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Modeling uncertainty in estimation of carbon dioxide abatement costs of energy-saving technologies for passenger cars in China

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ABSTRACT

Estimation of carbon dioxide abatement cost is of the essence to promote energy-saving technologies (ESTs) in the passenger car sector, while the existence of various uncertainties of abatement cost may be major barriers for technology promotion. This study establishes the projected marginal abatement cost (MAC) curve of China's passenger car sector over the 2016–2030 period and conducts uncertainty modeling through Monte Carlo simulation. The impacts of uncertainties from oil price, electricity cost, energy-saving potential, incremental investment cost, and emission factor for electricity consumption on emission abatement costs of ESTs are analyzed separately and compared together. Results show that among the five uncertainties, oil price uncertainty has the largest impact on ESTs' emission abatement cost, but the impact does not differ significantly among different technology bundles. Uncertainties in electricity cost and in electricity emission factor affect significantly the MACs of new-energy paths. Compared with the above two uncertainties, uncertainties in energy-saving potential and in incremental investment cost have larger impacts on the MACs of traditional energy-saving paths. Among different vehicle types, the MACs of ESTs on small-displacement private cars are the least affected by various uncertainties.

1. Introduction

The passenger car sector is one of the major sources of energy use and carbon dioxide (CO_2) emissions in China. As an important part of the passenger car sector, the energy consumption of private cars increased from 7.48 million tons of coal equivalent (Mtce) in 1997 to 108.48 Mtce in 2012, accounting for 3% of China's final energy use.[1] With rapid urbanization, China's demand for passenger cars will keep growing in the foreseeable future, leading to more severe energy and environmental problems.

It is effective to save energy and reduce CO_2 emissions by promoting energy-saving technologies (ESTs) for passenger cars. Key vehicle technologies have already been proposed by the State Council since 2012 in the *Planning for the Development of the Energy-saving and New-energy Automobile Industry (2012–2020)*, including hybrid technology, advanced internal combustion engine, high-performance transmission, electronics, and lightweight materials (The State Council, 2012). China's new-energy vehicle industry developed rapidly but failed to reach the expected target during the 12th five-year period (2011–2015). The cumulative sales volume of the new-energy vehicles in China totaled about 450,000 in 2015 (China Association and Automobile Manufacturers, 2016), still less than the industrial target of 500,000.

There are many obstacles in the market promotion of ESTs for vehicles, such as slow technology progress, high emission abatement cost, incomplete facilities, low consumer acceptance, and so on. This study analyzes the ESTs for vehicles mainly from the perspective of emission abatement cost. According to Peng et al. (2016), the high abatement costs of some ESTs may result in underinvestment. Even when the abatement costs of some ESTs are low, they might obviously fluctuate with high cost risk due to various uncertainties, thus hindering the technology promotion. The phenomenon that the theoretically cost-effective technologies are delayed or not implemented is called the energy-efficiency paradox (DeCanio, 1998), of which future uncertainty is one of the potential causes (Hassett and Metcalf, 1993). Uncertainties that may influence the abatement cost of vehicle ESTs include oil price, electricity cost, and emission factor for electricity consumption, energy-saving potential, incremental investment cost, and discount rate, technology learning rate (TLR), and so on. These uncertainties together might result in large fluctuations of the abatement cost, and these impacts might probably differ among various ESTs. Therefore, to provide

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policy recommendations for promoting ESTs in the passenger car sector, it is essential to separately investigate the impact of each uncertainty on the emission abatement cost and try to answer the following questions: 1) How do the uncertainties from diverse sources impact the emission abatement costs of ESTs for passenger cars? 2) What is the heterogeneity of impact among various ESTs? 3) How to handle these uncertainties to promote low-carbon technologies in the transport sector?

Marginal abatement cost (MAC) is often used to present findings on the economics of climate change mitigation and to provide a basis for decision making in climate policymaking. The MAC is usually defined as the costs to pay for per additional unit of CO_2 abatement (Huang et al., 2016). The MAC curves can be divided into model-derived and expert-based types according to the modeling methods (Kesicki, 2013). Both the bottom-up and top-down models can generate the MAC curves. MARKAL/TIMES is one of the most widely-used bottom-up models to build the MAC curves of detailed technologies (Kesicki, 2012, 2013). Chen (2005) established China's MAC curves of carbon based on MARKAL-MACRO and simulated the impacts of carbon emission abatement on GDP. Kesicki (2012) derived the MAC curve for UK transport sector using UK MARKAL and tested the influence of path dependency and discount rate on MAC's shape and structure. Top-down approach focuses on the cost of reducing carbon emissions from a macroeconomic perspective and the derived MAC curve is continuous. Klepper and Peterson (2006) built the MAC curve based on CGE model and investigated the influence of energy prices on the MAC. Xia and Fan (2012) used input-output-econometrics optimal assembly model to investigate the dynamics of China's MAC.

