The integration of transportation with the energy system in China

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Abstract: Energy security and climate change are forcing China to change its inappropriate energy structure. Today, transport is the second largest energy consumer in China. No single method can achieve a fossil fuel independent transport and it is necessary to propose a comprehensive strategy which can benefit both transport and the energy system. This paper aims to evaluate different transport development strategies in terms of their effects on fossil fuel demand reduction and to explore to what extent renewable energy can contribute to the transport sector. With this objective, three investigations were carried out in sequence. Firstly, a Chinese transport model has been created and approach reliability has been examined. Secondly, two scenarios, continued improvement (CI) scenario and accelerated improvement (AI) scenario, have been designed and evaluated. The results indicate that evident fuel demand reduction can be achieved by formulated transport development planning but more alternative technologies and joint actions are needed in order to change the fuel structure. Finally, 100% non-fossil fuel transport was built up and analysed. The challenges of a transfer to a 100% non-fossil fuel transport in China are not severe at least in the perspectives of domestic biofuels potential and transmission capacity.

Keywords: transport development strategy, renewable energy, China

1 Introduction

Energy security and climate change are forcing China to change its inappropriate energy structure. Energy saving and emission reduction had been proposed with compulsory targets in the National Eleventh Five-Year Plan (2006-2010)[1] which attained a significant achievement in regard to decreasing energy intensity. Energy conservation, efficiency improvement as well as replacing fossil fuel with renewable energy are three essential strategies in Chinese energy planning to implement a sustainable development in the long term. However, most attention in Chinese energy planning has traditionally been given to the electricity and industry sectors due to their major roles in economic growth and contributions to energy consumption. The transport sector, as the fastest growing energy consuming sector [2,3] and the most challenging sector in terms of decreasing the dependence on fossil fuel [4], has been given increasing attention.
By the end of 2003, China had become the world's second largest oil consumer and again, in 2008 China surpassed Japan becoming the second largest oil importing country in the world. In 2009, China's oil consumption had reached 408.38 million ton with an annual increase rate of 8.8% in the past ten years [5]. However, China's domestic oil reserve is limited and today about 53.6% of oil demand in China is supplied by overseas oil [6]. An increased share of overseas oil has caused the energy security issue to become even more serious and has brought a large economic loss. In 2009, China spent 135.1 billion US dollars to import overseas crude oil and petroleum production[7]. The increase of Chinese oil consumption can be mainly attributed to the rapid expansion of transportation. The transport sector is responsible for more than 50% of China's petroleum production consumption (46% of gasoline and 57% of diesel) in 2009 [5] and this share will probably keep increasing due to the rapid growth of transport demand. If China continues the current growth rate and fuel consumption pattern, it would have to import 6.2 billion barrels of oil in total by 2030 [8]. In that case, China will pay a high price for such energy consumption pattern and face a severe challenge to ensure energy security of the whole country.
After the Renewable Energy Law had come into effect on 1st of January 2006, China has been experiencing an ambitious period to stimulate renewable energy development. The National 12th Five-Year Renewable Energy Plan (2011-2015) which includes the development plan of seven new strategic industries was launched at the beginning of 2011[9,10]. A major part of those new strategic industries are related to renewable energy such as energy saving and environment protection technology, new materials and new energy vehicles, new energy and high-end equipment manufacturing. Moreover, the Medium and Long Term

Development Plan for Renewable Energy in China has set the aim that non-fossil fuel will account for 15% of total energy supply in 2020 [11]. All this planning creates the picture of a booming future for renewable energy development in the coming decade and in the long term in China.

If the aim is to increase the share of renewable energy in China as described, the transport sector is one of the most important sectors in which to reduce the dependency on fossil fuel as well as to include in combination with other flexible technologies in the energy system [2,4,12]. Much research has been done on the application and potential utilisation of different alternative fuels, such as bioethanol, biodiesel, battery electric vehicles as well as hybrid electric vehicles, and those applications show the potential to reduce the oil consumption in transport. However, no single method can achieve a sustainable transport and it is necessary to analyse the joint actions in the context of the surrounding energy system.

This paper aims to evaluate different transport development strategies in terms of their effects on fossil fuel demand reduction and to explore to what extent renewable energy can contribute to the transport sector. With this objective, a Chinese transport model has been created and three investigations have been carried out. Firstly, the model has been used to calculate the energy demand of the Chinese transport sector in the reference years. Secondly, the continued improvement (CI) scenario and the accelerated improvement (AI) scenario have been designed and all the assumptions in these were applied to the existing Chinese transport sector. Finally, a transport sector with 100% non-fossil fuel was created and discussed in order to identify the limitations and barriers of this transformation in terms of domestic resources.

2 Current status of China's transport sector

2.1 Transport demand

China has been witnessing a rapid increase of transport demand. Historically, passenger and freight transport demands have a high correlation with GDP growth in China. Increasing incomes, more leisure time and diversity of activities have resulted in a significant passenger transport demand growth while rapid infrastructure construction and unbalanced distribution of raw materials and energy resources have led to an increasing growth of freight traffic demand [13]. Passenger and freight transport demands have grown along with the economic development with an average annual growth rate of 8.4% and 8.8%, respectively.

In 2010, the total passenger transport demand was 2,777.82 billion passenger-km, of which road accounted for 53.7%, railway 31.5%, air transport 14.5% and waterway 0.3% [14]. The average annual growth rate of road, railway, air and waterway transport in the last two decades was 9.2%, 6.4%, 15.8% and -3.5%, respectively. Road transport plays an influential role in passenger transport and its demand has kept a stable share of around half of passenger transport demands. The air transport is the fastest growing sector although the gross transport demand in air transport is now relatively low. Railway has been experiencing a stable growth period; moreover, this growth rate is expected to increase due to the large scale of high speed rail (HSR) construction in China.

