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Economic impacts from $PM_{2.5}$ pollution-related health effects in China's road transport sector: A provincial-level analysis

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ABSTRACT

Economic impact assessments of air pollution-related health effects from a sectoral perspective in China is still deficient. This study evaluates the $PM_{2.5}$ pollution-related health impacts of the road transport sector on China's economy at both national and provincial levels in 2030 under various air mitigation technologies scenarios. Health impacts are estimated using an integrated approach that combines the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, a computable general equilibrium (CGE) model and a health model. Results show that at a national level, the road transport sector leads to 163.64 thousand deaths per year, increases the per capita risk of morbidity by 0.37% and accounts for 1.43 billion Yuan in health care expenditures. We estimate 442.90 billion Yuan of the value of statistical life loss and 2.09 h/capita of work time loss in 2015. Without additional control measures, air pollution related to the transport sector will cause 177.50 thousand deaths in 2030, a 0.40% per capita increase in the risk of morbidity, accounting for 4.12 billion Yuan in health care expenditures, 737.15 billion Yuan of statistical life loss and 2.23 h/capita of work time loss. Based on our model, implementing the most strict control strategy scenario would decrease mortality by 42.14%, morbidity risk by 42.14%, health care expenditures by 41.94%, statistical life loss by 26.22% and hours of work time loss by 42.65%, comparing with the no control measure scenario. In addition, $PM_{2.5}$ pollution from the road transport sector will cause 0.68% GDP loss in 2030. At a provincial level, GDP losses in 14 out of 30 provinces far exceed the national rate. Henan (1.20%), Sichuan (1.07%), Chongqing (0.99%), Hubei (0.94%), and Shandong (0.90%) would experience the highest GDP loss in 2030. Implementing control strategies to reduce $PM_{2.5}$ pollution in the road transport sector could bring positive benefits in half of the Chinese provinces especially in provinces that suffer greater health impacts from the road transport sector (such as Henan and Sichuan).

1. Introduction

As the largest single environmental health risk, air pollution caused approximately 3.7 million outdoor deaths in 2012 (WHO, 2014). It would become the top factor of environmental mortality by the year 2050 worldwide (OECD, 2012). The effects of air pollution on human's health were studied at global (Apte et al., 2015; OECD, 2014; West et al., 2013; Q. Zhang et al., 2017), national (Hao et al., 2017; Latif et al., 2018; Xie et al., 2016; X. Zhang et al., 2017), sub-national (Gu and Yim, 2016; Lanzi et al., 2018; Wang et al., 2015; Wu et al., 2017), city (Aggarwal and Jain, 2015; Ren et al., 2015; Silveira et al., 2016; Wu et al., 2016), and sectoral (Giannadaki et al., 2017; Lei and Ke, 2018; Wyrwa, 2015; Zhang et al., 2016) levels worldwide. For instance, Q. Zhang et al. (2017) identified the effects of international trade on air pollutant emissions and health from the global perspective, showing that approximately 762,400 global premature deaths were associated with goods and services produced in one region for consumption in another in 2007. Silveira et al. (2016) evaluated the effects of air quality improvement on air pollution-related health and economic aspects in Portuguese urban area, pointing that the implementations of these measures resulted in air pollutants reduction by almost 8%, air quality improvement by 1% and an economic benefit of 8.8 million Euro/year. However, few attentions have been paid to sectoral level. Actually, studies at sectoral level could provide useful insights for

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making appropriate mitigation policies.

