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Energy consumption and GHG emissions from China's freight transport sector: Scenarios through 2050

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HIGHLIGHTS

- A bottom-up model was established to predict energy consumption and GHG emissions from China's freight transport sector.
- Energy consumption and GHG emissions may experience 3.3 and 2.8 times increases under BAU scenario.
- GHG emissions may reach the peak as early as around 2030 under aggressive scenario.

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ABSTRACT

China's freight transport volume experienced rapid growth over recent years, causing great concerns over its energy and environmental impacts. In this study, by establishing a bottom-up accounting framework, a set of scenarios reflecting the possible future trajectories of energy consumption and Greenhouse Gas (GHG) emissions from China's freight transport sector are developed. According to our estimation, GHG emissions from China's freight transport sector were 788 mt CO_2e in 2013, roughly accounting for 8% of nationwide GHG emissions. Under Business-As-Usual (BAU) scenario, energy consumption and GHG emissions in 2050 will be 2.5 and 2.4 times the current levels. GHG emissions will peak by 2045 at the level of 1918 mt CO_2e. With all major mitigation measures implemented, energy consumption and GHG emissions in 2050 can be reduced by 30% and 32%, respectively. Besides, GHG emissions will peak earlier by around 2035 at a much lower level than under BAU scenario. Our study suggests that in order to keep in pace with China's overall mitigation agenda, aggressive efforts should be made to reduce GHG emissions from freight transport sector.

1. Introduction

Freight transport is defined as moving freight from one location to another, normally driven by economic activities. Road, rail, water, aviation and pipeline are the major motorized freight transport modals. Freight transport is an important source of energy consumption and Greenhouse Gas (GHG) emissions. As reported by the 5th assessment report (AR5) from Intergovernmental Panel on Climate Change (IPCC), global freight transport consumed 40 EJ energy in 2009, accounting for about 45% of total transport energy consumption (Sims et al., 2014). More specifically, heavy duty vehicles consumed over half of total energy by freight transport. Energy conservation and GHG mitigation have become the most important agenda in the global freight transport sector.

Driven by the fast economic development, China's freight transport volume experienced rapid growth over recent years, from 4.4 trillion ton-kilometer (tkm) in 2000 to 16.8 trillion tkm in 2013, with an annual growth rate of 10.8% (NBS, 2014). During the same period, the numbers of road trucks, locomotives and aircrafts had been increased by 1.8, 0.4 and 3.1 times, respectively. Also, the total length of pipelines had been increased by 3 times. Such a growth in freight transport caused great increases of energy consumption and GHG emissions (Guo et al., 2014; Hao et al., 2011c). As estimated by DRC (2013), energy consumption by China's freight transport sector increased from 79 megaton of coal equivalent (mtce) in 2005 to 142 mtce in 2010, with an annual growth rate of 12%. Freight transport is likely to continue its growth trend in the coming decades. Under such a circumstance, it

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is critical to predict the future growth pattern of China's freight transport and prepare appropriate policies to address the related energy and GHG emissions issues.

The energy and environmental impacts from transport sector have been intensively studied over recent years (Geng et al., 2013; Hao et al., 2014, 2011b). Regarding freight transport, existing studies were typically based on bottom-up accounting frameworks. International Energy Agency (IEA) established the Mobility Model to estimate CO_2 emissions from global freight transport (IEA, 2012). Under the Mobility Model, CO_2 emissions were decomposed into freight transport volume, energy intensity and emission intensity. One major merit of this approach is its low data requirement to populate the model. Freight transport volume can be normally collected from national official statistics. Energy intensity and emission intensity have been well captured by existing studies, and can be well transplanted from one region to another by making some adjustments. Fu et al. (2011) projected the energy consumption of China's freight transport sector by employing a three-factor decomposition approach, under which energy consumption is decomposed into total freight transport volume, modal mix, and energy intensity. Future trends were presented with one Business-As-Usual (BAU) scenario and multiple alternative scenarios reflecting different policy impacts. Factors that were addressed include transport volume change, energy efficiency improvements, etc. However, their study focused on energy consumption only, and did not incorporate emissions factors into estimating emissions. Furthermore, the base year of their study was 2008, which could not reflect the fast changes of freight transport characteristics in China over recent years. As a result, their study tended to underestimate China's freight transport volumes and associated energy consumption. DRC (2013) also estimated energy consumption of China's freight transport sector based on a bottom-up approach. Future projections were presented through one Business-As-Usual (BAU) scenario and one low-carbon scenario. However, the assumptions behind the scenarios were not explicitly explained.

One major gap of existing studies is the limited coverage of mitigation measures and the lack of synthesis among various measures. Under such a circumstance, it is difficult to quantify the impacts from each measure and possible combinations of different measures. In order to fill such gaps, a transparent bottom-up framework is established to provide comprehensive policy insights. Several scenarios with different energy consumption and GHG emissions from China's freight transport sector are developed, with focuses on predicting the impacts from different mitigation measures, performing policy simulation and delivering explicit policy implications. This study will contribute to extending the scope and improving the transparency of mitigation measure evaluation. The whole paper is organized as follows. After this introduction section, the study scope, accounting framework and scenario development methodologies are described. Then the research results are presented and discussed, with a focus on detailing the comparisons between BAU scenario and the alternative scenarios. Finally, policy recommendations are raised.