In 2010, the total freight transport demand was 13,516.96 billion ton-km, in which the share of road, railway, air and waterway transport was 31.8%, 20.2%, 0.1% and 47.6%, respectively. Waterway freight transport has played a major role with an annual growth rate of 9.4% since 1990. The air transport is the fastest growing sector in freight transport with an annual growth rate of 16%.

The passenger travel times, freight carried weights and travel distance are three key elements to determine the transport demand. Both passenger and freight travel distance in China have been increasing slightly in the last two decades; however, in some individual areas the passenger and freight travel distance decreased. In this case, the passenger travel times and freight carried weights have determined the rapid growth of transport demands.

2.2 Infrastructure development

Infrastructure plays an influential role in transport development. The Chinese government has invested massively in transport infrastructure construction. Take the road transport as an example, China's total highway and expressway lengths have increased from 1.02 to 3.86 million km and 0.5 to 65.1 thousand km, respectively, in the last two decades.

The railway infrastructure has been promoted in many aspects, such as railway length, electrification rate and high speed rail (HRS) development. The railway length has increased from 57.9 to 85.8 thousand km in the last two decades. The railway electrification rate of China reached 45% in 2010 and it will approach 60% in 2020 according to the Medium and Long-term Railway Network Planning [15]. Moreover, the high speed rail (HSR), which refers to a train with an average speed of 200km/h or higher, has been in a booming development period in China. Today, China has the world's longest HSR network with about 9,676 km in service by June 2011 including 3,515 km of railway lines with top speeds of 300 km/h. China's HSR network consists of 1) upgraded pre-existing railway lines that can accommodate high-speed trains, 2) a national grid of passenger dedicated HSR lines, 3) other newly built conventional rail lines, mostly in western China, that can carry high speed passenger and freight trains, and 4) certain regional intercity HSR lines. Total investment in new railway lines grew from 14 billion US dollars in 2004 to 88 billion US dollars in 2009.
Moreover, the air transport infrastructure has increased dramatically. The domestic and international airline lengths have increased from 0.51 and 0.17 million km to 2.35 and 0.92 million km, respectively, from 1990 to 2009.

2.3 Energy demand

Energy demand in the transport sector has witnessed a fast growth in the last decade with an annual growth rate of 9%. The energy intensity of the transport sector has been keeping steady in the last decade with the passenger transport energy intensity of 2.9 PJ/billion person-km and the freight transport energy intensity of 0.7 PJ/billion ton-km. Thus, the expansion of the transport demand is the main driving factor for this increasing energy demand.
As can be seen in Fig. 1, about three quarters of the total energy demand came from road transport [3]. The energy consumed by railway, waterway and air transport was approximately the same level for all three. With regard to different energy fuels, gasoline and diesel are two major fuels. Diesel has been consumed by road, railway and waterway transport, however, almost all the gasoline has been consumed by road transport, especially the passenger transport. In 2008, there was a consumption of 8.65PJ, 44.22PJ and 14.72PJ of natural gas, bioethanol and biodiesel, respectively with little proportion.

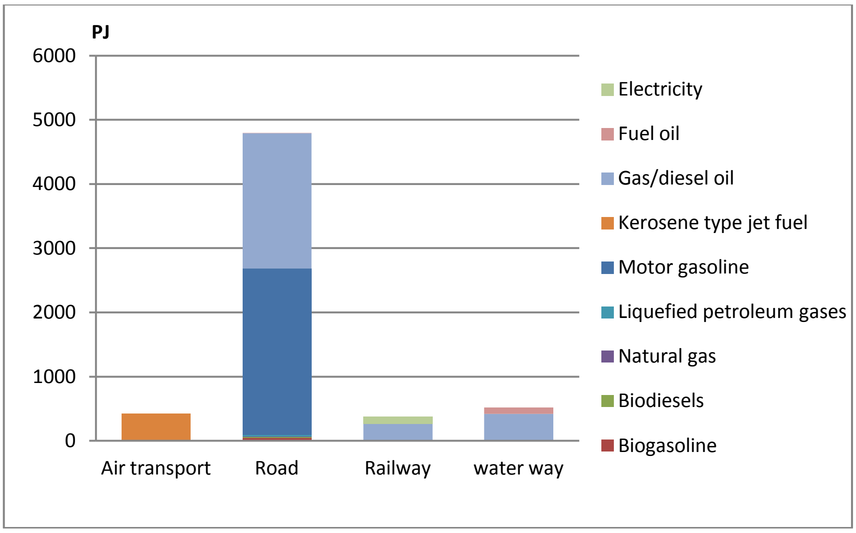

Fig. 1. Energy consumed in the transport sector in 2008

Many research works have been launched regarding how to achieve an energy saving and oil independent transport sector in China. Those studies can be roughly classified into four categories: forecast of the transport demands and vehicle population [16,17]; investigation of the shift between different transport models and strategies to develop an integrated transport system [18-20], analysis of the energy saving by using alternative fuels in the transport sector and their life cycle impacts [2,21-23] and prediction of the future energy demand and CO_2 emission of the transport sector [2,13,24-30]. Road transport has been paid special attention in previous studies due to its major role in both vehicle population and energy consumption. Although many research works have been investigated in detail, there are still some limitations which should be addressed in future work: 1) most of the research took different parts of transport as an individual research objective, like road transport, railway and air transport. However, different sectors in transport are interrelated; one sector's change can lead to another sector's change. For instance, the rapid development of HSR may influence the transport demand of air transport, especially the short-medium travel distance [31]. It is helpful to take the whole transport sector into consideration when evaluating the different transport development strategies. 2) Fossil fuels, especially oil, are the major consideration when discussing the energy demand in the transport sector. However, the renewable energy has been stimulated and implemented in the national energy plan. It is necessary to integrate transport with the energy plan especially as more and more alternative fuels will be applied in the future [4,32,33].

