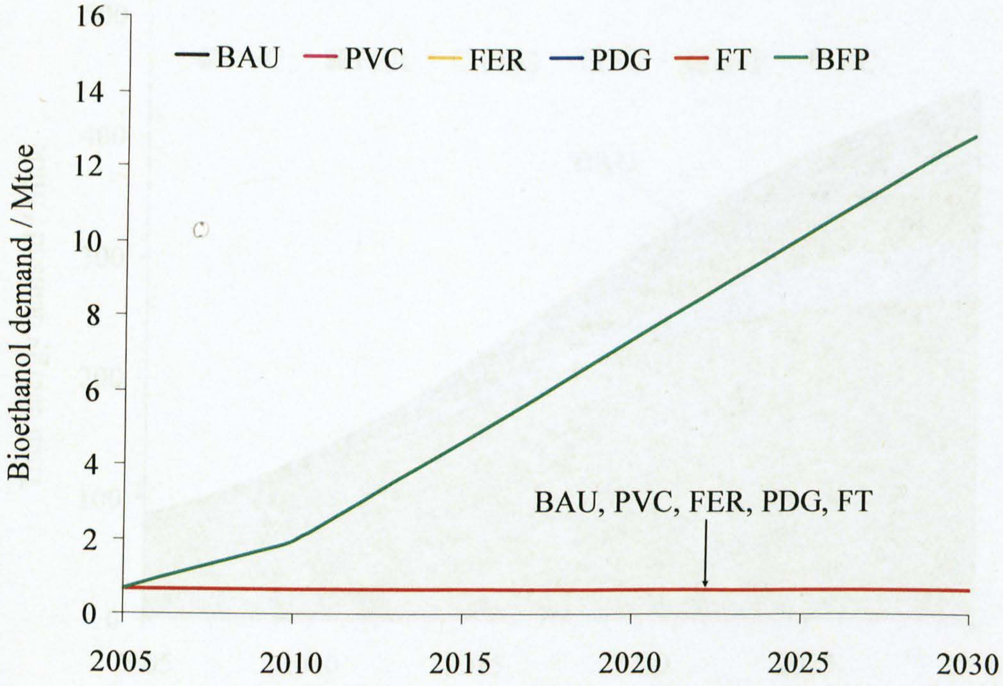

Figure 5.8 Bioethanol demand in China's road transport sector after each kind of measures were implemented 2005-2030

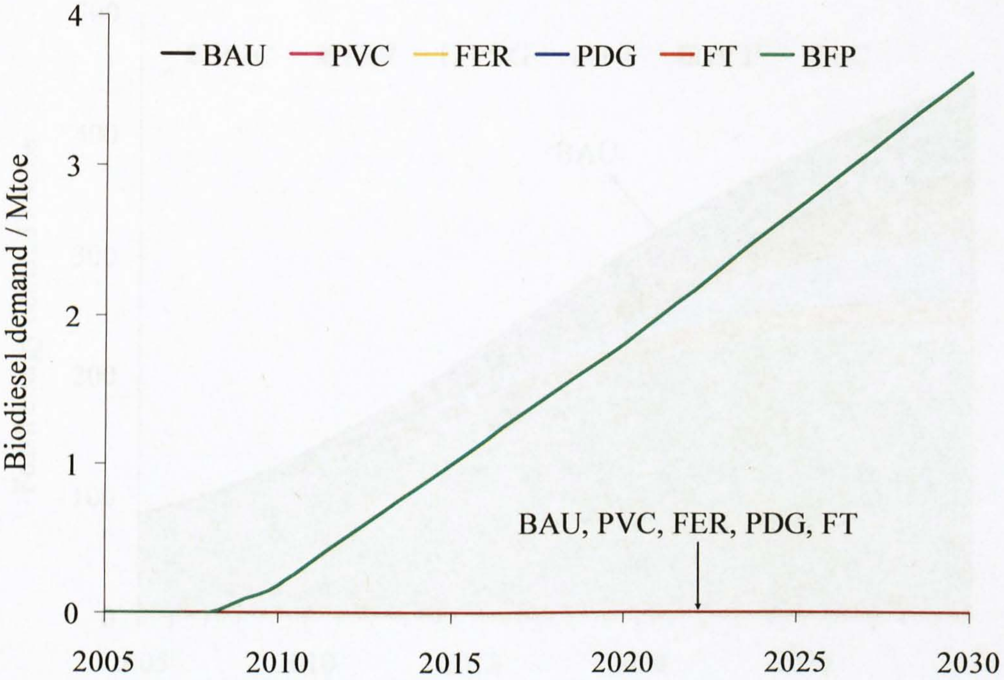

Figure 5.9 Biodiesel demand in China's road transport sector after each kind of measures were implemented 2005-2030

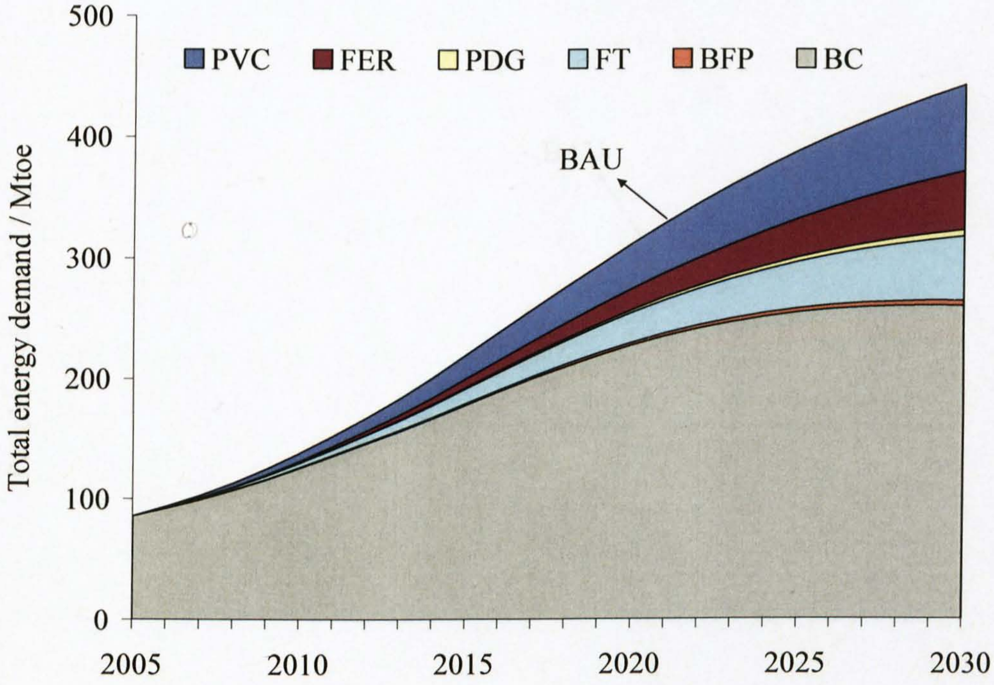

Figure 5.10 Reduction potentials of total energy demand in China's road transport sector for each kind of measure 2005-2030

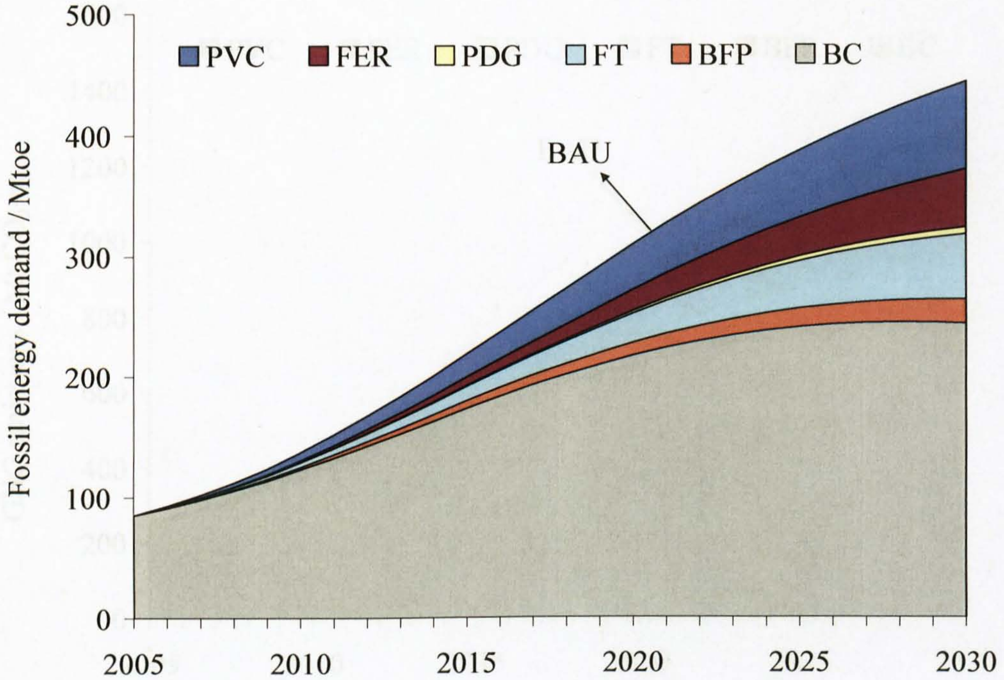

Figure 5.11 Reduction potentials of fossil energy demand in China's road transport sector for each kind of measure 2005-2030

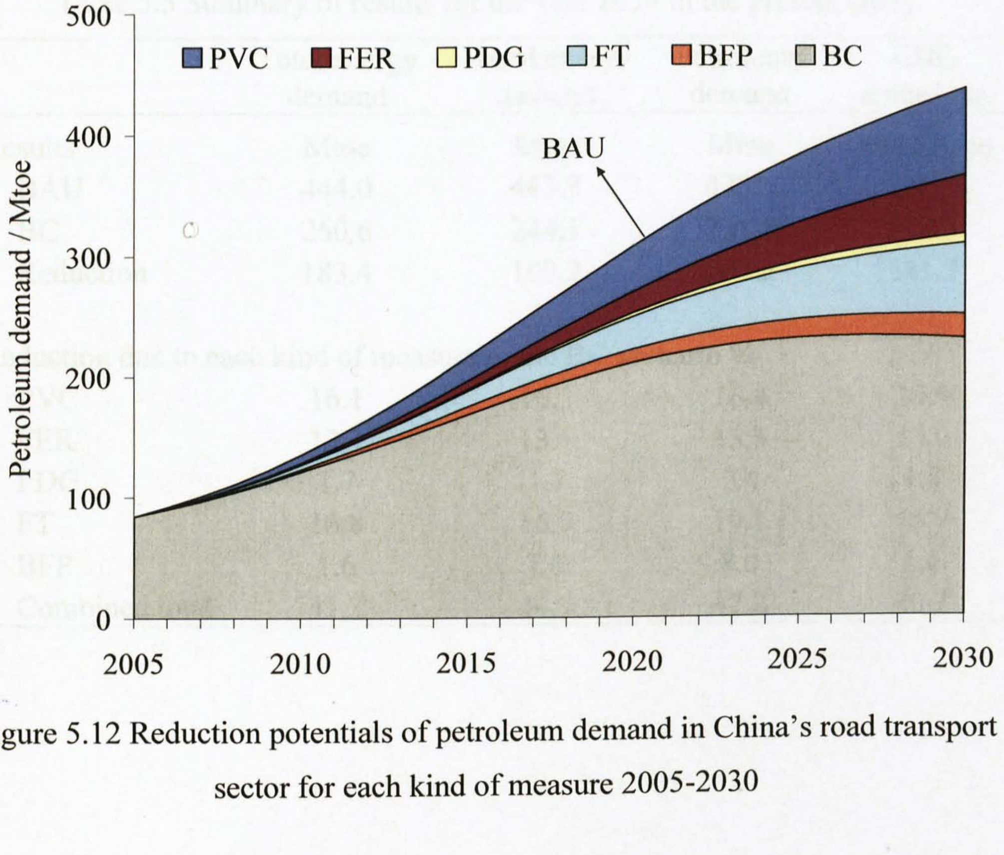

Figure 5.12 Reduction potentials of petroleum demand in China's road transport sector for each kind of measure 2005-2030

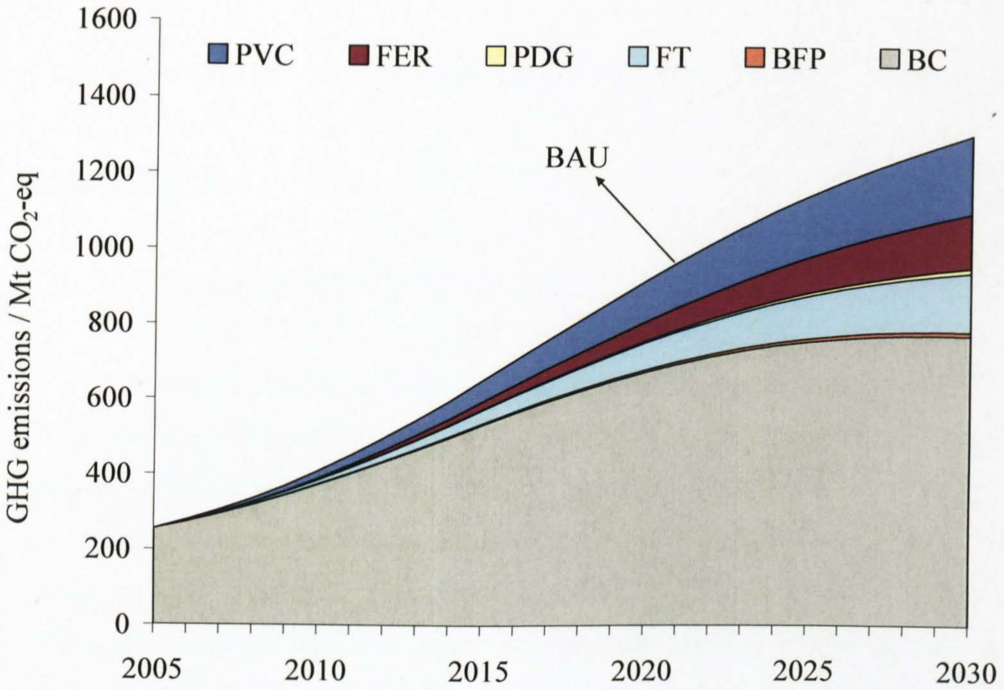

Figure 5.13 Reduction potentials of GHG emissions from China's road transport sector for each kind of measure 2005-2030

Table 5.5 Summary of results for the year 2030 in the present study

	Total energy demand	Fossil energy demand	Petroleum demand	GHG emissions
Results	Mtoe	Mtoe	Mtoe	Mt CO_2-eq
BAU	444.0	443.3	438.5	1303.7
BC	260.6	244.1	231.3	772.5
Reduction	183.4	199.2	207.2	531.2
Reduction due to each kind of measure in the BC scenario %				
PVC	16.1	16.2	16.4	15.9
FER	13.1	13.1	13.3	13.0
PDG	1.7	1.7	2.4	1.3
FT	16.8	16.9	19.1	16.7
BFP	1.6	7.6	8.0	1.4
Combined total	41.3	44.9	47.2	40.7

Chapter 6

Chapter 6 Life Cycle Assessment for China's Road Transport Sector

6.1 Introduction

6.1.1 Brief History of Life Cycle Assessment

Life cycle assessment (LCA) is a technique designed to assess potential impacts of a product over its full life cycle, by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; and interpreting the results in relation to the objectives of the study (Liamsanguan and Gheewala, 2008). LCA helps to avoid problem shifting between the different processes which are part of the life cycle of a product and has been proven to be a valuable tool for decision making towards sustainability (UNEP, 2003).

The concept of LCA originated in the early 1970s in four countries, the UK, Switzerland, Sweden and the US. The modelling was rather simple at that time, focussing on the use of energy and the production of final waste for household products. Individual LCA studies could produce quite conflicting results due to the fact that the methodological basis at that time was chaotic. The results generally pointed at the environmental superiority of the product of the company which performed the study and which also defined its own methods. In 1989 the Society of Environmental Toxicology and Chemistry brought a big step forward for the LCA methodology development, by initiatives undertaken to establish a fixed technical framework. In the 1990s, LCA methodology was further standardized by the International Organisation for Standardisation (Udo de Haes and Heijungs, 2007).

6.1.2 Objective and Scope of the Present Life Cycle Analysis

LCA can be applied to analyse energy systems, ranging from small scale, like the comparison of two types of batteries, intermediate scale, like the comparison of fossil fuels with biofuels, to the grand scale of comparing the fuel structures of whole countries or sectors (Udo de Haes and Heijungs, 2007).

The road transport sector mainly includes infrastructures and road vehicles. The life cycle of infrastructures usually includes raw material production, construction and maintenance, while the life cycle of road vehicles includes two major cycles: the 'vehicle cycle' and the 'fuel cycle' (Figure 6.1).

The 'vehicle cycle' includes the following main stages:

- Vehicle production: raw materials production, vehicle assembly and vehicle distribution.
- Vehicle operation
- Vehicle disposal (recycling)

While, the 'fuel cycle' includes the following main stages:

- Feedstock recovery: production and transportation of raw materials.
- Fuel production: production and distribution of fuel products.
- Fuel use (exactly the same process as in the vehicle operation stage in the vehicle cycle): fuel consumption in vehicle engines.

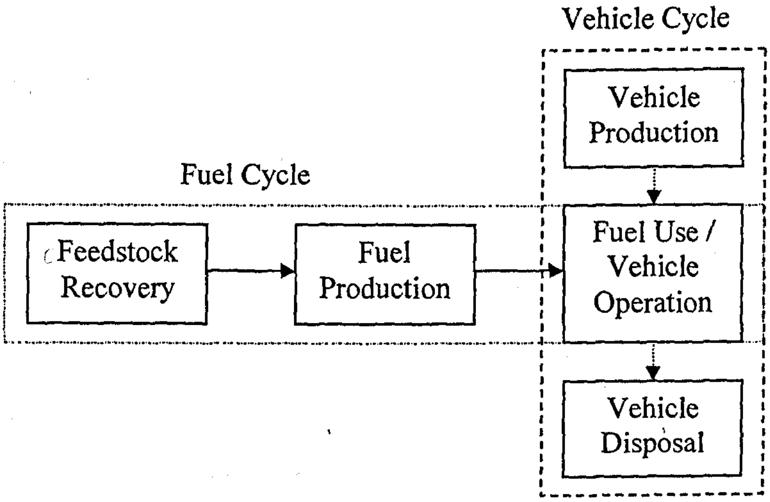

Figure 6.1 Life cycle framework for road vehicles

The whole fuel cycle is also known as the 'Well-to-Wheel' (WtW) process. The 'feedstock recovery' and 'fuel production' stage together are also known as 'Well-to-Tank' (WtT), while the 'fuel use' or 'vehicle operation' stage as 'Tank-to-Wheel' (TtW).

Most LCA applications for the transport sector so far have been focused on comparisons between different fuel life cycles or comparisons between different vehicle life cycles, to support decision-making in the choice of different fuel/vehicle technologies. Moreover, when assessing the effects of different policy measures on future energy demand and GHG emissions in the road transport sector, earlier studies (He et al., 2005; Wang et al., 2007) and Chapter 5 in the present study were focused on energy demand and GHG emissions in the TtW stage only, and could therefore be misleading to a certain degree because it does not show the whole picture.

The objectives of the present study are to develop a life cycle model for the road transport sector and use it to estimate the life cycle energy demand and GHG emissions in China's road transport sector up to 2030 based on the TtW results obtained in Chapter 5, and to re-evaluate the energy and environmental impacts of those policy measures in the BC scenario from a life cycle perspective and compare the results with those from a TtW perspective in Chapter 5.

The scope of the present study includes all the stages in the life cycle of road vehicles as illustrated in Figure 6.1 but excludes the life cycle of infrastructures due to lack of data. Nevertheless, the life cycle of infrastructures should be included whenever data were available.

6.2 Methodology

The life cycle model in this study was developed in EXCEL and it included three assessment indicators: life cycle fossil energy demand F_{LC} (MJ), life cycle petroleum demand P_{LC} (MJ) and life cycle GHG emissions G_{LC} (g CO_2-eq).

F_{LC} is the sum of the fossil energy demand at each stage during the vehicle cycle and the fuel cycle. The following expression is used to calculate F_{LC}.

$$F_{\mathrm{LC}y} = \sum_{\mathrm{i}} (Sales_{\mathrm{i},y} \times FR_{\mathrm{VPi},y} + Scrapage_{\mathrm{i},y} \times FR_{\mathrm{VDi},y}) + \sum_{\mathrm{j}} [E_{\mathrm{j},y} \times (FR_{\mathrm{WtTj},y} + FR_{\mathrm{TtWj},y})] \tag{6.1}$$

Where y is the calendar year; i is the vehicle type; j is the fuel type; *Sales* is the number of newly-added vehicles; FR_{VP} (MJ/vehicle) is the fossil energy consumption rate at the vehicle production stage; FR_{VD} (MJ/vehicle) is the fossil energy consumption rate at the vehicle disposal stage; E (MJ) is the delivered energy demand (energy delivered to vehicles); FR_{WtT} (MJ/MJ) is the fossil energy consumption rate at the WtT stage (a measure of the amount of fossil energy consumption to produce one unit of delivered energy); FR_{TtW} (MJ/MJ) is the fossil energy consumption rate at the TtW stage (a measure of the amount of fossil energy consumption per unit of delivered energy—therefore, FR_{TtW} should be 1 MJ/MJ for fossil fuels and 0 MJ/MJ for biofuels); *Scrapage* is the number of vehicles scrapped, which is calculated using the following expression.

$$Scrapage_{\mathrm{i},y} = Sales_{\mathrm{i},y} + VP_{\mathrm{i},y-1} - VP_{\mathrm{i},y} \tag{6.2}$$

Similarly, P_{LC} (MJ) is calculated using the following expression.

$$\begin{aligned} P_{\mathrm{LC}y} = {} & \sum_{\mathrm{i}} (Sales_{\mathrm{i},y} \times PR_{\mathrm{VPi},y} + Scrapage_{\mathrm{i},y} \times PR_{\mathrm{VDi},y}) + \\ & \sum_{\mathrm{j}} [E_{\mathrm{j},y} \times (PR_{\mathrm{WtTj},y} + PR_{\mathrm{TtWj},y})] \end{aligned} \tag{6.3}$$

Where PR_{VP} (MJ/vehicle) is the petroleum consumption rate at the vehicle production stage; PR_{VD} (MJ/vehicle) is the petroleum consumption rate at the vehicle disposal stage; PR_{WtT} (MJ/MJ) is the petroleum consumption rate at the WtT stage; PR_{TtW} (MJ/MJ) is the petroleum consumption rate at the TtW stage (therefore, PR_{TtW} should be 1 MJ/MJ for petroleum fuels and 0 MJ/MJ for non-petroleum fuels).

