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Toward the 2-degree target: Evaluating co-benefits of road transportation in China

Xu Tian [a,b], Hancheng Dai [c], Yong Geng [a,d,e,h,*], Shaohui Zhang [f,g], Yang Xie [f,**], Xiaorui Liu [c], Pantao Lu [c], Raimund Bleischwitz [b,***]

[a] School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai, 200030, China
[b] Institute for Sustainable Resources, Bartlett School of Environment, Energy and Resources, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom
[c] College of Environmental Sciences and Engineering, Peking University, No.5 Yiheyuan Road, Beijing, 100871, China
[d] China Institute of Urban Governance, Shanghai Jiao Tong University, No. 1954, Huashan Road, Shanghai, 200030, China
[e] Shanghai Institute of Pollution Control and Ecological Security, Shanghai, 200092, China
[f] School of Economics and Management, Beihang University, Beijing, 100191, China
[g] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361, Laxenburg, Austria
[h] School of Management, China University of Mining and Technology, No.1 Daxue Road, Xuzhou, China

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ABSTRACT

Background: Co-benefit assessments on health and economic impacts of climate change mitigation towards the 2-degree target are still largely insufficient in literature, especially from a sectoral perspective.
Objectives: This study aims to (1) evaluate $PM_{2.5}$ pollution-related health impacts on China's road transport sector at both national and provincial levels towards the 2-degree target by 2050; (2) uncover the contribution from the road transport sector compared with that of all sectors; (3) distinguish the contribution from climate change mitigation actions compared with air pollution control oriented actions in road transport sector; and (4) identify the heterogeneous influences at the provincial level.
Methods: Health and economic impacts are estimated using an integrated approach that combines the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model, the IMED/CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development/computable general equilibrium) model and IMED/HEL (Health) model. Five scenarios are proposed based on climate change mitigation and stringency of air pollution control policy.
Results: It is found that China's road transport sector could contribute to around 10.6% of total $PM_{2.5}$ concentration reduction resulting from all sectors' participation in achieving the 2-degree target, equivalent to 10.8% of the monetized health benefits obtained from achieving the 2-degree target by all sectors. Populous provinces dependent on secondary industries would benefit more under the 2-degree target. Meanwhile, compared with the potential maximum benefits from air pollution control oriented measures in the road transport sector, such climate actions could bring noticeable synergies as well. Approximately climate change mitigation action alone can lead to 70% reduction of health impacts by applying air pollution control measures.

* Corresponding author. School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai, 200030, China.
** Corresponding author.
*** Corresponding author.
E-mail addresses: ygeng@sjtu.edu.cn (Y. Geng), xieyangdaisy@buaa.edu.cn (Y. Xie), r.bleischwitz@ucl.ac.uk (R. Bleischwitz).

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Conclusions: This research has implications for other emerging economies and those reluctant to engage in climate action and is deserving of further attention. The government should also realize the heterogeneity of road transport sector development in different provinces, and adopt a more flexible policy approach to take into account regional pollution levels and abatement options.

1. Introduction

In order to build up a low carbon future, the Paris Agreement set the 'well below 2-degree target' for strengthening the global response to the threat of climate change (UNFCCC, 2018). This ambitious target leads to manifold questions over trade-offs and synergies related to abatement strategies. Although many countries pledged to combat climate change via nationally determined contributions (NDCs), the implications such as co-benefits and trade-offs toward a 2-degree target are not fully explored and still have a lot of uncertainty (Hanaoka and Masui, 2017). The related uncertainty would further challenge those policymakers and affect the achievement of the 2-degree target.

As the world's largest carbon emitter, China has made great efforts on responding to climate change. Pledging that by around 2030, China would lower carbon dioxide emissions per unit of GDP (Gross Domestic Product) by 60%–65% from the 2005 level (UNFCCC, 2018). In addition, China is facing severe challenges in treating air pollution. China's outdoor air pollution caused more deaths with high concentrations of fine particulate matter pollutant ($PM_{2.5}$) than in any other countries (Lelieveld et al., 2015; Meng et al., 2015; Cai et al., 2017; Lanzi et al., 2018). Therefore, the analysis of co-benefits related to climate change mitigation and health problems caused by air pollutants is crucial for China. In particular, it is necessary to investigate the co-benefits between carbon emission reduction and air pollutants for China as a whole, as well as across different Chinese provinces.

In order to achieve such a research goal, methodological assessment challenges need to be addressed. Previous studies show that climate change mitigation could bring co-benefits to the improvement of air quality, mainly from climate policy (Liu et al., 2014; Dong et al., 2015), air pollution regulation (Nam et al., 2013; Li et al., 2017), energy policy (Peng et al., 2018), economic instruments (Mao et al., 2012) and consumer behaviors (Liang et al., 2016). In terms of air pollutants reduction, previous studies have found that climate change mitigation could bring the co-benefits to offset the related health issues and economic impacts. For instance, Peng et al. (2018) found that half decarbonized power supply (~50% coal) for electrification of the transport and/or residential sectors leads to a 14–16% reduction in carbon emissions and air quality and health co-benefits (55,000–69,000 avoided deaths in China annually) than coal intensive electrification in 2030. Xie et al. (2018) estimate that the climate change mitigation could reduce premature deaths in Asia by 0.79 million by 2050, which is equivalent to a life value savings of approximately 2.8 trillion USD. Although such previous studies identified the co-benefits between climate change mitigation and air pollutants reduction (He et al., 2010; Takeshita, 2012; Dong and Liang, 2014; Dong et al., 2015; Liang et al., 2016), a comprehensive study that assesses co-benefit of the 2-degree target is still lacking. In addition, there are few studies focusing on the economic impacts of one certain sector, especially the major sectors that contribute to ambient air pollution. Therefore, it is important to initiate such studies for preparing national policies on both climate actions and public health, and in particular for the wider debates on economic impacts (Hanaoka and Masui, 2017; Wu et al., 2017; Watts et al., 2018; Xie et al., 2018).