3 Methodology

The methodology of this research comprises a combination of a model development and scenario designs. To evaluate different sustainable strategies in the whole transport sector and identify to what extent renewable energy can contribute to the transport sector, the first step is to create a model to investigate the energy demand of China's transport sector. Energy demands of China's transport sector in the reference years (2007-2009) have been investigated and the reliability of the model approach has been examined by comparing the model results with the real energy consumption.

Two scenarios, which are continued improvement (CI) scenario and accelerated improvement (AI) scenario, have been designed. All the assumptions in CI and AI scenarios considered the formulated national transport planning and much more aggressive objectives in the medium term (2030) and long term (2050). Two scenarios represent the influence and consequence of applying the medium and long term formulated planning and more aggressive objectives to the existing Chinese transport sector. The reasons for this application are: 1) this study aims to evaluate effects and influences of future formulated transport development strategies rather than forecasting the future transport demand and trends, 2) to identify to what extent renewable energy can contribute to the transport sector rather than predicting future transport energy demand.

3.1 Model description

Some bottom-up models have been developed to evaluate the reduction potential of energy demand and the consequence of stimulating alternative fuels in China's road transport [2,13,28]. In order to reflect a comprehensive picture of different transport strategies and energy demand in the whole Chinese transport sector, the model applied here can be seen as an improvement and expansion of the model developed by [4,31]. That model has been used in Denmark to analyse the integration of transport into a 100% renewable energy system and in Sweden to assess the impact of HSR on the mitigation of climate change. The total energy demand can be expressed as follows:

$$E_y = E_{py} + E_{fy}$$

E (PJ) is the energy demand of the transport sector, y is the calendar year, p is the passenger transport and f is the freight transport. E_{py}(PJ) is the energy demand of passenger transport and E_{fy} (PJ) is the energy demand of freight transport.

The passenger and freight transport has then been further classified into four subcategories, which are road, railway, air transport and waterway. In the model, energy demand in the transport sector is calculated as a result of several important driving factors, which are transport demand (TD), average fuel economy (AFE), and vehicle load factor (VLF). All those important driving factors can be modelled in detail and China's recent efforts in public transport and alternative fuel promotion are incorporated.

$$E_{py} = \sum_{ij} TD_{pijy}\ AFE_{pijy}^{-1} AVL_{pij}^{-1}$$
$$E_{fy} = \sum_{ij} TD_{fijy}\ AFE_{fijy}^{-1} AVL_{fij}^{-1}$$

i is the vehicle type, j is the fuel type, TD_{pijy} (billion passenger-km) is the passenger transport demand of the fuel type j for the vehicle type i in the year y, AFE_{ijy} (km/MJ) is the average fuel economy of the fuel type j for the vehicle type i in the year y and the AVL_{pij} (persons) is the number of persons in the vehicle with type i and fuel type j and AVL_{fij} (ton) is the weight of the cargo in the vehicle with type i and fuel type j.

$$AVL_{pij} = VC_{pij} \times AVLF_{pij}$$
$$AVL_{fij} = VC_{fij} \times AVLF_{fij}$$

VC_{pij} (persons) is the capacity of the passenger vehicle with vehicle type i and fuel type j, VC_{fij} (ton) is the capacity of the freight vehicle with vehicle type i and fuel type j, $AVLF$ (%) is the average vehicle load factor. Fuel economy in different transport types has been listed in detail in Table 1.

Table 1
Transport demand and fuel economy of the Chinese transport sector in 2008

Transport sector			Transport demand (billion person km)[14]	Average fuel economy (km/MJ)
Passenger Transport	Road [2,13,34]	Car	1247,61	0,3846
		Taxi	133,77	0,3846
		Bus	541,41	0,0998
	Railway[35]	Diesel powered rail		0,0089
		Electricity powered rail		0,0296
	Air transport [36,36]	National airline	228,64	0,0067
		International airline	59,64	0,0033
	Water way [37]	Shipping	5,92	0,0015
Freight Transport	Road [2,13]	Truck	3286,82	0,0885
	Railway [35]	Diesel powered train		0,0022
		Electricity powered train		0,0048
	Air transport [36,36]	National airline	7,67	0,0091
		International airline	4,29	0,0046
	Water way [37]	National shipping	1741,17	0,0044
		International shipping	3285,10	0,0023

3.2 Scenario design

CI and AI scenarios represent the influence and consequence of applying the medium and long term formulated planning and more aggressive objectives to the existing Chinese transport sector. The assumptions in the two scenarios can be classified into three steps: improvement of vehicle efficiency and railway electrification rate, transfer to public transport as well as implementation of alternative fuels.
The key assumption in the CI scenario is that no additional measures will be implemented to reduce the energy demand in the transport sector. Policies, planning and measures, which have already been formulated and implemented, have been taken into consideration. The assumptions in the AI scenario include the same steps as the CI scenario, however, with even more aggressive objectives towards future fuel reduction plans and implementation of important alternative technologies. All the assumptions in the two scenarios have been briefly listed in Table 2.