Emissions of atmospheric pollutants have become the major environmental issues in most cities. A recent research pointed that the global economic costs of outdoor air pollution will gradually increase to 1% of global GDP by 2060, with highest GDP losses in China. Particularly, China's outdoor air pollution caused more deaths with high concentrations of fine particulate matter pollutant ($PM_{2.5}$) every year than in any other countries worldwide (Lanzi et al., 2018; Lelieveld et al., 2015; Meng et al., 2015; Cai et al., 2017). $PM_{2.5}$ is not only linked to visibility degradation and global climate change (Menon et al., 2002; Ciscar et al., 2011; Bond et al., 2013; Mccollum et al., 2013), but also causes adverse health effects (Nemet et al., 2010; West et al., 2013; Xie et al., 2016). Technology investment and control strategies on reducing $PM_{2.5}$ may have certain economic impact on some sectors and in some regions (Thompson et al., 2014; Wang et al., 2015; Xie et al., 2016; Zhang et al., 2016; Hao et al., 2017; Wu et al., 2017). In this regard, several studies identified $PM_{2.5}$ problems in China mainly from two perspectives, in which one aspect focused on the impacts of $PM_{2.5}$ on human's health. For instance, Gu and Yim (2016) applied an air quality model to evaluate the $PM_{2.5}$'s health impacts in China, showing that $PM_{2.5}$ caused almost 870,000 premature mortalities in China in 2010, of which on average 18% were attributed to trans-boundary impacts. Zhang et al. (2018) found that Beijing and Hebei consumption-based premature deaths attributable to ambient $PM_{2.5}$ were respectively 22,500 and 49,700 in 2007, highlighting the large and broad impact of domestic trade on regional air quality. Another aspect was to further evaluate the effects of $PM_{2.5}$ pollution on economic development. For instance, X. Zhang et al. (2017) pointed that exposure to $PM_{2.5}$ caused a nationwide welfare loss of 248 billion USD in China in 2015. Xie et al. (2016) evaluated the health and economic impacts of $PM_{2.5}$ at the provincial level in China, showing that without any pollution control policies, China would experience a 2.00% GDP loss and 25.2 billion USD in health expenditure from $PM_{2.5}$ pollution in 2030. In general, several studies (such as Gu and Yim, 2016; Wang et al., 2015; Zhang et al., 2016; Zhang et al., 2018) uncovered the health impacts of all-source or sector specific air pollution, but didn't evaluate their economic impacts. By contrast, other studies (Hao et al., 2017; Xie et al., 2016; X. Zhang et al., 2017) quantified the economic impacts of $PM_{2.5}$ pollution related health effects. Unfortunately, few studies focused on the economic impacts of one certain sector, especially the major sectors that contribute to ambient air pollution.

Road transport accounts for 18.4% of total PM emissions worldwide (Xia et al., 2015). Traffic-related air pollution has received increasing attentions because more clinical evidences show a relationship between levels of $PM_{2.5}$ and negative health outcomes (Jakubiak-Lasocka et al., 2014; Z. H. Zhang et al., 2017). Long-term exposure to traffic-related air pollution is associated with increased mortality from respiratory and cardiovascular disease and lung cancer, which shortens life expectancy (Z. H. Zhang et al., 2017). For example, it is found that traffic-related air pollution in Austria, France, and Switzerland caused more than 25,000 new cases of chronic bronchitis (adults) per year and more than 0.5 million asthma attacks per year (Künzli et al., 2000), indicating that more detailed chemical components of $PM_{2.5}$ should be explored. Also, the emissions of toxic elements from non-exhaust sources could pose a higher carcinogenic risk to both adults and children than other chemical components (Z. H. Zhang et al., 2017). Brunelle-Yeung et al. (2014) attributed 210 deaths per year in the USA to aircraft emissions in the year 2000 associated with mortality and increased morbidity. In addition to direct health impacts, several studies estimated the indirect costs. For instance, Michiels et al. (2012) showed that the marginal external health costs of traffic-related $PM_{2.5}$ in Belgium in 2007 amounted to approximately 100,000 Euro. The Organization for Economic Co-operation and Development (OECD) estimated that the cost of health impacts associated with road transport was close to 1 trillion USD in 2010. Moreover, the OECD study estimated the associated health costs in China and India at probably 0.70 trillion USD and 0.25 trillion USD respectively in 2010 (OECD, 2014). Currently, China has the largest passenger vehicle fleet in the world, surpassing the United States in 2009 (Helveston et al., 2015). Air pollution from the road transport sector has led to substantial increases in the risk of lung cancer, respiratory and cardiovascular diseases (He and Qiu, 2016). It was reported that 31.1% of the $PM_{2.5}$ in the Beijing area was caused by motor vehicles, making the transport sector the leading sector of air pollution-related health impacts (Pan et al., 2016). Although several studies explored the health impacts of air pollution from the transport sector, few studies estimated associated health costs, especially in China, where the car ownership is expected to grow due to increasing household incomes. 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 impacts of $PM_{2.5}$ from road transport sector 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 those decision-makers.