Road transport is a key sector, as it is critical to both economic development and environmental protection. It is reported that road transport has the largest effect on global warming (Berntsen and Fuglestvedt, 2008). In addition, road transport accounts for 18.4% of total PM emissions worldwide (Xia et al., 2015). Long-term exposure to traffic-related air pollution is associated with increased mortality from respiratory and cardiovascular diseases and lung cancer, which shortens life expectancy (Künzli et al., 2000; Zhang et al., 2017). For China, carbon emissions from China's transport sector accounted for 10% of the overall emissions in 2012, contributing to the largest portion in the whole transport sector (Dai et al., 2017). Furthermore, it is predicted that rapid growth of road transportation in China would likely continue in the next two to three decades (Yan and Crookes, 2010). In addition, He and Qiu, (2016) found that air pollution from the road transport sector in China has led to substantial increases in the risk of lung cancer, respiratory and cardiovascular diseases. Although several studies explored the health impacts of air pollution from the transport sector (Pan et al., 2016; Liu et al., 2018), few studies estimated the associated health and economic benefits, especially in China (Tian et al., 2018). In addition, given the provincial heterogeneity of air quality and socio-economic conditions, the health impacts would be region-specific across the whole country. However, to the best of our knowledge, the co-benefits impact of China's road transport sector toward the 2-degree target on human's health and regional economy at the provincial level in China have not been investigated. Consequently, it is critical to initiate such a study so that valuable policy insights can be provided to the Chinese decision-makers, which might also be valuable to other countries with similar challenges.

Under such circumstances, this study aims to uncover both health and economic impacts caused by $PM_{2.5}$ pollution from the road transport sector in 30 Chinese provinces toward the 2-degree target, to answer three questions: (1) Identifying the role and co-benefits of China's road transport sector toward the 2-degree target at national and provincial levels (2) Exploring the differences in health and economic impacts of climate change mitigation toward the 2-degree target at provincial level (3) Assessing co-benefits in terms of health and air quality improvement brought by climate change mitigation, compared with the maximum benefits resulting from technology upgrade. This study adopts an integrated approach, which closes the economy-environment-health loop by combining an air quality assessment model, an economic model, and a health assessment model so that the complex interactions between the environment, public health, and economic aspects can be uncovered.

2. Methods

This study integrates three models, including the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model, the IMED/HEL (Integrated Model of Energy, Environment and Economy for Sustainable Development/health) model and the IMED/CGE (Computable General Equilibrium) model, to identify the health and economic impacts of $PM_{2.5}$ pollution from the road transport sector at the national and provincial levels in China toward 2-degree target. Both IMED models are developed by the Laboratory of Energy & Environmental Economics and Policy (LEEEP) at Peking University. All three models cover 30 Chinese provinces except for Tibet, Hong Kong, Macau and Taiwan. Fig. 1 shows the interactions between these models. In this study, emissions such as NO_X, SO_2, $PM_{2.5}$ and CO_2 are from the GAINS model. Health impacts such as annual mortality, risk of morbidity and work time loss caused by $PM_{2.5}$ pollution are identified via the IMED/HEL model. After combining IMED/HEL and IMED/CGE models, economic impacts such as extra health care expenditures and the maximized embodied economic value (MEEV) based on the values of statistical life (Andersson and Treich, 2011) are presented in our current study. The technical introduction on the IMED model framework, including the IMED/CGE and IMED/HEL models, is available at http://scholar.pku.edu.cn/hanchengdai/imed_general.

Five scenarios are established based on various climate change mitigation and air pollution control policies. Table 1 shows the details of these five scenarios.

The BaU (business-as-usual) scenario is the baseline scenario in this CGE model, which assumes that the health impacts from $PM_{2.5}$ pollution are ignored. Although this scenario simulates an ideal situation that does not exist in reality, it can be used to evaluate the negative macroeconomic impacts of pollution and benefits by comparing with other scenarios. The other four scenarios consider the health impacts caused by $PM_{2.5}$ pollution.

REF scenario assumes that except for the current legislations, no additional air pollution controls are applied in the GAINS model.

2DEG_all scenario assumes all sectors will take actions toward achieving 2-degree scenario, implying that the total energy consumption of China is in line with the decarbonization scenario in the International Energy Agency (IEA) report, which has the objective of limiting the average global temperature increase in 2100 to 2 degrees Celsius above pre-industrial levels (IEA, 2016).

2DEG_RT scenario assumes that only the road transport sector will take action to achieve the 2-degree target. Energy consumption of transport sector will be in line with the 450 scenario in IEA report whereas that of other sectors will be in line with the REF scenario. After comparing 2DEG_all scenario and 2DEG_RT scenario, the contribution of the road transport sector in all sectors can be assessed.

The TECH scenario assumes strict air pollution controls associated with fuel standards and vehicle technology standards will be implemented beyond the current legislations. By comparing the REF scenario with both 2DEG_RT and TECH scenarios, the health and economic impacts of the different control measures can be quantified. Furthermore, after comparing the above impacts from 2DEG_RT and TECH scenarios, co-benefits can be evaluated in terms of climate change mitigation.