3.2.1 Step 1: Improvement of vehicle efficiency and railway electrification rate

Average fuel economy in road transport was assumed to increase 20% in 2030 and 30% in 2050 in both CI and AI scenarios. Taking an internal combustion engine (ICE) vehicle as an example, the average fuel economy of a gasoline automobile sold after 2000 is 0.38 km/MJ and it will increase to 0.48 km/MJ in 2030 and to 0.54 km/MJ in 2050. In railway, water and air transport, the average fuel efficiency was assumed to increase 10% in 2030 and 20% in 2050 in the two scenarios.

China has achieved a remarkable progress in railway electrification and the electrification rate has approached 45% in 2010 [15]. Today, most passenger trains and a part of the freight trains are powered by electricity and the electrification rate has been assumed to reach 70% in 2030 and 90% in 2050 according to the national railway network planning in 2020, in which the railway electrification rate will increase to 60% by 2020 [15].

3.2.2 Step 2: Transfer to public transport

Traffic congestion is becoming a serious problem in most Chinese cities. This problem used to occur in some large cities in eastern China, but now it has already influenced the traffic situation in the cities in mid and western China, such as Urumqi and Lan Zhou [38]. Beijing has launched a new regulation to stimulate public transport and the price of a bus ticket has been reduced from one or two Chinese Yuan to 0.4 Chinese Yuan. The latest policy, in which the parking price has been tripled within the third ring area in Beijing, has relieved the congestion situation in the central area of Beijing [39].

Moreover, high speed railway is in a booming development in China. According to the Medium to Long Term Railway Network Plan (revised in 2008), issued by the Ministry of Railway (MOR) [15], China plans to spend 300 billion US dollars to build a 25,000 km HSR network by 2020. The main objective of China's HSR expansion is to build a new national HSR grid. This grid is composed by 8 HSR corridors, four running north-south and four going east-west with a total length of 12,000 km. Most of the new lines follow the routes of existing trunk train route and are designed for passenger travel only, known as passenger-dedicated lines (PDL). As that network starts running, many existing lines will become freight-only lines so overall freight capacity will be improved as well. It has been estimated that the booming development of HSR in China will affect the load rate of airline, especially in the short-middle travel distance. Since the 300km/h Beijing-Shanghai rail service started on 30th June 2011, the number of passengers on its Beijing-Shanghai flights dropped by 18% in the first ten days of July compared to the same period last year [40]. HSR has been expected to take 20%-30% of airline passengers in the long term, although those impacts will depend on the safety and punctuality of HSR [41].

3.2.3 Step 3: Implementation of alternative fuel

China has been very active in promoting alternative fuels to replace conventional gasoline and diesel in recent years. In 2008, the production capacity of ethanol reached 1.94 Mt [42] and the share of biofuels in Chinese road transport was about 1%. The Chinese government is planning to increase fuel ethanol and biodiesel production to 10 and 2 Mt, respectively, by 2020 [11], which is about six times as much as in 2008. It is assumed that the share of biofuels in road transport will increase from 1% in 2008 to 5% and 10% in the medium and long term, respectively, in the CI scenario.

Many policies and regulations have been formulated and implemented in China in order to stimulate the electric vehicle development. The Chinese Ministry of Finance announced a plan in five cities (Shanghai, Changchun, Shenzhen, Hangzhou and Hefei) in June 2010 to pay subsidies of 50,000 Chinese Yuan (5,690 US dollars) to each sold plug-in hybrid vehicle (PHEV) and 60,000 Chinese Yuan (8,784 US dollar) to battery electric vehicles (BEV) [43,44]. In the same year, the Shenzhen government announced to subsidise each sold PHEV and BEV 30,000 Chinese Yuan (4,392 US dollar) and 60,000 Chinese Yuan (8,784 US dollar), respectively, in addition to central government subsidies. Those policies make BEV and PHEV more competitive in the automobile market. The 12th Five Year Plan (2011 to 2015) of Electric Vehicles has gone into implementation in 2011[45]. This plan aims to achieve one million electric vehicle ownerships in China by 2015 and to build more than 2,000 electric charging stations. Moreover, China plans to attain the capacity of 10 million electric vehicles by 2020 in the draft plan of Energy-Saving and New Energy Automotive Industry Development, which will be issued soon [45]. This capacity has been estimated to be about 30-40 million in 2030 in many investigations [46,47]. This amount will correspond to 10% of the total automobile population in China by 2030 according to the projected results of automobile ownership in China [2,16,48]. This study considered 10% and 20% as the electric vehicle penetration in the medium and long term, respectively, in the CI scenario. The objective of the AI scenario is to illuminate a more positive future of

alternative vehicles in China. Based on suggestions from [49-51], electric vehicles have great development potential in China in the next half-century. This is supported by two efforts: battery/vehicle technology improvement and recharge grid/station infrastructure construction.
As the increasingly intensive policies and initiatives have been introduced, the share of biofuels will be higher in the future. The European Union set a 10% target for the share of biofuels in road transport in 2020. This study uses this target as the biofuel share in the medium term's AI scenario and as broadly consistent, the share of biofuels in road transport is 25% in the long term.