2. Methodology and data

In this section, the overarching methodology is firstly introduced. Then three essential factors, including freight transport volume, energy intensity, and GHG emissions intensity, are elaborated. Each factor is introduced in the order of history and future projection.

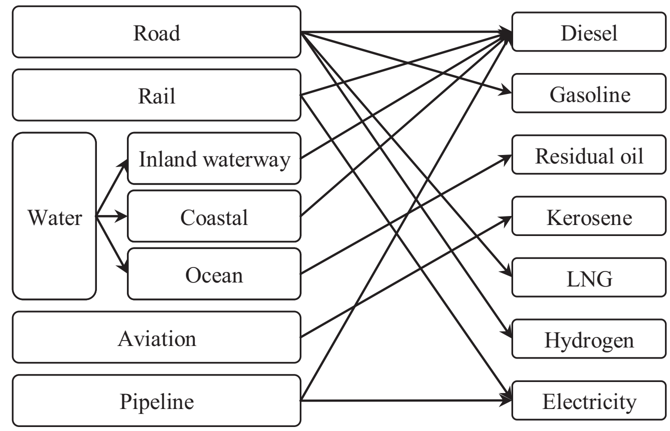

Fig. 1. Transport modals and fuels covered in this study.

2.1. Accounting framework

Fig. 1 presents the scope and accounting framework of this study. Five transport modes are included, namely, road, rail, water, aviation and pipeline. Water transport is further categorized into inland waterway, coastal and ocean transport. Seven transport fuels are covered, including diesel, gasoline, residual oil, kerosene, liquefied natural gas (LNG), hydrogen and electricity.

Eqs. (1) and (2) show the overarching methodology of this study. The bottom-up approach described in the Mobility Model (IEA, 2012) is employed as our accounting framework. Energy consumption is decomposed into freight transport volume, technology share, energy intensity, and energy share. GHG emissions are obtained based on energy consumptions and the GHG emissions intensities. Note that the GHG emissions intensities quoted in this study are based on the life cycle perspective, with both direct emissions from energy use and indirect emissions from energy production included.

$$EC_{i,r} = \sum_{p} FTV_{i,p} \cdot TS_{i,p}^{i,p,q} \cdot EI_{i,p,q} \cdot ES_{i,q}^{i,q,r} \tag{1}$$

$$GE_i = \sum_{r} EC_{i,r} \cdot GI_{i,r} \tag{2}$$

where, $EC_{i,r}$ is the energy consumption of type r fuel in year i (MJ); GE_i is the GHG emissions in year i (t CO_2e); $FTV_{i,p}$ is the freight transport volume by mode p in year i (tkm); $TS_{i,p}^{i,p,q}$ is the share of freight transport volume by technology set q out of total freight transport volume by mode p in year i; $EI_{i,p,q}$ is the energy intensity of technology set q of mode p in year i (MJ/tkm); $ES_{i,q}^{i,q,r}$ is the share of energy consumption of type r fuel out of total energy consumption of technology set q in year i; $GI_{i,r}$ is the GHG emissions intensity of type r fuel in year i (t CO_2e/MJ).

Scenario analysis is the common method of predicting future trends and identifying key influencing factors for freight transport sector (Zanni and Bristow, 2010). The major characteristics of China's freight transport, such as freight transport volume, energy intensity, etc., are in the process of rapid changes. The future trends of these factors are quite uncertain, and can pose significant impacts on our estimations. For these reasons, multiple scenarios are assumed for these factors so that future emission patterns under different policy and technology contexts can be presented.

2.2. Freight transport volume

2.2.1. History

Fig. 2 shows China's historical freight transport volume from

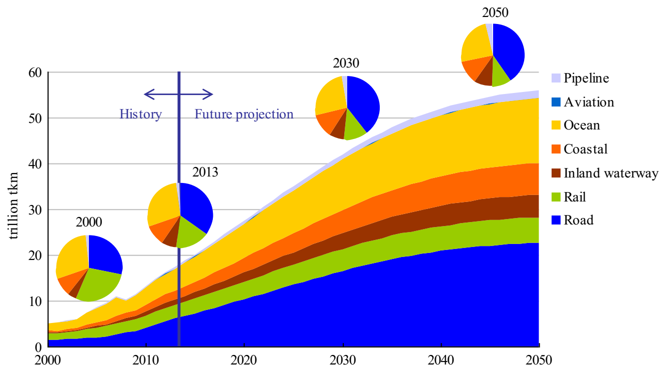

Fig. 2. China's freight transport volume under BAU scenario.