2.1. Modelling the emissions and $PM_{2.5}$ concentration scenarios

The GAINS-China model is applied for estimating air-pollutants and $PM_{2.5}$ concentration from the road transport sector in 30

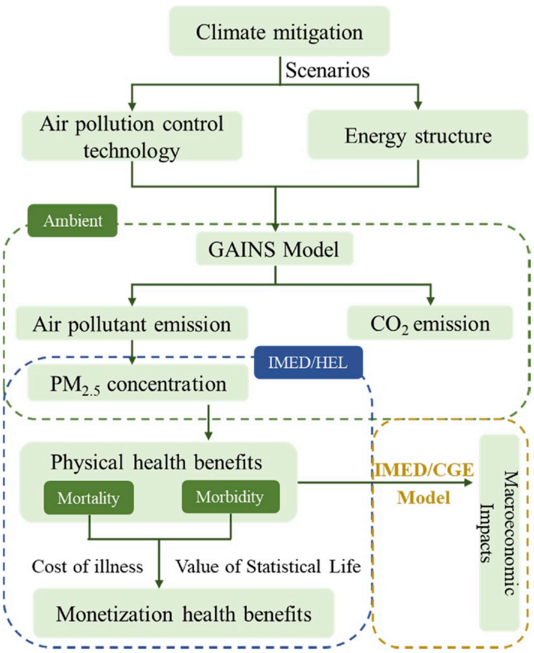

Fig. 1. Research framework.

Table 1
Explanations of five scenarios.

Scenario	Health impact	Climate change mitigation measure	Air pollution control measure
BaU	Ignored	None	None
REF	Not ignored	None	Current legislation without additional control
2DEG_all	Not ignored	2-degree standard in all sectors	Current legislation without additional control
2DEG_RT	Not ignored	2-degree standard in road transport sector only	Current legislation without additional control
TECH	Not ignored	None	Strict additional control

Chinese provinces. It allows for a comprehensive and integrated analysis on air pollution and climate change mitigation strategies, which generates important synergies and trade-offs between these policies. GAINS quantifies technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases (Amann et al., 2008). The basic principle of calculating emissions is presented in Equation (1).

$$Emissions = \sum_i Activity_i \times F \times (1 - r) \times C \tag{1}$$

Where, F (emission factors of activities), r (removal efficiencies of control technologies), C (control technologies) for each activity are specified in control strategies.

We set up the REF scenario, assuming that no climate policies and air mitigation technology measures are applied in the GAINS model.

Two climate control scenarios toward 2-degree target (2DEG_all and 2DEG_RT) were also set up in this GAINS model. 2DEG_all scenario assumes that all sectors will take actions toward the 2-degree target. All the parameters in this scenario are from the WEO2016_450 scenario in the GAINS model, which keeps consistent with the decarbonization scenario in the IEA report. The major character of energy consumption in China's 2-degree scenario is that electricity dominates the total final energy consumption, following by oil. In particular, different sectors have different energy consumption features. For instance, energy consumption in the transport sector is mainly driven by oil and electricity, while energy consumption in the building sector is mainly driven by electricity and bioenergy.

Under the 2DEG_RT scenario, the pathway of China's road transport sector is changed in the GAINS model according to the energy consumption of IEA report under China's 2-degree scenario. The major character of China's 2-degree scenario is that although oil is still the most important energy source, the proportion of electricity, natural gas and biofuels will increase significantly in the future.

Strict air mitigation technology measure implemented in road transport sector is presented by the TECH scenario in the GAINS model. Control strategy for road transport sources and control strategy for SO_2 are changed according to the fuel standards and vehicle technology standards. Fuel standards mainly include natural gas, gasoline, biofuels, electricity, etc. Vehicle technology standards are from low to high with different types of vehicles, such as the EURO 1–6 on light duty spark ignition road vehicles. The setting of this TECH scenario is kept consistent with our previous study (Tian et al., 2018). In our current study, we assume that each province would apply the strictest standards for road vehicles in 2050 based on the implementation of new vehicle emission standards in China. Take China's light vehicle-VI emission standard as an example, this standard would be implemented in different provinces in late 2019 or 2020. This standard stipulates the emission limits and measurement methods of exhaust pollutants, actual driving exhaust pollutants, crankcase pollutants, evaporative pollutants, and refueling pollutants of light vehicles at normal temperature and low temperature, and pollution control devices. It also includes technical requirements and measurement methods for on-board diagnostics (OBD) systems. Two emission limit schemes exist, namely, VI-a and VI-b. VI-b is stricter than the EURO VI standard. by considering these conditions, we assume that all road transport vehicles will follow the strictest emission standard in 2050.

Based on the detailed spatial and sectoral GAINS emissions inventory, GAINS computes ambient concentrations of $PM_{2.5}$ with the help of source-receptor relationships derived from an atmospheric chemistry-transport model (the TM5 model) (Amann et al., 2008). By comparing the REF scenario with 2DEG_all/2DEG_RT/TECH scenarios, the emissions and $PM_{2.5}$ concentrations of the different control measures can be quantified.

2.2. Modelling health impacts

The IMED/HEL model is used to quantify the health impacts of $PM_{2.5}$ concentration on six morbidity endpoints (respiratory hospital admissions, cerebrovascular hospital admission, cardiovascular hospital admissions, chronic bronchitis, asthma attacks, respiratory symptoms days), the chronic mortality and the work-loss day. The advantage of this model is that both linear and non-linear exposure-response functions (ERFs) with concentration level are identified. The function of our health model is to quantify the health burden from air pollution and the benefits of air pollution control policy. The health burden mainly includes health expenditure on air pollution-related diseases and work time loss of air pollution-related mortality and morbidity. Using this health model, medical expenditure and the value of statistical life (VSL) loss caused by $PM_{2.5}$ pollution could be estimated. In this study, the settings of IMED/HEL model refer to our previous studies (Xie et al., 2016; Wu et al., 2017; Tian et al., 2018). After this, the health impacts from different scenarios are quantified and compared.