G_{LC} (g CO_2-eq) is calculated using the following expression.

$$\begin{aligned} G_{\mathrm{LC}y} = {} & \sum_{\mathrm{i}} (Sales_{\mathrm{i},y} \times GR_{\mathrm{VPi},y} + Scrapage_{\mathrm{i},y} \times GR_{\mathrm{VDi},y}) + \\ & \sum_{\mathrm{j}} [E_{\mathrm{j},y} \times (GR_{\mathrm{WtTj},y} + GR_{\mathrm{TtWj},y})] \end{aligned} \tag{6.4}$$

Where GR_{VP} (g CO_2-eq/vehicle) is the GHG emission rate at the vehicle production stage; GR_{VD} (g CO_2-eq/vehicle) is the GHG emission rate at the vehicle disposal stage; GR_{WtT} (g CO_2-eq/MJ) is the WtT GHG emission rate; GR_{TtW} (g CO_2-eq/MJ) is the TtW GHG emission rate (therefore, GR_{TtW} is equal to the combustion GHG emission rate (*CGR*) for fossil fuels and 0 for biofuels because the carbon released from biofuel combustion is absorbed from the atmosphere during the feedstock cultivation).

Since *Sales*, *VP* and *E* can be obtained from the calculations in Chapter 5 and exported from LEAP into the model, if FR_{VP}, FR_{VD}, PR_{VP}, PR_{VD}, GR_{VP}, GR_{VD}, FR_{WtT} and GR_{WtT} can be determined and input into the model, then F_{LC}, P_{LC} and G_{LC} can be calculated using the above equations.

6.3 Data Collection

6.3.1 Vehicle Cycle Data

The necessary data for the vehicle cycle analysis is the mass of the vehicle, the distribution of the materials used in the vehicle by mass and the fossil energy consumption and GHG emissions associated with the production of these materials, and vehicle assembly and disposal. Since there is very limited data available concerning production and disposal of various vehicle types in China, a review of vehicle life cycle studies in recent years was carried out to collect relevant data.

Most of the reviewed studies were focused on the analysis of medium-size gasoline car (car-G) and their results are listed in Table 6.1. Since the fossil energy consumption and GHG emissions for a vehicle in the production and disposal stage is closely related to the vehicle mass (VM), all the results based on a vehicle unit were converted to be based on per kg VM, i.e. specific values, in order to be compared with each other. It was considered to be insufficient to draw conclusions from Wu et al. (2006) and Eriksson et al. (1996) since their results were incomplete (only the production of main materials was included). Results from Zamel and Li (2006) were not considered in the assessment since they were significantly higher than those from other studies. Therefore, a reasonable range of fossil energy consumption and GHG emissions per kg VM for a car-G should be 56.05-60.94 MJ and 4135-4244 g CO_2-eq in the production stage and 0.24-0.68 MJ and 0-33 g CO_2-eq in the disposal stage, respectively. These estimations for heavy-duty truck (HDT) (Eriksson et al., 1996) and fuel-cell car (car-FC) (Zamel and Li, 2006) were very close to those for car-G. GHG emissions in the production stage for CNG/LPG car were found to be slightly higher than those for car-G (Michaelis and Davidson, 1996). Therefore, it is assumed that for all vehicle types with all fuel types in the present study, fossil energy consumption and GHG emissions per kg VM are 60 MJ and 4200 g CO_2-eq in the production stage and 0.6 MJ and 30 g CO_2-eq in the disposal stage, respectively. The average VM for each vehicle type was estimated based on the specifications of some new vehicle models in the Chinese market (CATRC and CAAM, 2004-2006). FR_{VP}, FR_{VD}, GR_{VP} and GR_{VD} for each vehicle type were then able to be determined (Table 6.2). Petroleum consumption for a vehicle in the production and disposal stage was not available through literature research. Since the majority of the energy consumed to produce and dispose a vehicle is electricity, and the percentage of electricity produced from petroleum is very small in China, it is assumed that there is no petroleum consumption in the production and disposal of a vehicle. Therefore, PR_{VP} and PR_{VD} are both assumed to be 0 in the present study.

Since for a given vehicle type, the FR_{VD} is only about 1% of the FR_{VP}, and the *Scrapage* is less than the *Sales* (Table 6.3), the fossil energy consumed in vehicle disposal ($Scrapage_{i,y} \times FR_{VDi,y}$) would be insignificant compared to the fossil energy consumed in vehicle production ($Sales_{i,y} \times FR_{VPi,y}$) in a given year. Therefore, the fossil energy consumed in vehicle disposal was disregarded in the calculations in the present study. For the same reason, GHG emissions in vehicle disposal were also disregarded.

Table 6.1 Main findings from selected life cycle studies for medium-size gasoline cars

	Studied country	Studied vehicle type	Vehicle mass kg	Fossil energy consumption				Greenhouse gas emission			
				MJ/vehicle		MJ/kg VM		g CO_2-eq/vehicle		g CO_2-eq/kg VM	
				Production	Disposal	Production	Disposal	Production	Disposal	Production	Disposal
Eriksson et al., 1996	Sweden	Car-G	1300	54000	1500	41.54	1.15				
		HDT	7500	309000	6000	41.20	0.80				
Hakamada et al., 2007	Japan	Car-G	1214	68100	650	56.10	0.54	5100000	28	4201	0.02
Zamel and Li, 2006	US	Car-G	1324	119630	490	90.35	0.37	10480000	0	7915	0
		Car-FC	1306	121390	480	92.95	0.37	10660000	0	8162	0
Hussain et al., 2007	Canada	Car-G	1270	77400	300	60.94	0.24	5390000	0	4244	0
		Car-FC		81000	300			5390000	0		
Wu et al., 2006	China	Car-G	1140					3799000	154000	3332	135
Schafer et al., 2006	US	Car-G	1322	74101	899	56.05	0.68	5467000	44000	4135	33

Table 6.2 Vehicle mass and vehicle life cycle data used in the base year for each vehicle type

	HDT	MDT	LDT	MT	HDB	LDB	TA	PC	MV	MC
VM (kg)	9000	6000	2500	1000	12000	2000	1300	1300	1000	300
FR_{VP} (MJ/vehicle)	540000	360000	150000	60000	720000	120000	78000	78000	60000	18000
FR_{VD} (MJ/vehicle)	5400	3600	1500	600	7200	1200	780	780	600	180
GR_{VP} (g CO_2-eq/vehicle)	37800000	25200000	10500000	4200000	50400000	8400000	5460000	5460000	4200000	1260000
GR_{VD} (g CO_2-eq/vehicle)	270000	180000	75000	30000	360000	60000	39000	39000	30000	9000

Table 6.3 A sample result from the *Scrapage* calculation for the year 2015 (10^6)

	HDT	MDT	LDT	MT	HDB	LDB	TA	PC	MV	MC
Sales	0.42	0.18	1.84	0.42	0.18	0.62	0.33	12.17	1.79	14.14
Scrapage	0.29	0.18	0.76	0.32	0.06	0.25	0.23	0.94	0.42	11.71

6.3.2 Fuel Cycle Data

To assess the whole life cycle for a fuel is a complex problem because it requires large amount of data collection, analysis and modelling. Thus an extensive review of recent published fuel life cycle studies has been carried out to find the appropriate data for each fuel in the present study.

a) Conventional Gasoline and Diesel

FR_{WtT} and GR_{WtT} for conventional gasoline (CG) in developed countries were typically estimated to be 0.21-0.22 MJ/MJ and 15-18 g CO_2-eq/MJ respectively, while those for conventional diesel (CD) were 0.14 MJ/MJ and 9-12.1 g CO_2-eq/MJ respectively (Table 6.4). Hu et al. (2004), Dai et al. (2006) and Zhou et al. (2007) did their assessments using the Greenhouse gases, Regulated Emissions and Energy use in Transportation model developed at Argonne National Laboratory after adjustments for China's situation. Therefore, their results should be more appropriate for China. The base year FR_{WtT} for CG and CD are 0.24 and 0.2 MJ/MJ respectively and GR_{WtT} for CG and CD are 20.6 and 17.3 g CO_2-eq/MJ (estimated proportionally by the current author based on results from Schafer et al. (2006) and Zhou et al. (2007)) for the present study. The percentage of petroleum in the FR_{WtT} for CG and CD was estimated to be 46-47% (Wang, 1999b; General Motors, 2001). Therefore, PR_{WtT} for CG and CD are 0.11 and 0.09 MJ/MJ in the present study, respectively.

Table 6.4 FR_{WtT} and GR_{WtT} estimates for CG and CD in selected studies

Fuel type	Studies	Country studied	FR_{WtT} MJ/MJ	GR_{WtT} g CO_2-eq/MJ
CG	Malca and Freire, 2006	France	0.22	
	Hekkert et al., 2005	US	0.22	15
	Schafer et al., 2006	US	0.21	18
	Svenssona et al., 2007	Norway	0.21	
	Hu et al., 2004	China	0.23	16
	Dai et al., 2006	China	0.24	
	Zhou et al., 2007	China	0.24	
CD	Hekkert et al., 2005	US	0.14	9
	Schafer et al., 2006	US	0.14	12.1
	Svenssona et al., 2007	Norway	0.14	
	Silva et al., 2006	Portugal	0.15	14.2
	Rabl, 2002	France		7.2
	Beer et al., 2002	Australia		11
	Dai et al., 2006	China	0.19	
	Zhou et al., 2007	China	0.2	

b) Gas

There were not many LCA studies for liquefied petroleum gas (LPG) and compressed natural gas (CNG) during the literature searching (Table 6.5). The base year FR_{WtT} for LPG and CNG are 0.18 and 0.21 MJ/MJ respectively and GR_{WtT} for LPG and CNG are 13 and 14 g CO_2-eq/MJ (estimated proportionally by the author based on results from Hekkert et al., 2005 and Zhou et al., 2007) for the present study. The percentages of petroleum in the FR_{WtT} for LPG and CNG were estimated to be 44% (Wang, 1999b) and 3-4% (Wang, 1999b; General Motors, 2001), respectively. Therefore, PR_{WtT} for LPG and CNG are 0.08 and 0.01 MJ/MJ in the present study, respectively.

Table 6.5 FR_{WtT} and GR_{WtT} estimates for CNG and LPG in selected studies

Fuel type	Studies	Country studied	FR_{WtT} MJ/MJ	GR_{WtT} g CO_2-eq/MJ
LPG	Hekkert et al., 2005	US	0.18	13
	Beer, et al. 2002	Australia		11
CNG	Rabl, 2002	France		9.2
	Hekkert et al., 2005	US	0.15	10
	Silva et al., 2006	Portugal	0.07	9.1
	Zhou et al., 2007	China	0.21	

c) Bioethanol

Corn is the most common feedstock for fuel ethanol worldwide. Corn-based ethanol (E-corn) life cycle has been studied extensively. Cassava is a promising feedstock for bioethanol in China. Cassava-based ethanol (E-cassava) life cycle has been studied extensively in recent years in China. Findings from these studies are listed in Table 6.6.

Table 6.6 FR_{WtT} and GR_{WtT} estimates for E-corn and E-cassava in selected studies

Fuel type	Studies	Country studied	FR_{WtT} MJ/MJ	GR_{WtT} g CO_2-eq/MJ
E-corn	IEA, 2004b	Various	0.73-1.34	
	Kim and Dale, 2008	US	0.74	56.7
	Lavigne and Powers, 2007	US	0.72	
	Zhang and Yuan, 2006a	China	0.88	
	Zhang and Yuan, 2006b	China		94.2
E-cassava	Hu et al., 2004	China	0.63	71.9*
	Dai et al., 2006	China	0.65	
	Zhou, et al. 2007	China	0.7	64.5*
	Leng, et al. 2008	China	0.64	71.4
	Nguyen et al., 2007	Thailand	0.58	45.5

* only CO_2 emissions included

Results of FR_{WtT} and GR_{WtT} for E-corn from Zhang and Yuan (2006a; 2006b) were used in the present study because they are specific studies for China. The percentage of petroleum in the FR_{WtT} for E-corn was estimated to be 13% (General Motors, 2001). Therefore, the PR_{WtT} for E-corn is 0.11 MJ/MJ in the present study.

FR_{WtT} and GR_{WtT} for E-cassava in China are much higher than in Thailand (Nguyen et al., 2007), mainly because of coal burning in the ethanol conversion process. Results from Leng et al. (2008) were used in this study because it is the most recent and detailed study and it took N_2O and CH_4 into account when calculating GHG emissions (Table 6.7).

Table 6.7 FR_{WtT} and GR_{WtT} at each process during the WtT process for E-cassava before co-products allocation (data from Leng et al. (2008))

	FR_{WtT} MJ/MJ	GR_{WtT} (g CO_2-eq/MJ)			
		CO_2	CH_4	N_2O	Total
Cassava cultivation and treatment	0.2109	20.358	0.980	6.140	26.497
Transport of cassava dry chips	0.0107	0.282	0.028	-	0.299
Denatured ethanol conversion	0.5532	62.686	0.140	0.018	60.188
Transport of denatured ethanol	0.0057	0.080	0.012	-	0.088
Blending of ethanol gasoline	0.0004	0.014	-	-	0.013
Total	0.7808				87.085

Petroleum consumption at the WtT stage for E-cassava should include the petroleum consumed at transportation stages (all the transportation energy was diesel) and chemical production stage. Based on the fertilizers and herbicides consumption in the cassava cultivation process from Leng et al. (2008) and the share of fuel consumption to produce fertilizers and herbicides (Table 6.8), the percentage of petroleum in the FR_{WtT} for E-cassava was estimated to be 6% by the author. Therefore, the PR_{WtT} for E-cassava is 0.04 MJ/MJ in the present study.

Table 6.8 Percentage share of fuel consumption in fertilizers and herbicides manufacture (data from Wang (1999b))

	Fertilizers			Herbicides
	N	P_2O_5	K_2O	
Diesel	0	27	31	30
Natural gas	90	26	27	23
Electricity	10	47	42	17
Residual oil	0	0	0	30

d) Biodiesel

The life cycle energy and GHG emissions for soybean-derived biodiesel in China have been studied by Hu et al. (2008) recently. However, considering the constraints on soybean supply in China, soybean-derived biodiesel is not included in the present study. The biodiesel considered includes only rapeseed methyl ether (RME).

Williamson and Badr (1998) found the FR_{WtT} and GR_{WtT} for RME in the UK to be 0.34-0.57 MJ/MJ and 37.9-53.4 g CO_2-eq/MJ, based on a review of several analyses. Frondel and Peters (2007) found the FR_{WtT} and GR_{WtT} for RME to be 0.35-0.65 MJ/MJ and 22.7-50.8 g CO_2-eq/MJ, based on a review of several analyses recently performed by institutions such as the IEA. Janulis (2004) found that under Lithuania condition, FR_{WtT} for RME to be 0.41 MJ/MJ. FR_{WtT} for RME was found to be 0.33-0.82 MJ/MJ in an IEA review study (IEA, 2004b). These founding are listed in Table 6.9.

Table 6.9 FR_{WtT} and GR_{WtT} estimates for RME in selected studies

Fuel type	Studies	Country studied	FR_{WtT} MJ/MJ	GR_{WtT} g CO_2-eq/MJ
RME	Williamson and Badr, 1998	UK	0.34-0.57	37.9-53.4
	Hovelius and Hansson, 1999	Sweden	0.54	
	Bernesson et al., 2004	Sweden	0.28-0.36	39.5-51.1
	Janulis, 2004	Lithuania	0.41	
	IEA, 2004b	Various	0.33-0.82	
	Frondel and Peters, 2007	Various	0.35-0.65	22.7-50.8

FR_{WtT} and GR_{WtT} for RME are assumed to be 0.5 MJ/MJ and 50 g CO_2-eq/MJ for the present study. The petroleum percentage in FR_{WtT} for RME was estimated to be 24% by the author based on the results from Hovelius and Hansson (1999). Therefore, the PR_{WtT} for RME is 0.12 MJ/MJ in the present study.

e) Adoption of Fuel Cycle Parameters

Table 6.10 provides a comparative summary of the adopted values of the fuel cycle parameters in the base year for all the fuel types included in the present study. In fact, these values can only represent the current technology level. Considering the CG, CD, LPG and CNG industries have been developed for many decades and the primary energy structure will not change much, it is assumed that the FR_{WtT}, PR_{WtT} and GR_{WtT} for these fuel types would remain at the base year level between 2005 and 2030. However, development of biofuel industries is still at its early stages, and large potentials of WtT efficiency improvements exist for biofuels. For example, WtT energy efficiencies for E-corn could be improved effectively by technology improvements such as: more advanced manufacturing technology which requires less energy to produce fertilizers; more advanced corn cultivation technology which requires less use of fertilizers; more advanced bioethanol conversion technology which has higher energy efficiencies during the conversion process. Therefore, it is assumed that there will be a 25% linear reduction of FR_{WtT}, PR_{WtT} and GR_{WtT} for biofuels between 2005 and 2030.

Table 6.10 Fuel cycle data in the base year for each fuel type

	FR_{WtT} MJ/MJ	FR_{TtW} MJ/MJ	PR_{WtT} MJ/MJ	PR_{TtW} MJ/MJ	GR_{WtT} g CO_2-eq/MJ	GR_{TtW} g CO_2-eq/MJ
CG	0.24	1	0.11	1	20.6	69.2
CD	0.2	1	0.09	1	17.3	73.2
LPG	0.18	1	0.08	1	13	63.6
CNG	0.21	1	0.01	0	14	63.9
E-Corn	0.88	0	0.11	0	94.2	0
E-Cassava	0.64	0	0.04	0	71.4	0
RME	0.5	0	0.12	0	50	0

6.4 Results

Future trends of life cycle fossil energy demand in China's road transport sector and reduction potentials of each kind of measure are shown in Figure 6.2. Life cycle fossil energy demand would reach 621.4 Mtoe in 2030 in the BAU case, more than 5 times that in 2005. It would be reduced by 15.6% to 524.2 Mtoe if PVC measures were introduced. The remainder amount would be further reduced by 11.4% to 464.4 Mtoe if FER measures were introduced. The remainder amount would be further reduced by 1.7% to 456.6 Mtoe if PDG measures were introduced. The remainder amount would be further reduced by 14.9% to 388.6 Mtoe if FT measures were introduced. The remainder amount would be further reduced by 4.3% to 371.8 Mtoe if BFP measures were introduced.

Future trends of life cycle petroleum demand in China's road transport sector and reduction potentials of each kind of measure are shown in Figure 6.3. Life cycle petroleum demand would reach 484.6 Mtoe in 2030 in the BAU case, more than

5 times that in 2005. It would be reduced by 16.5% to 404.8 Mtoe if PVC measures were introduced. The remainder amount would be further reduced by 13.3% to 351 Mtoe if FER measures were introduced. The remainder amount would be further reduced by 2.5% to 342.2 Mtoe if PDG measures were introduced. The remainder amount would be further reduced by 19.2% to 276.6 Mtoe if FT measures were introduced. The remainder amount would be further reduced by 7.7% to 255.3 Mtoe if BFP measures were introduced.

Future trends of life cycle GHG emissions from China's road transport sector and reduction potentials of each kind of measure are shown in Figure 6.4. Life cycle GHG emissions would reach 1891 Mt CO_2-eq in 2030 in the BAU case, more than 5 times of that in 2005. It would be reduced by 15.5% to 1597.3 Mt CO_2-eq if PVC measures were introduced. It would be further reduced by 11.5% to 1414.2 Mt CO_2-eq if FER measures were introduced. It would be further reduced by 1.5% to 1393 Mt CO_2-eq if PDG measures were introduced. It would be further reduced by 15.1% to 1183.1 Mt CO_2-eq if FT measures were introduced. It would be further reduced by 3.3% to 1143.6 Mt CO_2-eq if BFP measures were introduced.

6.5 Comparisons with the Assessment in Chapter 5

Reduction potentials of fossil energy demand in 2030 for each kind of measure from a TtW and life cycle perspective are compared in Figure 6.5. For PVC measure, reduction potential from a life cycle perspective is 4% lower than from a TtW perspective, mainly because the reduction potential in the vehicle production stage is not as large as the TtW stage. For FER measure, reduction potential from a life cycle perspective is 13% lower than from a TtW perspective, mainly because there is no reduction potential in the vehicle production stage. For PDG measure, reduction potential from a life cycle perspective is the same as from a TtW perspective, mainly because there is no reduction potential in the vehicle production stage and switching from CG to CD and gas offers a higher reduction potential in the WtT stage. For FT measure, reduction potential from a life cycle perspective is 12% lower than from a TtW perspective, mainly because the reduction potential in the vehicle production stage is not as large as the TtW stage and switching from CG to CD and gas offers a higher reduction potential in the WtT stage. For BFP measure, reduction potential from a life cycle perspective is 43% lower than from a TtW perspective, mainly because there is no reduction potential in the vehicle production stage and biofuel use requires large amount of fossil energy input in the WtT stage. Consequently, the total reduction potential for all the measures combined is about 10% lower from a life cycle perspective than from a TtW perspective.

There is not much difference in the reduction potentials of petroleum demand in 2030 for each kind of measure from a TtW and life cycle perspective, as shown in Figure 6.6, mainly because of the assumption that there is no petroleum consumption in the vehicle production stage. For PVC, PDG and FT measures, reduction potentials from a life cycle perspective are slightly higher than from a TtW perspective, mainly because switching from CG to CD and gas offers a higher reduction potential in the WtT stage. For BFP measure, reduction potential from a life cycle perspective is 4% lower than from a TtW perspective, mainly because biofuel use requires a small amount of petroleum input in the WtT stage. Consequently, the total reduction potential for all the measures combined is about the same from a life cycle perspective and from a TtW perspective.