2000 to 2013, as well as the projection through 2050. Data are compiled based on multiple sources (MOT, 2013; NBS, 2014). Note that the Ministry of Transport (MOT) conducted nationwide transport surveys twice in 2008 and 2013, respectively. The surveys were accompanied by adjustments of survey scope and methodologies. Therefore, the official statistics of freight transport volumes in 2008 and 2013 showed significant discontinuity. To ensure data consistency, historical freight transport volumes are calibrated by using the 2013 survey standards. Also note that the sudden change of ocean freight transport volume between 2007 and 2008 is a normal fluctuation caused by the global financial crisis.

The statistics of road transport volume cover only freight transport by vehicles registered under the MOT administrative system, which is normally referred to as commercial transport. On the other hand, there is also considerable amount of road transport activities not captured by the official statistics, mostly short-distance transport activities in urban and suburb areas. These transport activities are normally referred to as non-commercial transport. According to MOT (2010), freight transport volume with transport distance of lower than 100 km accounted for 12% of total commercial freight transport volume. With the regard that the average load and transport distance of non-commercial road transport could be even lower than this, it is assumed that non-commercial volume is about 10% of commercial volume.

By using Eq. (3), the elasticity of freight transport volume to GDP during the period of 2000–2013 can be estimated. The elasticity of a certain transport mode reflects the transport demand increase in response to GDP growth. An elasticity value of higher than 1.0 implies that transport volume growth rate is higher than the GDP growth rate, and vice versa.

$$EL_{i1,i2,p} = \frac{(FTV_{i2,p}/FTV_{i1,p})^{1/(i2-i1)} - 1}{(GDP_{i2}/GDP_{i1})^{1/(i2-i1)} - 1} \tag{3}$$

where, $EL_{i1,i2,p}$ is the elasticity of freight transport volume by mode p to GDP between year i_1 and i_2; GDP_i is the gross domestic production in year i.

According to our estimation, the elasticity values of road, rail, inland waterway, coastal, ocean, aviation and pipeline transport were 1.21, 0.60, 1.34, 1.18, 0.99, 0.99 and 1.41, respectively. Pipeline transport had the highest growth rate, followed by inland waterway, road, and coastal transport, the elasticity values of which were all higher than 1.0. The elasticity values of ocean and aviation transport were around 1.0. The elasticity of rail transport was the lowest and showed a significant gap compared with other transport modes. The slow growth of rail transport volume can be mostly attributed to China's limited freight rail capacity during the estimated period.

2.2.2. Future projection

As demonstrated by developed countries, the elasticity of freight transport volume tends to decrease as GDP grows. For this reason, the elasticity values of all transport modes are assumed to be in downtrend in the coming decades. Under BAU scenario, the elasticity values will be 90%, 60%, 30% and 10% of the historical values at the end of each ten-year period after 2013. On the corresponding time nodes, GDP growth rates are assumed to be 6%, 5%, 4% and 3%. Fig. 2 shows China's freight transport volume through 2050 under BAU scenario. Total freight transport volume will maintain rapid growth in the coming decades, from 17.4 trillion tkm in 2013 to 55.9 trillion tkm in 2050. Besides, two alternative scenarios are also developed for freight transport volumes, which are named as demand management (DM) scenario and mode shift (MS) scenario.

2.2.2.1. DM scenario. Freight transport volume can be reduced through transport demand management, including reconciling manufacturing and consumption locations, refining supply chains, etc. The DM scenario is established to reflect the impacts under transport demand management measures, under which the elasticity of freight transport will be lower than under BAU scenario, that is, 80%, 50%, 20% and 5% at the end of each ten-year period after 2013. Under the DM scenario, total freight transport volume will be 47.6 trillion tkm in 2050, 15% lower than under the BAU scenario.

2.2.2.2. MS scenario. In China's context, the major opportunity for mode shift is from road to rail freight transport. As mentioned above, China's rail transport volume has been growing slowly due to the limitation of freight rail capacity. Under such a circumstance, a large amount of long-distance bulk transport, such as the inter-provincial coal transport, has been undertaken by road trucks rather than rail. However, with enhanced freight rail capacity, a considerable amount of freight transport can be shifted from road to rail. Under the MS scenario, 2.5%, 5%, 7.5% and 10% of road freight transport volumes are diverted to rail in 2020, 2030, 2040 and 2050, respectively.

2.3. Energy intensity

2.3.1. History

2.3.1.1. Road. Table 1 presents the fleet characteristics of China's on-road commercial trucks. Trucks are classified into five categories based on their load capacities. Vehicle stock, average load capacity, vehicle travel, mileage utilization rate and fuel consumption rate are compiled based on multiple sources (CATARC,

Table 1
Characteristics of China's commercial trucks in 2008.