2.3. Modelling economic impacts

The IMED/CGE model evaluates macro economic impacts. It can be classified as a multi-sectors, multi-regions, recursive dynamic CGE model that covers 22 economic commodities and corresponding sectors. It could capture the full range of interaction and feedback effects between different components in the economic system, which provides a more systematic estimation on measuring the economic impact of air pollution. The results of work time loss from this health model are inputs as disturbance variables to the CGE model so that macroeconomic impacts can be simulated. It also allows the comparison and quantification of different impacts from different scenarios. More details of this IMED/CGE model could be found in our previous studies (Tian et al., 2018; Wu et al., 2017; Xie et al., 2016). In addition, The BaU scenario in this CGE model assumes that the health impacts from $PM_{2.5}$ pollution are ignored. The socio-economic assumptions in China can be found in Supporting Information (SI)-Table S1.

3. Results

3.1. The role of road transport sector toward the 2-degree target

Table 2 shows the effects of climate change mitigation on emissions reduction of all sectors under the 2DEG_all scenario and the road transport sector alone under the 2DEG_RT scenario in 2050, as well as the corresponding health and economic impacts. For the whole China, due to the reduction of energy consumption, the climate policy toward the 2-degree target would lead to 11.9 million ton (Mt) of NO_X, 3.0 Mt of $PM_{2.5}$, 12.4 Mt of SO_2, and 12493.3 Mt of CO_2 emissions reduction. In terms of air quality improvement, the $PM_{2.5}$ concentration would be reduced by 23.5 μg/m^3 in 2050. Consequently, the health indicators would improve significantly. For instance, mortality would be reduced by 837.1 thousand, morbidity risk would be reduced by 2.0%, 31.5 billion USD (B.USD) of additional expenditure would be saved, per capital work time loss would be lowered by 4.0 h, and 582.3 B.USD of MEEV would be recovered. As a whole, after achieving the 2-degree target, the whole country would gain 613.8 B.USD (about 4.2% of GDP) in 2050.

When the climate change mitigation strategy is only implemented in the road transport sector, the above indicators will decrease as well. By comparing the reductions in the 2DEG_RT scenario with those in the 2DEG_all scenario in which all sectors cut emissions, the contribution of the road transport sector could be distinguished. For instance, 20.9% of NO_X emission reduction (2.5 instead of 11.9 Mt) could be attributable to road transport sector. Similarly, climate actions in this sector account for 7.6% of total $PM_{2.5}$ emission reductions, 0.4% of total SO_2 reductions, 5.4% of total CO_2 reductions and 10.6% of $PM_{2.5}$ reduction. As a result, among all health benefits due to climate change mitigation, 10.7% of mortality, 10.8% of morbidity, 11.0% of additional expenditure, 8.7% of work time loss, and 10.7% of MEEV are attributable to the road transport sector. By using VSL and Cost of Illness (COI) approaches, the economic benefit is equivalent to 10.8% of the whole China's economic gain.

3.2. The impact of road transport sector toward the 2-degree target at the provincial level

3.2.1. Emissions and additional $PM_{2.5}$ concentration

Fig. 2 shows the reduction of emission and $PM_{2.5}$ concentration under climate change mitigation at the provincial level in 2050. In accordance with energy consumption saving in each province in 2050, the emissions would also be reduced. For instance, the climate change mitigation effort will bring the highest reduction in NO_X, SO_2, and $PM_{2.5}$ emissions in those populous regions which are more dependent on industries such as Shandong, Guangdong, Jiangsu, Hebei and Henan provinces. On the other hand, those provinces with less population or less developed industries such as Ningxia, Qinghai and Shaanxi provinces have the lowest emission reduction.

Emissions reduction could further lead to the reduction of $PM_{2.5}$ concentrations. Compared with REF scenario, $PM_{2.5}$ concentration would decrease by around 1.3%–6.0% in most provinces. The top reduction provinces mainly locate in central and eastern China, such

Table 2
The role of the road transport sector towards 2-degree goal in 2050.

Items	2DEG_all	2DEG_RT	Road transport sector contribution (%)
Emission (Mt) and $PM_{2.5}$ concentration (ug/m^3) reduction			
NO_X	11.9	2.5	20.9%
$PM_{2.5}$	3.0	0.9	7.6%
SO_2	12.4	0.1	0.4%
CO_2	12493.3	677.6	5.4%
$PM_{2.5}$ concentration	23.5	2.5	10.6%
Health impacts reduction			
Mortality (Thousand deaths)	837.1	90.0	10.7%
Morbidity (%)	2.0%	0.2%	10.8%
Expenditure (Billion USD)	31.5	3.5	11.0%
Work time loss (Per capital-hours)	4.0	0.3	8.7%
MEEV (Billion USD)	582.3	62.5	10.7%
Economic impacts reduction (Billion USD)			
Benefit	613.8	66	10.8%