Reduction potentials of GHG emissions in 2030 for each kind of measure from a TtW and life cycle perspective are compared in Figure 6.7. For PVC measure, reduction potential from a life cycle perspective is 3% lower than from a TtW perspective, mainly because the reduction potential in the vehicle production stage is not as large as the TtW stage. For FER measure, reduction potential from a life cycle perspective is 12% lower than from a TtW perspective, mainly because there is no reduction potential in the vehicle production stage. For PDG measure, reduction potential from a life cycle perspective is 15% higher from a TtW perspective, mainly because switching from CG to CD and gas offers a higher reduction potential in the WtT stage. For FT measure, reduction potential from a life cycle perspective is 10% lower than from a TtW perspective, mainly because the reduction potential in the vehicle production stage is not as large as the TtW stage and switching from CG to CD and gas offers a higher reduction potential in the WtT stage. For BFP measure, reduction potential from a life cycle perspective is 136% higher than from a TtW perspective, mainly because there is no reduction potential in the vehicle production stage while biofuel use offers a great reduction potential in the fuel cycle. Consequently, the total reduction potential for all the measures combined is about 3% lower from a life cycle perspective than from a TtW perspective.

6.6 Limitations

One of the major limitations of the present LCA study is that whether or not the vehicle and fuel cycle data adopted could represent the average level in China. For example, the wide range of estimates of FR_{WtT} and GR_{WtT} for biofuel production is usually due to varying assumptions: the definition of the system boundary—at which level are processes to be included? (for example, energy consumed in cassava transportation by trucks is included but energy consumed in the production of the trucks is not); feedstock yields—subject to geographical and climate conditions; fuel production process efficiency—subject to technology development; whether or not by-products are included in the energy and emissions balance, etc.

Another major limitation is the uncertainties and validity of various assumptions made. For example, the assumption that there is no petroleum consumption in the vehicle production stage may not represent the reality because the production of some vehicle components such as tyres and glass do require petroleum input. The assumption that there will be a 25% linear reduction of FR_{WtT}, PR_{WtT} and GR_{WtT} for biofuels between 2005 and 2030 may be conservative considering the rapid development in biotechnology.

6.7 Summary and Conclusions

In this section the LCA method has been applied to estimate the life cycle energy demand and GHG emissions in China's road transport sector up to 2030 based on the results obtained in Chapter 5. The necessary vehicle and fuel cycle data for China have been collected through a comprehensive review of recent LCA studies. The energy and environmental impacts of those policy measures in the BC scenario have been re-evaluated from a life cycle perspective and compared with those from a TtW perspective in Chapter 5.

The present LCA study suggests that in the BAU, life cycle fossil energy demand, petroleum demand and GHG emissions in China's road transport sector in 2030 would reach 621.4 Mtoe, 484.6 Mtoe and 1891 Mt CO_2-eq, respectively. While in the BC scenario these would be 371.8 Mtoe, 255.3 Mtoe and 1143.6 Mt CO_2-eq, with reduction potentials of 40.2%, 47.3%, and 39.5% achieved, respectively. The reduction potentials of fossil energy demand and GHG emissions for each kind of measure are generally lower from a life cycle perspective than from a TtW perspective, except that the reduction potential of GHG emissions for the BFP measure is much higher from a life cycle perspective than from a TtW perspective. The reduction potentials of petroleum demand for each kind of measure are slightly higher from a life cycle perspective than from a TtW perspective, except that those for the BFP measure are lower.

Due to the limitations of the present LCA study, the results would be subject to the assumptions made. For the sensitivity analysis to the assumptions made, see Chapter 7 and Appendix D.

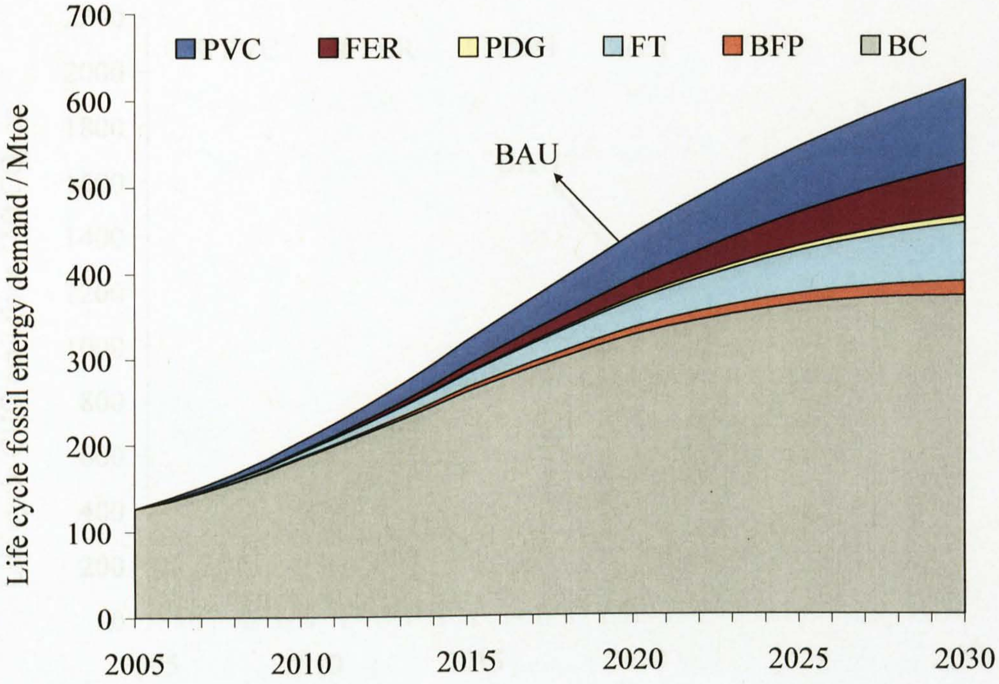

Figure 6.2 Reduction potentials of life cycle fossil energy demand in China's road transport sector for each kind of measure 2005-2030

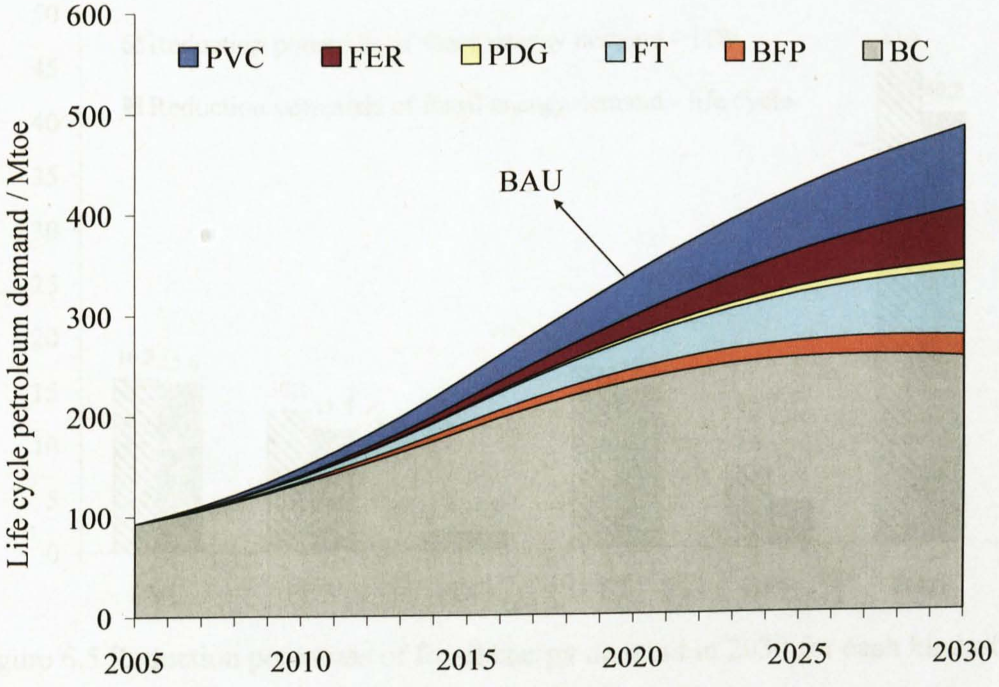

Figure 6.3 Reduction potentials of life cycle petroleum demand in China's road transport sector for each kind of measure 2005-2030

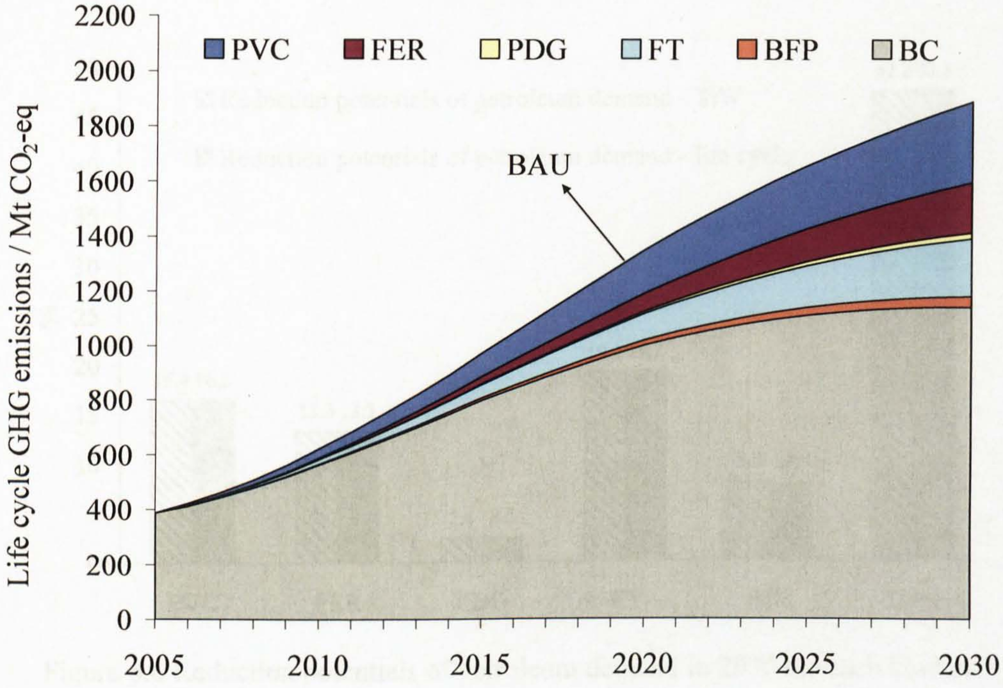

Figure 6.4 Reduction potentials of life cycle GHG emissions from China's road transport sector for each kind of measure 2005-2030

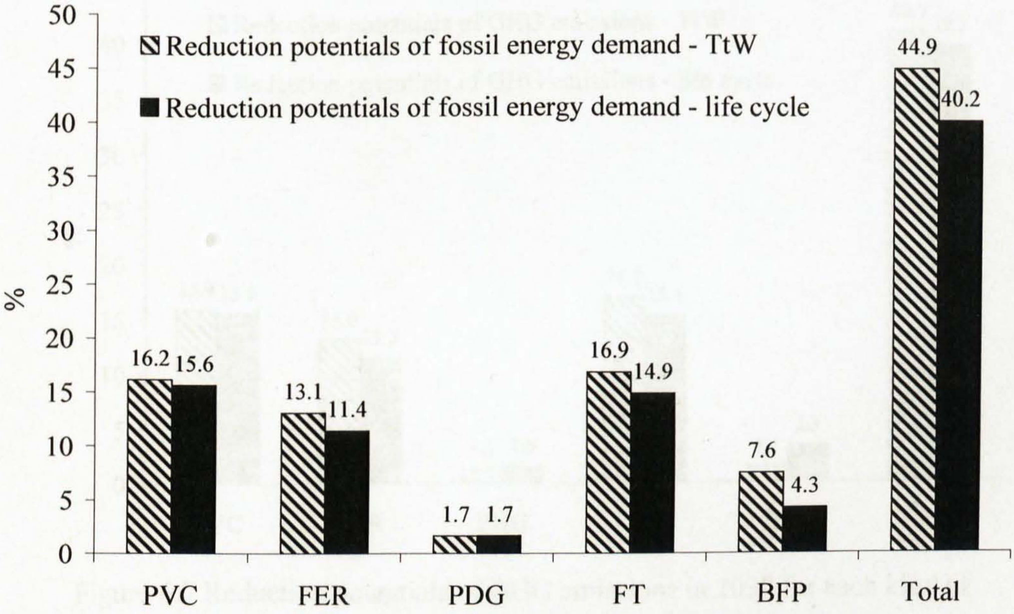

Figure 6.5 Reduction potentials of fossil energy demand in 2030 for each kind of measure from a TtW and a life cycle perspective

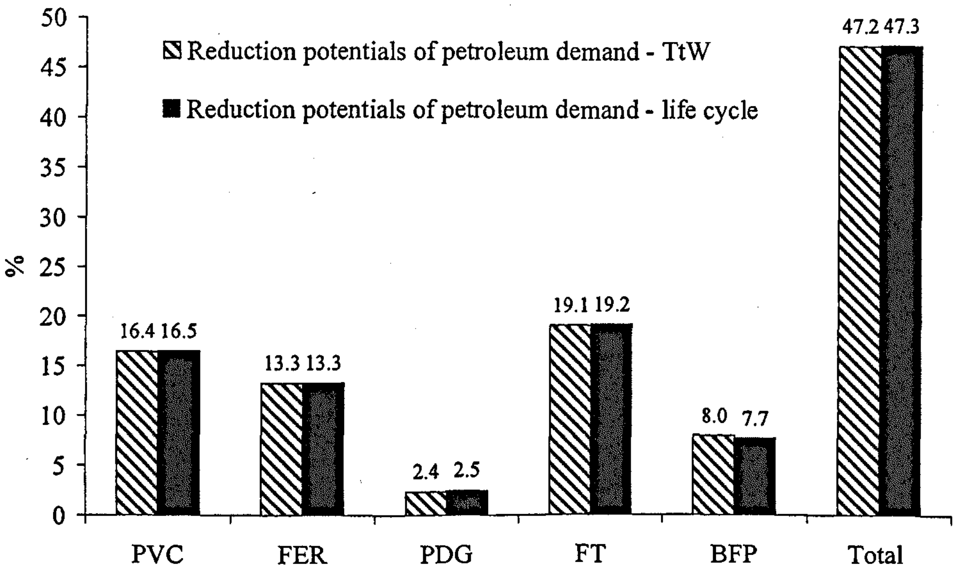

Figure 6.6 Reduction potentials of petroleum demand in 2030 for each kind of measure from a TtW and a life cycle perspective

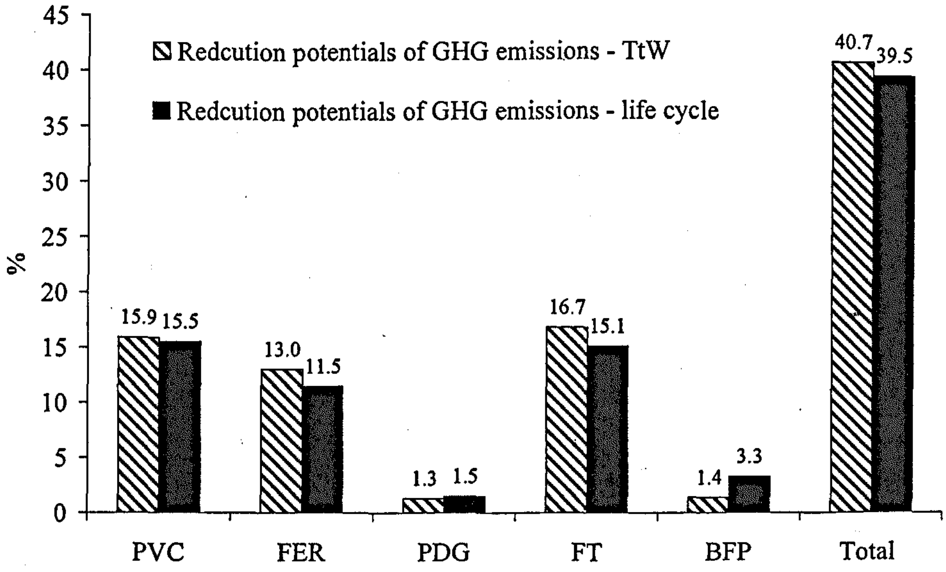

Figure 6.7 Reduction potentials of GHG emissions in 2030 for each kind of measure from a TtW and a life cycle perspective

Chapter 7

Chapter 7 Discussion of Model Results and Further Implications

7.1 Summary of Methodology and Results

A detailed model has been developed using the Long-range Energy Alternatives Planning System (LEAP) software, to estimate future energy demand and greenhouse gas (GHG) emissions in China's road transport sector, incorporating China's recent efforts in alternative fuel promotion. The modelling approach and historical data used have been tested and verified to ensure reliability.

The key driving factors for future growth in energy demand and GHG emissions in China's road transport sector have been analyzed. Available policy measures that could have potential impacts on these driving factors have been reviewed. These measures include: private vehicle control (PVC), fuel economy regulation (FER), promoting diesel and gas vehicles (PDG), fuel tax (FT) and biofuel promotion (BFP).

Two scenarios have been designed to describe the future strategies relating to the development of China's road transport sector between 2005 and 2030. The 'Business as Usual' (BAU) scenario is used as a baseline reference scenario, in which the government is assumed to do nothing to influence the long-term trends of road transport energy demand. The 'Best Case' (BC) scenario is considered to be the most optimized case where all the reduction measures reviewed in Chapter 4 are assumed to be implemented. The Tank-to-Wheel (TtW) energy demand and GHG emissions in China's road transport sector up to 2030 are estimated in these two scenarios. The reduction potential and the relative contribution of each measure have been estimated.

A 'life cycle assessment' model for the road transport sector has been developed. The life cycle energy demand and GHG emissions in China's road transport sector are estimated using the model. The reduction potential and the relative contribution of each measure have been re-assessed from a life cycle perspective.

The results are summarized in Table 7.1.

Table 7.1 A summary of results in 2030

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.6	244.1	371.8	231.3	255.3	772.5	1143.6
Reduction	183.4	199.2	249.5	207.2	229.3	531.2	747.3
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Combined total	41.3	44.9	40.2	47.2	47.3	40.7	39.5

The TtW results suggest that PVC, FER and FT would be the most effective measures to reduce the demand of total energy, fossil energy and petroleum, and GHG emissions. PDG measure would not be very effective in reducing energy demand and GHG emissions. It would have a larger effect in reducing the demand of petroleum than that of total energy and fossil energy and a smaller effect in reducing GHG emissions than energy demand. BFP measure would not be very effective in reducing total energy demand. However, it would have a much larger effect in reducing fossil energy and petroleum demand and a smaller effect in reducing GHG emissions than total energy demand.

The results of the life cycle assessment suggest that reduction potentials of fossil energy demand and GHG emissions for each kind of measure are generally lower from a life cycle perspective than from a TtW perspective, except that the reduction potential of GHG emissions for the BFP measure is much higher from a life cycle perspective than from a TtW perspective. The reduction potentials of petroleum demand for each kind of measure are slightly higher from a life cycle perspective than from a TtW perspective, except that those for the BFP measure are lower.

7.2 Global Impacts

IEA's latest predictions (IEA, 2006) showed that China's oil demand and import in 2030 would reach 762 and 588 Mt in the Reference Case Scenario and 652 and 478 Mt in the Alternative Policy Scenario, respectively. EIA's latest predictions (EIA, 2007) showed that China's oil demand in 2030 would reach 872, 782 and 697 Mt in the High Economic Growth Case, the Reference Case and the Low Economic Growth Case, respectively. In all of these predictions, China's oil demand in 2030 would account for about 13% of the world total, and of the demand increase between 2005 and 2030, China would account for 26-33% of the world total. Furthermore, Nel and Cooper (2008) believed that IEA's estimation of Chinese oil demand based on concerns related to Peak Oil and resource scarcity, was conservative because it diverged significantly from historical trends, and the underestimation could be as high as 680 Mt in 2030 if China follows the lower-bound historical trends exhibited by developed countries. If the predicted peak in oil production before 2020 is correct, the Chinese oil demand could result in severe shortages of international oil supply. From an economic perspective, the rapid rising oil price in recent years has already started to affect global economy growth. Oil price reached a new record high of $126 per barrel in early May 2008 mainly because of strong demand from Asia, China in particular (IEA, 2008). Moreover, Zhao and Wu (2007) believed that the international oil price was not a major determinant in China's oil imports, and China's rising imports would add further pressure on world oil prices. As for the environmental perspective, China would be likely to surpass the US and become the biggest CO_2 emitter around 2010, and its CO_2 emissions are likely to reach 11239 Mt in 2030, accounting for 26% of world total (EIA, 2007). These facts and arguments could be interpreted that any amount of reduction in China's future oil demand and GHG emissions would be important to the world economy and human welfare.

The assessment in the present study shows that 229 Mt of oil could be saved and 747 Mt CO_2-eq of GHG emissions could be avoided from China's road transport sector alone in 2030 if all the measures included in the BC scenario were well implemented. This would greatly reduce China's dependence on imported oil and the pressure on international oil supply and prices. And if oil price were still $126 per barrel in 2030, these measures could help China save $ 206 billion on its annual oil import bill. Furthermore, the accumulative reduction of oil demand in China's road transport sector between 2005 and 2030 would be 2372 Mt, which is more than the current proven oil reserves in China (2200 Mt). The accumulative reduction of GHG emissions in China's road transport sector between 2005 and 2030 would be 7823 Mt CO_2-eq. It is therefore strategically important that all the measures included in the BC scenario could be well implemented.

7.3 Importance of Life Cycle Assessment

The results from the present investigation have shown that when assessing the effect of different policy measures on future energy demand and GHG emissions in the road transport sector, only taking into account the vehicle operation stage could be misleading. For the PVC, FER and FT measures, the reduction potentials of fossil energy demand and GHG emissions are generally lower from a life cycle perspective than from a TtW perspective. For the BFP measure, reduction potential of fossil energy demand from a life cycle perspective is much lower than from a TtW perspective, while reduction potential of GHG emissions from a life cycle perspective is much higher than from a TtW perspective. It is therefore very important that LCA should be employed to assess these effects in order to avoid problem shifting between different life cycle stages.

For an assessment of a smaller scale options such as the choice between different urban passenger transport modes, LCA should also be employed. Currently, most of the environmental impact assessments for different transport modes in China have only taken into account the vehicle operation stage, and LCA has been proposed to be employed in the future work in this field (Zhang and Wei, 1999).

7.4 Key Barriers to Implementation of Each Kind of Measure

Data and information are becoming more and more important to make decisions. Inadequate data and information is considered to be one of the serious barriers faced by China in the process of implementation of energy-saving measures (Wang et al., 2008). For the road transport sector in particular, vehicle population, vehicle distance travelled and fuel economy by vehicle type and fuel type, need to be better documented to overcome this barrier.

