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The Optimal Oil-Saving Pathway Until 2030 for China Road Passenger Transportation Based on a Cost Optimisation Model

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Optimal planning of oil-saving pathway for road passenger transportation sector remains a challenging task, as it involves many powertrains and fuel alternatives in the course of traffic volume expansion. This manuscript proposed a cost-optimisation superstructure model (COSM) to derive the optimal oil-saving pathway for road passenger transportation up to 2030. In each year of the planning horizon, the model considered eight options of alternative fuels and powertrains for seven categories of newly registered passenger vehicles which was derived from the projected vehicle population and survival rates. The optimisation objective of the model was to minimize the accumulated costs of fuels and vehicles over the planning horizon, and the optimal oil saving pathway was then decided by choosing the most cost-effective options of alternative fuels and powertrains for annual newly registered vehicles from 2010 to 2030. Based on the COSM, the empirical study of China indicated that the cost-optimal oil saving potential was 61 and 126 Mt (OE) in 2020 and 2030. The sensitivity analysis indicated that supply amount of vehicular natural gas was more sensitivity than that of vehicular gasoline, gasoline price was more sensitivity than natural gas price, and acquisition cost of PEV (pure electricity vehicle) was more sensitive than that of HFCV (hydrogen fuel cell vehicle).

1. Introduction

In recent years, vehicle population of road passenger transportation grew rapidly in China. During the period from 2001 to 2011, the passenger vehicle population had grown for 7.5 times, from 9.94 M in 2001 to 74.78 M in 2011 (China, 2013). In future, vehicle population would continue to increase rapidly because the vehicle ownership per thousand people was still low compared to developed countries even the world average level (Ou et al., 2010). According to the statistics database (Wang, 2011), road passenger transportation of China consumed nearly all the gasoline (69 Mt) and a portion of diesel (89 Mt). Considering road passenger transportation was the main consumer of gasoline and diesel among all the end users, the rapid increase of oil consumption from road passenger transportation was the main driver for the increase of OID (oil imported dependency), which raised concerns for energy supply security.

To mitigate the rapid increase of OID and oil consumption, it has become a common understanding of developing alternative fuels and powertrains (Börjesson and Ahlgren, 2012), such as natural gas vehicle (Ou et al., 2010a), hybrid vehicle (Baran and Legey, 2013), pure electric vehicle (PEV) (Kyle and Kim, 2011), and hydrogen fuel cell vehicle (HFCV) (Ouyang, 2006). Several studies had evaluated the oil saving potential of these advanced vehicles based on designed share of specific alternative fuels and powertrains over a specific planning horizon. For instance, in the study of Hao et al. (2011a), it designed a scenario of promoting EV penetration that the proportion of electricity vehicle (EV) in all newly registered vehicle was assumed to be 20 %, among which HEVs account for 70 %, PHEVs accounted for 24 %, and BEV accounted for 6 % in 2030. In the study of Yan and Crookes (2009), it assumed that the share for private car using CNG will increase to 5 % by 2030, and the share for heavy duty bus and taxi using CNG will increase by 50 % by 2030. All of these studies evaluated oil saving potential of several possible

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reduction measures by deploying a specific scale of alternative vehicles or fuels in a specific time, and designed the process of changing share. However, the deployment time and scale of alternative fuels and powertrains differed significantly for different studies.

In this study, the optimal deployment of alternative fuels and powertrains for newly registered vehicles in each year over the planning horizon was defined as the optimal oil saving pathway, which was determined in the most cost-effective way because cost is a key factor in assessing the likelihood of alternative fuels and technologies becoming widely adopted (Gass et al., 2014). Firstly, a cost-optimisation model of China's road passenger transportation was proposed to describe the interlinked relationship among the physical factors, and the fuel and powertrain option for newly registered vehicle was selected as the variable to be optimised. Secondly, based on the model, we developed an empirical study of China to derive the optimal oil saving pathway. Thirdly, we conducted a sensitivity analysis of some important impacted factors to check their influence on the optimal results.