	Unit	0–2 t	2–4 t	4–8 t	8–20 t	20 t+
Stock	10,000	444	80	83	119	36
Average load capacity	t	1.2	3.2	5.7	14.0	28.0
Load capacity utilization rate		90%	110%	120%	130%	140%
Vehicle travel	1000 km/year	20	40	50	60	95
Mileage utilization rate		56.7%	61.0%	65.8%	65.8%	65.8%
Freight transport volume share		2.7%	3.4%	9.1%	41.9%	42.9%
Fuel consumption rate (loaded)	L/100 km	15.1	20.2	25.1	30.7	35.0
Energy intensity caused by utilized mileage	MJ/tkm	5.00	2.05	1.32	0.60	0.32
Fuel consumption rate (unloaded)	L/100 km	10.1	13.5	16.7	20.5	23.3
Energy intensity caused by unutilized mileage	MJ/tkm	2.54	0.87	0.46	0.21	0.11

2013; CATS, 2010; MOT, 2010). The load capacity utilization rate is estimated based on our interviews with the related stakeholders. The heavy duty trucks in China normally operate under an overload condition in order to reduce cost and maximum operating benefits. Freight transport volumes by each category are calculated by multiplying vehicle stock, load capacity, load capacity utilization rate, vehicle travel and mileage utilization rate. According to our estimation, the categories of 8–20 t and 20 t+ are the dominating categories of freight transport volume, with each accounting for higher than 40% of the total volume.

Fuel consumption rate is converted to energy intensity by using load capacity and load capacity utilization rate. The differences of energy intensities among different categories are significant. The energy intensity of 20 t+ category is only 6% of that of 0–2 t category. The mileage utilization rate in China is currently very low compared with developed countries due to the lack of efficient organization and information platform. Many trucks carrying coal and construction materials are only one-way loaded, and unloaded on their return trips. This low mileage utilization rate causes significant additional energy consumption. Therefore, energy consumption caused by 'unutilized mileage' is also included in the calculations. The energy intensity for unutilized mileage is calculated using fuel consumption rate (unloaded), load capacity, load capacity utilization rate, and mileage utilization rate. The energy intensities of gasoline, LNG and hydrogen fueled road transport are assumed to be 115%, 110%, and 40% of diesel fueled road transport. Considering technology share, for the 0–2 t category, the shares of freight transport volume by diesel and gasoline trucks were about 90% and 10%. Other categories were almost 100% diesel trucks.

2.3.1.2. Rail. Two locomotive propulsion technologies are considered in the analysis, namely, Internal Combustion Engine (ICE) and electric engine. Steam powered rail transport has almost been eliminated over recent years, for which its energy consumption is ignored. The freight transport volumes are calculated by multiplying the number of locomotives and their per locomotive freight transport output (NBS, 2014). The share of electric rail transport has been growing rapidly over recent years, from 24% in 2000 to 61% in 2013. Energy intensities of ICE and electric rail transport are extracted from NBS (2014), which were about 0.12 and 0.04 MJ/tkm in 2013.

2.3.1.3. Water. For water transport, energy intensities are extracted from Hao et al. (2015). It is assumed that all inland waterway and coastal transport are fueled by diesel, while all ocean transport is fueled by residual oil.

2.3.1.4. Aviation. For aviation transport, the energy intensity decreased from 17.07 MJ/tkm in 2000 to 12.63 MJ/tkm in 2012 (MOT, 2012). All aircrafts are assumed to be fueled by kerosene.

2.3.1.5. . Pipeline. Pipeline transport is mainly powered by diesel and electricity, with a small share of natural gas, which is ignored in this study. According to Fu et al. (2011), the energy intensity of pipeline transport was 0.22 MJ/tkm in 2007. The ratio of diesel consumption to electricity consumption was about 7:3 on an energy basis.

Fig. 3 presents the comparison of energy intensities of different freight transport modes. Rail, water and pipeline transport have the lowest energy intensities, while aviation and road transport show relatively higher energy intensities. Note that the energy intensity caused by unutilized mileage poses significant impacts on energy intensity of road transport. As mentioned above, the major opportunity for mode shift is from road to rail transport. Taking the shift from road (20 t+) to rail (electric) for example, energy intensity can be reduced from 0.43 MJ/tkm (0.32 MJ/tkm caused by utilized mileage and 0.11 MJ/tkm caused by unutilized mileage) to 0.04 MJ/tkm, implying an over 90% reduction.

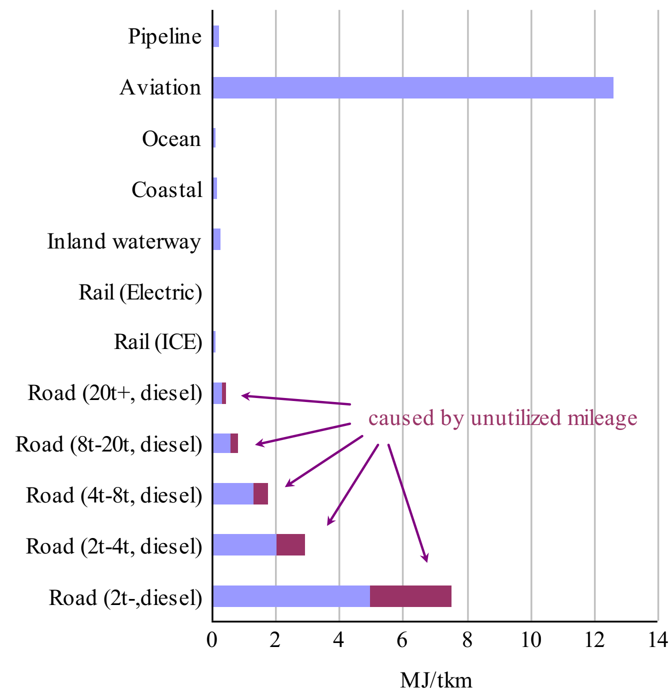

Fig. 3. Comparison of energy intensities of different freight transport modals. Note: Energy intensities of road, rail, water, aviation and pipeline transport are based on the 2008, 2013, 2012, 2012 and 2007 data, respectively.