China has not agreed to binding CO_2 emissions reductions in the Kyoto Protocol (Lu and Ma, 2004). Therefore, lack of climate change concerns of policy makers and the public could be one of the key barriers. The government and the academic communities should increase the knowledge available on the consequences of overusing fossil energy and try to express climate change issues to the public, through methods such as awareness campaigns.

The government's attitude towards private motorization is considered to be the key barrier to implementing the PVC measure. Rapid increase in the use of private vehicles in China is largely the result of government policy to promote economic development through development of the automobile industry and the infrastructure (Liu et al, 2007). The long-term economic, energy and environmental impacts of private motorization need to be carefully assessed and fully understood by the government to establish a proper policy direction.

High costs and lack of research and development capabilities for advanced vehicle performance, emission and fuel related technologies are considered as key barriers to implementing the PDG measure. International financial and technical aid such as loans, technology transfer and cooperation would help China to overcome these barriers in an effective and efficient way (Wang et al., 2007).

The key barrier to implementing the FT measure is the political concerns, which include: that higher fuel prices could cause inflation and a lower competitiveness of export goods, and consequently slow down the economic growth in China; that it is difficult to distinguish road vehicle fuel use and agricultural vehicle fuel use in a large and populated country like China; that it is difficult to decide an appropriate tax rate because China has various levels of economic development in different regions, if the tax rate were too low, it would not be effective in reducing fuel demand in developed regions such as the coastal areas, and if the tax rate were too high, the economic development of the poor inland regions would be seriously effected. These political issues need to be carefully evaluated before a comprehensive fuel tax can be implemented.

The key barrier to implementing the BFP measure is the growing concern over food security, which has been considered to be China's first priority. It is therefore very important for China to diversify the feedstock for biofuels from the current grain source, to non-food sources.

7.5 Critical Analysis of the Assumptions and Estimates Made

A critical analysis of the sensitivity of the assumptions and estimates made in the present study has been conducted. The results are shown in Appendix D (Table D.1-32). In most cases, there are no noticeable differences (less than 1%) in the final results when the assumed or estimated values vary by 10%, except for the following cases:

When the *Sales* for PC and MV due to the PVC measure vary by 10%, the reduction potentials of energy demand and GHG emissions due to the PVC measure vary by about 7%, while the total reduction potentials of energy demand and GHG emissions in the BC scenario vary by about 2%.

When the *FE* improvements for PC, TA, MV, LDB, LDT and MT due to the FER measure vary by 10%, the reduction potentials of energy demand and GHG emissions due to the FER measure vary by about 6-8%, while the total reduction potentials of energy demand and GHG emissions in the BC scenario vary by about 1%.

When the *FE* improvements for all the vehicle types due to the FT measure vary by 10%, the reduction potentials of energy demand and GHG emissions due to the FT measure vary by about 3-4%, while the total reduction potentials of energy demand and GHG emissions in the BC scenario vary by about 1%.

When the biofuel use due to the BFP measure vary by 10%, the reduction potentials of energy demand and GHG emissions due to the BFP measure vary by about 10-12%, while the total reduction potentials of fossil energy demand, petroleum demand and life cycle GHG emissions in the BC scenario vary by about 1%.

When the FR_{WtT} and GR_{WtT} for E-cassava in Thailand are used, the reduction potentials of life cycle fossil energy demand and life cycle GHG emissions due to the BFP measure vary by about 2% and 17% respectively, while the total reduction potentials of life cycle GHG emissions in the BC scenario vary by about 1%.

With the analysis and comparisons, the author feels confident with the results obtained.

Chapter 8

Chapter 8 Conclusions and Future Recommendations

8.1 Conclusions

From the present investigation, the following conclusions can be drawn:

- China has experienced remarkable economic growth over the last two decades, which has been accompanied by a corresponding growth in energy demand and GHG emissions. The scale of the growth suggests that China will have a profound impact on the global energy markets and the environment.

- Rapid growth of road vehicles, private vehicles in particular, has resulted in continuing growth in China's oil demand and imports, which has been widely accepted as a major factor effecting future oil availability and prices, and a major contributor to China's GHG emission increase.

- Total energy demand in China's road transport sector is estimated using a model developed in LEAP software to increase from 57 Mtoe in 2000 to 86 Mtoe in 2005 (published statistics not yet available). The private passenger vehicle fleet contributes nearly half of the demand growth, with its share in the total demand increasing from 12% to 24% between 2000 and 2005. Despite recent growth in alternative fuel use, petroleum still accounts for 98% of total energy demand in China's road transport sector in 2005. GHG emissions are estimated to increase from 168.6 Mt CO_2-eq in 2000 to 254.9 Mt CO_2-eq in 2005.Comparison of the results from the present study with those from earlier studies and statistical data have suggested that the present model and historical data used is fairly reliable.

- The key driving factors for future growth in energy demand and GHG emissions in China's road transport sector have been identified as growth in private vehicle use, vehicle fuel economy and vehicle/fuel switching.

Available policy measures that could have potential impact on these driving factors have been reviewed. These measures include: private vehicle control (PVC), fuel economy regulation (FER), promoting diesel and gas vehicles (PDG), fuel tax (FT) and biofuel promotion (BFP).

- Two scenarios have been designed to describe the future strategies relating to the development of China's road transport sector between 2005 and 2030. The 'Business as Usual' (BAU) scenario is used as a baseline reference scenario, in which the government is assumed to do nothing to influence the long-term trends of road transport energy demand. The 'Best Case' (BC) scenario is considered to be the most optimized case where all the reduction measures reviewed in Chapter 4 are assumed to be implemented. The TtW total energy demand, fossil energy demand, petroleum demand and GHG emissions in China's road transport sector in 2030 are estimated to be 444 Mtoe, 443.3 Mtoe, 438.5 Mtoe and 1303.7 Mt CO_2-eq in the BAU scenario. In the BC scenario these would be 260.6 Mtoe, 244.1 Mtoe, 231.3 Mtoe and 772.5 Mt CO_2-eq. Reduction potentials as large as 41.3%, 44.9%, 47.2% and 40.7% are achieved, respectively. The relative reduction potentials of each measure are:

  in terms of TtW total energy demand

  16.1% for PVC, 13.1% for FER, 1.7% for PDG, 16.8% for FT and 1.6% for BFP;

  in terms of TtW fossil energy demand

  16.2% for PVC, 13.1% for FER, 1.7% for PDG, 16.9% for FT and 7.6% for BFP;

  in terms of TtW petroleum demand

  16.4% for PVC, 13.3% for FER, 2.4% for PDG, 19.1% for FT and 8.0% for BFP;

  in terms of TtW GHG emissions

  15.9% for PVC, 13.0% for FER, 1.3% for PDG, 16.7% for FT and 1.4% for BFP.

- The TtW results suggest that PVC, FER and FT would be the most effective measures to reduce the demand of total energy, fossil energy and petroleum, and GHG emissions. PDG measure would not be very effective in reducing energy demand and GHG emissions. It would have a larger effect in reducing the demand of petroleum than that of total energy and fossil energy and a smaller effect in reducing GHG emissions than energy demand. BFP measure would not be very effective in reducing total energy demand. However, it would have a much larger effect in reducing fossil energy and petroleum demand and a smaller effect in reducing GHG emissions than total energy demand.

- The present life cycle assessment suggests that in the BAU, life cycle fossil energy demand, petroleum demand and GHG emissions in China's road transport sector in 2030 would reach 621.4 Mtoe, 484.6 Mtoe and 1891 Mt CO_2-eq, respectively. In the BC scenario these would be 371.8 Mtoe, 255.3 Mtoe and 1143.6 Mt CO_2-eq. Reduction potentials of 40.2%, 47.3%, and 39.5% are achieved, respectively. The relative reduction potential of each measure are:
  in terms of life cycle fossil energy demand
  15.6% for PVC, 11.4% for FER, 1.7% for PDG, 14.9% for FT and 4.3% for BFP;
  in terms of life cycle petroleum demand
  16.5% for PVC, 13.3% for FER, 2.5% for PDG, 19.2% for FT and 7.7% for BFP;
  in terms of life cycle GHG emissions
  15.5% for PVC, 11.5% for FER, 1.5% for PDG, 15.1% for FT and 3.3% for BFP.

- The results of the life cycle assessment suggest that reduction potentials of fossil energy demand and GHG emissions for each kind of measure are generally lower from a life cycle perspective than from a TtW perspective, except that the reduction potentials of GHG emissions for the PDG and BFP measure are 15% and 136% higher from a life cycle perspective than from a TtW perspective, respectively. The reduction potentials of petroleum demand for each kind of measure are marginally higher from a life cycle perspective than from a TtW perspective, except that those for the BFP measure are 4% lower. These results also indicate that it is very important to employ 'life cycle assessment' in evaluating the effects of different reduction measures, BFP measure in particular, in order to prevent problem shifting between different life cycle stages.

- Future growth of energy demand and GHG emissions in China's road transport sector will substantially affect global oil resources, availability and prices, and contribute to China's GHG emissions increase. It is strategically important that all the measures included in the BC scenario could be well implemented. Key barriers to the implementation of each kind of measure are identified as: government's attitude towards private motorization for PVC; high costs and lack of research and development capabilities for PDG; political issues for FT; growing concern over food security for BFP; inadequate data and information, and lack of concerns of policy makers and the public over climate change which would influence all reduction measures.

- A critical analysis of the sensitivity of the assumptions and estimates made in the present study has shown that in most cases, there are no noticeable differences (less than 1%) in the final results when the assumed or estimated values vary by 10%.

8.2 Further Work

The present study has provided a detailed and reliable data set of China's motor vehicle population, vehicle fuel economy and vehicle distance travelled by vehicle type and fuel type in recent years. These data have been used to derive a reliable historical trend of energy demand and GHG emissions in China's road transport sector, based on which future trends can be better projected. Furthermore, the present study lays a foundation for assessing the effects of various policy measures from a life cycle perspective, which could be helpful in decision-making by avoiding problem shifting. The recommendations for further work are as follows:

- The quantification of the impacts of different policy measures needs to be backed up with more solid evidence, and the interactions between different measures need to be better understood and modelled.

- The sensitivity to different assumptions and estimates needs to be further assessed.

- Life cycle assessment needs to be carried out in terms of the fossil energy demand, petroleum demand and environmental impacts for a wider range of alternative fuels, vehicles and feedstock such as hybrid vehicles, fuel cell vehicles, bioethanol derived from sugarcane and agricultural residues, and biodiesel derived from soybean and coconut.

- The assessment of environmental impact needs to take into account not only GHG emissions but also emissions of atmospheric pollutants such as HC, CO, NO_x and PM.

- The approaches to overcome the barriers to successful implementation for each promising measure need to be evaluated.

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Appendices

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Appendix A: Energy Conversion Factors and Fuel Properties

Table A.1General conversion factors for energy (data from IEA (2007a))

One	Equals Mtoe	 TBtu	 GWh	 TJ
Mtoe	1	39.68	1.163×10^4	4.1868×10^4
TBtu	0.0252	1	293.1	1055.1
GWh	8.6×10^{-5}	3.412×10^{-3}	1	3.6
TJ	2.388×10^{-5}	9.478×10^{-4}	0.2778	1

Table A.2 Oil equivalents for each fuel (data from IEA (2007a))

	Tonne of oil equivalents per tonne
Average Chinese Coal	0.541
Average Chinese Crude Oil	1
Natural Gas	0.9*
Petroleum Products	
LPG	1.13
CG	1.07
CD	1.035

* Tonne of oil equivalents per billion cubic metres

Table A.3 Properties of each fuel

	Density kg/l	Net energy content MJ/kg	 MJ/l
CG	0.74	44.8	33.152
CD	0.87	43.33	37.697
LPG	0.54	47.31	25.547
CNG	0.128	43.04	5.509
Bioethanol	0.785	27	21.185
Biodiesel	0.88	38	33.44

Appendix B: Additional Data Used in the Present Model

Table B.1 Number of vehicles sold in China by vehicle type (data from CATRC and CAAM (1991-2006))

	HDT	MDT	LDT	MT	HDB	LDB	Car	MV
1988	15485	206745	225016	35843	19301	35562	36798	21025
1989	18400	208514	172596	35487	14102	33430	35450	21175
1990	18032	171970	122551	34470	17787	78881	42409	9010
1991	19026	203951	179327	49719	24427	131501	81055	19814
1992	25391	259795	278526	62702	37420	193899	162725	41263
1993	33782	334656	330685	75745	29097	191194	229697	71922
1994	35920	307183	333138	97916	23839	185891	250780	102634
1995	37173	313308	334706	100689	23565	189272	250333	104322
1996	31376	209950	302635	141791	22099	194856	386743	169216
1997	30646	188047	297515	149676	20794	189157	479601	210468
1998	36676	187661	292469	141245	22505	180166	508284	234048
1999	47789	181646	384726	136717	36788	181503	570777	293030
2000	83056	155429	385764	132250	43795	254512	614411	409165
2001	147258	162745	369535	140037	64666	276810	721463	488575
2002	247997	164308	514500	146486	82021	335725	1126468	631006
2003	255600	136698	681201	137130	72306	441834	1990925	675948
2004	354108	204345	766203	202374	80287	356095	2351483	756753
2005	236586	194344	853624	233402	82189	383344	2943250	831450

Note: data in 1993 and before are number of vehicles produced due to lack of sales statistics

Table B.2 Number of diesel vehicles sold in China by vehicle type (data from CATRC and CAAM (1998-2004))

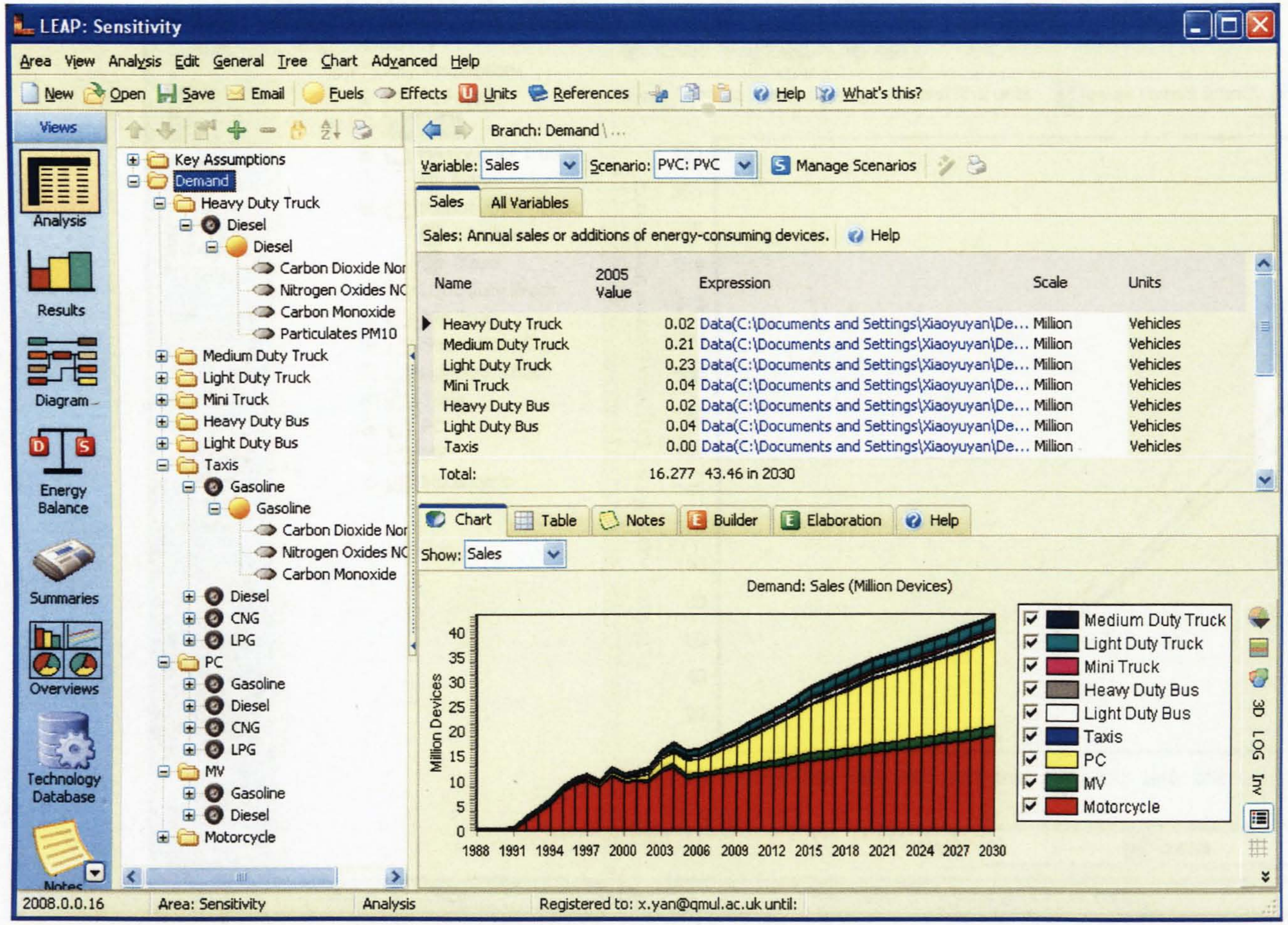
	HDT-D	MDT-D	LDT-D	MT-D	HDB-D	LDB-D	Car-D	MV-D
1997	30629	122083	164380	482	13485	55963	0	0
1999	47505	120797	286319	99	22907	58880	0	0
2000	82988	110975	311005	837	28175	70156	0	0
2001	147118	148239	310288	7857	64107	85919	0	0
2002	247909	151626	453938	95	73511	90607	0	2
2003	255550	125317	600121	23	63186	66651	4995	16

Table B.3 Number of gas vehicles sold in China by vehicle type

	HDB-CNG	HDB-LPG	TA-CNG	TA-LPG
1999	1000	3000	3000	36000
2000	2000	3000	9000	19000
2001	3000	2000	7060	22720
2002	6000	1500	26360	12040
2003	8010	1530	15041	22414
2004	7532	1637	16999	7767
2005	6638	683	23162	13464

Note: data in this table are estimated by the author based on the number of LPG vehicles and CNG vehicles 1999-2005 from Li and Gu (2006), the number of HDB-LPG, HDB-CNG, TA-LPG and TA-CNG in 2004 from Ren (2006) and the estimated survival rates for each vehicle type

Appendix C: LEAP Software



Branch: Demand \ ...

Variable: Sales Scenario: PVC: PVC

Sales: Annual sales or additions of energy-consuming devices.

Name	2005 Value	Expression	Scale	Units
Heavy Duty Truck	0.02	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Medium Duty Truck	0.21	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Light Duty Truck	0.23	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Mini Truck	0.04	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Heavy Duty Bus	0.02	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Light Duty Bus	0.04	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Taxis	0.00	Data(C:\Documents and Settings\Xiaoyuyan\De...	Million	Vehicles
Total:	16.277	43.46 in 2030		

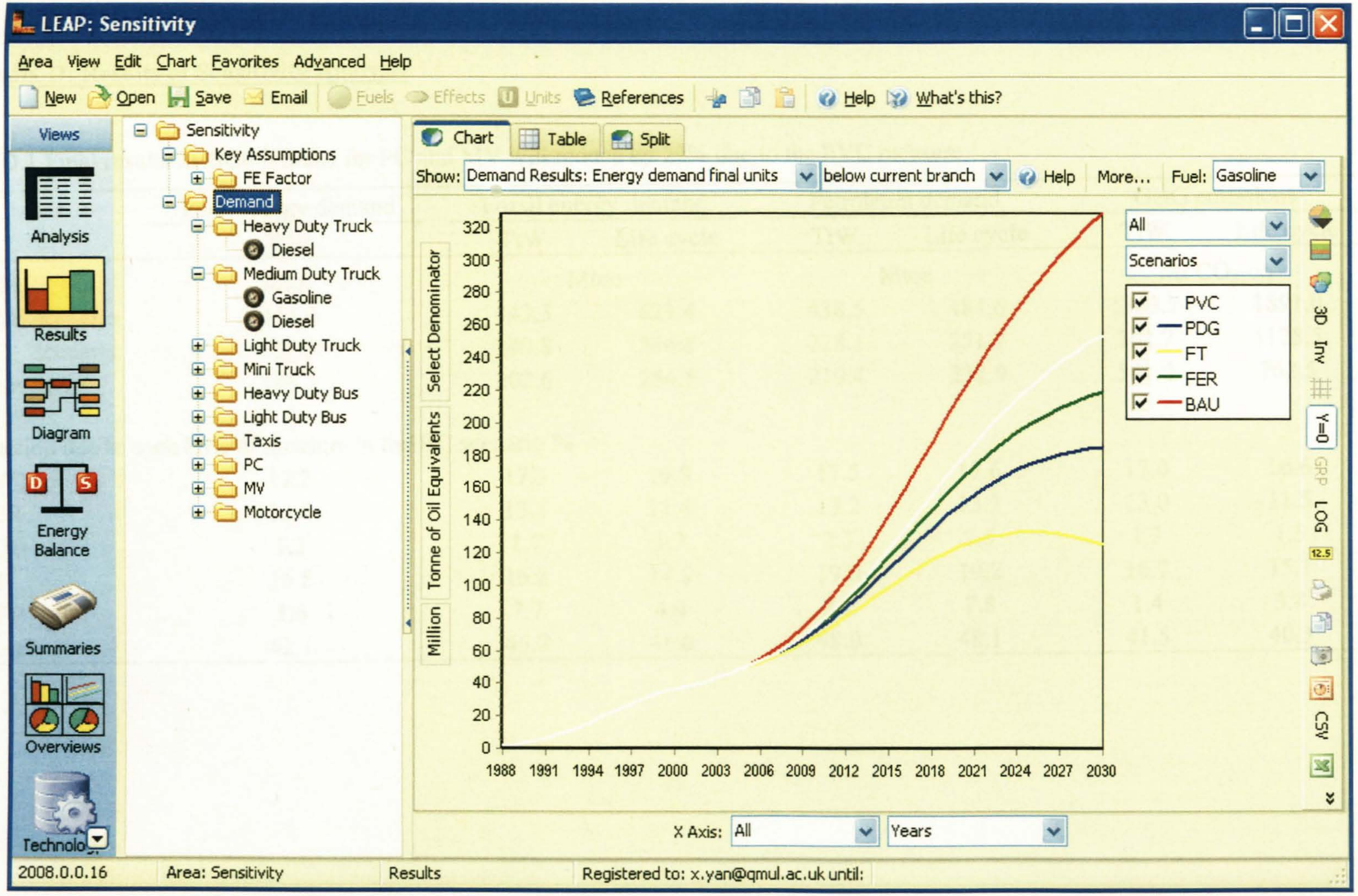
Show: Sales

2008.0.0.16 Area: Sensitivity Analysis Registered to: x.yan@qmul.ac.uk until:

Figure C.1 Analysis view window in LEAP

Figure C.1 shows the analysis view window in LEAP. The structure of the model and different scenarios can be managed here. Historical data and future assumptions for each driving factors can be either input directly as expressions or imported from EXCEL data sheets.