Under such a circumstance and our recent studies (Xie et al., 2016; Wu et al., 2017), this study aims to uncover the health and economic impacts caused by $PM_{2.5}$ pollution from the road transport sector in 30 Chinese provinces, targeting to fill three important gaps in the literatures: (1) Quantifying the health and economic impacts from sectoral perspective at 30 Chinese provinces; (2) Identifying the health effects of air-pollution control measures on the transport sector; (3) Predicting economic benefits of control measures, including GDP values, medical expenditures and the values of statistical life (VSL) loss. Three research questions will be addressed in this study: (1) What will be the trends of air pollutants from the road transport sector at the national and provincial levels towards 2030? (2) What are the health and costs-benefits impacts of $PM_{2.5}$ pollution from the road transport sector at the national and provincial levels? (3) What will be the health and economic benefits of air pollution control strategy in the road transport sector? A novel methodological approach is adopted in this study, which closes the economy-environment-health loop by combining an air pollutant and 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 addressed.

2. Methods and data

2.1. Integrated health and economic IMED framework

This study integrates three models, including GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model, IMED/HEL (Integrated Model of Energy, Environment and economy for Sustainable Development) model and 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. Due to data availability, all three models cover 30 Chinese provinces, except for Tibet, Hong Kong, Macau and Taiwan.

The IMED/CGE model was selected in this study to evaluate economic costs. Based on the literature review, econometric methods such as willingness-to-pay (WTP), human capital approach (HCA) and cost of illness (COI) were applied in most published studies. However, compared with these methods, the IMED/CGE model could capture the full range of interaction and feedback effects between different components in the economic system, which can provide a more systematic estimation on measuring the economic impact of air pollutions. In addition, several studies confirmed the advantages of one CGE model for such evaluations (Lanzi et al., 2018; Wu et al., 2017; Xie et al., 2016; X. Zhang et al., 2017).

Fig. 1 shows the interactions between these three models. The technical introduction to the IMED model framework, including the IMED/CGE and IMED/HEL model, is available at http://scholar.pku.

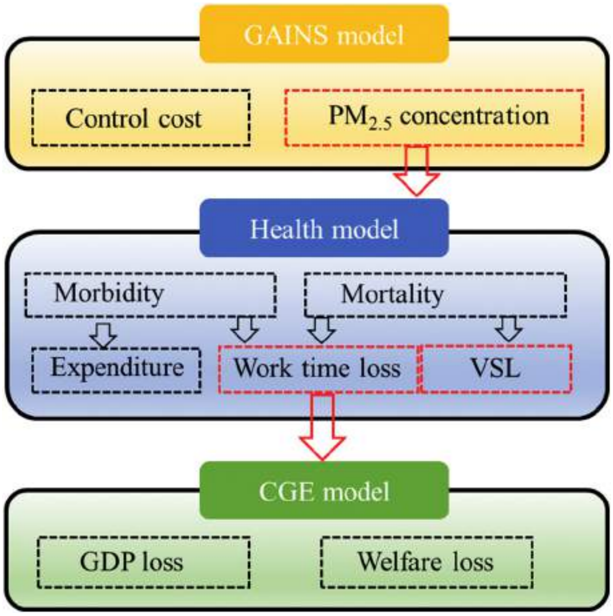

Fig. 1. Research framework.

edu.cn/hanchengdai/imed_general.

2.1.1. GAINS model

GAINS-China model is applied for estimating air-pollutants and $PM_{2.5}$ concentration from the road transport sector for 30 provinces in China as well as theirs control costs. The basic principles of calculating emissions and emission control costs in the model present in Eqs. (1) and (2).

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

$$Costs = \sum_i Activity_i \times U \times C \tag{2}$$

where, F (emission factors of activities), r (removal efficiencies of control technologies), U (unit cost of control technologies), together with all background information, form the so-called emission vectors. Finally, C (control technologies) for each activity are specified in control strategies. Emissions and control costs of each emission scenario are the sum of all i activities. Components appearing on the right side of the equations are organized into three different data categories: activity pathways, emission vectors, and control strategies. Each emission scenario in GAINS is created through a combination of these three data categories. Based on the detailed spatial and sectoral GAINS emission inventory, GAINS computes fields of ambient concentrations of $PM_{2.5}$ with the help of source-receptor relationships derived from an atmospheric chemistry-transport model named TM5 model. The model is useful as it also includes many sector-technology linkages for the road transport sector. In order to clarify the impacts of $PM_{2.5}$ associated with the road transport sector, two scenarios are proposed to improve the technical standard and to estimate the cost of pollution controls. More details related to variables in GAINS model could be found in Supporting Information (SI).