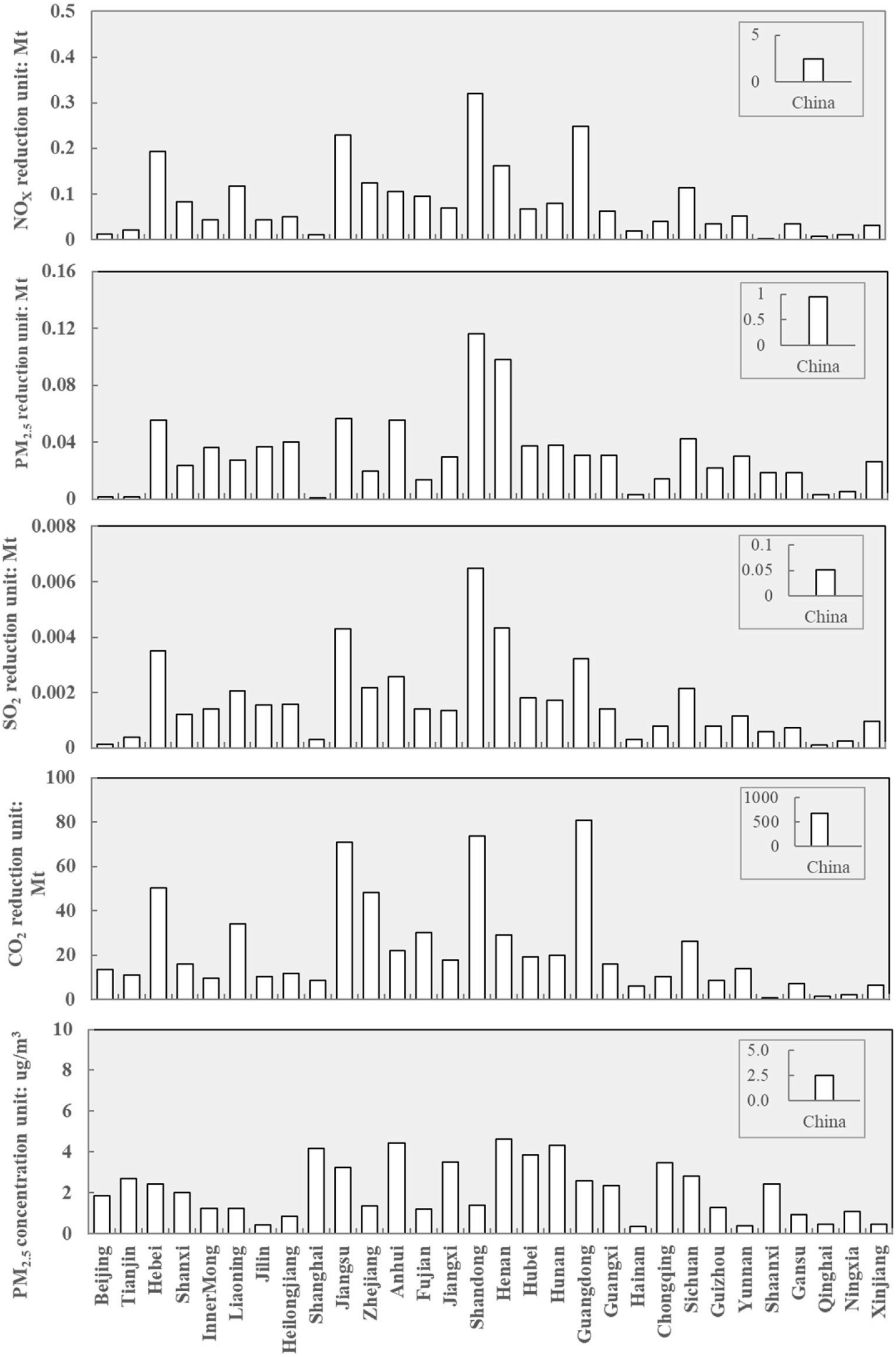

Fig. 2. The emission and $PM_{2.5}$ concentration reductions under climate change mitigation in 2050.

as Henan (reduction by 5.6%, or 4.6 μg/m^3), Anhui (by 5.8%, or 4.4 μg/m^3), Hunan (by 5.5%, or 4.3 μg/m^3), Shanghai (by 6.0%, or 4.2 μg/m^3) and Hubei (by 5.0%, or 3.9 μg/m^3). By contrast, provinces such as Hainan (by 1.7%, or 0.3 μg/m^3), Yunnan (by 1.3%, or 0.4 μg/m^3) and Qinghai (by 3.2%, or 0.5 μg/m^3) would experience lower reduction.

3.2.2. The health and economic impacts

Exposure to a high level of $PM_{2.5}$ concentrations could increase the risk of suffering from $PM_{2.5}$ pollution-related health problems. The implementation of climate change mitigation under the 2DEG_RT scenario could reduce the number of patients by around 2.0%–45.5% in most provinces, and the provinces with a higher reduction in $PM_{2.5}$ concentration would avoid more health loss. For instance, Henan would avoid annual mortality by 12.4 thousand people, while Hainan would only avoid 0.07 thousand of annual mortality.

The health problem caused by $PM_{2.5}$ pollution would lead to additional health expenditure, the magnitude of which depends on climate change mitigation, income level and medical facility level in different provinces. The top provinces with the most reduction of extra medical expenditures under the 2DEG_RT scenario are Sichuan, Hunan, Hubei and Anhui, decreased by 54.2 Million USD (M. USD), 45.0 M.USD, 36.8 M.USD and 42.8 M.USD, respectively, equivalent to 0.01% of their GDPs.

In terms of mortality risk reduction after climate change mitigation, avoided MEEV loss would be more in Henan and Hunan provinces which have the most $PM_{2.5}$ pollutant reductions. Besides that, high-income and more developed provinces such as Jiangsu and Guangdong would also avoid more MEEV loss. It is probable that with better quality of life, people would pay more attention to health effects. Meanwhile, investment for environmental improvement in developed regions would bring substantial benefits to their residents.