Figure C.2 shows the results view window in LEAP. The results of energy demand and GHG emissions for each fuel type and vehicle type in each scenario can be viewed here. The results also can be exported to EXCEL data sheets.



Show: Demand Results: Energy demand final units | below current branch

Fuel: Gasoline

X Axis: All | Years

2008.0.0.16 | Area: Sensitivity | Results | Registered to: x.yan@qmul.ac.uk until:

Figure C.2 Results view window in LEAP

Appendix D: Results of Sensitivity Analysis

Table D.1 Final results in 2030 if *Sales* for PC and MV will reduce by 22% due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	257.3	240.8	366.8	228.1	251.7	762.7	1128.5
Reduction	186.7	202.6	254.5	210.4	232.9	541.0	762.5
Reduction due to each kind of measure in the BC scenario %							
PVC	17.2	17.3	16.8	17.5	17.6	17.0	16.6
FER	13.0	13.1	11.4	13.2	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.3	2.5	1.3	1.5
FT	16.8	16.8	14.9	19.0	19.2	16.7	15.1
BFP	1.6	7.7	4.4	8.1	7.8	1.4	3.4
Total	42.1	45.7	41.0	48.0	48.1	41.5	40.3

Table D.2 Final results in 2030 if *Sales* for PC and MV will reduce by 18% due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	264.0	247.5	376.8	234.6	258.9	782.4	1158.8
Reduction	180.0	195.9	244.5	204.0	225.8	521.3	732.2
Reduction due to each kind of measure in the BC scenario %							
PVC	15.0	15.0	14.5	15.3	15.4	14.8	14.4
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.8	15.1
BFP	1.6	7.5	4.3	7.9	7.6	1.4	3.3
Total	40.5	44.2	39.4	46.5	46.6	40.0	38.7

Table D.3 Final results in 2030 if *Sales* for HDB and LDB will increase by 11% due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	261.1	244.5	372.4	231.7	255.7	773.8	1145.3
Reduction	183.0	198.8	249.0	206.8	228.9	530.0	745.6
Reduction due to each kind of measure in the BC scenario %							
PVC	16.0	16.0	15.5	16.3	16.4	15.8	15.4
FER	13.0	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.8	14.9	19.0	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.2	44.8	40.1	47.2	47.2	40.6	39.4

Table D.4 Final results in 2030 if *Sales* for HDB and LDB will increase by 9% due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.2	243.7	371.3	231.0	254.9	771.3	1142.0
Reduction	183.8	199.6	250.1	207.6	229.7	532.4	749.0
Reduction due to each kind of measure in the BC scenario %							
PVC	16.2	16.3	15.7	16.5	16.6	16.0	15.6
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.8	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.4	45.0	40.2	47.3	47.4	40.8	39.6

Table D.5 Final results in 2030 if *FAVDT* for PC and MV will reduce by 9% by 2030 due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	262.3	245.8	373.8	232.9	257.1	777.5	1149.7
Reduction	181.7	197.6	247.5	205.6	227.6	526.3	741.2
Reduction due to each kind of measure in the BC scenario %							
PVC	15.6	15.7	15.2	15.9	16.0	15.4	15.1
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.8	14.9	19.0	19.1	16.7	15.0
BFP	1.6	7.5	4.3	7.9	7.6	1.4	3.3
Total	40.9	44.6	39.8	46.9	47.0	40.4	39.2

Table D.6 Final results in 2030 if *FAVDT* for PC and MV will reduce by 11% by 2030 due to the PVC measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	259.0	242.4	369.7	229.7	253.5	767.6	1137.2
Reduction	185.1	200.9	251.7	208.8	231.1	536.1	753.8
Reduction due to each kind of measure in the BC scenario %							
PVC	16.6	16.7	16.1	16.9	17.0	16.4	16.0
FER	13.0	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.9	16.9	14.9	19.1	19.2	16.8	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.4
Total	41.7	45.3	40.5	47.6	47.7	41.1	39.9

Table D.7 Final results in 2030 if *FE* for PC, TA, MV, LDB, LDT and MT will increase by 44% by 2030 due to the FER measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	258.7	242.2	369.5	229.4	253.2	766.9	1136.4
Reduction	185.3	201.1	251.9	209.1	231.4	536.8	754.5
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.9	14.0	12.2	14.1	14.2	13.9	12.2
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.6	16.6	14.7	18.8	19.0	16.5	14.9
BFP	1.6	7.6	4.3	8.0	7.8	1.4	3.4
Total	41.7	45.4	40.5	47.7	47.8	41.2	39.9

Table D.8 Final results in 2030 if *FE* for PC, TA, MV, LDB, LDT and MT will increase by 36% by 2030 due to the FER measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	262.7	246.1	374.3	233.3	257.5	778.5	1151.2
Reduction	181.4	197.2	247.1	205.2	227.1	525.2	739.7
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	12.1	12.1	10.6	12.3	12.3	12.1	10.6
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	17.1	17.1	15.1	19.3	19.4	17.0	15.3
BFP	1.6	7.5	4.3	7.9	7.6	1.4	3.3
Total	40.8	44.5	39.8	46.8	46.9	40.3	39.1

Table D.9 Final results in 2030 if *FShare* for MDT-G and HDB-G will reduce to 0 by 2012 while that for LDT-D will increase to 100% by 2019 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.6	244.1	371.8	231.3	255.3	772.5	1143.6
Reduction	183.4	199.2	249.5	207.2	229.3	531.2	747.3
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.2	47.3	40.7	39.5

Table D.10 Final results in 2030 if *FShare* for MDT-G and HDB-G will reduce to 0 by 2008 while that for LDT-D will increase to 100% by 2011 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.6	244.1	371.8	231.3	255.3	772.5	1143.6
Reduction	183.4	199.2	249.5	207.2	229.3	531.2	747.3
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.2	47.3	40.7	39.5

Table D.11 Final results in 2030 if *FShare* for PC-D, TA-D and MV-D will increase from 0 to 18% by 2030 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	261.2	244.6	372.5	231.8	255.9	773.8	1145.5
Reduction	182.9	198.7	248.8	206.7	228.8	529.9	745.5
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.5	1.5	1.5	2.2	2.3	1.1	1.3
FT	16.8	16.8	14.9	19.0	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.2	44.8	40.0	47.1	47.2	40.6	39.4

Table D.12 Final results in 2030 if *FShare* for PC-D, TA-D and MV-D will increase from 0 to 22% by 2030 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.1	243.6	371.1	230.8	254.7	771.3	1141.8
Reduction	183.9	199.7	250.2	207.7	229.9	532.4	749.2
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.9	1.9	1.9	2.5	2.7	1.4	1.7
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.4	45.1	40.3	47.4	47.4	40.8	39.6

Table D.13 Final results in 2030 if *FShare* for HDB-LPG/CNG, TA-LPG/CNG, LDB-D and MT-D will increase by 45% by 2030 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.6	244.1	371.8	231.5	255.4	772.4	1143.6
Reduction	183.4	199.3	249.6	207.1	229.2	531.3	747.4
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.3	2.5	1.3	1.5
FT	16.8	16.8	14.9	19.0	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.2	47.3	40.7	39.5

Table D.14 Final results in 2030 if *FShare* for HDB-LPG/CNG, TA-LPG/CNG, LDB-D and MT-D will increase by 55% by 2030 due to the PDG measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.7	244.2	371.9	231.2	255.1	772.6	1143.7
Reduction	183.3	199.2	249.5	207.3	229.5	531.1	747.3
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.6	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.3	47.4	40.7	39.5

Table D.15 Final results in 2030 if *Sales* for LDT, MT and LDB will reduce by 18% due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	261.8	245.3	373.4	232.3	256.3	775.9	1148.4
Reduction	182.2	198.1	248.0	206.2	228.3	527.8	742.5
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.6	1.6	1.6	2.3	2.5	1.2	1.4
FT	16.5	16.6	14.6	18.8	18.9	16.5	14.8
BFP	1.6	7.6	4.3	7.9	7.7	1.4	3.3
Total	41.0	44.7	39.9	47.0	47.1	40.5	39.3

Table D.16 Final results in 2030 if *Sales* for LDT, MT and LDB will reduce by 22% due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.0	243.4	370.8	230.5	254.4	770.4	1140.4
Reduction	184.1	199.9	250.6	208.1	230.3	533.3	750.6
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.6	1.6	1.6	2.3	2.5	1.2	1.4
FT	17.1	17.1	15.2	19.3	19.5	17.0	15.4
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.5	45.1	40.3	47.4	47.5	40.9	39.7

Table D.17 Final results in 2030 if *Sales* for HDT and HDB increase by 9% due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.1	243.6	371.1	230.9	254.8	771.0	1141.5
Reduction	183.9	199.7	250.2	207.7	229.9	532.7	749.5
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	17.0	17.0	15.0	19.2	19.3	16.9	15.2
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.4	45.1	40.3	47.4	47.4	40.9	39.6

Table D.18 Final results in 2030 if *Sales* for HDT and HDB increase by 11% due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	261.1	244.6	372.5	231.8	255.8	774.1	1145.8
Reduction	182.9	198.7	248.8	206.7	228.8	529.6	745.1
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.7	16.7	14.7	18.9	19.0	16.6	14.9
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.2	44.8	40.0	47.1	47.2	40.6	39.4

Table D.19 Final results in 2030 if *FShare* for PC-CNG and PC-LPG will increase from 0 to 4.5% and 2.7% by 2030, respectively due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.6	244.1	371.8	231.8	255.8	772.6	1143.9
Reduction	183.4	199.3	249.6	206.8	228.9	531.1	747.1
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	18.9	19.0	16.7	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.1	47.2	40.7	39.5

Table D.20 Final results in 2030 if *FShare* for PC-CNG and PC-LPG will increase from 0 to 5.5% and 3.3% by 2030, respectively due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.7	244.2	371.8	230.9	254.8	772.5	1143.4
Reduction	183.3	199.2	249.5	207.6	229.8	531.2	747.6
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.8	14.9	19.2	19.3	16.8	15.1
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.3	44.9	40.2	47.4	47.4	40.7	39.5

Table D.21 Final results in 2030 if *FE* for all vehicle types will increase by 18% by 2030 due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	262.8	246.3	374.4	233.3	257.4	778.9	1151.6
Reduction	181.2	197.1	246.9	205.2	227.2	524.8	739.4
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.1	16.2	14.3	18.4	18.6	16.1	14.5
BFP	1.6	7.5	4.3	7.9	7.6	1.4	3.3
Total	40.8	44.5	39.7	46.8	46.9	40.3	39.1

Table D.22 Final results in 2030 if *FE* for all vehicle types will increase by 22% by 2030 due to the FT measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	258.6	242.0	369.3	229.4	253.2	766.4	1135.9
Reduction	185.5	201.3	252.1	209.1	231.4	537.3	755.0
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	17.5	17.5	15.4	19.7	19.8	17.4	15.6
BFP	1.6	7.6	4.3	8.0	7.8	1.4	3.4
Total	41.8	45.4	40.6	47.7	47.8	41.2	39.9

Table D.23 Final results in 2030 if biofuel use will be 10% lower than the government's target due to the BFP measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	261.1	246.2	373.6	233.4	257.5	773.7	1147.8
Reduction	182.9	197.1	247.8	205.1	227.1	530.0	743.2
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.4	6.8	3.9	7.1	6.9	1.3	3.0
Total	41.2	44.5	39.9	46.8	46.9	40.7	39.3

Table D.24 Final results in 2030 if biofuel use will be 10% higher than the government's target due to the BFP measure

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	260.2	242.0	370.1	229.2	253.1	771.4	1139.5
Reduction	183.8	201.3	251.3	209.3	231.6	532.3	751.4
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.1	13.1	11.4	13.3	13.3	13.0	11.5
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.8	16.9	14.9	19.1	19.2	16.7	15.1
BFP	1.7	8.4	4.8	8.8	8.5	1.6	3.7
Total	41.4	45.4	40.4	47.7	47.8	40.8	39.7

Table D.25 Final results in 2030 if the 'rebound effect' is 27% for PC and MV

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	259.2	242.7	370.0	229.9	253.7	768.3	1138.2
Reduction	184.8	200.7	251.3	208.6	230.9	535.4	752.8
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	13.4	13.4	11.7	13.6	13.6	13.4	11.8
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.9	17.0	15.0	19.2	19.3	16.9	15.2
BFP	1.6	7.6	4.3	8.0	7.7	1.4	3.3
Total	41.6	45.3	40.4	47.6	47.7	41.1	39.8

Table D.26 Final results in 2030 if the 'rebound effect' is 33% for PC and MV

	Total energy demand	Fossil energy demand		Petroleum demand		GHG emissions	
	TtW	TtW	Life cycle	TtW	Life cycle	TtW	Life cycle
Results	Mtoe	Mtoe		Mtoe		Mt CO_2-eq	
BAU scenario	444.0	443.3	621.4	438.5	484.6	1303.7	1891.0
BC scenario	262.1	245.6	373.6	232.8	256.9	776.8	1149.1
Reduction	181.9	197.8	247.8	205.8	227.8	526.9	741.9
Reduction due to each kind of measure in the BC scenario %							
PVC	16.1	16.2	15.6	16.4	16.5	15.9	15.5
FER	12.7	12.7	11.1	12.9	12.9	12.7	11.1
PDG	1.7	1.7	1.7	2.4	2.5	1.3	1.5
FT	16.7	16.7	14.8	18.9	19.1	16.6	15.0
BFP	1.6	7.5	4.3	7.9	7.7	1.4	3.3
Total	41.0	44.6	39.9	46.9	47.0	40.4	39.2

Table D.27 Final results in 2030 if there is 20% linear reduction of FR_{WtT}, PR_{WtT} and GR_{WtT} for biofuels between 2005 and 2030

	Life cycle fossil energy demand	Life cycle petroleum demand	Life cycle GHG emissions
Results	Mtoe	Mtoe	Mt CO_2-eq
BAU	621.4	484.6	1891.1
BC	372.4	255.3	1146.2
Reduction	249.0	229.3	744.9
Reduction due to each kind of measure in the BC scenario %			
PVC	15.6	16.5	15.5
FER	11.4	13.3	11.5
PDG	1.7	2.5	1.5
FT	14.9	19.2	15.1
BFP	4.2	7.7	3.1
Total	40.1	47.3	39.4

Table D.28 Final results in 2030 if there is 30% linear reduction of FR_{WtT}, PR_{WtT} and GR_{WtT} for biofuels between 2005 and 2030

	Life cycle fossil energy demand	Life cycle petroleum demand	Life cycle GHG emissions
Results	Mtoe	Mtoe	Mt CO_2-eq
BAU	621.3	484.6	1890.9
BC	371.3	255.2	1141.1
Reduction	250.1	229.4	749.7
Reduction due to each kind of measure in the BC scenario %			
PVC	15.6	16.5	15.5
FER	11.4	13.3	11.5
PDG	1.7	2.5	1.5
FT	14.9	19.2	15.1
BFP	4.4	7.7	3.5
Total	40.2	47.3	39.7

Table D.29 Final results in 2030 if 10% fossil energy consumption is petroleum during vehicle production stage

	Life cycle petroleum demand
Results	Mtoe
BAU	484.6
BC	255.2
Reduction	229.4
Reduction due to each kind of measure in the BC scenario %	
PVC	16.5
FER	13.3
PDG	2.5
FT	19.2
BFP	7.7
Total	47.3

Table D.30 Final results in 2030 if *FR*$_{WtT}$ and *GR*$_{WtT}$ for E-corn in the US (0.74 MJ/MJ and 56.7 g CO_2-eq) were used

	Life cycle fossil energy demand	Life cycle petroleum demand	Life cycle GHG emissions
Results	Mtoe	Mtoe	Mt CO_2-eq
BAU	621.3	484.6	1890.7
BC	371.4	255.3	1138.6
Reduction	250.0	229.3	752.1
Reduction due to each kind of measure in the BC scenario %			
PVC	15.6	16.5	15.5
FER	11.4	13.3	11.5
PDG	1.7	2.5	1.5
FT	14.9	19.2	15.1
BFP	4.4	7.7	3.7
Total	40.2	47.3	39.8

Table D.31 Final results in 2030 if FR_{WtT} and GR_{WtT} for E-cassava in Thailand (0.58 MJ/MJ and 45.5 g CO_2-eq) were used

	Life cycle fossil energy demand	Life cycle petroleum demand	Life cycle GHG emissions
Results	Mtoe	Mtoe	Mt CO_2-eq
BAU	621.3	484.6	1890.6
BC	371.4	255.3	1136.6
Reduction	249.9	229.3	754.0
Reduction due to each kind of measure in the BC scenario %			
PVC	15.6	16.5	15.5
FER	11.4	13.3	11.5
PDG	1.7	2.5	1.5
FT	14.9	19.2	15.1
BFP	4.4	7.7	3.9
Total	40.2	47.3	39.9

Table D.32 Final results in 2030 if FR_{WtT} and GR_{WtT} for CG, CD and CNG in the US (0.21 MJ/MJ and 18 g CO_2-eq for CG, 0.14 MJ/MJ and 12.1 g CO_2-eq for CD, 0.15 MJ/MJ and 10 g CO_2-eq for CNG) were used

	Life cycle fossil energy demand	Life cycle petroleum demand	Life cycle GHG emissions
Results	Mtoe	Mtoe	Mt CO_2-eq
BAU	604.7	477.5	1831.1
BC	360.7	250.7	1104.1
Reduction	244.0	226.8	727.0
Reduction due to each kind of measure in the BC scenario %			
PVC	15.7	16.5	15.6
FER	11.4	13.3	11.4
PDG	1.9	2.6	1.7
FT	15.0	19.3	15.2
BFP	4.3	7.7	3.2
Total	40.4	47.5	39.7

Appendix E: List of Publications

Yan, X. and Crookes, R. J., 2007, Study on energy use in China, Journal of the Energy Institute, 2, 110-115

Yan, X. and Crookes, R. J., 2007, A Study of energy use in China, Proceedings of the 20th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Padova, Italy, June 25-28, Vol.2, 1661-1668

Hu, Z., Tan, P., Yan, X. and Lou, D., 2008, Life cycle energy, environment and economic assessment of soybean-based biodiesel as an alternative automotive fuel in China, Energy, 33, 1654-1658

Yan, X. and Crookes, R. J., 2008, Reduction potentials of energy demand and GHG emissions in China's road transport sector, *Submitted* to Energy Policy

Study on energy use in China

X. Yan and R. J. Crookes*

Rapidly rising energy consumption in China has attracted worldwide attention. This paper provides some insights into future energy supply and demand based on an analysis of the current situation and unique features of energy use in China. With a population of over 1·3 billion, China will need a massive amount of energy to maintain its high economic growth rate. Fast development, in the transportation sector, in particular, has resulted in continuing growth in oil imports, threatening China's energy security. Heavy reliance on coal has caused serious environment problems in China and possibly more widely, mainly by the emission of greenhouse gases such as carbon dioxide, a major contributor to global warming. The Chinese government has been taking measures to improve energy efficiency and energy conservation to control energy consumption as well as promoting the use of clean energy such as hydroelectricity and natural gas, to replace coal, to reduce energy related pollution.

Keywords: Energy consumption and supply, Environment, Transportation

Introduction

China is the third largest economy in the world, after the United States and the European Union. The transformation into a market economy and participation in world trade has led China to sustained high rates of economic growth for more than two decades. The annual gross domestic product (GDP) growth rate in China was 10·3% between 1980 and 1990 and 9·6% between 1990 and 2003.[1] This rapid economic expansion has made China one of the largest energy consuming nations, with growth in demand continuing. Its future energy demand will be a major influence on global energy markets, affecting the availability and price of energy resources more widely.[2] Currently China is the world's second largest energy consumer (after the US) and the third largest energy producer (after the US and Russia). The growth in energy consumption has outpaced growth in domestic energy supply since the early 1980s, leading to a significant expansion in energy imports, mainly oil. Transportation, the main oil consumer worldwide, has been among the most rapidly growing energy users. This has been more serious in developing countries such as China, where road transport is expected to be the primary factor in growing demand for transportation fuels.

Several features of energy use in China are notable: energy consumption and carbon dioxide (CO_2) emissions are both large in absolute terms, but on a per capita basis, both are far below those of most developed economies and are even lower than the world's average; heavy reliance on coal has made China the biggest sulphur dioxide (SO_2) and second biggest (behind the US) CO_2 emitting country in the world; there has been a considerable decline of energy intensity (energy intensity: the ratio of energy consumption to constant value of GDP) over recent years; an energy structural shift from coal to cleaner energy has occurred.

Primary energy supply and consumption and CO_2 emissions

Figure 1 shows the historical trend of total primary energy consumption (TPEC) in China, compared with developed economies during 1965–2005. Total primary energy consumption in Japan and UK was very stable, with a slightly growing trend, while TPEC in the US has been rising steadily except for two remarkable declines mainly because of the two oil crises. Total primary energy consumption in China increased at an average annual growth rate of 4% from 182·4 Mtoe (million tonnes of oil equivalent) in 1965 to 972·6 Mtoe in 1996. Despite continued strong growth in GDP, energy consumption fell in 1997 to 960·9 Mtoe, and by 1998 to 916·9 Mtoe. By 1999, it had recovered to 934·1 Mtoe and had risen to 1554 Mtoe by 2005, with a rapidly growing trend after 2000. China is reported to have accounted for 36·9% of world coal consumption, 8·5% of oil, 13·6% of hydroelectricity, 1·9% of nuclear energy and 1·7% of gas consumption in 2005.[3]

Since the market reform, the coastal region of China has become the centre of economic activity, with the associated high energy demand, while the energy resources are remotely located from the new economic zones. The distribution of energy resources varies widely from region to region. Nearly 79% of coal reserves are situated in north and north-western China, while oil and gas reserves are concentrated principally in the northeast, east, far west, and off-shore.[4]

China consumes over a 10th of the world's total energy, however, its per capita primary energy consumption (1·1 toe in 2004) is far lower than that of many

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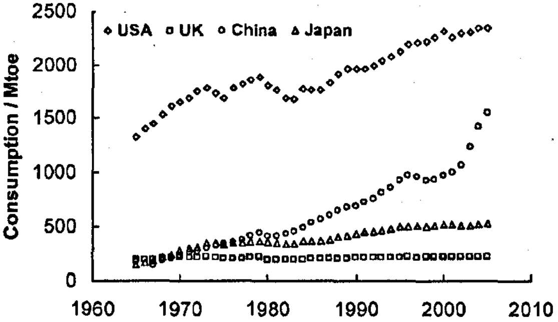


1 TPEC in China compared with developed countries[3]

developed economies and is below the world average.[1,3] As growth continues and its level of energy consumption per capita approaches levels of developed economies, the influence on global energy markets will be enormous.