Table 2
Main assumption in the CI and AI scenarios

		Medium term strategies		Long term strategies	
		CI scenario	AI scenario	CI scenario	AI scenario
Step 1	Fuel efficiency	road: increase 20%; Other transport: increase 10% [4,31]		Road : increase 30%; Other transport: increase 20% [2,13]	
	Railway Electrification Rate	70% [15]		90%[15]	
Step 2	Public transport	Road: 5% freight transfer to railway and 5% to water transport; 5% passenger transfer to bus and railway [52,53] Air transport: 20% passenger transfer to railway [40,41]	Road: 10% freight transfer to railway and 10% to water transport; 10% passenger transfer to bus and railway [52,53] Air transport: 20% passenger transfer to railway [40,41]	Road: 10% freight transfer to railway and 10% to water transport; 5% passenger transfer to bus and railway [52,53] Air transport: 20% passenger transfer to railway [40,41]	Road: 20% freight transfer to railway and 20% to water transport; 10% passenger transfer to bus and railway [52,53] Air transport: 20% passenger transfer to railway [40,41]
Step 3	Share of biofuels	5 % of road energy demand	10% of road energy demand	10% of road energy demand	25% of road energy demand
	Penetration of electric drive vehicle	10 % of road passenger vehicles (HEV: 4%; PHEV: 2%; BEV: 4%) [2,16,45-48]	45 % of road passenger vehicle (HEV: 25%; PHEV: 5%; BEV: 15%) [49-51]	20 % of road passenger vehicle (HEV: 7%; PHEV: 5%; BEV: 8%) [2,16,45-48]	90 % of road passenger vehicle (HEV: 35%; PHEV: 25%; BEV: 30%) [49-51]

3.2.4 Conversion to a 100% non-fossil fuel transport
Assumptions in all CI and AI scenarios have considered different formulated future planning and aggressive development objectives. Eventually, the ideal situation will be 100% non-fossil fuel in the transport sector. In this case, hydrogen is an important energy carrier and many technical, economic and infrastructural barriers need to be overcome. This study only aims to evaluate the possibility of converting to a 100% non-fossil fuel transport in China in terms of domestic resources. The main assumptions in this ideal situation are summarised in the following:

- the point of departure for a 100% non-fossil fuel transport is the transport sector in the AI scenario with the long term aggressive objectives
- road passenger transport is supplied 20% by bioethanol and 80% by electricity
- road freight transport is supplied 20% by biodiesel and 80% by hydrogen or electricity
- air transport is fuelled by bioethanol
- waterway is fuelled by biodiesel
- railway is supplied by electricity

4 Results
4.1 Reference scenario

Once the model was developed, the energy demand in the transport sector was investigated. The results of the energy demand were 5,533 PJ, 6,130 PJ and 6,819 PJ in 2007, 2008 and 2009, respectively. The differences between model results and real energy consumption [3,5,54] are 1%, 0.32% and 0.35% in 2007, 2008 and 2009, respectively.

The detailed comparisons between model results and real fuel demand of different transport sectors in 2008 are elaborated in Table 3. As can be seen in the table, the largest difference was natural gas consumption with the difference of -2.04% which shows that the reliability of the model approach is acceptable and that the model can be used in further investigations.

Table 3
Comparisons between model results and real fuel consumption of the whole transport sector in 2008

	Calculation results (PJ)				
	Road	Railway	Air transport	Water way	Total
Biogasoline	44,24	-	-	-	44,24
Biodiesel	14,73	-	-	-	14,73
Natural gas	8,18	-	-	-	8,18
Gasoline	2634,13	-	-	-	2634,13
Diesel	2109,80	271,76	-	414,24	2795,80
Kerosene type jet fuel	-	-	425,92	-	425,92
Fuel oil	-	-	-	101,30	101,30
Electricity	-	105,99	-	-	105,99
Total	4861,56	377,75	425,92	515,54	6130,29
	Statistic (PJ)				
	Road	Railway	Air transport	Water way	Total
Biogasoline	44,22	-	-	-	44,22
Biodiesel	14,72	-	-	-	14,72
Natural gas	8,35	-	-	-	8,35
Gasoline	2614,95	-	-	-	2614,95
Diesel	2108,79	266,44	-	417,40	2792,63
Kerosene type jet fuel	-	-	425,03	-	425,03
Fuel oil	-	-	-	102,07	103,37
Electricity	-	107,75	-	-	107,75
Total	4791,96	374,85	425,03	519,47	6111,02
	Difference (%)				
	Road	Railway	Air transport	Water way	Total
Biogasoline	0,05	-	-	-	0,05
Biodiesel	0,07	-	-	-	0,07
Natural gas	-2,04	-	-	-	-2,04
Gasoline	0,73	-	-	-	0,73
Diesel	0,05	-	-	-0,76	0,11
Kerosene type jet fuel	-	-	0,21	-	0,21
Fuel oil	-	-	-	-0,75	-2,00
Electricity	-	-1,63	-	-	-1,63
Total	1,45	0,77	0,21	-0,76	0,32

4.2 Fuel demand in the whole transport sector

Once the reliability of the model was proved, all the assumptions have been modelled step by step. The results of fuel demand in the whole transport sector under different strategies and objectives were discussed in detail.
As mentioned previously, the energy demand of the whole transport sector in 2008 was 6130 PJ and Fig. 2 shows the reduction potential of fuel demand in different strategies. Step 1 shows that an improvement of the fuel economy is one of the essential methods for creating a direct fuel demand reduction. In step 2, the continued development of HSR offers a good opportunity for the freight transport, which can transfer from road to railway since many existing passenger lines are increasingly becoming freight-only lines. Step 2 can achieve 5% and 8% fuel demand reductions, respectively, with the medium and long term formulated planning; moreover, in the two AI scenarios, transfer to public transport can achieve 10% and 15% fuel demand reductions. Step 3 shows that in the CI scenario, the achievements are moderate concerning fuel demand reduction of EVs and biofuels promotion planning of both medium and long term; however, in the AI scenario the fuel demand reduction at step 3 can be more significant.
When combining the three steps, the medium and long term formulated planning attain 25% and 40% fuel demand reductions in the CI scenario. Moreover, with medium and long term aggressive objectives, the fuel demand reductions can reach 37% and 52%, respectively.