2.3.2. Future projection

Considerable potential of energy intensity reduction exists in the freight transport sector, which can be exploited by technology improvement and logistic optimization (Ruzzenenti and Basosi, 2009). For future projection of energy intensity, one BAU scenario and one alternative scenario are developed, as Table 2 shows. Under BAU scenario, the energy intensities of road (2 t−, 2–4 t), inland waterway and aviation, which are considered having higher potentials of energy efficiency improvements, will decline by 10%, 10%, 5% and 5% for each ten-year period after 2013. While the energy intensities of other transport modes are assumed to decline by 5% during the same time periods. No efficiency improvement is assumed for electric rail because its energy efficiency is already quite high and the reduction potential is limited. Under the alternative scenario, energy intensities of all transport modes will decrease more aggressively compared with the BAU scenario. For road transport, the energy intensity caused by unutilized mileage depends not only on technology improvements, but also on the mileage utilization rate changes. Mileage utilization rate is assumed to increase steadily, with the average level reaching around 80% in 2050.

Regarding the vehicle technology share in the future, major changes will occur in the road and rail sectors. For road transport, LNG and hydrogen technologies will have great penetration potentials, especially in the heavy duty truck fleet. The penetration rates of LNG and hydrogen technologies under BAU and alternative scenarios are presented in Table 3. For rail transport, as China is promoting rail electrification aggressively over recent years, it is assumed that the share of electric rail will continue to grow, and completely replace ICE locomotives by 2040.

2.4. GHG emissions intensity

The emission intensities of diesel, gasoline, residual oil and LNG

Table 2
Energy intensity changes of different transport modals.

Scenario	Category	Energy intensity (ratio of base year level)			
		2020 (%)	2030 (%)	2040 (%)	2050 (%)
BAU	Road (2 t−, diesel)	90	90	95	95
	Road (2–4 t, diesel)	90	90	95	95
	Road (4–8 t, diesel)	95	95	95	95
	Road (8–20 t, diesel)	95	95	95	95
	Road (20 t+, diesel)	95	95	95	95
	Rail (ICE)	95	95	95	95
	Rail (Electric)	100	100	100	100
	Inland waterway	90	90	95	95
	Coastal	95	95	95	95
	Ocean	95	95	95	95
	Aviation	90	90	95	95
	Pipeline	95	95	95	95
Alternative	Road (2 t−, diesel)	85	90	90	95
	Road (2–4 t, diesel)	85	90	90	95
	Road (4–8 t, diesel)	90	90	95	95
	Road (8–20 t, diesel)	90	90	95	95
	Road (20 t+, diesel)	90	90	95	95
	Rail (ICE)	90	90	95	95
	Rail (Electric)	100	100	100	100
	Inland waterway	85	90	90	95
	Coastal	90	90	95	95
	Ocean	90	90	95	95
	Aviation	85	90	90	95
	Pipeline	90	90	95	95

are extracted from Ou et al. (2013), which were estimated to be 102.4, 98.9, 102.9, and 75.7 g CO_2e/MJ, respectively. These estimations are generally higher than estimations from the U.S., mostly due to the intensive use of coal as process fuel in China. Emission intensity of kerosene in China is not available in public literatures. Based on estimations from the U.S. (Skone and Gerdes, 2008), the emission intensity of kerosene is assumed to be 98.5% of gasoline. Generally, the emission intensities of fossil fuels do not change significantly over time, because the production pathways are quite mature with limited improvement potentials.

With regard to hydrogen fuel, the production pathway is quite diverse, with a wide range of possible emission intensities. As Deng (2010) estimated, the emission intensity of hydrogen fuel in China's context ranged from 53 g CO_2e/MJ (coke oven gas recovery) to 437 g CO_2e/MJ (on-site water electrolysis with coal-based electricity). In this study, it is assumed that the average emission intensity of hydrogen will decrease from 200 g CO_2e/MJ in 2010 to 50 g CO_2e/MJ in 2050. Regarding electricity, as IEA estimated, emission intensity of power generation in China decreased from 869 g CO_2/kWh in 2000 to 766 g CO_2/kWh in 2010. The current emission intensity of power generation in China is significantly higher than the global average. With the reduction of coal use and efficiency improvement, as well as the possible application of carbon capture and storage (CCS) technologies, the emission intensity of power generation in China is expected to decrease to about 400 g CO_2e/kWh in 2050. The line loss factor is assumed to be 6%.