Coal

China is the largest producer and consumer of coal in the world. It had reported coal reserves of 114·5 billion tonnes at the end of 2005, about 12·6% of the world's proven recoverable reserves, with an *R/P* ratio (*R/P* ratio: reserves divided by current annual production rate) of 52 (Ref. 3).

There is a well established infrastructure for coal supply and utilisation in China and, unlike oil and gas, it has a relatively low and stable price, not influenced by international events. Coal accounts for 73·4% of the proven reserves of conventional energy in China and 94·3% of fossil energy, and accounts for 70% of China's power generation. The rapid growth in electricity demand with increased manufacturing and residential use has been difficult to sustain as illustrated by power shortages in 75% of China's provinces in recent years, often prompted by lack of coal supplies.[2] It is thus inevitable that this fuel will continue to play the major role in supplying China's energy needs in the future.

The clean coal experience of the world suggests that the power generation sector is best developed for using coal cleanly, with clean coal technologies closely related to power generation. Up to 90% of coal use in many developed economies is for power generation while this percentage in China was 48% in 2003. Given the major pollution from energy use in China is the direct result of the combustion of coal, it is reasonable that cleaner energy sources such as oil and natural gas will replace coal in residential use and transportation. This would leave most coal for power generation, where clean technology better permits easing the problem of heavy pollution. The share of coal used in total household energy has been dropping from 86% in 1980 to 29·7% in 2003, a significant shift in the structure of household fuel consumption.[5,6]

Oil

China had proven oil reserves of 2·3 Gt at the end of 2005 and stood 13th in the world, with an *R/P* ratio of 12·1. Its per capita reserve however, is only 17% of the world average.[3]

Most of China's oil production is onshore, mainly at its largest production fields in the northeast at Daqing and Liaohe. Production from the east is starting to show a declining trend, but currently accounts for 65% of the total. Production from the west and offshore in recent years has increased rapidly. During 1990–2004, the contribution from these sources rose from 7·5 to 21·7% and 0·9 to 13% respectively. Therefore, a likely trend will be an increase in production from the west and offshore making up for the decrease in supply from the east.[7]

China experienced an annual rate of increase of 4% in oil consumption over the past 20 years. By the end of 2002, it had overtaken Japan to become the second biggest oil consumer behind the US. It has accounted for 40% of the world's demand growth of crude oil since 2000. In 2004, China consumed 327·3 Mt of oil. After a long period of being a net oil exporter, China became a net oil importer in 1993. The supply of crude oil and petroleum products in 2005 grew by ~4·2% over the previous year. Net import of crude oil and petroleum products reached ~146·2 Mt in 2005, accounting for almost 45% of China's total oil consumption. This level of dependence on imported oil increases the vulnerability for China's economic development.

The Middle East is the principal source of China's oil imports, accounting for 40·4% in 2005. Another 21·1% came from the Asia Pacific region, about 23·1% from Africa, and 11·7% from Former Soviet Union.[3] The main way of importing oil is by ocean tankers, which accounts for 93% of the total. Nearly 80% of these oil imports pass through the Strait of Malacca, exposing China to the insecurities of over dependence on a congested passage.[8] China must then start looking for new supplies for oil. It has been suggested that Russia and Central Asia would account for an increasing share of China's oil imports by means of a pipeline.

The demand for oil products follows an increase in private vehicles and a failure of the economy to use energy efficiently. Domestic oil pricing is not fully market based and while global oil prices rose 30% in the first seven months of 2005, the retail price of gasoline in China rose by half that rate, causing a short fall for the oil companies. Price controls have reduced gasoline availability in some cities, such as in the Pearl River Delta. This is partly because oil companies chose to export the fuel. Reforms to the pricing system are being considered. Without more responsive pricing China may face increasing energy restrictions, unless energy conservation and efficiency measures are encouraged.[9]

Natural gas

China's natural gas production has been gradually rising since the mid 1990s, as new fields, particularly offshore, came on line, and new pipelines were built. Despite recent growth, natural gas accounts only for about 3% of China's energy output in 2004, much as it did in 1980.

Natural gas use is now being encouraged by the Chinese authorities because of the relatively low emissions of atmospheric pollutants and CO_2. A new target is to be set in the 11th Five-year Plan (2006–2010) for the energy sector to increase the share of natural gas in the energy supply mix in the next five years and beyond. This would double the share of natural gas in the total primary energy supply by 2010.

The trans-China West to East natural gas pipeline, started in 2002, began full commercial operation in 2004. An investment of over 140 billion yuan (16·9 billion US dollars) was expected to bring 12 billion cubic meters of gas per year from the Tarim and Changqing gas fields in western Xinjiang and Shaanxi provinces to Shanghai. The completion and operation of the gas pipeline extending 4200 km through 10 provinces should increase China's gas supply by almost 50% and increase the share of gas in the total energy consumption mix by up to 2%.[10]

China will still need more gas than can be produced domestically. A gas pipeline from the Irkutsk area of Siberia is another option, though imports of liquid natural gas (LNG) and compressed natural gas (CNG), are more likely to help meet future demand.[11] Sustained growth of supply will need investment in developing new resources and extending the infrastructure for importation.

Hydroelectricity

China has a large geographical area and a number of rivers, which give it one of the largest hydroelectricity resources in the world. This is currently developed to a degree that is less than 20% of its potential. Hydroelectric systems have several advantages: they are relatively independent of price increases for fossil fuels, they tend to have longer lives than those using fuel fired generation, they have negligible emissions of CO_2 and methane, and they do not emit other pollutants associated with combustion process.

China is making an enormous effort to develop hydroelectricity (Table 1). A series of large scale hydroelectricity schemes, such as the Three Gorge project, has already been completed and is now in production. According to the goal of the development of a modern society, hydroelectric installed capacity should reach 160 gega watts (GW) by 2010, representing 23% of the total installed electricity capacity; by 2015 this will reach 270 GW (27% of the total). If official plans are realised, the level of development of hydroelectricity will reach 40%, making China the leading producer of hydroelectricity in the world.[13]

Nuclear energy

Nuclear power generation does not lead directly to the emissions of such pollutants as SO_2, nitrogen oxides (NO_x) and CO_2. In comparison with fossil fuels, nuclear energy is considered a clean energy in terms of atmospheric environmental protection. There are however obvious problems of containment and long term radioactive product disposal. Nuclear energy is currently the only energy that can substitute fossil fuels in a centralised way and to a significant extent with commercial availability and economic competitiveness. It would be expected to play a prominent role in the future energy supply strategy of China.

The development of China's nuclear power started late. Six nuclear power plants with an installed capacity of 8700 MW were built in China by 2004, accounting for 2·3% of China's total capacity. At present, due to a limited technology reserve and a shortage of funds for construction, the growth rate of nuclear power capacity is likely to be low in the short term.[14]

Energy structural shift

The proportion of coal in the TPEC fell from 72·2% in 1980 to 69·6% in 2004. The proportion of oil, natural gas and hydropower changed from 20·7, 3·1 and 4·0% respectively in 1980 to 21·1, 2·7 and 5·8% in 2005, when there was also 0·8% of nuclear energy. This implies that China is developing a more 'environment-friendly' energy supply system. Compared with more developed economies, however, China's energy structure is heavily reliant on coal. (Table 2)

Electricity

The electricity industry is a fundamental component of the national economy, and the supply of electricity is crucial to socioeconomic development and improvement of living standards. Rapid economic development will require a large supply of electricity in China, where ~75% of electricity demand comes from industry.

China's total electricity generation was 2187 TWh in 2004, 14·8% higher than in 2003. The commissioning of a series of large scale hydroelectricity schemes brought hydroelectricity generation to 328 TWh, 16·6% higher than in 2003. Increase in thermal electricity generation was restricted to some degree by the supply of coal. A 14·5% growth however was achieved in 2004, with a total thermal electricity generation level of 1807·3 TWh. Generation from nuclear power stations grew 14·1% from 2003 to 50·1 TWh in 2004.

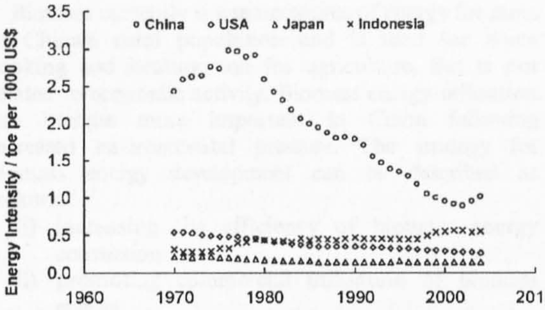
After 2003, 2004 had the second fastest growth in yearly electricity consumption (of 2173·5 TWh, 14·9% higher than in 2003) since the end of the 1970s, though shortage of power was a major characteristic of electricity market in 2004. There were power shortages in 21 provinces in 2003 with a total shortfall of generated output of ~10 GWh. Twenty four provinces in 2004 experienced power shortages with a total shortfall of 30 GWh (Ref. 15).

Table 2 Energy structure (percent mix) of world's big economies in 2005[3]

	Oil	Natural gas	Coal	Nuclear energy	Hydro electricity
USA	40·4	24·4	24·6	8	2·6
Japan	46·6	13·9	23·1	12·6	3·8
Germany	37·5	23·8	25·3	11·4	2
UK	36·5	37·4	17·2	8·1	0·8
France	35·5	15·4	5·1	39·1	4·9
China	21·1	2·7	69·6	0·8	5·8
World	36·4	23·5	27·8	6	6·3

Table 1 Hydropower installed capacity and electricity generation in recent years[12]

Year	1999	2000	2001	2002	2003
Installed capacity, MW	72 971	79 352	83 006	86 075	94 896
Proportion in the total installed capacity, %	24·42	24·85	24·52	24·14	24·24
Net newly added capacity, MW	7906	6381	3654	3069	8822
Growth rate on a year-on-year basis, %	12·15	8·74	4·60	3·70	10·25
Electricity generation, Mtoe	18·3	20·9	22·5	23·6	24·2
Proportion in the total electricity generation, %	17·27	17·76	17·60	16·60	14·77
Growth rate on a year-on-year basis, %	4·22	14·18	7·40	5·15	2·46



2 **Energy intensity in selected countries[1,3] (GDP at constant value of US$ in year 1990)**

Energy intensity

Despite rising energy efficiency during the 1980s contributing to China's improved productivity, China's overall energy efficiency in 1990s lagged behind that of other countries with similar levels of per capita income. By 2003, a 75% reduction in energy intensity through the 1980s and 1990s enabled China to close the gap between its level of energy efficiency and that in more developed economies (Fig 2). Even so, China's energy intensity in 2002 was three times of that in the US and six times of that in Japan, also there was a rising trend after 2002, leaving a significant potential for further efficiency increases.

CO_2 emissions

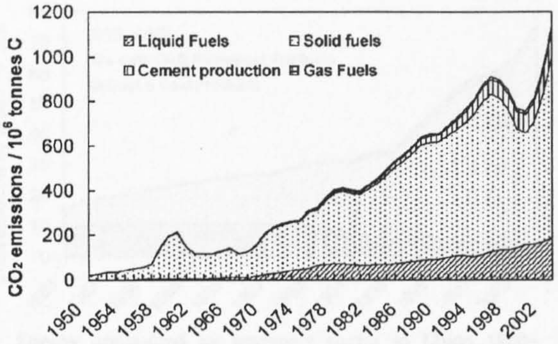
Chinese fossil fuel CO_2 emissions dropped 16·5% from 912 to 762 million metric tonnes of carbon in 2000. It then rapidly rose to an all-time high of 1131 million metric tonnes of carbon in 2003. Despite the recent four year decline, China's industrial emissions of CO_2 have grown steadily since 1950 (*see* Fig 3), when China's annual fossil fuel CO_2 emissions stood 10th in the world. From 1970 to 1996, China's fossil fuel CO_2 emissions grew at an annual rate of 5·3%. From 1990 to 1996, emissions rose 39%. This growth has occurred largely from the use of coal. Liquid fuels now contribute 16·5% of emissions and have grown appreciably over the past decade. Emissions from cement production account for 10·4%. Per capita CO_2 emissions in China increased considerably over the past 50 years though the 2002 rate of 0·86 metric tons of carbon is well below the global average and is only 15·8% of that of the US. China's total annual CO_2 emissions are already ~15% of the world's total, so China is likely to become the country having the highest emissions.[16]

Renewable energy

Currently, renewable energy resources (except for hydropower) account for only a small fraction of total energy consumption in China. The estimated growth in greenhouse gas emissions, as well as serious local and regional environmental pollution problems caused by combustion of fossil fuels, however, provide strong arguments for the accelerated development of renewable energy resources.

Solar energy

China has a large potential solar resource especially in the northwest, Tibet and Yunnan. Power shortages and concern over environmental pollution would be expected to lead to development and utilisation of solar energy. Since there is little associated pollution, it could readily supplement present energy supplies and play a major role in the future energy structure. The most common use of solar energy in China is in the supply of hot water. The total installed capacity of solar water heaters by the end of 2004 was 70 million square meters of collector area, with an annual increase rate of 27% over the last 10 years.



3 **CO_2 emissions in China by source 1950–2003[16]**

Photovoltaic technology (PV) is the main technology used in China for the generation of electricity from solar energy. By the end of 2004, China's installed capacity of PV systems was over 60 MW. About 50% was used to supply electricity to residents of remote rural areas, with an annual growth rate of 20%. The production capacity for urban PV lighting systems in China is over 10 MW, 70% of the world total. Solar PV has the potential to become one of China's leading sustainable energy resources.[17]

Wind energy

China with a massive land territory and long coastline has great wind energy potential. The National Meteorology Institute has estimated a land based exploitable wind power resource of 253 GW. The installed capacity of wind power generation was ~764 MW at the end of 2004. The high potential wind energy is mainly located in the remote areas, away from the current industrialised regions. This area has little by way of other energy resources, which should enable these remote rural populations to use the power for their own needs. These would include areas such as Inner Mongolia and the islands in the eastern coastal regions. A further 750 GW capacity could be derived from the ocean based wind resources. A total wind power capacity of 4000 MW is predicted by the end of 2010, with a long term target of 20 GW for 2020 currently planned by the Chinese government.[18]

Biomass

China possesses a wide range of biomass sources which can be used for energy purposes including firewood, straw and stalks, agriculture and forestry residues and organic wastes. Among them, crop stalks suitable for energy production are estimated to represent a potential of 12 000 PJ (~287 Mtoe) annually. Forestry residues represent a resource equivalent to 8000 PJ (~191 Mtoe). Wastes from the processing of agricultural products and manure from livestock farms could, in theory, yield nearly 80 billion cubic meters of biogas.[17]

Biomass currently is a main source of energy for most of China's rural population and is used for home cooking and heating and for agriculture, but is not related to economic activity. Biomass energy utilisation has become more important in China following increased environmental pressure. The strategy for biomass energy development can be described as follows:

(i) increasing the efficiency of biomass energy conversion
(ii) promoting commercial utilisation of biomass energy.

Currently the main full technologies developed and in use are for ethanol and bio-oil. China has already established two large ethanol fuel production bases, with a total annual production capacity of over one million tons. Annual production of bio-oils has reached ~500 000 tons. Power generation from biomass in China currently has an installed capacity of almost 2000 MW.[17]

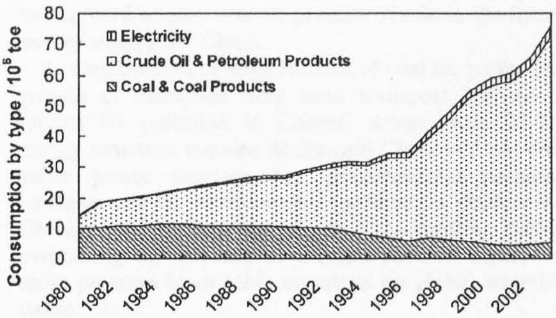
Prospects for renewable energy production in China

Sources of renewable energy are abundant in China and, using known technology have the potential of being developed for application for energy purposes. The process however is in the early stages and problems in exploitation include lack of readily available technology, low conversion efficiencies, high production costs and lack of competition. Existing technology has yet to be formed into full scale production and the service system perfected. The potential for renewable energy use in China is much greater than that indicated by the current level of use. The most significant barriers are the lack of available advanced practical technology and the lack of development funds. Development of policies and measures for development should allow renewables to play a far larger role in China's energy supply scenario.

Transportation sector in China and related environmental issues

Globally the transportation sector is responsible for over half of the world oil consumption and ~30% of total commercial energy consumption. It is also the most rapidly growing sector in terms of energy and particularly oil consumption. Over the past 20 years, energy use worldwide in the transportation sector increased at an average rate of 2·7% per year, more rapidly than any other sector. Growth in transport has been highest in the fastest growing economies: China, East Asia and parts of Latin America. However, in 2003, the transportation sector in China accounted for only 10·5% of the total end energy consumption there which is much lower than the world's average.

Transportation demand for urban residents has increased rapidly in China along with the economic growth and accelerating urbanisation. Passenger miles increased almost eightfold in the last two decades. Civilian motor vehicle number increased by more than an order of magnitude from 1·8 to 26·9 million between 1980 and 2004, while private owned vehicle number grew from 0·29 to 14·82 million between 1985 and 2004. Vehicle ownership in China is however about 1/40 of that in the United States on a per capita basis in 2003 and the potential for vehicle population growth is high.



4 Energy consumed by transport sector in China 1980–2003[21] (proportions of gas and other minor forms of energy are too small to show)

The need for buses is expected to rise rapidly with the extension of expressways in the south and west. Infrastructure development in preparation for the 2008 Beijing Olympic Games is likely to stimulate a further demand for heavy trucks.[19] The demand for transportation fuels mainly came from road transport. This indicates the need for comprehensive system prioritising public transportation to meet the increasing transportation demand and reduce fuel consumption.

Urban transport in China has experienced the most rapid development in the last decade. Public transport development is linked with development of cities and land. Links between cities, links between urban and rural areas, and between city and suburbs. Facilities and the volume of passengers have increased dramatically. Local bus stations have been linked with long distance bus stations.[20]

Transport in China over 20 years ago was mainly by railway, fuelled mostly by coal, 67·4% in 1980 (Fig. 4). Road transport growth has shifted total transport energy met by oil. It has now risen from 30·9% in 1980 to 88·3% in 2003, with coal reduced to 6·7%. The transportation sector accounted for about 30% of oil consumption in 2003, and is expected soon to rise to half of all oil use in China, in line with global patterns.[21]

Aviation passenger miles increased by a factor of 4 in the 1990s, the second fastest growing passenger transport mode. The increase in incomes and commercial activity are predicted to lead to continuing growth in air travel.[19]

Road transport is set to become the largest oil consumer dominating oil import strategy in China, and thus effecting national energy security and economic development, and threatening national development. The control of oil consumption by road transportation is thus an issue of major importance. Curbing oil demand would be the most effective measure in reducing oil imports. The fuel economy of new Chinese vehicles is now 10–15% lower than in Europe, 5–20% lower than in the US, and 20–25% lower than in Japan for an equivalent vehicle type.[22] The introduction of fuel economy standards and establishing a policy for oil conservation will thus be imperative for China.

Air pollution in Chinese cities mainly originates from coal combustion which has been largely controlled in large cities such as Beijing and Shanghai. Vehicle emissions associated with photochemical smog are however gradually increasing and NO_x and ozone in particular are well above accepted levels. Air quality appears to be deteriorating with the growing combined emissions of coal combustion and vehicle exhaust gas. Of 522 cities monitored in 2005, the air quality in 207 did not meet Grade 2 (of the National Standards for Ambient Air Quality) in terms of total suspended particulates, SO_2 and NO_x, while 55 cities did not meet Grade 3 (the minimum level). The estimated annual cost of air pollution in China is roughly 10% of GDP.[23]

Pollution control for automotive vehicles in China has traditionally been relatively weak. The European no. 2 Emission Standard currently adopted is equivalent to the control level in Europe in the mid 1990s. Incomplete implementation even of this standard in China and non-compliance has led to high numbers of heavily polluting vehicles causing environmental damage, particularly in the bigger cities where vehicle populations are high.

Transportation generated CO_2 in China accounts for ~10% of the total emission. By 2030, the CO_2 emissions from automotive vehicles will account for some 30% of the total with present growth. A more alarming statistic is that without transport energy saving controls, the growth of the CO_2 emitted by automotive vehicles in China will offset much of the reduction targets of other countries.

Conclusions

China has experienced remarkable economic growth over the last two decades, which has been accompanied by a corresponding growth in energy demand and the related emissions of green house gases.

1. Coal has traditionally supplied a large proportion of China's energy needs and is expected to remain the most important fuel in the near future. This is notable in terms of fossil fuel reserves (coal now constitutes more than 90%), primary energy consumption (coal supplies over 67%) and in power generation (more than 70% coal fired).

2. Soaring transportation demand has made oil the second fast growing energy source in China (after coal) and, by exceeding supply has led to an over dependence on imported oil. If demand continues to increase without the development of viable alternative fuels for road transportation the security of oil supply (an essential factor of economic development) will be a major uncertainty in the economy. This will also contribute to the rise in the associated CO_2 emissions in China.

3. The use of natural gas, hydropower, nuclear power and renewable energy has risen steadily, yet still accounts for a relatively small proportion of the total energy mix. Development has been relatively slow because of obstacles such as shortage of funds for infrastructure development and a limited available technology expertise. The Chinese government is making enormous efforts however, to develop the clean energy sources, to offset the shortage of fossil fuel and help to ease the growing pollution. Clean energy would be expected to play a more prominent role in the future energy supply for China.

4. Combustion of large amount of coal for power and growth of emissions from road transport has led to serious air pollution in Chinese urban areas. If the energy structure remains unchanged China will not only suffer power shortage but environmental pollution increase and its environment continue to deteriorate. China could become the largest CO_2 emitting nation overtaking the US and as a result start to experience more pressure from other countries on global warming issues.