The rest of the paper was organized as follows: an introduction of the methodology was provided in section 2; an empirical study of China was conducted following with sensitivity analysis in section 3; the conclusion and discussion were given in section 4.

2. Methodology

2.1 Passenger vehicle classification

In this study, passenger vehicles were classified into large-sized, middle-sized, and small-sized according to vehicle length (VL) and approved number (AN). In each of vehicle category, vehicle utility would influence vehicle travelled kilometres, vehicle acquisition cost, fuel economy, and further influence oil consumption. For instance, in small-sized vehicles, vehicles owned and used by enterprises and governments often travelled more kilometres than vehicles owned and used by individuals, and the acquisition cost of taxis were much lower than that of vehicles owned by enterprises and governments, and individuals. In large-sized vehicle, city buses used for carry passenger following a fixed route often travelled less kilometres than the other big buses. Therefore, we classified passenger vehicles into 7 categories by vehicle length and approved number, and vehicle utility: private passenger vehicles (PPVs), taxis (TAXs), business passenger vehicles (BPVs), city buses (CBs), big buses (BBs), middle buses (MBs), and small and mini buses (SBs), which was shown in Figure 1. For each category of vehicle, it also had several alternative fuels and powertrains to choose, which included internal combustion engine using gasoline (ICE-G), internal combustion engine using diesel (ICE-D), hybrid using gasoline (Hybrid-G), hybrid using diesel (Hybrid-D), internal combustion engine using natural gas (ICE-NG), hydrogen fuel cell vehicle (HFCV) and pure electric vehicle (PEV) [7]. In this study, it is assumed that there were 45 possible options of alternative fuels and powertrains for 7 categories of vehicles, which were shown in Figure 2.

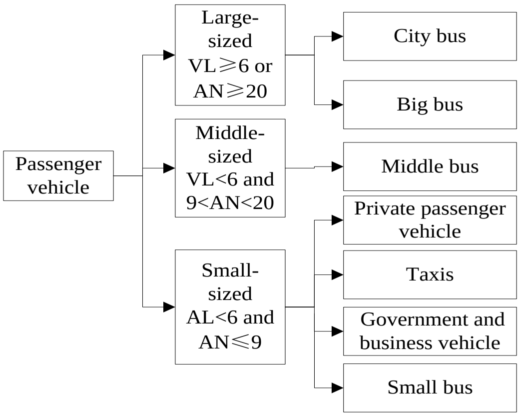


Figure 1: Passenger vehicle classification

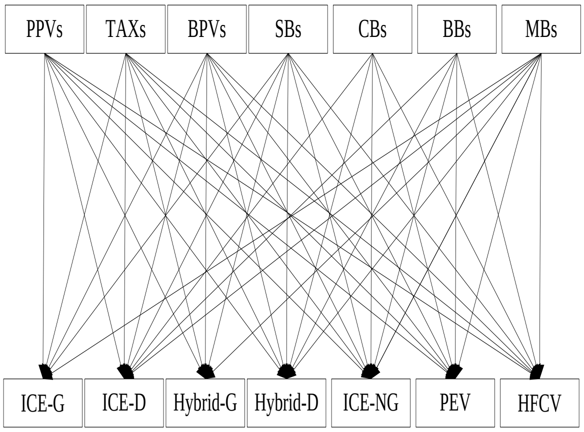


Figure 2: The options of alternative fuels and powertrains for different passenger vehicles

2.2 Problem description and Model structure

In this section, the problem of optimising oil-saving pathway until 2030 for China's road passenger transportation could be described as a linear programming problem, which widely used in a broad range of fields (Gabriela et al., 2013). The optimisation objective was to obtain the most cost-effective mix of alternative fuels and powertrain options. The optimisation objective of this model was the accumulated cost over the planning horizon including vehicle acquisition cost, operation and maintenance cost (O&M), and fuel cost. To calculate three parts of cost, newly registered vehicles should be calculated firstly through forecasted vehicle population and survival rates. Vehicle acquisition cost could be then calculated by unit acquisition cost, vehicle O&M cost could be calculated by unit O&M cost, and fuel cost could be calculated by vehicle travelled kilometres, fuel consumption rate and unit fuel cost.