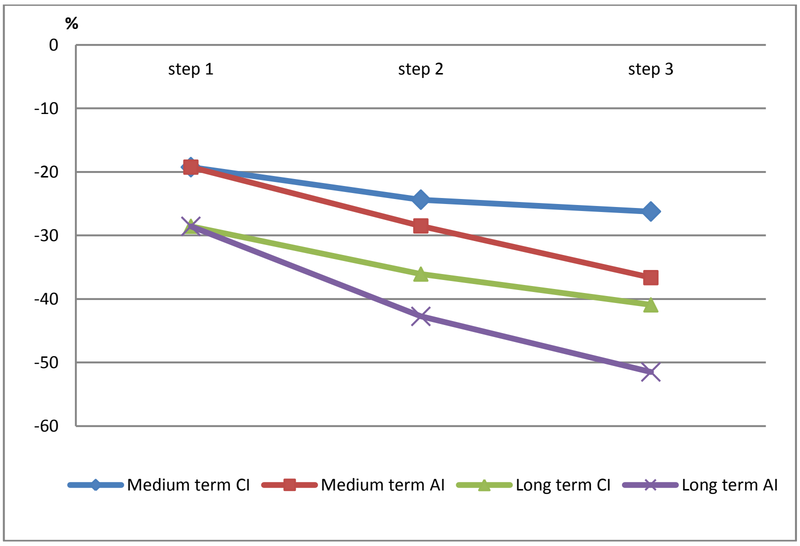

Fig. 2. Reduction potential of fuel demand in different strategies

Fig. 3 gives a picture of how the three steps working together can gradually affect the fuel demand and fuel structure in the whole transport sector. In the existing transport sector, diesel and gasoline demand accounted for 90% of total transport fuel demand and the entire electricity demand of around 106 PJ came from railway transport. The fuel demand decreased noticeably in both CI and AI scenarios with all medium term strategies, especially the gasoline demand in the AI scenario due to the increasing penetration into road passenger transport by EVs. Jet fuel in air transport decreased as air transport demand was transferred to HSR. However, the fuel structure did not change noticeably in those two scenarios.

In the two scenarios with long term strategies, the fuel demand reduction kept increasing and the structure of fuel demand varied moderately in the CI scenario and distinctly in the AI scenario. The gasoline percentage dropped to around 10% of total fuel demand and the share of biofuels and electricity increased distinctly in the AI scenario due to the large scale penetration of EVs in the passenger transport; however, the diesel demand still accounts for about half of the total fuel demand.