5. Oil consumption and exhaust emissions by road transport are functions of the number of road vehicles and the amount and type of fuels used, and it might be expedient to restrict the growing private vehicle utilisation while giving priority to public transport. At the same time, continued effort should be put to developing alternative automotive fuels.

6. The magnitude of the Chinese energy consumption and the rate of growth are on a scale that suggest future demand will have a major influence on world energy markets and resource supplies.

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A Study of Energy Use in China

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ABSTRACT: Rapid economic development has made China one of the two largest consumers in the global energy market. With a population of over 1.3 billion, China will need a massive amount of energy to maintain its high economic growth rate. This paper provides some insights into future energy supply and demand based on an analysis of the current situation and unique features of energy use in China. The authors also attempt to quantify possible high and low growth scenarios for oil consumption and CO_2 emissions in the rapid-growing Chinese road transport sector in the next two to three decades.

Keywords: energy, transport, growth scenario, CO_2, greenhouse gas

NOMENCLATURE

CE	CO_2 emissions [t]
EC	Energy consumption [Mtoe]
EI_{CO2}	the emission rate for CO_2 per unit of fuel consumed [t/toe]
FE	Fuel economy [km/l]
GW	Gigawatt
Mt	Million tonnes
Mtoe	Million tonnes of oil equivalent
Sales	the number of vehicles added in a particular year
Survival	the fraction of vehicles surviving after a number of years [%]
t	tonne
T	Type of vehicle
V	Vintage (year of purchase)
VDT	Vehicle distance travelled [km]
VP	Vehicle population
Y	Calendar year

1. INTRODUCTION

The rapid economic expansion in the last two decades has made China one of the two largest energy-consuming nations, with growth in demand continuing. Its future energy demand will be a major influence on global energy markets, affecting the availability and price of energy resources more widely.

Transportation, the main oil consumer worldwide, has been among the most rapidly growing energy users in China, where road transport is expected to be the primary factor in growing demand for transportation fuels. Energy consumption (*EC*) and carbon dioxide (CO_2) emissions by road transport are functions of the motor vehicle population (*VP*), annual vehicle distance travelled (*VDT*), fuel economy (*FE*) and type of fuels used. Zhang [1] forecast the growth of *VP* and *EC* of the Chinese road vehicles up to 2020. He concluded that *EC* by motor vehicles in China would reach 115 million tonnes (Mt) of gasoline and 95 Mt of diesel in 2020. He et al. [2] did a predictive-analysis of oil demand and CO_2 emissions (*CE*) in China's road transport sector under three different *FE* improvement scenarios. His results for oil demand and *CE* in 2030 were 363 Mt and 1146 Mt in the worst case, 278 Mt and 879 Mt in the best.

Their results, however, are less reliable than those in developed economies, because of higher uncertainties in the Chinese energy use trend statistics (population and economy growth, motor vehicle market development, transportation infrastructures and policies etc). In this paper, a set of more comprehensive *EC* and *CE* scenarios for the Chinese road transport sector under different policy measures and technology options have been developed using the Long-range Energy Alternatives Planning system (LEAP) software [3].

2. PRIMARY ENERGY SITUATION

Currently China is the world's second largest energy consumer and producer (after the US). Total primary *EC* in China (Figure 1) increased at an average annual growth rate of 5.5% from 182.4 million tonnes of oil equivalent (Mtoe) in 1965 to 1554 Mtoe in 2005, with a rapidly growing trend after 2000. China was reported to have accounted for 36.9% of world coal consumption, 8.5% of oil, 13.6% of hydroelectricity, 1.9% of nuclear energy and 1.7% of gas in 2005 and more than half of global *EC* growth [4].

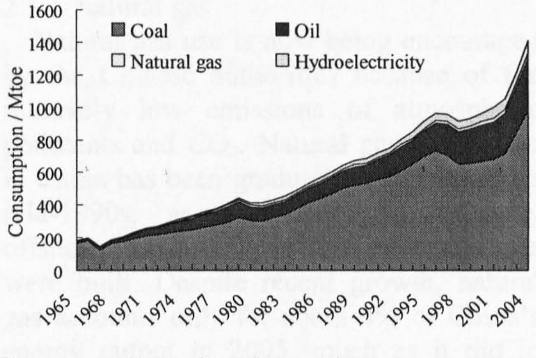

Figure 1: Total primary energy consumption in China 1965-2005 [4]

Although China consumes over a tenth of the world's total energy, its per capita primary *EC* (1.1 toe in 2004) is far lower than that in many developed economies and is below the world average. As growth continues and its level of *EC* per capita approaches levels in developed economies, the impact on energy markets and the environment will have global repercussions.

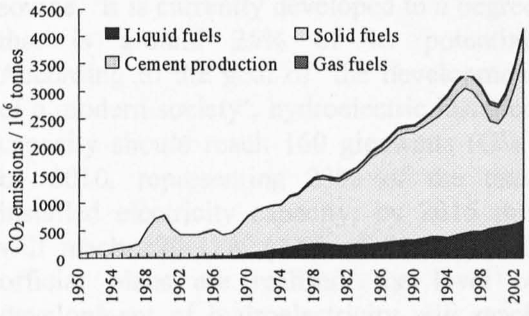

Figure 2: Fossil-fuel CO_2 emissions in China by source 1950-2003 [5]

China's fossil-fuel *CE* has grown steadily since 1950. After the recent four-year decline, it then rapidly rose to an all-time high of 4148 Mt in 2003 (Figure 2), making China the second largest CO_2 emitter just behind the US.

2.1 Coal

Coal accounts for 73% of the proven reserves of conventional energy in China and 94% of fossil energy, and accounts for more than 80% of China's power generation. China is the largest producer and consumer of coal in the world. Its coal consumption rose by 11% in 2005, accounting for 80% of global growth [4]. It is inevitable that this fuel will continue to play the major role in supplying China's energy needs in the future mainly because of the rapid growth in electricity demand with increased manufacturing and residential use.

Given the major part of *CE* from energy use in China is the direct result of the combustion of coal, it is reasonable to expect that cleaner energy sources such as oil and natural gas will be sought to replace coal in transport and residential use.

2.2 Oil

China experienced an annual rate of 4% increase in oil consumption over the past 20 years. By the end of 2002, it had overtaken Japan to become the second biggest oil consumer behind the US. It has accounted for 40% of the world's demand growth of crude oil since 2000. After a long period of being a net oil exporter, China became a net oil importer in 1993. Net import of crude oil and petroleum products reached approximately 146.2 Mt in 2005, accounting for almost 45% of China's total oil consumption [4]. This level of dependence on imported oil increases the vulnerability of China's economic development.

The Middle East is the principal source of China's oil imports, accounting for 40% in 2005. Another 21% came from the Asia Pacific region, about 23% from Africa, and 12% from the Former Soviet Union [4]. The main way of importing oil is by ocean tanker, which accounts for 93% of the total. Nearly 80% of these oil imports pass through the Strait of Malacca, exposing China to the insecurities of over dependence on a congested passage [6]. China must then start looking for new supplies to ensure its oil security. It has been suggested that Russia and Central Asia would account for an increasing share of China's oil imports by means of a pipeline.

2.3 Natural gas

Natural gas use is now being encouraged by the Chinese authorities because of the relatively low emissions of atmospheric pollutants and CO_2. Natural gas production in China has been gradually rising since the mid-1990s, as new fields, particularly offshore, came on line, and new pipelines were built. Despite recent growth, natural gas accounts only for about 3% of China's energy output in 2005, much as it did in 1980.

China will still need more gas than can be produced domestically. Imports of liquefied natural gas through pipelines are more likely to help meet future demand [7]. Sustained growth of supply will need investment in developing new resources and extending the infrastructure for importation.

2.4 Hydroelectricity

With one of the largest hydroelectricity resources in the world, China is making an enormous effort to develop this clean energy source. It is currently developed to a degree that is around 25% of its potential. According to the goal of 'the development of a modern society', hydroelectric installed capacity should reach 160 gigawatts (GW) by 2010, representing 23% of the total installed electricity capacity; by 2015 this will reach 270 GW (27% of the total). If official plans are realised, the level of development of hydroelectricity will reach 40%, making China the leading producer of hydroelectricity in the world [8].

2.5 Nuclear energy

The development of China's nuclear power started late. Six nuclear power plants with an installed capacity of 8.7 GW were built in China by 2004, accounting for 2.3% of China's total electric capacity. At present, due to a limited technology reserve and a shortage of funds for construction, the growth rate of nuclear power capacity is likely to be low in the short term [9].

Nuclear energy is currently the only energy that can substitute fossil fuels in a centralized way and to a significant extent with commercial availability and economic competitiveness. It would be expected to play a prominent role in the future energy supply strategy of China.

3. DEVELOPMENT IN CHINA'S ROAD TRANSPORT SECTOR

With the fast growing economy, transport has become a crucial component of modern urban life. Urbanization, increasing incomes, more social and leisure time and the diversity of activities has led to the requirement of people for ever-greater mobility and consequently substantial increase in overall passenger travel in China.

VP in China grew by more than 7 times from 3.2 to 26.9 million between 1985 and 2004, among which the private-owned *VP* grew by more than 50 times from 0.29 to 14.82 million over the same period, with the percentage in the total *VP* up from 9% to 55% [10]. China is now the fourth largest auto producer and the second largest auto market in the world. Vehicle ownership in China was however about 1/40 of that in the United States on a per capita basis in 2003 and the potential for *VP* growth is high.

Transport in China over 20 years ago was mainly by railway, fuelled mostly by coal, 67.4% in 1980. Road transport growth has shifted the total transport energy met by oil. It has now risen from 30.9% in 1980 to 88.3% in 2003, with coal reduced to 6.7% (Figure 3). Corresponding *CE* would show similar trends to those in Figure 3. The motor vehicle sector accounted for about 25% of oil use in China in 2004, and is expected to rise to 40% of all oil use in 2030, in line with global patterns [11].

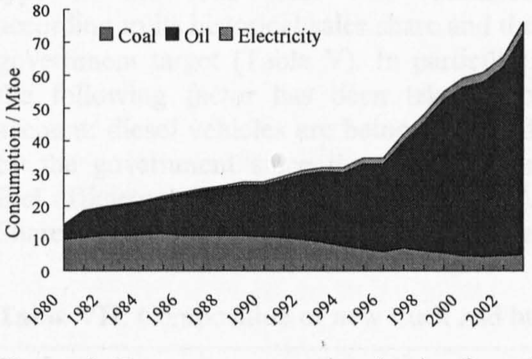

Figure 3: Energy consumption (major forms) in the Chinese transport sector [12]

4. ENERGY CONSUMPTION AND CO$_2$ EMISSIONS IN ROAD TRANSPORT

4.1 Methodology and data

LEAP is a scenario-based energy-environment modelling tool. With its flexible data structures, LEAP allows for analysis in technological specification and end-use detail. [3] With LEAP's Transport Analysis methodology, *EC* is calculated as the product of *VP*, *VDT* and *FE*:

$$EC_{T,Y,V} = VP_{T,Y,V} \times VDT_T \times FE_T \quad (1)$$

$$EC_Y = \sum_T \sum_V EC_{T,Y,V} \quad (2)$$

CE is calculated by assuming all the carbon in the fuel becomes CO$_2$ after combustion:

$$CE_{T,Y,V} = EC_{T,Y,V} \times EI_{CO2} \quad (3)$$

$$CE_Y = \sum_T \sum_V CE_{T,Y,V} \quad (4)$$

Vehicle types and fuel types included in this study are listed in Table I.

Table II: Classifications of motor vehicles

Truck	HDT-G(D)	heavy duty gasoline(diesel) truck
	MDT-G(D)	medium duty gasoline(diesel) truck
	LDT-G(D)	light duty gasoline(diesel) truck
	MT-G(D)	mini gasoline(diesel) truck
Bus	HDB-G(D)	heavy duty gasoline(diesel) bus
	MDB-G(D)	medium duty gasoline(diesel) bus
	LDB-G(D)	light duty gasoline(diesel) bus
Car	C-G(D)	gasoline(diesel) car
MV	MV-G(D)	mini gasoline(diesel) van

All the data used for the chosen base year 2002 is listed in Table III.

VP: total *VP* data in the base year was from [10]; historical sales data of each vehicle type was obtained from [13]; due to lack of statistics, survival data of each vehicle type was estimated by the authors according to the vehicle-scrapping standard in China; *VP* of each vehicle type in the base year was then calculated according to its historical sales and survival data:

$$VP_{T,Y,V} = Sales_{T,V} \times Survival_{T,Y-V} \quad (5)$$

$$VP_{T,Y} = \sum_V VP_{T,Y,V} \quad (6)$$

A vintage profile describing the age distribution for the existing stock of each vehicle type in 2002 was also obtained from the above calculation.

VDT: *VDT* data of each vehicle type was determined by taking several studies into consideration. [2, 14 and 15] and selecting appropriate values.

FE: the actual on-road *FE* data for each vehicle type during lifetime was from [2].

Table IV: Data of *VP*, *VDT* and *FE* in 2002

	VP / 10^6	*VDT* / 10^3km	*FE* / km/l
HDT-D	0.98	40	3.32
MDT-G	0.56	30	2.99
MDT-D	1.92	30	4.28
LDT-G	0.70	30	5.90
LDT-D	2.69	30	6.53
MT-G	1.27	20	11.54
HDB-G	0.007	40	2.21
HDB-D	0.071	40	3.02
MDB-G	0.07	40	2.68
MDB-D	0.26	40	3.91
LDB-G	1.61	30	7.90
LDB-D	0.66	30	8.82
Car-G	6.10	26	11.03
MV-G	3.24	30	11.90

The future composition of each vehicle type in the total fleet was estimated according to its historical sales share and the government target (Table V). In particular, the following factor has been taken into account: diesel vehicles are being promoted by the government since they have better fuel efficiency than the gasoline ones [13]. Shares of diesel vehicles in the total fleet are likely to increase. Shares of diesel vehicles in the new car and MV fleets were assumed to increase linearly from 0 in 2005 to 50% and 40% in 2030, respectively.

4.2 Scenario design

A: Transport mode

Which transport mode people choose is greatly influenced and directed by the government. Beijing Municipal Government has adopted a few policies to stimulate the use of private vehicles, such as provision of car mortgages and deduction of relevant fees for vehicle use [16], while Shanghai Municipal Government has adopted policies to restrict the use of private vehicles such as a high registration fee for new vehicles. The result of their different policies is that, although GDP per capita in Beijing is lower than it is in Shanghai, private vehicle ownership is 4 times greater [10].

The options considered are:

A1: Promotion of private vehicle purchases and no promotion of public transport. Growth rates for car and MV sales will be high while those for bus sales will be low. (Table VI)

A2: Restriction of private vehicle purchases and promotion of public transport. Growth rates for car and MV sales will be low while those for bus sales will be high.

Table VII: Composition of new truck and bus fleets in China (%)

Vehicle type		Composition of new truck fleet								Composition of new bus fleet					
		HDT	D[a]	**MDT**	D	**LDT**	D	**MT**	D	**HDB**	D	**MDB**	D	**LDB**	D
Historical sales share [13]	1994	**4.6**	n/a	**39.7**	n/a	**43.0**	n/a	**12.7**	n/a	**2.3**	n/a	**9.1**	n/a	**88.6**	n/a
	1997	**4.6**	99.9	**28.2**	64.9	**44.7**	55.3	**22.5**	0.3	**2.2**	99.2	**7.7**	54.9	**90.1**	29.6
	2000	**11**	99.9	**20.5**	71.4	**51.0**	80.6	**17.5**	0.6	**2.6**	90.1	**12.1**	58.9	**85.3**	27.6
	2002	**23.1**	100	**15.3**	92.3	**47.9**	88.2	**13.7**	0.1	**4**	87.5	**15.6**	90.2	**80.4**	27
	2004	**24.3**	n/a	**11.5**	n/a	**53.0**	n/a	**11.2**	n/a	**6.8**	n/a	**11.6**	n/a	**81.6**	n/a
	2005[b]	**15.6**	98.8	**12.8**	96.5	**56.2**	89.1	**15.4**	16.1	**7.3**	86.6	**10.4**	88.7	**82.3**	50.1
Prediction of future sales share	2010	**18**	100	**9**	98	**58**	95	**15**	15	**8**	90	**10**	90	**82**	60
	2015	**20**	100	**5**	100	**60**	98	**15**	25	**8**	95	**10**	90	**82**	60
	2030	**20**	100	**5**	100	**60**	98	**15**	50	**8**	95	**10**	90	**82**	60

a. *Diesel vehicle share of this vehicle type.*

b. *Production data in 2005 was used since sales data in this year was not available.*

Table VIII: Assumption of annual *VP* growth rates (%) under scenarios A1 and A2.

	1996-2005	Scenario	2006-2010	2011-2020	2021-2030
Truck	6.8		9	5	3
Bus	8.1	A1	7	4	2
		A2	10	6	3
Car	28	A1	20	10	5
		A2	10	6	3
MV	23.1	A1	15	8	3
		A2	8	4	2

B: VDT of car and MV fleets

How much people use their vehicles is also greatly influenced by government policies. Fuel price is much higher in European countries like the UK than in the US because of high fuel taxation, and people tend to use their vehicles less and use public transport more (see Table IX). The *VDT* of car and MV fleets in China has been traditionally much higher than in developed countries. As the *VP* grows, the proportion of private vehicles becomes bigger and the private light-duty passenger vehicle service-year limit in the new vehicle-scrapping standard is eliminated, the *VDT* of Chinese car and MV fleets will be expected to gradually move in line with the values in developed countries.

Table X: Transport mode to workplace and car *VDT* in USA and UK in 2005 [17 and 18]

	Mode to work (%)			Car *VDT*
	Car	Public	Total	/ 10^3 km
USA	88.4	4.4	100	20.12
UK	71.2	14.6	100	14.68

From the above consideration, the two options included are:

B1: *VDT* for car and MV will be reduced from 30000km in 2006 to 20000km in 2015 and remain at that level from then on.

B2: the Chinese government will take measures to control private vehicle usage. *VDT* for car and MV will be reduced from 30000 km in 2006 to 15000 km in 2015 and remain at that level from then on.

C: FE improvement for new vehicles

Assumptions were made according to China's first *FE* standard [19] and one still in draft [20]. Targeted vehicle types are: car, MV, LDB, LDT and MT. Measures will be implemented in four phases—2005, 2008, 2013, and 2018 for car and MV and 2008, 2012, 2017 and 2022 for LDB, LDT and MT.

The options considered are:

C1: Low-improvement: in each phase there will be 10% improvement, resulting in 46% total improvement over 14 years.

C2: High-improvement: in each phase there will be 15% improvement, resulting in 75% total improvement over 14 years.

4.3 Results of current predictions

A comparison is made in Figure 4 between eight projections of *EC* in road transport in China up to 2030 using scenarios A1 and A2 together with combinations of either B1 or B2 and C1 or C2. Of these scenarios, A1B1C1 is the most liberal to private vehicle growth while A2B2C2 is the most restrictive. Figure 5 shows the corresponding growth in *CE* from vehicles with these scenarios.

From the projections, differences of the order of a factor of two can be observed between these scenarios. Under the worst scenario, *VP*, *EC* and *CE* in 2030 reach 378 million, 467 Mtoe and 1467 Mt, respectively, while at best, these are 196 million, 272 Mtoe and 857 Mt, which is close to [2].

The implications of these trends are global. Even with the best case scenario China from transport alone could treble its requirement in 25 years from the current level of 8.5 % of the world oil consumption of 3837 Mtoe [4]. With China's annual *CE* already at about 15% of the world's total in 2003 [5], a corresponding trebling from vehicular source would double the current production from liquid fuels and raise total production by around 12%.

These results are preliminary attempts to predict quantitatively the possible magnitude of *EC* and *CE* in the Chinese road transport sector up to 2030. There are several obvious limitations: results are subject to the assumptions made; alternative fuels and vehicles were not taken into account; effect of policy measures and new technology was not quantified, etc. These assumptions will be assessed in more detail in future work.

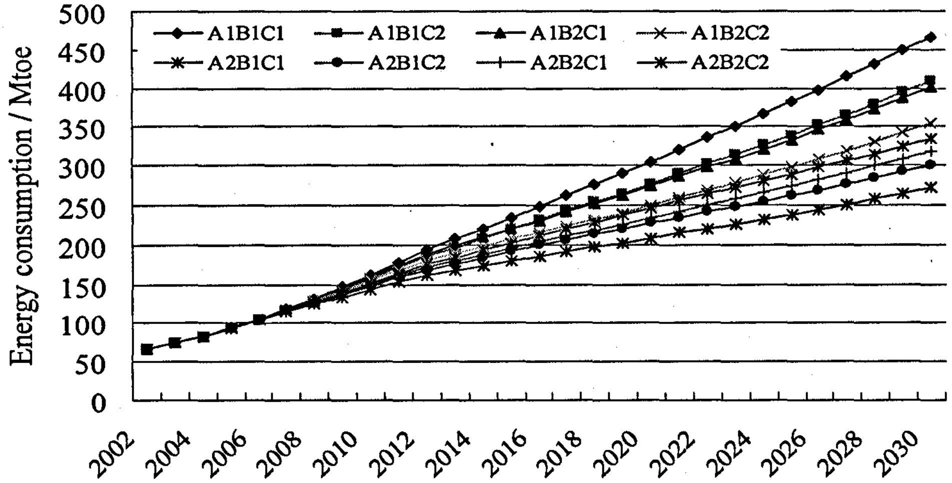

Figure 4: Energy consumption of China's motor vehicles, 2002—2030

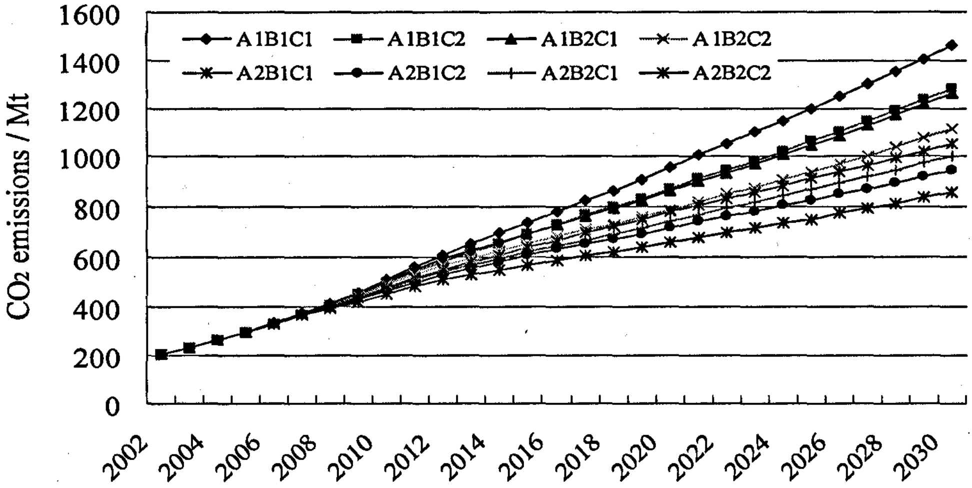

Figure 5: CO_2 emissions of China's motor vehicles, 2002—2030

5. CONCLUSION

China has experienced remarkable economic growth over the last two decades, which has been accompanied by a corresponding growth in *EC* and the related *CE*. Soaring transport demand has made oil the second fastest-growing energy source in China (after coal) and, by exceeding supply has led to an over-dependence on imported oil. If demand continues to increase with current trends the security of oil supply (an essential factor of economic development) will be a major uncertainty in the economy.