2.3 Mathematical formulation

According to the module structure presented in section 2.2, the module could be divided into two types: vehicle module and cost module. The mathematical formulation of each module and some key constraints of the module were presented in the rest of this section. The physical meanings of all variables with lowercase letters and parameters with capital letters were collected in Table 1.

Table 1 Physical meanings of the variables and parameters in the model

Symbol	Physical meaning
$(VP/cap)_t$	In year t, vehicle population per capita
Et	In year t, elasticity coefficient of GDP
(GDP/cap)t	In year t, GDP per capita
pm	For m category of vehicle, the slope of linear extrapolation
qm	For m category of vehicle, the intercept of linear extrapolation
SRm,t,a	In year t, survival rate of m category of vehicle registered in year a
VPm,t,a	In year t, vehicle population of m category of vehicle registered in year a
VPm,t	In year t, vehicle population of m category vehicle
NRm,a	For m vehicle, newly registered vehicle in year a
km,a	For m vehicle, survival parameter for vehicle registered in y a
km,a0	For m vehicle, survival parameter for vehicle registered in base y
Tm,a	For m vehicle, survival parameter for vehicle registered in year a
TR	For m vehicle, annual changing rate of parameter Tm, a
kr	For m vehicle, annual changing rate of parameter km, a
VKTm,f,t	In year t, vehicle travelled km for m vehicle with f fuel
VFEm,f,t,a	In year t, fuel economy for m^{th} vehicle with f^{th} fuel registered in year a
FCm,f,t,a	In year t, annual fuel cost of m^{th} vehicle with f^{th} fuel registered in year a
FPf,t	In year t, the unit cost of f^{th} fuel
VACm,f,t,a	In year t, annual acquisition cost of m^{th} vehicle with f^{th} fuel registered in year a
AFRm,f,t,a	In year t, equal share coefficient of annual acquisition cost for m^{th} vehicle with f^{th} fuel registered in year a
i	Discount rate
OMCm,f,t,a	In year t, single O&M cost of m vehicle with f^{th} fuel registered in year a
OMPRm,f,t,a	In year t, the factor of O&M cost for singe m^{th} vehicle with f fuel in year a
ACOm,f,t,a	In year t, the cost of single m^{th} vehicle with f^{th} fuel registered in year a
ATC	The accumulated cost over the planning horizon
INCNRF	Constrained parameters of annual vehicle production capacity
FSGS,t	In year t, constrained supply of gasoline
FSDS,t	In year t, constrained supply of diesel
FSNG,t	In year t, constrained supply of natural gas

Considering private passenger vehicle increased rapidly while the other categories of passenger vehicle increased moderately, the method of GDP elasticity coefficient was employed to forecast private passenger vehicle population while that of linear extrapolation was employed to forecast the other categories of passenger vehicles:

$$\frac{(VP/cap)_t - (VP/cap)_{t-1}}{(VP/cap)_{t-1}} = E_t \cdot \frac{(GDP/cap)_t - (GDP/cap)_{t-1}}{(GDP/cap)_{t-1}} \tag{1}$$

$$\left(\frac{VP}{cap}\right)_{m,t} = p_m \cdot g_t + q_m \tag{2}$$

$$SR_{m,t,a} = \frac{VP_{m,t,a}}{NR_{m,a}} = \exp\left(-\left(\frac{t\text{-}a}{T_{m,a}}\right)^{k_{m,a}}\right) \tag{3}$$

In the planning horizon, the changing law of survival parameters were shown as follows:

$$\begin{gathered} T_{m,a1} = \left(1+TR\right)T_{m,a0} \\ k_{m,a1} = \left(1+kr\right)k_{m,a0} \\ SR_{m,t,a} = \exp\left(-\left(\frac{t-a}{T_{m,a}}\right)^{k_{m,a}}\right) \end{gathered} \tag{4}$$