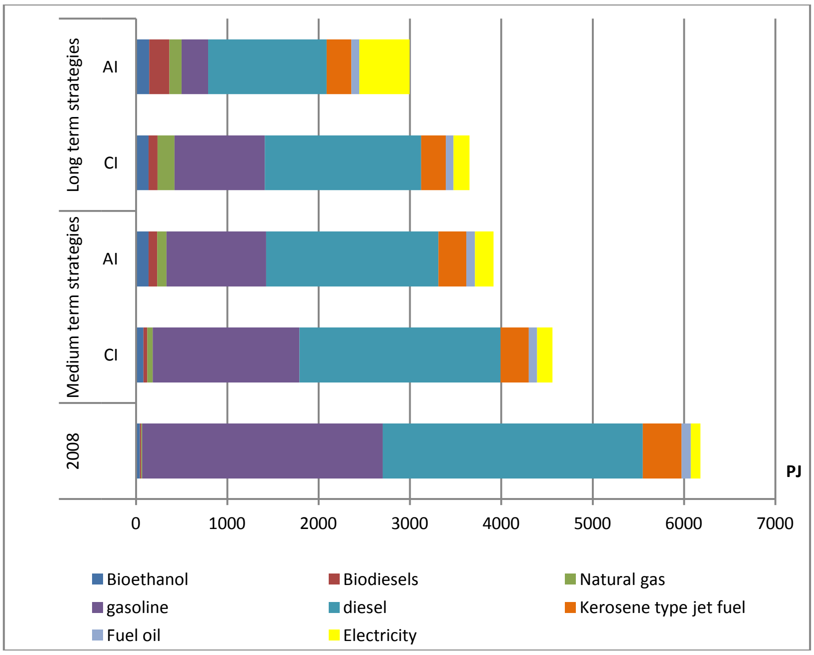

Fig. 3. Fuel demand of the whole transport sector

4.3 Fuel demand in road transport

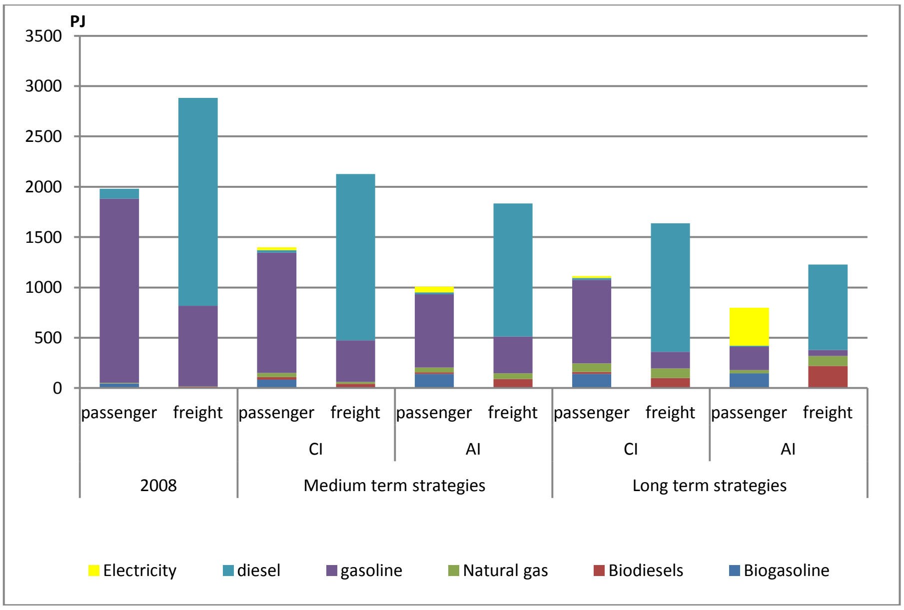

Fig. 4. Fuel demand of road transport in different strategies

In current road transport, gasoline and diesel have dominated almost 100% of the fuel demand. An improving fuel economy plays a significant role in road transport as well as in terms of fuel demand reduction. The results occurred similarly in the whole transport sector as in the two CI scenarios; fuel demand reduction is more significant than fuel structure change. With long term aggressive objectives, the achievements of fuel reduction and fuel structure change are both evident in the AI scenario, in which the fuel demand in road transport is about 40% of fuel demand in 2008 and electricity demand accounts for half of the fuel demand in road passenger transport.

4.4 Non-fossil fuel contributions in the whole transport sector

Fig. 5 gives a visible result of the extent to which renewable energy can contribute to the transport sector with different development strategies. The current share of non-fossil fuel in the transport sector is about 2.7% and this share has grown in all scenarios. In the two CI scenarios, the share of non-fossil fuel increased from the current 2.7% to about 6.4% and 11.2%, respectively, based on the medium and long term formulated planning. Those improvements can mainly be attributed to the increasing enhancement of electrification in railway, the rapid development of HSR as well as national plans to stimulate the EVs' development in private automobiles. In the two AI scenarios, the shares of non-fossil fuel have grown to 11% and 30%, respectively, based on the medium and long term aggressive objectives. 30% non-fossil fuel in the whole transport sector is a big progress; however, it is not progressive enough considering the efforts to replace 90% of the passenger vehicles by different electric drive vehicles. It shows that road passenger transport is very important, but other elements, such as road and waterway freight transport, are also significant in terms of achieving fossil fuel independent transport in China.

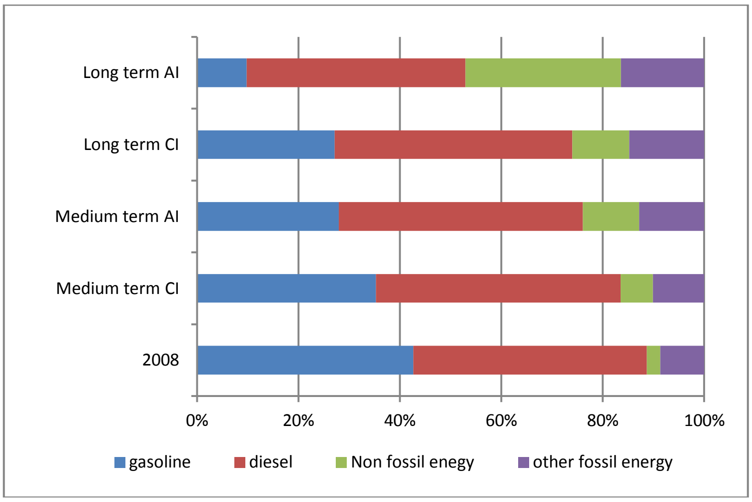

Fig. 5. Fuel structure variation in the whole transport sector

4.5 Conversion to 100% non-fossil fuel transport

Fig. 6 shows the results of converting to 100% non-fossil fuel transport which takes the transport sector in the IA scenario with long term aggressive objectives as a departure point. In this case, 40.5% of total transport fuel demand is supplied by electricity, 28.5% is supplied by bioethanol and another 31% by biodiesel. The total fuel demand has dropped to 36.4% of the fuel demand in 2008. This is only one case of future transport sectors with 100% non-fossil fuel. The share of electricity would increase if hydrogen was utilised in air and water transport in the future.

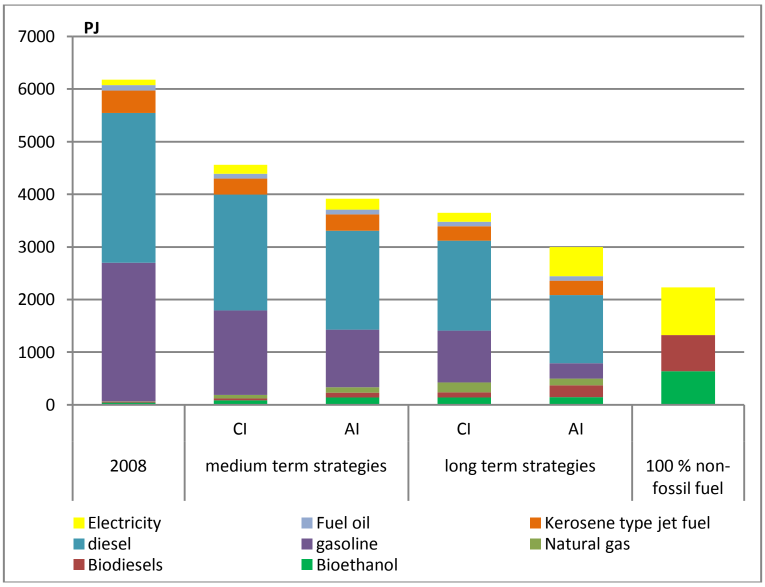

Fig. 6. Fuel structure variation in the whole transport sector

4.6 Sensitivity analysis

All analyses and results in this study are based on applying the formulated future transport development planning and other aggressive objectives to the existing Chinese transport sector. Given the rapid development of China, uncertainty should be considered. Transport demand is the main driving factor to influence the energy demand. In the sensitivity analysis, the transport demand has simply been doubled in order to represent the energy demand in a different scale of transport demand. Fig. 7 exhibits the comparisons between three elements: fuel demand of transport sectors with twice the transport demand, national electricity demand in 2008 and annual production potential of biofuel. The comparisons show that the electricity demand in non-fossil fuel transport with twice the transport demand is only 15% of national electricity demand in 2008. It further indicates that the pressure to enhance transmission capacity caused by increasing penetration of EVs is not going to be overwhelming. Moreover, the biofuel demands in all scenarios and in the 100% non-fossil fuel transport with twice the transport demand are much lower than the minimum biofuel production potential. Therefore, the limitations of converting to non-fossil fuel transport in China are not severe at least in the perspectives of domestic resources and transmission capacity. However, more technical, economic and infrastructural challenges should be discussed further.