This will also contribute to the rise in the associated *CE* in China.

The results of our model suggest that *VP*, *EC* and *CE* in the Chinese road transport sector will grow substantially under all the scenarios, but policies in favour of public transit and improvements in vehicle *FE* can have large oil-saving and environmental benefits. Therefore, it would be reasonable to restrict private transport expansion and promote public transport in China, as well as to develop and implement aggressive *FE* standards and regulations to reduce fuel consumption.

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Life cycle energy, environment and economic assessment of soybean-based biodiesel as an alternative automotive fuel in China

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ABSTRACT

Life cycle energy, environment and economic assessment for conventional diesel (CD) and soybean-based biodiesel (SB) in China was carried out in this paper. The results of the assessment have shown that compared with CD, SB has similar source-to-tank (StT) total energy consumption, 76% lower StT fossil energy consumption, 79% higher source-to-wheel (StW) nitrogen oxides (NO_X) emissions, 31%, 44%, 36%, 29%, and 67% lower StW hydrocarbon (HC), carbon monoxide (CO), particulate matter (PM), sulfur oxides (SO_X), and carbon dioxide (CO_2) emissions, respectively. SB is thus considered to be much more renewable and cleaner than CD. However, the retail price of SB at gas stations would be about 86% higher than that of CD without government subsidy according to the cost assessment and China had to import large amount of soybean to meet the demand in recent years. Therefore, although SB is one of the most promising clean and alternative fuels, currently it is not a good choice for China. It is strategically important for China to diversify the feedstock for biodiesel and to consider other kinds of alternative fuels to substitute CD.

1. Introduction

Conventional diesel (CD) and gasoline, derived from crude oil, are the two main fuels for transportation vehicles currently. Motor vehicle population in China has been soaring in recent years due to its flourishing economy, accompanied by rapid-growing oil demand and carbon dioxide (CO_2) emissions and deteriorating environment. There were 24.6 million gasoline vehicles and 8.6 million diesel vehicles in China in 2005. About 41.48 million metric tons (Mt) gasoline and 33.25 Mt diesel were consumed by motor vehicles in 2005, accounting for 76.6% of the total gasoline consumption and 27% of the total diesel consumption in China. The rapid increase of vehicular emissions has been shifting urban air pollution from a predominantly coal-burning type to a vehicular pollution dominant type [1]. Moreover, China is experiencing more and more pressure from other countries on global warming issues.

Biodiesel is one of the renewable and clean alternative fuels for motor vehicles. It can be derived from plant's fruit, seed, latex, animal fats, wasted oil, frying oil, etc. by transesterification with methanol or ethanol. Results from many studies have shown that compared with CD, biodiesel has better degradation characteristic and lower hydrocarbon (HC), carbon monoxide (CO), particulate matter (PM), sulfur oxides (SO_X) emissions, and CO_2 emissions, but higher nitrogen oxides (NO_X) emissions [2–5]. Promotion of biodiesel in China is promising because it can help not only to reduce the dependence on imported oil but also to ease the problem of pollutions and global warming. Several biodiesel plants have already been established in China to produce biodiesel for transportation use.

Life cycle assessment (LCA) is a method to define and reduce the environmental burdens from a product, process or activity by identifying and quantifying energy and materials usage and waste discharges, assessing the impacts of the wastes on the environment and evaluating opportunities for environmental improvements over the whole life cycle [6]. LCA has become an important decision-making tool for promoting alternative fuels because it is very important to study the fuel life cycle systematically in terms of energy efficiencies, environmental impacts and cost benefits before implementing a fuel policy. Many LCA studies have been carried out on alternative fuels such as biodiesel, methanol, ethanol, and fuel cell, etc. [7–9]. LCA for ethanol and methanol has been done in China [10,11] except for soybean-based biodiesel (SB). Almost all of the earlier biodiesel studies were focused on the power, fuel economy and exhaust emissions performance of biodiesel fueled engines [12–14]. The objective of this study is to carry out a life cycle energy, environment and economy assessment to compare SB with CD, and to understand the advantages and disadvantages in SB implementation in China.

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2. Methodology

2.1. Life cycle framework

Fuel life cycle boundary in this study is from the source of fuel to fuel combustion in vehicle engines, i.e., the 'source-to-wheel' (StW) process. It includes stages of feedstock, fuel production, and fuel use. Feedstock and fuel production together is also known as the 'source-to-tank' (StT) stage while fuel use as the 'tank-to-wheel' (TtW) stage. The SB life cycle includes chemicals production and transportation, soybean cultivation, harvesting and transportation, soybean oil conversion and transportation, biodiesel conversion, storage and distribution, and SB combustion. This framework is illustrated in Fig. 1. The CD life cycle begins from crude oil extraction and ends at CD combustion.

2.2. Assessment indicators

2.2.1. Energy indicators

Energy indicators include StT total energy consumption and StT fossil energy consumption.

StT total energy consumption (MJ/MJ) is defined as the amount of energy input per unit of fuel output. It was calculated as the sum of the energy input per unit of fuel output at each stage during the StT process such as energy consumed to produce the chemicals used (such as fertilizers and plant protection materials), energy accumulated in the feedstock, life cycle energy consumption of processing fuels (such as coal, electricity, residual oil and natural gas) consumed in conversion stages and transportation fuels (such as diesel and residual oil) consumed in transportation stages, i.e., not only processing and transportation fuels consumed are included, energy consumed to produce these fuels was also included.

StT fossil energy consumption (MJ/MJ) is defined as the amount of fossil energy input per unit of fuel output. It was calculated as the sum of the fossil energy input per unit of fuel output at each stage in the StT process.

2.2.2. Environment indicators

Environment indicators include StW HC, CO, PM, NO_X, SO_X, and CO_2 emissions. StW emission (g/MJ) is defined as the amount of emissions per unit of fuel output in the whole life cycle. It was calculated as the sum of the emissions per unit of fuel output at each stage during the fuel life cycle.

2.2.3. Cost indicator

Cost indicator is the retail price at gas stations. The retail price of CD was assumed to be the average retail price in 2005 in China. The retail price of SB was calculated as the sum of all the direct and indirect costs, taxes and profits during the SB life cycle. The following components were taken into account in the calculation: the costs of materials (such as fertilizer, pesticide, and seeds) input, costs of materials, soybean, soybean oil and SB transportation, costs of processing fuel input, costs of labor input, costs of co-products (soybean meal and glycerin) output (negative value), costs of equipment maintenance, repair and depreciation, costs of management, financing and marketing, taxes at soybean oil, biodiesel production and gas station stage, profits at soybean cultivation, soybean oil production, biodiesel production, and gas station stage.

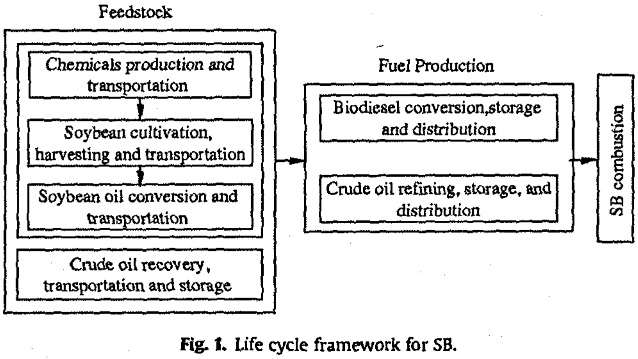

Fig. 1. Life cycle framework for SB.

2.3. Assessment model and data collection

The assessment model developed is a set of computer-based Excel spreadsheets, which calculates the StT energy consumption and pollutants emissions for coal, natural gas, electricity, CD, gasoline, residual oil, SB, etc., and the cost for CD and SB.

In particular, the energy and emissions calculations for a fuel need to cite the results of itself and those for other fuels for the calculations to be close-loop. For example, in the CD life cycle, petroleum recovery stage and refinery stage require use of CD and other processing fuels and transportation stages also require use of CD and other fuels. Therefore, the results of StT energy consumption for CD and other fuels are needed to calculate StT energy consumption for CD. In this paper, the energy consumption and pollutants emissions calculations for each fuel are carried out in separate Excel work sheet, and then the iterative loops are conducted by the circular calculation feature in Excel.

A significant amount of data, such as the demand for fertilizers, pesticides, herbicides, seeds and labor during soybean cultivation, transportation distance, fuel economy and emissions at each transportation stage, and cost of soybean, meal, and glycerin, was obtained through on site data collection in China. HC, CO, NO_X, PM emissions at fuel combustion stage were taken from Ref. [15], while those for SO_X and CO_2 were calculated using the sulfur balance and carbon balance method. Energy consumption during methanol and biodiesel production, and pollutants emissions during fossil fuel production was taken from journals [14,16] and books [17,18] published in China. Data concerning recovery and transportation of fossil fuels was taken from statistics [19–22]. The life cycle energy consumption and pollutants emissions for foreign (imported) petroleum, fertilizers, pesticides, and herbicides were taken from the GREET model developed at Argonne National Laboratory [15,23]. Annual yield capacity of SB plant was assumed to be 10,000 Mt of biodiesel. All calculations were based on lower heating value (35.817 MJ/l for CD and 32.637 MJ/l for SB) for each fuel.

2.4. Data allocation

In the SB life cycle, there are co-products such as soybean meal at the soybean oil conversion stage and glycerin at the biodiesel conversion stage. The energy uses and environmental emissions need to be allocated between the main products and the co-products. An allocation technique based on the product mass was used in this study. For example, the environmental emissions of soybean oil and soybean meal at the soybean oil conversion stage are in proportion to their mass output at this stage.

2.5. Data quality and modeling error analysis

The reliability and applicability of the results from a LCA study depend largely on the quality of the original data collected. The management and assessment of data quality must, therefore, be an integrated part of the LCA. In this study, all data have been carefully assessed to make sure they are precise, complete, representative, and consistent.

To what degree the collected data are precise depends on the origins of the data, e.g., measured data are usually considered to be very precise while data derived from simulations or estimations are much less precise. The data concerning petroleum refining, coal extraction, electricity generation, natural gas exploitation, and so on, are based on the average level in China and are thus considered to be fairly complete and representative. Some data based on specific cases may be less complete and representative, e.g., data concerning soybean oil conversion and biodiesel conversion are collected from specific production sites, and thus may not represent the average level of these industries in China. The data concerning foreign petroleum, fertilizers, pesticides, and herbicides are taken from the GREET model and thus may just represent a typical level in the United States.

All data were reviewed and verified based on the best knowledge available in China, and were double checked with the original data when inputting to the Excel worksheets. These procedures helped to ensure a high degree of data consistency.

3. Assessment results and discussions

3.1. *Source-to-tank energy consumption*

Results of the energy indicators for CD and SB are listed in Table 1. StT total energy consumption for SB is 1.307 MJ/MJ, about 4% higher than that for CD. StT fossil energy consumption for SB is 0.306 MJ/MJ, about 76% lower than that for CD, indicating for every one unit fuel output, SB would require 76% lower fossil energy input than CD. Therefore, CD is non-renewable and SB is much more renewable than CD.

Total energy and fossil energy consumption at each stage in the StT process for CD and SB are shown in Figs. 2 and 3, respectively. For CD, crude oil extraction (domestic and foreign) and crude oil refining are the key stages responsible for total energy and fossil energy consumption, accounting for 82% and 15% of the StT total energy consumption, 83% and 15% of the StT fossil energy consumption, respectively. As for SB, biodiesel conversion is the key stage responsible for total energy consumption because of the feedstock energy input which accounts for 84% the StT total energy consumption, while soybean cultivation and biodiesel conversion are the two main stages responsible for fossil energy consumption, accounting for 55% and 31% of the StT fossil energy consumption, respectively. Therefore, StT fossil energy consumption for SB production could be reduced effectively by: adopting more advanced manufacturing technology which requires less energy to produce fertilizers; adopting more advanced soybean cultivation technology which requires less use of fertilizers; adopting more advanced biodiesel conversion technology which has higher energy efficiencies during the conversion process.

3.2. *Source-to-wheel emissions*

The results of the environmental indicators for CD and SB are listed in Table 2. Compared with CD, the StW HC, CO, PM, SO_X, and CO_2 emissions for SB are 31%, 44%, 36%, 29%, and 67% lower, respectively. The StW NO_X emissions for SB is about 79% higher than that for CD, and this could be one of the barriers for implementing SB in the future. However, there are several ways to reduce NO_X emissions from SB fueled engines such as more advanced fuel injection timing and special NO_X amendment additive [24]. Therefore, SB is considered to be more environmental friendly than CD.

Table 1
Source-to-tank energy consumption and fossil energy ratio for CD and SB (MJ/MJ)

Fuel type	Source-to-tank total energy consumption	Source-to-tank fossil energy consumption
CD	1.261	1.256
SB	1.307	0.306

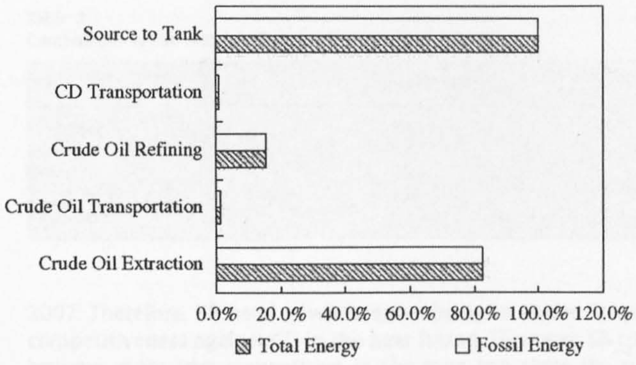

Fig. 2. Energy consumption at each stage during the source-to-tank process for CD (MJ/MJ).

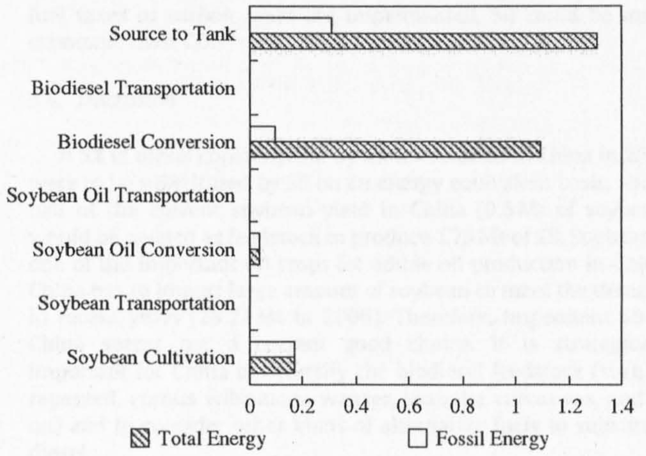

Fig. 3. Energy consumption at each stage during the source-to-tank process for SB (MJ/MJ).

Table 2
Source-to-wheel emissions for CD and SB (g/MJ)

Fuel type	HC	CO	PM	NO_X	SO_X	CO_2
CD	0.041	0.427	0.053	0.371	0.125	91.365
SB	0.028	0.240	0.034	0.663	0.089	29.749

The proportions of HC, CO, PM, NO_X, SO_X, and CO_2 emissions at each stage during the CD life cycle are shown in Fig. 4. CD combustion is the key stage responsible for pollutants and CO_2 emissions. Therefore, more advanced engine and tail gas treatment technology would be effective to reduce pollutants and CO_2 emissions during the CD life cycle.

The proportions of HC, CO, PM, NO_X, SO_X, and CO_2 emissions at each stage in the SB life cycle are shown in Fig. 5. SB combustion is the key stage responsible for HC, CO, and NO_X emissions. Soybean cultivation, biodiesel conversion and SB combustion are the three

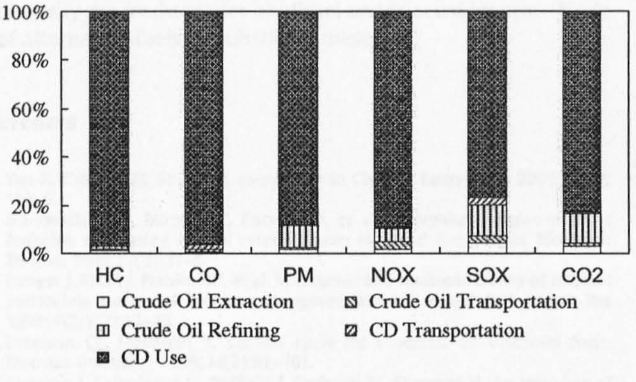

Fig. 4. Proportions of pollutants and CO_2 emissions at each stage during the CD life cycle.

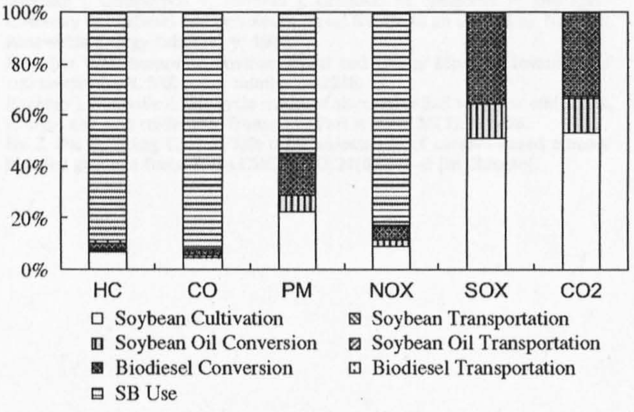

Fig. 5. Proportions of pollutants and CO_2 emissions at each stage during the SB life cycle.

main stages responsible for PM emissions. Soybean cultivation and biodiesel conversion are the two main stages responsible for SO_X and CO_2 emissions. SO_X emission at biodiesel use stage is almost zero because SB has almost zero sulfur content. CO_2 emission at biodiesel use stage is zero because the carbon in SB is absorbed from the atmosphere via photosynthesis during soybean cultivation. Therefore, more advanced engine and tail gas treatment technology would be effective to reduce the HC, CO, NO_X, and PM emissions during the SB life cycle, while adopting more advanced soybean cultivation and biodiesel conversion technology would be effective to reduce the PM, SO_X, and CO_2 emissions.

3.3. *Life cycle cost*

The cost of SB at the biodiesel plant gateway is 5.86 RMB/l. From Table 3, it can be observed that the costs for feedstock and by-products are the key factors affecting the cost of SB at the biodiesel plant gateway. The retail price of SB is 8.60 RMB/l at gas stations, based on the tax ratio of 14.3%, profit ratio of 8% of biodiesel production and gas station stage and the average price of soybean, glycerin, electricity, and water, etc. in 2005 in China. The retail price of SB is about 86% higher than that of CD (4.62 RMB/l), which could be one of the critical obstacles for implementing SB in China.

The retail price of SB would be the same as that of CD if the price of soybean were 2.213 RMB/kg. The average price of soybean in China was 2.574 RMB/kg in 2006 and 2.731 RMB/kg in January 2007. Therefore, SB need government subsidy to assure its price competitiveness against CD in the near future. However, SB could become more cost competitive in the long run since the price of CD would become higher as the oil reserves gets less and the CD demand gets higher, while the cost of SB could become lower due to the development of more advanced soybean cultivation and biodiesel conversion technologies. Moreover, if fuel taxes or carbon taxes are implemented, SB could be more economic than CD.

Table 3
Components of the cost for SB

Items	Cost (RMB/l)
Feedstock	7.15
Energy	0.06
Other	0.34
By-product	−1.69
Biodiesel cost	5.86

3.4. *Discussion*

If 5% of diesel consumption by motor vehicles in China in 2005 were to be substituted by SB on an energy equivalent basis, about half of the current soybean yield in China (9.6 Mt of soybean) would be needed as feedstock to produce 1.76 Mt of SB. Soybean is one of the important oil crops for edible oil production in China. China has to import large amount of soybean to meet the demand in recent years (28.27 Mt in 2006). Therefore, impenitent SB in China seems not a current good choice. It is strategically important for China to diversify the biodiesel feedstock (such as rapeseed, cornus wilsoniana wanaer, jatropha curcaswas, and so on) and to consider other kinds of alternative fuels to substitute diesel.

4. Conclusion

1. Compared with CD, SB has about 4% higher StT total energy consumption, about 76% lower StT fossil energy consumption. SB is considered to be much more renewable than CD.
2. Crude oil extraction and crude oil refinery are the key stages for total energy and fossil energy consumption during StT process for CD. As for the StT process for SB, biodiesel conversion is the key stage responsible for total energy consumption, while soybean cultivation and biodiesel conversion are the two main stages responsible for fossil energy consumption.
3. Compared with CD, SB has 31%, 44%, 36%, 29%, and 67% lower StW HC, CO, PM, SO_X, and CO_2 emissions, respectively, and about 79% higher StW NO_X emissions.
4. CD combustion is the key stage responsible for the pollutants and CO_2 emissions during the CD life cycle. As for the SB life cycle, SB combustion is the key stage responsible for HC, CO, and NO_X emissions, soybean cultivation, biodiesel conversion, and SB combustion are the three main stages responsible for PM emissions, while soybean cultivation and biodiesel conversion are the two main stages responsible for SO_X and CO_2 emissions.
5. The price of SB would be 8.60 RMB/l at gas stations without government subsidy, about 86% higher than that of CD.
6. Given the significantly higher cost of SB than that of CD and the fact that China needs to import large amount of soybean, implementing SB in China currently seems not a good choice. It is strategically important for the Chinese government to

diversify the feedstock for biodiesel and to consider other kinds of alternative fuels to substitute diesel.

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