The population of m category vehicles using f powertrain and fuel could be calculated as follows:

$$VP_{m,t} = \sum_{a=t-TL_m+1}^{t} NR_{m,a} \times S_{m,t-a+1} = \sum_{f} \sum_{a=t-TL_m+1}^{t} (nr_{m,f,a} \times S_{m,t-a+1}) \tag{5}$$

In year t, fuel cost of m category vehicle registered in year a using f type fuel and powertrain:

$$FC_{m,f,t,a} = VKT_{m,f,t} / VFE_{m,f,a} \times FP_{f,t} \tag{6}$$

In year t, the acquisition cost of m category vehicle registered in year a using f type fuel and powertrain:

$$VAC_{m,f,t,a} = VC_{m,f,a} \Bigg/ \sum_{t=a}^{\infty} \frac{SR_{m,t,a}}{\left(1+i\right)^{(t-a)}} \tag{7}$$

In year t, the operation and maintenance cost of m category vehicle registered in year a using fth fuel:

$$OMC_{m,f,t,a} = OMPR \times VC_{m,f,a} \tag{8}$$

In year t, the total cost of m category vehicle registered in year a using f type fuel and powertrain:

$$ACO_{m,f,t,a} = VAC_{m,f,t,a} + OMC_{m,f,t,a} + FC_{m,f,t,a} \tag{9}$$

Over the planning horizon, the accumulated cost of road passenger transport in China, considering the discount rate, could be calculated using the following formula:

$$ATC = \sum_{t=2011}^{2030} \sum_{a=1996}^{t} \sum_{m} \sum_{f} \frac{ACO_{m,f,t,a} \times NRF_{m,f,a} \times SR_{m,t,a}}{\left(1+i\right)^{(t-2011)}} \tag{10}$$

Constrained infrastructure construction cycle of vehicle production and fuel filling station, an upper limit was set for the annual increase of each category of vehicle, as presented in Eq(11), in which INCNRF stand for the upper increase speed:

$$NRF_{m,f,a} \le NRF_{m,f,a-1} + INCNRF \tag{11}$$

Constrained by limited supply of various fuel sources, there existed an upper limit for the annual supply capability of each type of fuel, as presented by Eq(12), in which FS stands for the upper limit:

$$\begin{gathered} \sum_{a=1996}^{t} \sum_{m} FD_{m,GSL,t,a} \times NRF_{m,GSL,t,a} \times SR_{m,t,a} + \sum_{a=1996}^{t} \sum_{m} FD_{m,GSL,t,a} \times NRF_{m,GSL,t,a} \times SR_{m,t,a} \le FS_{GSL,t} \\ \sum_{a=1996}^{t} \sum_{m} FD_{m,DSL,t,a} \times NRF_{m,DSL,t,a} \times SR_{m,t,a} + \sum_{a=1996}^{t} \sum_{m} FD_{m,DSL,t,a} \times NRF_{m,DSL,t,a} \times SR_{m,t,a} \le FS_{DSL,t} \\ \sum_{a=1996}^{t} \sum_{m} FD_{m,NG,t,a} \times NRF_{m,NG,t,a} \times SR_{m,t,a} \le FS_{NG,t} \end{gathered} \tag{12}$$

Based on the modules presented above, the problem of optimising oil-saving pathway for road passenger transportation could be formulated as the linear programming:

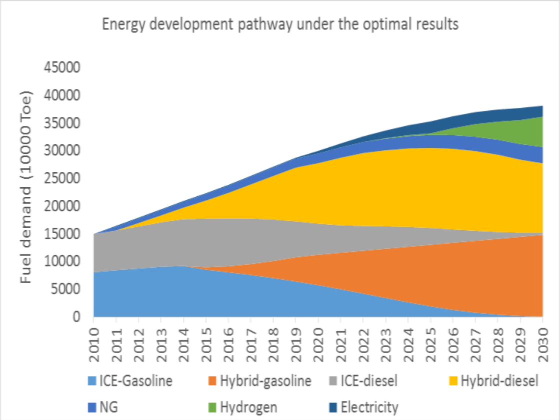
$$\begin{cases} min(ATC) = min \sum_{t=2011}^{2030} \sum_{a=1996}^{t} \sum_{m} \sum_{f} \frac{ACO_{m,f,t,a} \times NRF_{m,f,a} \times SR_{m,t,a}}{\left(1+i\right)^{(t-2011)}} \\ \qquad s.t.\ Eq(1)-(12) \end{cases} \tag{13}$$

3. An empirical study of China

In this section, an empirical study of China was developed with the data input and assumptions, and along with the optimal results.