2.1.2. The IMED/HEL model

The IMED/HEL model quantifies the health impacts of $PM_{2.5}$ concentration on six morbidity endpoints, chronic mortality and work-loss day based on linear exposure-response functions (ERFs) from reference Cao et al. (2011) and Apte et al. (2015). Using the health model, medical expenditure and the value of statistical life (VSL) loss caused by $PM_{2.5}$ pollution are estimated. In this study, the settings of IMED/HEL model is referring our previous studies Xie et al. (2016) and Wu et al. (2017). More details could be found in SI or available at http://scholar.pku.edu.cn/hanchengdai/imedhel.

Table 1
Explanations of five scenarios.

Scenario	Health impact	Air mitigation technology measure
BaU	Ignored	None
REF	Not ignored	Current legislation without additional control
TSP0	Not ignored	Complete reduction to zero
TECL	Not ignored	Moderate additional control
TECH	Not ignored	Strict additional control

2.1.3. The IMED/CGE model

The IMED/CGE model applied in this study can be classified as a multi-sectors, multi-regions, recursive dynamic CGE model continuously developed by the Institute of Environment and Economy (IoEE) at Peking University. It covers 22 economic commodities and corresponding sectors and eight power generation technologies. One special feature of this model is its capacity to flexibly adjust the number of modeling regions, both international and within China, to allow for a wide range of studies. This CGE model can simulate the macroeconomic impacts, such as GDP loss and welfare loss. More details could be found in SI or available at http://scholar.pku.edu.cn/hanchengdai/imedcge (Xie et al., 2016; Wu et al., 2017).

2.2. Scenarios setting

In this study, five scenarios are proposed based on the stringency of air pollution control policy. Table 1 shows the details of these five scenarios. The BaU (business-as-usual) scenario is the reference 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 the reality, it can be used to evaluate the negative macroeconomic impacts of pollution and benefits by comparing with other scenarios. Background information is available in Table S10 (in SI). 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 mitigation technology measures are applied in the GAINS model. TSP0 scenario assumes that emissions from the road transport sector are reduced to zero. Under such a circumstance, the health impacts of emissions from the road transport sector could be identified by comparing with the REF scenario. Both TECL and TECH scenarios assume moderate and strict air mitigation technology measures associated with fuel standards and vehicle technology standards in addition to the current legislations. The TECL scenario assumes that the technology standards of vehicles in all provinces will be better in 2030 than those in 2015, with higher standards in eastern provinces than in central and western provinces. The TECH scenario assumes high standards across all vehicles in all provinces. The difference between these two technologies scenarios with gas vehicles in provinces are shown in Fig. 2. More information regarding scenario assumptions is available in SI Table S1–S3. By comparing the REF scenario with TECL/TECH scenarios, the health and economic impacts of the different control measures can be quantified and compared.

3. Results

3.1. Air pollutants emissions and additional $PM_{2.5}$ concentration caused by road transport sector

Fig. 3 shows the main air-pollutants emissions of $PM_{2.5}$, NO_X, and SO_2 from the road transport sector at national and provincial levels in 2015 and 2030. It is clear that comparing 2030 with 2015, if no additional control measures are implemented under the REF scenario, the

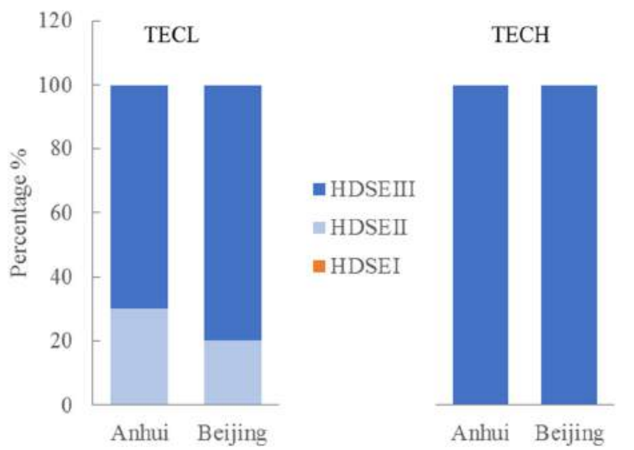

Fig. 2. The technology settings in moderate and strict scenarios (HDSEI- present the different standards of gas vehicles, HDSEIII is the highest standard one; Beijing is China's eastern province, Anhui is China's central province).

national emissions of NO_X and SO_2 from the road transport sector would increase by 9.06% and 30.11% to 5.74 million tons (Mt) and 0.71 Mt, respectively, whereas the primary $PM_{2.5}$ emissions would decrease by 21.60% to 0.35 Mt.