3. Results

According to our estimation, energy consumption of China's freight transport sector increased from 53 mtoe (megaton of oil equivalent) in 2000 to 181 mtoe in 2013, with an annual growth rate of 9.9%. Accordingly, GHG emissions increased from 232 mt CO_2e to 788 mt CO_2e during the same period. GHG emissions from freight transport sector in 2013 roughly accounted for 8% of nationwide GHG emissions.

Regarding future projection, based on the multiple scenarios for the input factors as introduced in the last section, five output scenarios are established, as presented in Table 4. The BAU scenario is a combination of the BAU scenarios of all input factors, which reflects the future trend of energy consumption and GHG emissions with all technology and policy factors maintaining their current trends. On the other hand, the Maximum Mitigation (MM) scenario is a combination of the alternative scenarios of all input factors, which reflects the highest mitigation potential with all mitigation measures implemented. Between BAU scenario and MM scenario, three partial mitigation scenarios are established, namely, M1, M2 and M3, under which mitigation measures are implemented to different extents. By comparing these partial mitigation scenarios with BAU scenario and MM scenario, the impact from each mitigation measure can be separated and assessed.

3.1. BAU scenario

Fig. 4 presents the energy consumption and GHG emissions from China's freight transport under the BAU scenario. Total energy consumption will keep an increasing trend, reaching 453 mtoe in 2050. Specifically, the growth rates of energy consumption will be 7.9%, 3.6%, 1.6% and 0.1% during each ten-year period from 2010 to 2050. GHG emissions show a similar growth trend. The peak of GHG emissions will appear by around 2045 at the level of

Table 3
Technology penetration rates in road transport sector.

Scenario	Category	LNG				Hydrogen			
		2020 (%)	2030 (%)	2040 (%)	2050 (%)	2020 (%)	2030 (%)	2040 (%)	2050 (%)
BAU	2–4 t	2.5	5.0	7.5	10.0	0.0	0.8	1.7	2.5
	4–8 t	3.3	6.7	10.0	13.3	0.0	1.1	2.2	3.3
	8–20 t	4.2	8.3	12.5	16.7	0.0	1.4	2.8	4.2
	20 t+	5.0	10.0	15.0	20.0	0.0	1.7	3.3	5.0
Alternative	2–4 t	5.0	10.0	15.0	20.0	0.0	1.7	3.3	5.0
	4–8 t	6.7	13.3	20.0	26.7	0.0	2.2	4.4	6.7
	8–20 t	8.3	16.7	25.0	33.3	0.0	2.8	5.6	8.3
	20 t+	10.0	20.0	30.0	40.0	0.0	3.3	6.7	10.0

Table 4
Assumptions for the output scenarios.

	Freight transport volume	Energy intensity	Technology penetration
BAU	BAU	BAU	BAU
M1	DM	BAU	BAU
M2	DM+MS	BAU	BAU
M3	DM+MS	Alternative	BAU
MM	DM+MS	Alternative	Alternative

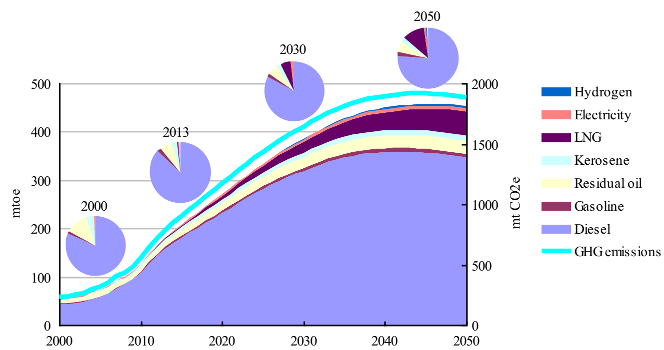

Fig. 4. Energy consumption and GHG emissions under BAU scenario.

1918 mt CO_2e, which is about 2.4 times the 2013 level.

Diesel takes the dominating share of energy consumption all the way through 2050, although the share will decrease from 87% in 2013 to 76% in 2050. With diesel, gasoline, residual oil and kerosene combined, petroleum-derived transport fuels account for 98% and 86% of the total energy consumption in 2013 and 2050, respectively. This highlights the robust role petroleum plays in fueling freight transport. LNG could be a major alternative to petroleum-derived fuels, with its share of energy consumption increasing to 11.2% in 2050. Hydrogen and electricity consumptions are quite low, together accounting for 2.5% of total energy consumption.

Fig. 5 presents the breakdown of energy consumption by transport modes. Road transport takes the dominating share of energy consumption, maintaining its level at around 80% of total energy consumption. Water transport is the second largest energy consuming sector, with its share maintaining at around 15% of total energy consumption. The share of energy consumption by rail transport will decrease from 2.6% in 2010 to 1.1% in 2050, mostly because of the overall energy intensity reduction by replacing ICE powered locomotives with electric ones. Energy consumptions by aviation and pipeline are very low, altogether accounting for around 4% of total energy consumption in 2050.