3.1 Data input and assumptions

Based on the proposed model, we developed an empirical study of China. In this study, 2010 was selected as the base year, and from 2011 to 2030 was selected as the planning horizon. For the optimisation, there were three types of essential data including vehicle data, cost data and constrained fuel supply amount. The data of historical sales and vehicle population of different categories of vehicles was collected from several yearbooks and studies. Survival rate was mainly derived from the study of Hao (2011b), to make the data of historical population and sales keep consistent, some modifications had been made. Vehicle acquisition cost of different categories of vehicles was also collected from several studies (CAERC, 2012). The data of annual travelled distance was mainly derived from studies of Hong H. Over the planning horizon, the annual change rate for the fuel consumption rate was assumed as 0.5 %, 0.75 % and 1 % for light duty vehicle, middle duty vehicle and heavy duty vehicle. The operation and maintenance cost of each vehicle was assumed 4 % of the vehicle acquisition cost. Discount rate was set as 0.1. Considering the infrastructure construction cycle of vehicle production and fuel filling station, the annual newly increased vehicle number was assumed to be less than 300M. It also assumed that the supply amount of gasoline would be 94 and 144 Mt in 2020 and 2030, the supply amount of diesel would be 124 Mt and 199 Mt in 2020 and 2030. The supply amount of vehicular natural gas would be 16.1 Gm^3 and 27.3 Gm^3 in 2020 and 2030 (CAERC, 2012).



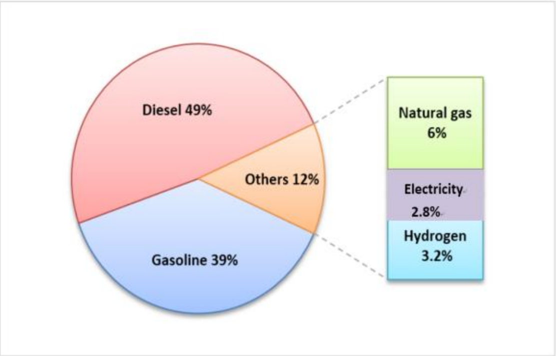


Figure 3: The optimal pathway in terms of vehicle category, powertrain and fuel for road passenger transportation in China

Figure 4: The decomposition of accumulated passenger vehicle fuel demand

3.2 Results

On the basis of the methodology presented in section 2, and data input and assumptions presented in section 3.1, the optimal development pathway of road passenger transportation was obtained, which was shown in Figure.3. It could be seen that: (1) the demand of natural gas and PEV increased slowly with a small amount; (2) the demand of HFCV began to increase moderately in the year of 2023; (3) gasoline and diesel used in the powertrain of ICE increased slightly until 2014 and 2015, then decreased gradually because newly registered vehicles began to choose the powertrain of hybrid along with its acquisition cost decrease. The optimal results also indicated that oil would still remain the dominant vehicle fuel for road passenger transportation. Accumulated oil demand accounted for 88 % of the total fuel demand, amongst which gasoline accounted for 39 % and diesel accounted for 49 %. The amount of diesel demand surpassed that of gasoline, and would be the largest among all the other fuels because the dieselization of private passenger vehicles. The accumulated demand of natural gas, hydrogen and electricity was 1.3, 0.61, and 0.91 Gt (OE) and accounted for 6 %, 3.2 % and 2.8 %, which was shown in Figure.4.