Most provincial $PM_{2.5}$ emissions are projected to decrease by 2030 when compared to 2015 levels except for Guizhou province which increases by 10.45%. In 2030, $PM_{2.5}$ emissions would be highest in Shandong (0.031 Mt), Hebei (0.028 Mt), Henan (0.027 Mt), Guangdong (0.023 Mt) and Jiangsu (0.021 Mt). NO_X emissions are projected to increase by 2030 over 2015 levels in all provinces except for Beijing, Zhejiang, Shanghai, Shandong, Tianjin and Jiangsu. In 2030, NO_X emissions will be highest in Shandong (0.50 Mt), Hebei (0.46 Mt), Henan (0.43 Mt), Guangdong (0.37 Mt) and Jiangsu (0.35 Mt). SO_2 emissions are projected to increase by 2030 over 2015 levels in all provinces. Provinces projected to have the highest SO_2 emissions in 2030 are Shandong (0.066 Mt), Hebei (0.065 Mt), Henan (0.061 Mt), Jiangsu (0.043 Mt) and Anhui (0.040 Mt). The results show that even with national emissions reduction targets in place for 2030, air pollutant levels will vary at the provincial level. Generally speaking, more developed provinces such as Beijing, Zhejiang, Shanghai, Shandong, Tianjin and Jiangsu will see substantial reduction rates in air-pollutants compared to most western and central provinces where emissions will either increase or be more or less stable.

Fig. 3 also shows the contribution of the road transport sector to $PM_{2.5}$ concentration levels, which is obtained by the difference between REF and TSP0 scenarios. It shows that $PM_{2.5}$ concentrations attributable to the road transport sector are highest in Hunan (9.08 $\mu g/m^3$), Anhui (7.06 $\mu g/m^3$), Hubei (6.98 $\mu g/m^3$), Jiangxi (6.73 $\mu g/m^3$) and Chongqing (6.14 $\mu g/m^3$) in 2015. In 2030, their respective $PM_{2.5}$ concentrations would increase by 12.78% (to 10.24 $\mu g/m^3$), 3.26% (to 7.29 $\mu g/m^3$), 10.32% (to 7.70 $\mu g/m^3$), 12.04% (to 7.54 $\mu g/m^3$) and 20.85% (to 7.42 $\mu g/m^3$). In addition, most provinces show higher concentrations in 2030 over 2015 levels except for Shandong, Jilin, Beijing, Liaoning, Tianjin, Hebei, Zhejiang, and Jiangsu. Such results indicate that if emissions from the road transport sector are not controlled, most provinces will experience higher levels of transport-related air pollution, even though the overall air quality will improve under the REF scenario.

3.2. The health and macroeconomic impacts attributable to road transport sector

Long-term exposure to traffic-related air pollution is associated with increased mortality from respiratory and cardiovascular diseases and lung cancer and decreased life expectancy (Künzli et al., 2000; Michiels et al., 2012; Jakubiak-Lasocka et al., 2014). Fig. 4 shows the health impacts attributable to the road transport sector, including mortality, risk of morbidity, total additional medical expenditure, VSL loss and work time loss. It is clear that from a national perspective, the road transport sector led to 163.64 thousand deaths (95% CI: 12.27–327.27), a 0.37% (95% CI: 0.14%–0.50%) increased risk of morbidity (which means the possibility each person may suffer from $PM_{2.5}$ pollution-related health problems) in 2015. The combined increased rates of mortality and morbidity result in additional health care expenditures of 1.43 billion Yuan (BilYuan) (95% CI: 0.55–2.02), most of which are caused by upper respiratory symptoms. Additional costs include 442.90 BilYuan (95% CI: 33.22–885.80) of VSL loss and 2.09 h/capita of work time loss (95% CI: 1.77–2.40). VSL is an aggregation of individuals' willingness to pay to secure a marginal reduction in the risk of premature death (OECD, 2014). Without additional control measures, mortality would increase by 8.47% to 177.50 (95% CI: 13.31–354.99) thousands of premature deaths, morbidity risk would increase by 7.11% to 0.40% (95% CI: 0.15%–0.53%), health expenditures would increase by 113.83% to 4.12 BilYuan (95% CI: 1.57–5.81), VSL loss would increase by 66.44% to 737.15 (95% CI: 55.29–1474.29) and hour/capita of work time loss would increase by 6.90% to 2.23 (95% CI: 1.90–2.56) in 2030.