Due to the low mileage utilization rate, considerable amount of

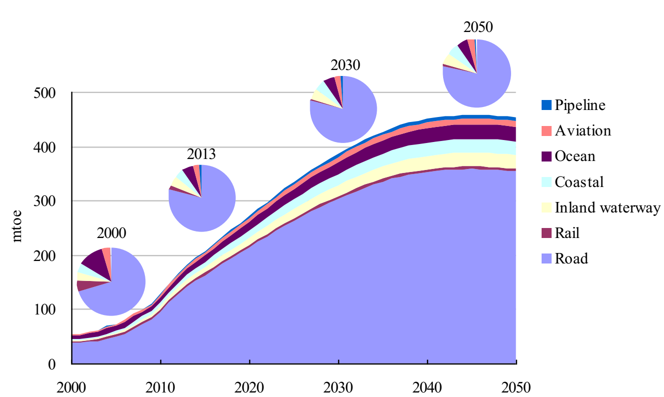

Fig. 5. Breakdown of energy consumption by transport modals under BAU scenario.

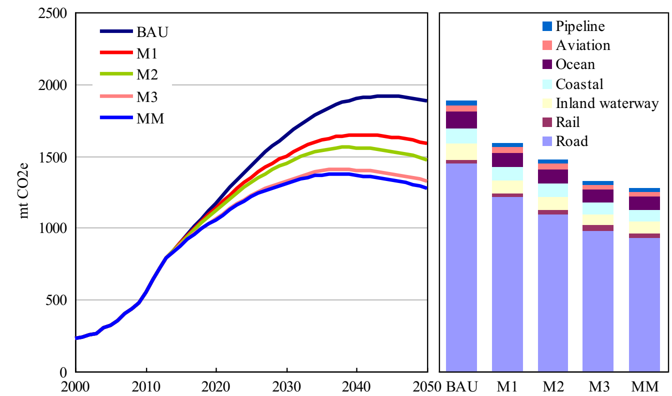

Fig. 6. GHG emissions from China's freight transport under different scenarios.

energy is wasted on unutilized mileage. The energy consumption caused by unutilized mileage is estimated to be 40 mtoe, or 28% of energy consumption by road transport in 2013. This huge waste of energy highlights the necessity of increasing mileage utilization rate through effective measures. With mileage utilization rate improving over time, the share of energy consumption caused by unutilized mileage is expected to decrease to 16% in 2050.

3.2. Alternative scenarios

Fig. 6 presents the comparison of GHG emissions under different scenarios. Generally, with more measures implemented, GHG emissions will be cut to larger extents. GHG emissions in 2050 will range from 1275 to 1885 mt CO_2e, that is, 1.6 to 2.4 times the GHG emissions in 2013. Compared with the BAU scenario, GHG emissions in 2050 will be reduced by 16%, 22%, 30% and 32% under M1, M2, M3 and MM scenarios. In other words, the mitigation measures of transport demand management, mode shift, energy intensity reduction, and advanced technology penetration contribute to 49%, 18%, 24% and 8% of the GHG emissions reduction from BAU scenario to MM scenario, respectively.

Meanwhile, with more measures implemented, total GHG emissions will peak earlier. Under the MM scenario, GHG emissions will peak by around 2035 at the level of 1375 mt CO_2e, which is about ten years earlier than under the BAU scenario. For the other scenarios between BAU scenario and MM scenario, GHG emissions will peak between 2035 and 2045. Our analysis demonstrates the possibility of achieving earlier peak of GHG emissions through aggressive mitigation measures.

Road transport contributes the most to the overall GHG emissions reduction. From BAU scenario to MM scenario, GHG emissions from road freight transport are reduced by 518 mt CO_2e, accounting for 85% of the overall reduction. This highlights the critical role road transport plays in mitigating GHG emissions from the freight transport sector.

4. Discussions and policy implications

Compared with previous studies, this study generally presents higher estimations of energy consumption and GHG emissions from China's freight transport sector. For example, IEA estimated that CO_2 emissions from China's transport sector, with both passenger transport and freight transport included, were 513.6 mt in 2010 (IEA, 2013), which is even lower than our estimation for freight transport sector only (555 mt CO_2e in 2010). There are several reasons behind this difference. Firstly, as suggested by Cai et al. (2012), IEA might have underestimated the CO_2 emissions from China's transport sector. According to their estimation, the actual CO_2 emissions from China's road transport in 2007 were 37% higher than the IEA estimation. Secondly, GHG emissions are accounted from the life-cycle perspective in this study, including both direct emissions from fuel combustion and indirect emissions from fuel production. However, many existing studies, including the IEA estimation, only accounted the direct emissions. For petroleum-derived fuels, the life cycle GHG emissions are about 20% higher than the direct emissions. Thirdly, the emission intensities employed in this study are based on GHG emissions rather than CO_2 emissions. GHG emissions induced by CH_4 and N_2O, together with CO_2, are included in our estimations. However, for the IEA estimation, only CO_2 emissions were included. With all these factors considered, our estimations are generally in line with existing studies.