$PM_{2.5}$ concentration reduction could also reduce people's work time loss. Provinces with high morbidity and mortality reduction such as Henan, Anhui, Hunan, Shanghai and Hubei would reduce their work time loss. The per capital work time loss in these provinces would be reduced by 6.0, 4.9, 4.1, 5.0 and 4.0 h under the 2DEG_RT scenario, respectively.

3.3. The co-benefits brought by climate change mitigation

In order to reduce air pollutants from the road transport sector, one effective measure is to upgrade vehicle technologies. In our previous study (Tian et al., 2018), we explored the health and economic impacts only from technology upgrade. In order to identify the co-benefits brought by climate change mitigation, we take technology upgrade control under the TECH scenario as a benchmark in road transport sector. After compared the $PM_{2.5}$ pollutant impact, the related health impacts and economic impacts under the 2DEG_RT scenario to these impacts under the TECH scenario, the co-benefits brought by climate change mitigation can be identified. The results at both national and provincial levels are shown in SI-Fig. S1 and Fig. S2.

At national level, 72.7% of the $PM_{2.5}$ reduction could be achieved by climate actions under the 2DEG_RT scenario. Accordingly, 72.9% of avoided morbidity and mortality, 88.0% of reduced work time loss, 68.9% of saved extra expenditure, and 73.7% of lowered MEEV could be realized under the 2DEG_RT scenario, indicating that climate actions could bring significant synergies in cleaning air pollution resulted from the road transport sector.

The co-benefits brought by climate change mitigation are significantly different at provincial level. For the $PM_{2.5}$ pollutant and health indicators, around 36% provinces (such as Beijing and Shanghai) show that they gain more benefits under the 2DEG_RT scenario than those under the TECH scenario. The main reason is due to the limited improvement space by air pollution-oriented technology upgrade in these more developed provinces. In the past, different provinces had different enforcement on vehicle emission standards. In megacities such as Shanghai and Beijing, both vehicle emission standards and monitoring capacities are much higher than other provinces, indicating that vehicles in such megacities are more efficient than those in the central and western provinces and their environmental and health impacts are relatively lower (Wu et al., 2016). Therefore, climate change mitigation would bring more additional space for Shanghai and Beijing to address their air pollutant issues from the road transport sector. By contrast, for most central and western provinces, the implementation of climate change mitigation would bring around 48%–90% $PM_{2.5}$ pollutant and health co-benefits compared to the implementation of technology upgrade.

Provincial economic benefits (including extra health care expenditures and maximized embodied economic value (MEEV) gains) after the implementation of climate or air pollution control measures are shown in Fig. 4. It is clear that economic trends are similar to the pollutant and health trends.

4. Discussions

4.1. Policy implications

Our study confirms that China's road transport sector could contribute to around 10.6% of total $PM_{2.5}$ concentration reduction resulted from all sectors' participation, equivalent to 10.8% of the monetized health benefits obtained from achieving the 2-degree target by all sectors. Furthermore, compared with the potential maximum benefits from air pollution control oriented measures in the road transport sector, such climate actions could bring noticeable synergies as well. For instance, 70% of avoided negative health impacts by air pollution control measures could be obtained by taking climate change mitigation actions alone. Therefore, it is beneficial for the road transportation sector to achieve the emissions reductions required by the 2 degree target climate change mitigation.

According to our scenarios, China's road transport sector toward the 2 degree target would be effected by energy consumption. The major character is that although oil is still the most important energy source, the proportion of electricity, natural gas and biofuels will increase significantly in the future. Therefore, ambitions of making such energy consumption transition in China's road transport sector at provincial level become more important.

For local government. It is necessary to integrate the road transport sector towards the 2 degree target into provincial planning, enhancing the awareness of different stakeholders to achieve such a target. For instance, the quality of road transport infrastructure is different at provincial level. Poor infrastructure quality would increase the corresponding emissions. Therefore, local government should reinforce the construction and maintenance of infrastructure, improving the transportation efficiency of vehicles via advanced communication and information technology, especially in provinces with populous and dense industries.

The electric vehicle-led road transportation system will be the future development trend toward the 2 degree target. Provinces should consider preparing medium- and long-term plan for the development of electric vehicles. For instance, for less developed provinces with low usage of electric vehicles, local government should increase the usage via intensifying financial subsidy. Besides that, the related infrastructure such as charging pile and charging service capacities should be consistent with the increasing demand of electric vehicles. The good experience in Chongqing is that owners of new energy electric vehicles can receive subsidies ranging from 10,000 RMB to 30,000 RMB from the local government. In addition, local government may consider the exemption of tolls for new energy electric vehicles (IEA, 2017).

Sharing economy could provide another solution for decreasing energy consumption in road transport. It is reported that per sharing car from Gofun company could reduce 30 ton emissions from vehicles per year.[1] Local government should encourage residents to use sharing electrical cars or sharing bikes instead of private cars through innovative policies. For instance, individuals may be granted with personal credits for their low carbon behaviors. Also, to increase parking fee and highway toll can also discourage the public to drive their own vehicles.

Upgrade of vehicle emission standards and fuel quality are required especially in central and western provinces. In the past few years, China's manufacturing industry has gradually transferred from eastern provinces to central and western provinces. Such shifts could bring certain economic benefits to these provinces, such as income growth and job opportunities. However, our analysis results indicate that there will be additional environmental burdens due to the increasing road transport loads. From the consumption perspective, taking Henan province as an example, it is reported that the total number of vehicles has increased significantly, leading to increasing emissions from road transport sector. However, as one central province, Henan's vehicle emission standards are lower than those in eastern provinces and the road transport infrastructure is less efficient. Therefore, it is of utmost importance to promote both vehicle emission standards and fuel quality. In this regard, Guangzhou province has decided to replace all their gasoline or diesel based buses by pure electric buses by the end of 2020 (IEA, 2017).