At a provincial level, mortality attributed to air-pollutants from the road transport sector are highest in Hunan (18.29 thousand people), Henan (17.49 thousand people), Anhui (13.04 thousand people), and Sichuan (11.07 thousand people) in 2015. Mortality rates are projected to increase in 2030 over 2015 levels in most provinces except Beijing, Tianjin, Shanghai, Zhejiang, Hebei and Shandong. Highest mortality attributed to air pollution will include Hunan (20.77 thousand people), Henan (18.89 thousand people), Anhui (13.77 thousand people) and Sichuan (13.70 thousand people) in 2030. However, Hainan, Qinghai and Ningxia had the lowest mortality in 2015 and will have the lowest mortality in 2030, with figures of 0.146 thousand people, 0.22 thousand people and 0.24 thousand people in 2015, and increased by 1.27% (to 0.148), 15.74% (to 0.26) and 15.74% (to 0.28) in 2030, respectively.

Morbidity risk is projected to increase in 22 out of 30 Chinese provinces in 2030 over 2015 levels. The most remarkable provinces include Hunan, Hubei, Jiangxi and Chongqing, where the risk of morbidity will increase from 0.78% to 0.88%, 0.60% to 0.66%, 0.58% to 0.64%, and 0.52% to 0.63% from 2015 to 2030, respectively. On the contrary, Beijing, Tianjin and Shanghai present decreasing trends, where the risk of morbidity will decrease from 0.46% to 0.35%, 0.28% to 0.25%, and 0.20% to 0.10% from 2015 to 2030, respectively. Upper respiratory health problems account for the largest proportion of increased morbidity in all provinces.

Total additional health care expenditures, VSL loss and work time loss are relatively high in provinces with high mortality and risk of morbidity. For example, in Hunan, Sichuan, Hubei, and Anhui, the health care expenditures are 0.23 BilYuan, 0.148 BilYuan, 0.148 BilYuan, and 0.15 BilYuan in 2015, respectively. Expenditures are projected to be 0.53 BilYuan, 0.47 BilYuan, 0.36 BilYuan and 0.34 BilYuan in 2030, respectively. Moreover, their VSL losses will increase from 44.68 to 84.47 BilYuan, 26.01 to 52.50 BilYuan, 31.08 to 56.23 BilYuan, and 30.41 to 51.98 BilYuan from 2015 to 2030, respectively. Accordingly, their work time losses are 4.52 h/capita, 2.24 h/capita, 3.48 h/capita, and 3.48 h/capita in 2015, and would increase to 5.07 h/capita, 2.73 h/capita, 3.83 h/capita, and 3.63 h/capita in 2030, respectively.

Fig. 5 shows the macro-economic impacts attributed to $PM_{2.5}$ pollutants from the road transport sector, including GDP loss and welfare loss caused by expenditure changes and work time loss. At a national level, GDP loss and welfare loss from the road transport sector are 0.37% (95% CI: 0.28%–0.47%) and 0.68% (95% CI: 0.51%–0.86%) respectively in 2015, and would increase to 0.68% (95% CI: 0.33%–1.05%) and 1.08% (95% CI: 0.53%–1.67%) respectively in 2030