4. Conclusion and discussion

This paper proposed a cost-optimisation superstructure model to plan the most cost-effective oil-saving pathway for road passenger transportation. Based on the model, an empirical study of China's road passenger transportation was developed over the planning horizon between 2010 and 2030. The optimal oil-saving pathway indicated that hybrid vehicle using gasoline and diesel would offer a promising path to achieve cost-effective reduction in oil use. At the same time, other advanced vehicles, including hydrogen fuel cell or pure electric vehicles, would continue to suffer from high cost and other limitations. Their limited market penetration means that their impact on fuel use is unlikely to be significant over the next two decades. Although vehicle powertrain would transfer to hybrid, gasoline and diesel would still remain the dominant vehicle fuel, and the accumulated demand of gasoline and diesel accounted for 88 % of total fuel demand, while electricity, hydrogen and natural gas accounted for approximately 3.2 %, 2.8 % and 7 %. From the optimal results, it also could be concluded that the cost-optimal oil saving potential was 61 and 126 Mt (OE) in 2020 and 2030 through comparing with another study.

Reference

Börjesson M., Ahlgren E.O., 2012. Modelling transport fuel pathways: Achieving cost-effective oil use reduction in passenger cars in Sweden. Technological Forecasting and Social Change, 79, 801-818.

Baran R., Legey L.F.L., 2013. The introduction of electric vehicles in Brazil: Impacts on oil and electricity consumption. Technological Forecasting and Social Change, 80, 907-917.

CAERC, 2012. China automotive energy outlook 2012. Science Press, Beijing, China.

NBSC-National Bureau of Statistics of China, 2013. China energy statistical yearbook 2013. China Statistics Press, Beijing, China.

Gabriela C., Yanina F., Jorge M., 2013. A Mixed-Integer Linear Programming Approach for Simultaneous Ethanol Supply Chain and Involved Plants Design Considering Production Scheduling. Chemical Engineering Transactions, 32.1159-1164.

Gass V., Schmidt J., Schmid, E., 2014. Analysis of alternative policy instruments to promote electric vehicles in Austria. Renewable Energy, 61, 96-101.

Hao H., Wang H., Ouyang M., 2011a. Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China’s passenger vehicle fleet. Energy, 36, 6520-6528.

Hao H., Wang H., Ouyang M., Cheng F., 2011b. Vehicle survival patterns in China. Science China Technological Sciences, 54, 625-629.

Hao H., Wang H.W., Ouyang M.G., Cheng, F., 2011c. Vehicle survival patterns in China. Science China Technological Sciences, 54, 625-629.

Houtang, C., 2012. Analytical Review of 2012 Middle and Large-size Bus and Coach Market. Data and industry analysis 2013, 110-118.

Kyle P., Kim S.H., 2011. Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. Energy Policy, 39, 3012-3024.

Ou X., Zhang X., Chang S., 2010a. Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. Energy Policy, 38, 406-418.

Ou X., Zhang X., Chang S., 2010b. Scenario analysis on alternative fuel/vehicle for China’s future road transport: Life-cycle energy demand and GHG emissions. Energy Policy, 38, 3943-3956.

Ouyang M.G., 2006. The development strategy and measures of energy conservation and new energy vehicle. Automotive Engineering, 28, 317-321.

Wang Q.Y., 2011. Reference Source of China Sustainable Energy Program: 2011 Energy Statistics, in: China Sustainable Energy Program funded by David and Lucille Pike Foundation, W.a.F.H.F. and US Energy Foundation (Ed.), Beijing, China.

Wei L., 2012. The research on the demand fluctuations and composite index of China's car market (In Chinese), Western economics. Anhui University, Hefei, China.

Xian Z., 2007 (In Chinese). The Analysis of The traffic Energy Demand and The Environmental Emissions for The Year 2008 in Beijing Environment Engineering. Beijing Jiaotong University, Beijing, China.

Xianjing R., 2010 (In Chinese). Research on The technical and Economies Comprehensive Evaluation of New Energy Vehicle and its development Strategy, Economics and Management of Technology. Wuhan University of Technology, Wuhan, China.

Yan X., Crookes, R.J., 2009. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Policy 37, 658-668.