For residents. It is critical to encourage all the citizens to take public transport system, such as buses, subways, and ferries. Similarly, the smart monitoring system should be established so that the emissions from vehicles can be better monitored. In addition, it would be necessary to encourage the general public to take the sharing bikes or even walk for short distance travel.

In addition, it is worth noting that emissions could be influenced by long-range atmospheric transport and chemistry effects. For instance, Sichuan is located in the Sichuan Basin, where it is quite difficult for the air pollutants to disperse. Consequently, it is crucial for different provinces to take co-control strategies to maximize the co-benefits of emissions reduction and health impacts (Wu et al., 2017).

4.2. Uncertainty analysis

Uncertainty analysis on ERFs used in the health model is carried out in this study, the error bars in Fig. 3 show 95% CI of ERFs. We use the high and low values of each indicator compared with their medium value. The risk of morbidity ranges between −63% and 36%, mortality between −93% and 100%, expenditure between −62% and 41%, MEEV between −93% and 100%, and work time loss between −58% and 62% under the 2DEG_RT scenario, indicating that chronic mortality and MEEV caused by ambient air pollution are sensitive to ERFs. Nonetheless, only 2% of work time loss will result from mortality so that the sensitive and variable mortality is not likely to influence the economic results considerably.

4.3. Limitations

Several research limitations exist and need to be improved in the future. For instance, this study does not provide detailed abatement costs due to limited data availability. Also, this study only focuses on the road transport sector rather than looking at all transport modes due to limited data availability in the shipping and air transport sectors.

Further, this study does not investigate more co-benefits combing these two transport sectors. In this current study, we did not consider non-road transport modes (such as railway) due to the rough structure of our model. Under such a circumstance, our results may underestimate the co-benefits from the 2-degree target measures. Take residential vehicles as an example, if more residents select subway as one transport tool instead of private cars, reduction of $PM_{2.5}$ concentration would be more obvious. Therefore, the health benefits would be more significant.

Finally, we did not identify the impacts of different specific measures, such as transitions to e-mobility. The work time loss could be underestimated in this study if only considering work loss hour while ignoring the impacts on productivity. This is because it is difficult to quantify the impact on labor productivity under the current technology.

[1] http://www.tanpaifang.com/ditanjingji/2017/0824/60378.html.

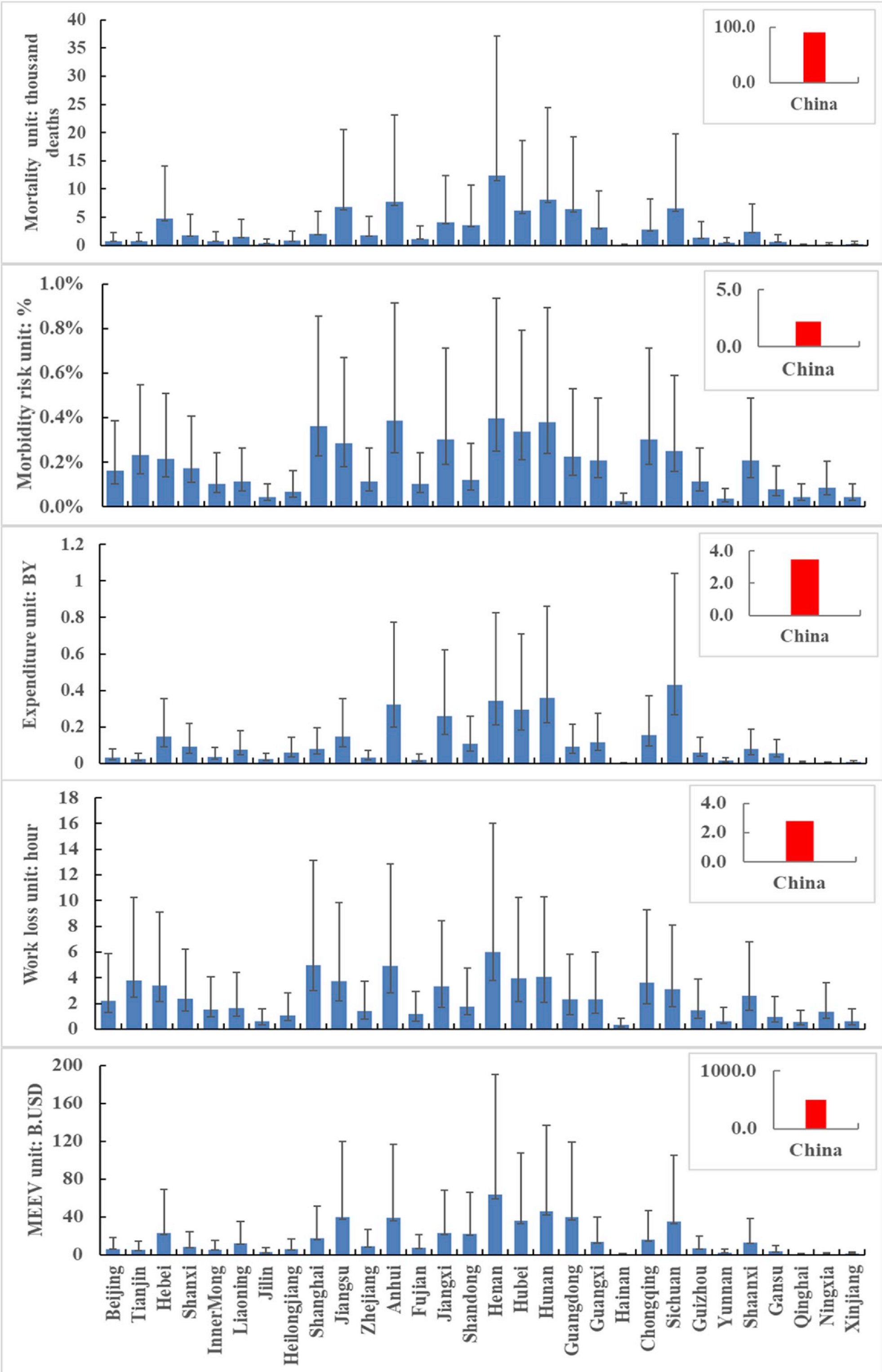

Fig. 3. The health and economic effects after climate change mitigation in 2050.