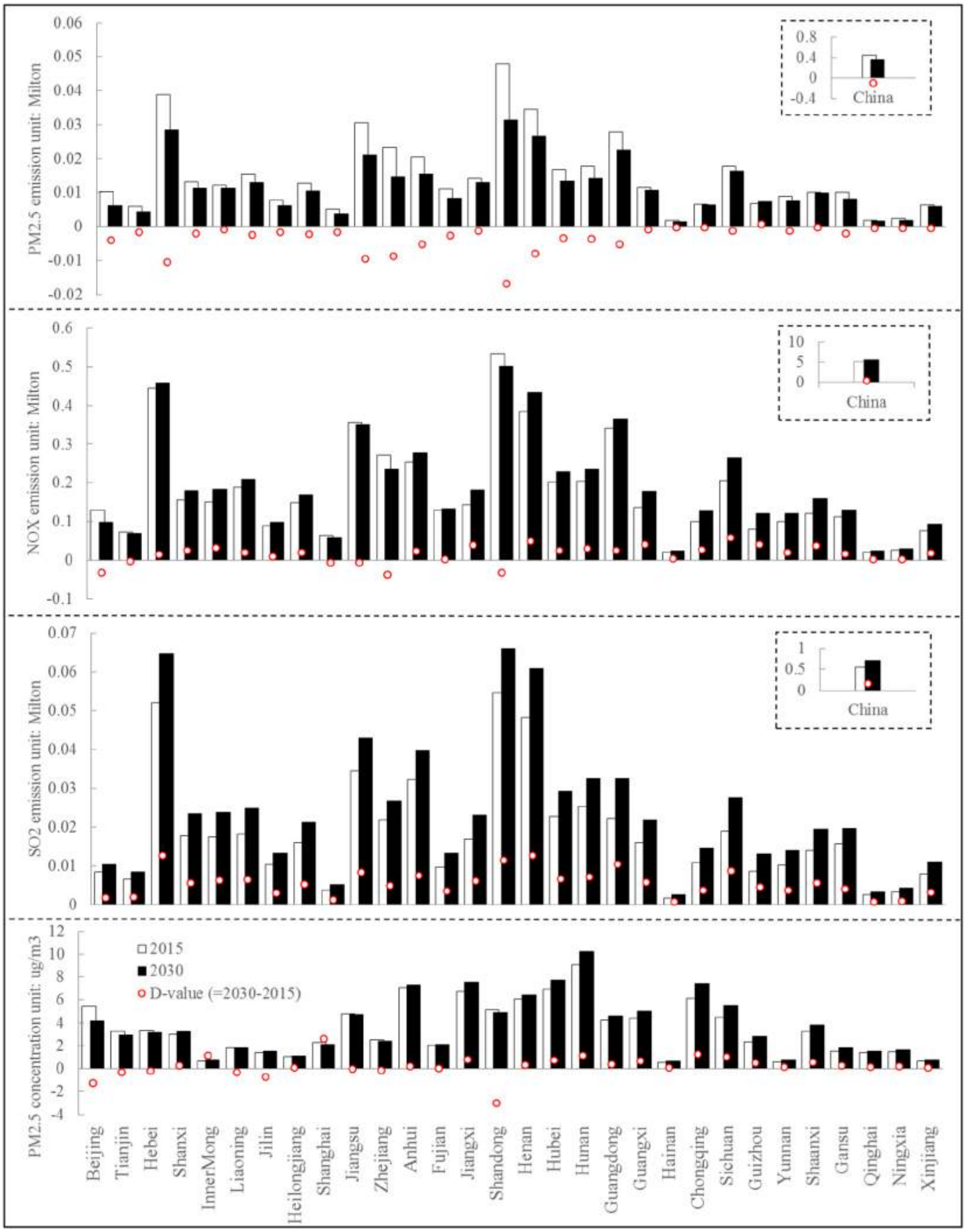

Fig. 3. Air-pollutants emissions and $PM_{2.5}$ concentrations caused by road transport sector in 2015 and 2030.

under the TSP0 scenario without control measures. At a provincial level, GDP losses in 14 out of 30 Chinese provinces far exceed the national rate. Henan (1.20%), Sichuan (1.07%), Chongqing (0.99%), Hubei (0.94%), and Shandong (0.90%) would experience the highest GDP loss in 2030. By contrast, Heilongjiang (0.08%), Inner Mongolia (0.10%), Xinjiang (0.15%), Qinghai (0.19%) and Hainan (0.22%) will have less GDP losses in 2030 when compared to 2015 levels. Similarly, 15 out of 30 Chinese provinces will have welfare losses that far exceed the national rate in 2030. Provinces with the highest projected welfare losses include Henan (2.08%), Tianjin (1.69%), Chongqing (1.68%), Sichuan (1.51%) and Shandong (1.46%). Projected welfare losses will be lowest in Inner Mongolia (0.19%), Hainan (0.32%), Heilongjiang (0.37%), Jilin (0.43%), and Gansu (0.44%).

3.3. The impact of the technology measures on road transport sector

The implementation of moderate and strict air mitigation technology measures (TECL and TECH scenarios) are simulated to understand the potential health and economic impacts. Fig. S3 in SI shows the emissions reduction from the road transport sector under these scenarios in 2030 compared with the REF scenario. Air mitigation technology measures would reduce $PM_{2.5}$, NO_X and SO_2 emissions by 0.05 Mt, 1.31 Mt and 0.04 Mt under the TECL scenario in 2030. Under the TECH scenario, emissions could be further reduced by 40.00%, 34.35%