This paper focuses on the expert-based (or measure-explicit) MAC curves, which are built using a bottom-up financial-accounting method and different from those derived from energy system optimization models (Huang et al., 2016). The expert-based MAC curves present the marginal abatement cost and abatement potentials for a set of ESTs on passenger vehicles, ranking the ESTs from the least to the most costly (Vogt-Schilb and Hallegatte, 2014). Some studies established the MAC curves for different countries or sectors from a global perspective (Enkvist et al., 2007, 2010; Wagner et al., 2012). More investigations were conducted for a specific country at the sector level, including industry sectors such as cement or iron and steel (Worrell et al., 2000; Hasanbeigi et al., 2013a, 2013b), land-use sectors such as agriculture and forestry (MacLeod et al., 2010; De Cara and Jayet, 2011; Moran et al., 2011), and the transport sector (Spencer, 2008; Lutsey and Sperling, 2009; Peng et al., 2016).

An obvious limitation of the MAC curve lies in its difficulty to characterize future uncertainties (Kesicki and Strachan, 2011; Kesicki and Ekins, 2012). Nevertheless, many studies have tried to quantify the impacts of uncertainties on the emission abatement cost. The uncertainties they discussed included the discount rate (Kesicki, 2012; Li and Zhu, 2014; Peng et al., 2016), scenario setting and path dependency (Kesicki, 2012; Wagner et al., 2012; Li and Zhu, 2014), and technology innovation or learning (Amir et al., 2008; Baker et al., 2008; Bauman et al., 2008), oil price (Klepper and Peterson, 2006; Kesicki, 2013), emission reduction target (De Cara and Jayet, 2011), and financial crisis (Enkvist et al., 2010), the greenhouse gas accounting method (O'Brien et al., 2014), and so on.

However, these studies usually considered only one or two specific uncertainties and they usually emphasized on the CO_2 abatement cost and potential rather than the impacts of uncertainties. In these studies, the uncertainties are analyzed as a secondary problem, often through scenario or sensitivity analysis. Monte Carlo simulation could provide the possibility of incorporating various uncertainties into the bottom-up expert-based framework, but has not been commonly used in literatures due to the lack of technological detail. Therefore, studies focusing on the impacts of uncertainties on the abatement cost, using probability assessment or stochastic modeling, are still insufficient. To the best of the authors' knowledge, only two studies have used Monte Carlo simulation to investigate the impacts of integrated uncertainty on the MACs in the transport sector (Valenzuela et al., 2017; Fan et al., 2017). However, neither of them has done a separate analysis on each of the major uncertainties or compared the impacts of different uncertainties. Therefore, this study attempts to fill the gaps in previous studies concerning uncertainty modeling in the marginal abatement cost.

This study establishes the projected MAC curve of China's passenger car sector over the 2016–2030 period, using bottom-up methods. Monte Carlo simulation is used to conduct the probability assessment of the MAC. Next, five uncertainties (oil price, electricity cost, energy-saving potential, incremental investment cost, and emission factor for electricity consumption) that influence the MAC are analyzed separately and compared together, focusing on the different impacts of uncertainties on the MACs. Finally, this study evaluates the major diffusion barriers to various ESTs in terms of cost-effective analysis and provides recommendations for technology promotion at last.

2. Methodology

2.1. Calculation of the abatement cost

CO_2 emissions abatement could provide many benefits in terms of environment, ecology and health. However, the benefits of CO_2 abatement in this study are limited to a relatively narrow sense, including only the energy-saving benefit, from a financial-accounting perspective. In this paper we focus on the expert-based marginal abatement cost curve which ranks the ESTs from the least to the most costly. The word "marginal" refers to per additional abatement technology (discrete ESTs) rather than per additional CO_2 reduction potential (continuous value). Though the average abatement cost for an EST is calculated, it is called the MAC of the EST and represents the cost to reduce an additional unit of CO_2 emissions when all the prior ESTs in the rank have been implemented.

The passenger cars in China are divided into 11 types, based on the demand-side purpose and vehicle engine displacement. The ESTs are classified into 5 paths or 7 technologies, and each path consists of 4 or 5 of the 7 technologies, according to National Research Council (NRC) (2011) and National Highway and Traffic Safety Administration (2008). In total, 55 type-path and 246 type-path-technology bundles are defined for the investigation of the emission abatement cost (Peng et al., 2016). Table 1 shows different vehicle types, paths, and technologies.

The CO_2 emission abatement cost is the incremental full cost due to the implementation of an EST (compared with the baseline option) divided by the total CO_2 reduction (Enkvist et al., 2010).

Table 1
Classification of vehicle type, path and technology.

11 vehicle types	5 vehicle paths	7 vehicle technologies
P-SCC	SI-path	SI-tech
P-CC	Diesel-path	Diesel-tech
P-MC	HEV-path	Elec_acc-tech
P-LC	PHEV-path	Trans-tech
P-HPC	EV-path	Hybrid-tech
B-SCC		Vehicle-tech
B-CC		Pure_elec-tech
B-MC		
B-LC		
B-HPC		
T-CC		

Note: P: Private; B: Business; T: Taxi; SCC: SubCompact Car; CC: Compact Car; MC: Midsize Car; LC: Large Car; HPC: High-performance Car; SI: spark ignition; HEV: hybrid electric vehicle; PHEV: plug-in hybrid electric vehicle; EV: electric vehicle; Elec_acc: electrification/accessory; Trans: transmission; Vehicle-tech: vehicle body technology; Pure_elec: pure electric.