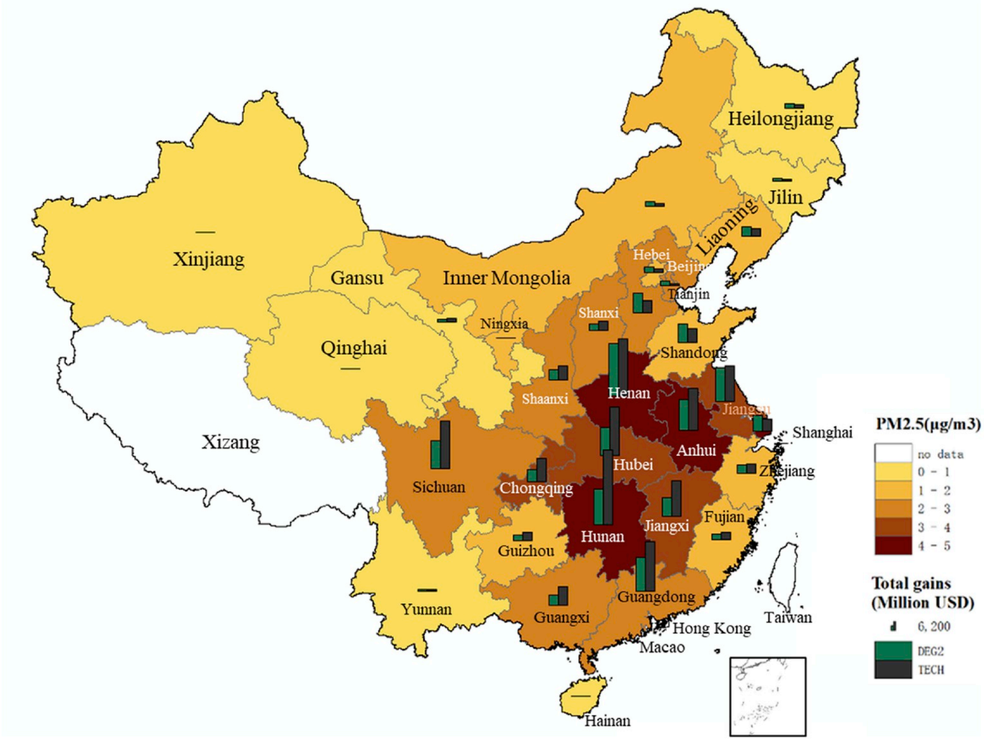

Fig. 4. The provincial economic benefits from climate and air pollution control actions (The background color represents the concentration of $PM_{2.5}$ and the column represents economic benefits under different scenarios). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions

The contribution of the road transport sector to co-benefits of achieving the 2-degree target at national and provincial levels in China is evaluated by combining the GAINS, IMED/HEL and IMED/CGE models. The main purpose of this study is to reveal the role of China's road transport sector toward the 2-degree target in 2050 and the synergies in creating public health co-benefits due to air pollution improvement. The results show that compared with the total emissions reduction from all sectors required by the 2-degree target, reductions from the road transport sector would account for 20.9% for NOx, 7.6% for $PM_{2.5}$, 0.4% for SO_2 and 5.4% for CO_2. Accordingly, the road transport sector would play a key role in terms of $PM_{2.5}$ concentration reduction, contributing to 10.6% of the total decrease. Furthermore, in terms of health impacts, the road transport sector could contribute to around 10.7% of decline in mortality and morbidity, and 8.7% of work time loss. Moreover, economic impacts are assessed. The avoided additional expenditure loss and MEEV loss would account for 11.0% and 10.7% of total avoided loss brought by achieving the 2-degree targets, respectively.

Provincial disparity is also evaluated. Overall, the climate change mitigation efforts will lead to emissions reduction in those populous provinces with more manufacturing industries. Provinces such as Henan, Hunan, Sichuan and Anhui would achieve more health impacts under the 2-degree target. Both economic development level and residential income influence provincial economic benefits brought by climate change mitigation.

Finally, this study confirms that mitigation efforts by China's road transport sector toward the 2-degree target could achieve significant co-benefits on air pollution improvement in the long run. Climate change mitigation can contribute to around 70% of the maximum health co-benefits obtained from air pollution control. With this regard, attaining the 2-degree target can help air pollution control avoid approximately 70% economic loss. In addition, those provinces which suffer more health impacts from the road transport sector (such as Henan and Sichuan) will gain more benefits after the implementation of control measures, which further confirms the necessity of control measures in the road transport sector.

All of these contributions have valuable implications to other countries, especially those emerging economies or those reluctant to engage in climate actions. With China being the leader for a global 'green shift' (Mathews, 2017), more simulation studies should be initiated so that more mitigation strategies and policies can be raised by considering the local concerns.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2019.100674.

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