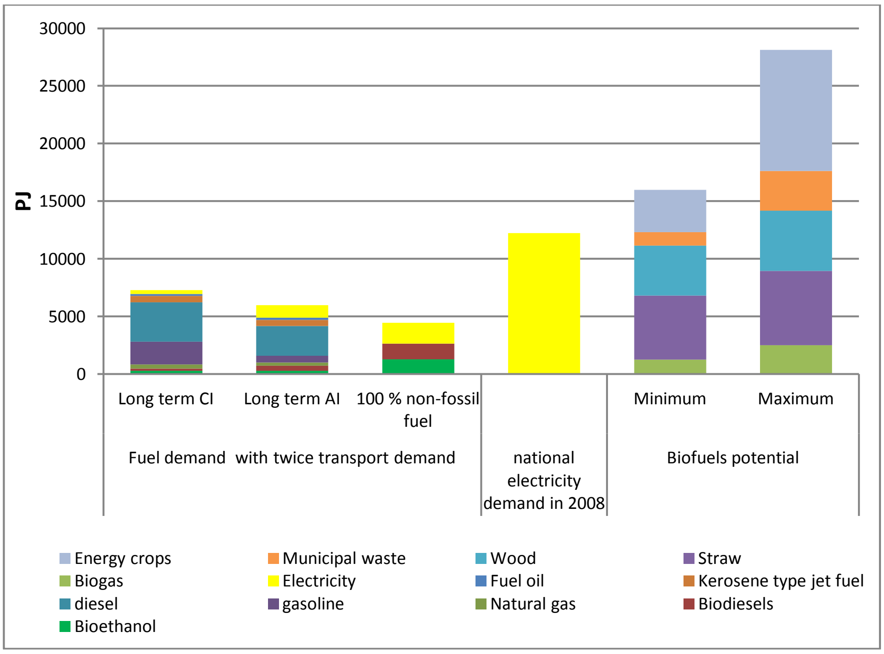

Fig. 7. Fuel demand in transport sectors with twice the transport demand and its comparison with national electricity demand and biofuels' potential [11,55,56]

5 Conclusion

Energy security and climate change are forcing China to change its inappropriate energy structure. Today, transport is the second largest energy consumer in China but with the fastest growth rate. No single method can achieve a fossil fuel independent transport and it is necessary to propose a comprehensive strategy which can achieve mutual benefits to both transport and energy systems.

This paper aims to evaluate different transport development strategies in terms of their effects on fossil fuel demand reduction and to explore to what extent renewable energy can contribute to the transport sector. With this objective, a Chinese transport model has been created and three investigations have been carried out in sequence. Firstly, the model has been used to calculate the energy demand of the Chinese transport sector in the reference years. Secondly, a continued improvement (CI) scenario and an accelerated improvement (AI) scenario have been designed which represent the influence and consequence of applying the medium and long term formulated planning and more aggressive objectives into the existing Chinese transport sector. Finally, a transport sector with 100% non-fossil fuel was built and discussed in order to identify the limitations and barriers of this transformation in terms of domestic resources.

The comparisons between model results and real energy demand show that the approach of the model is reliable and can be used for further investigations. In the two CI scenarios, both the medium and the long term formulated transport development planning can successfully achieve the fuel demand reduction. Improving vehicle efficiency is one of the crucial methods to reduce fuel demand. Current plans and policies mainly focus on increasing fuel economy in individual transport sectors, especially road transport. However, strategies are needed which can stimulate a transport demand transfer to sectors with higher energy efficiency. In this case, rapid HSR development is a good opportunity to decrease fuel demand in railway

transport, to expand the freight railway's capacity and to stimulate a transport demand transfer from air to railway transport.
The formulated transport development planning can achieve a remarkable fuel demand reduction but can still hardly change the fuel structure in the transport sector. In the CI scenario with the long term formulated planning, the share of non-fossil fuel in the whole transport is only about 11% and the share has grown to 30% with the long term aggressive objectives. 30% non-fossil fuel in the whole transport sector is a big progress; however, it is not progressive enough considering the efforts to replace 90% of the passenger vehicles by different electric drive vehicles. Road passenger transport is very important, but other elements, such as road and waterway freight transport, are also influential in terms of achieving fossil fuel independent transport in China.
In 100% non-fossil fuel transport with twice the transport demand, the electricity demand in all scenarios is a small part of the national electricity demand in 2008 and biofuel demand is much lower than the minimum production potential of biofuel as well. Moreover, it has left room for biomass to be applied in other energy sectors, such as biofuel's combined heat and power plants (CHPs). Therefore, the pressure to enhance transmission capacity caused by increasing penetration of EVs is not going to be overwhelming and the limitations of converting to non-fossil fuel transport are not severe at least in the perspectives of domestic resources and transmission capacity. Further technical, economic and infrastructural challenges still need to be investigated.

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