Regarding the reduction potential of GHG emissions, a maximum reduction of 32% of GHG emissions in 2050 compared with BAU scenario is presented. As a comparison, for the passenger transport sector, existing literatures suggested much higher mitigation potentials. As estimated by Hao et al. (2011a), with all possible measures implemented, 73.4% reduction of GHG emissions by passenger vehicles can be achieved in 2050 compared with the reference scenario. For the passenger transport sector, the mitigation measures are generally more abundant. The measures, such as vehicle electrification, constraining vehicle ownership, show great potentials of GHG mitigation. The fuel consumption regulations in the passenger transport sector are also progressing more aggressively than in the freight transport sector. Due to technical and behavior limitations, mitigation measures in freight transport sector show lower availabilities and potentials. In this regard, freight transport sector is likely to face more severe challenges in GHG mitigation than passenger transport sector.

Our estimation shows robust energy consumption and GHG emissions growth from China's freight transport sector in the coming decades. As specified by the 'U.S.–China Joint Announcement on Climate Change', China intends to achieve the peak of CO_2 emissions by around 2030 and to make best efforts to peak early (U.S. and China Governments, 2014). Compared with such an overall target, China's freight transport sector is likely to be lagging behind. Policy makers should place high priority on energy conservation and GHG mitigation in the freight transport sector, with dedicated plans and programs timely initiated.

From the central government perspective, nationwide policies can be developed in three major directions. Firstly, it will be necessary to incorporate the consideration of freight transport issues into the process of industrial and commercial planning. This is the most important measure, because the spatial distributions of industry and commerce have substantial impacts on freight transport demand. The more production locations and consumption locations are reconciled, the less freight transport demand will be created. This needs an overall balance among different regions. Secondly, it is critical to enhance freight rail capacity and promote mode shift form road to rail. China's freight rail transport market has experienced a lack of supply for decades. Freight rail infrastructure should be aggressively promoted, especially on the major coal-transporting lines. A seamless connection system between long-distance rail freight service and short-distance road freight service should be established in order to enhance the competitiveness of freight rail. Thirdly, it is appropriate to tighten the fuel consumption and emissions regulations. Currently, the fuel consumption and emissions regulations in China's transport sector have been comprehensively established. However, the stringency levels of the regulations are generally lagging behind those developed countries. For example, China's vehicle emissions standard is more than five years lagging behind the EU standard. In this regard, China should accelerate updating the regulation system and catch up with the global advanced level as early as possible. Besides, there are many useful practices that can reduce energy consumption with no or little technical updates, such as eco-driving, vehicle retrofit, etc. These measures can be implemented with lower costs but considerable benefits, thus should be considered with priority. Specifically, for the road transport sector, efforts should be made in order to increase the mileage utilization rate. Related measures include increasing concentration of road transport market, establishing uniform logistics information platform, etc.

From the local government perspective, demonstration programs with the aim of establishing good freight transport practices should be initiated. For example, Guangdong province initiated the 'Green freight transport' program in 2009 under the support from the Global Environment Foundation (GEF). Under this program, GHG mitigation is achieved by (a) tire retrofit, aerodynamic optimization, eco-driving; (b) avoiding unutilized mileage of tow trucks; and (c) improving logistics management through information platform. It is claimed that there will be 0.15 mt CO_2 mitigation in the next 3–4 years. Good practices demonstrated by such programs can be promoted nationwide.

5. Conclusions

In this study, by establishing a bottom-up accounting framework, a set of scenarios reflecting the possible trajectories of energy consumption and GHG emissions from China's freight transport sector through 2050 are developed. Compared with existing studies, this paper contributes to extending the scope and improving the transparency of mitigation measure evaluation. Besides, by employing the most up-to-date data, recent trends of energy consumption and GHG emissions from China's freight transport sector can be well reflected.

Our study suggests that GHG emissions from China's freight transport sector were 788 mt CO_2e in 2013, roughly accounting for 8% of nationwide GHG emissions. Under BAU scenario, energy consumption and GHG emissions will grow fast in the coming decades, with about 1.5 times increases from 2010 to 2050. GHG emissions will peak by around 2045. Road transport is the dominating source of GHG emissions. Under MM scenario, under which transport demand management, transport mode shift, energy efficiency improvement, and advanced technology penetration are assumed, energy consumption and GHG emissions in 2050 can be reduced by 30% and 32% compared with BAU scenario. Besides, GHG emissions will peak earlier by around 2035.

One major gap in freight transport research is the growth pattern of freight transport volume in China's context. As studied by Hao et al. (2012), the freight transport intensity in China is much higher than in other countries. The uniqueness of China's freight transport can be interpreted from several perspectives, including the huge demand for coal transportation, the infrastructure construction driven by economic growth, the long distance of inter-province transport, etc. Thus, China's freight transport volume cannot be well projected by referring to the history of developed countries (Sorrell et al., 2012). In this study, the assumed elasticity values have substantial impact on the energy consumption and GHG emissions estimations. The rationale behind the elasticity assumptions can be an important topic for further studies.

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