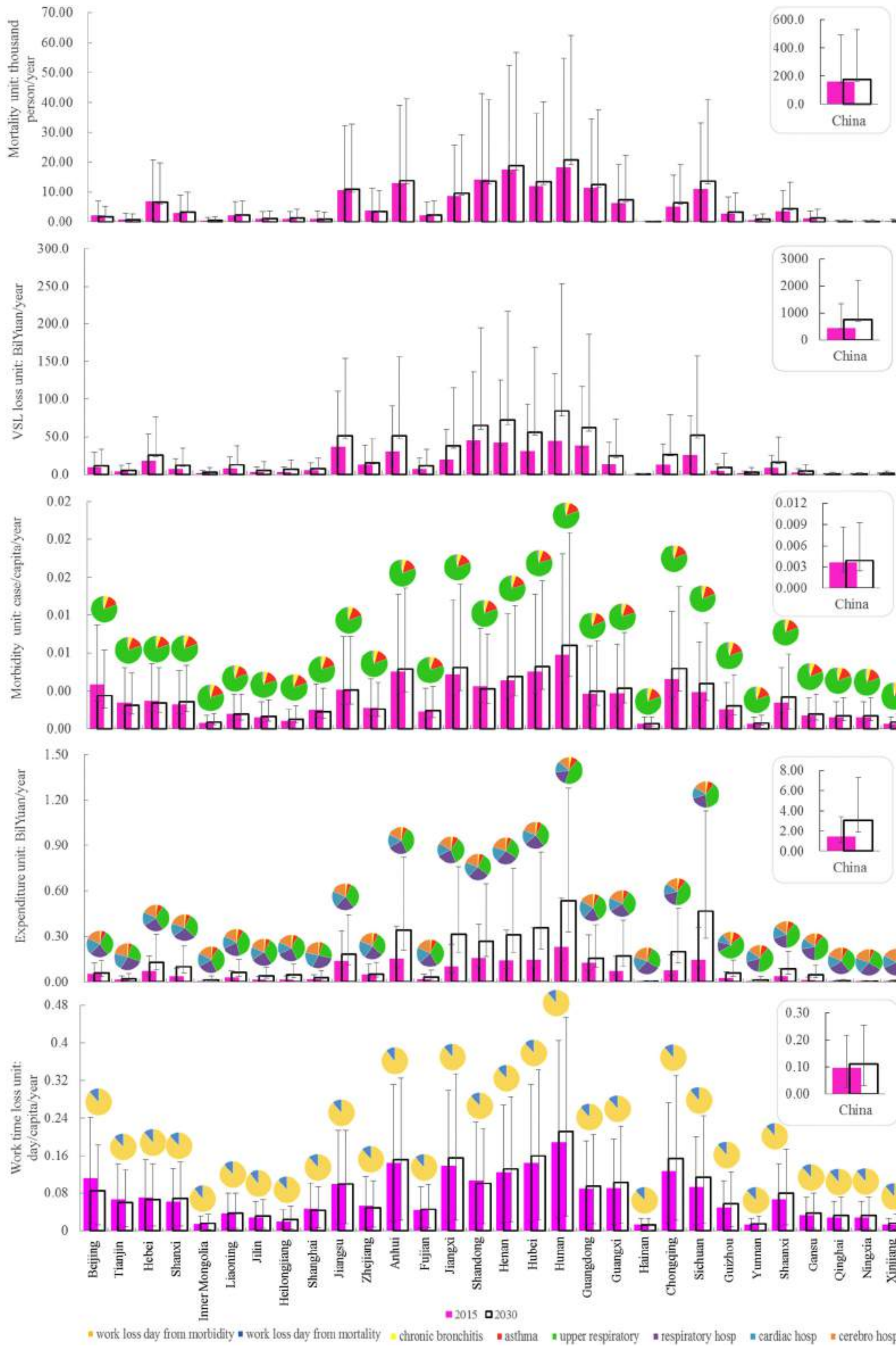

Fig. 4. Health impacts attributable to the road transport sector from 2015 to 2030.

and 275.00% compared with the TECL scenario. At a provincial level, under the TECH scenario, Guangdong, Shandong, Jiangsu, Henan and Sichuan, the highest emission provinces, would reduce $PM_{2.5}$ emissions by 0.007 Mt, 0.007 Mt, 0.005 Mt, 0.005 Mt and 0.004 Mt, NO_X emissions by 0.17 Mt, 0.16 Mt, 0.12 Mt, 0.11 Mt and SO_2 emissions by 0.014 Mt, 0.013 Mt, 0.010 Mt, 0.009 Mt, 0.009 Mt, in 2030, respectively.

Under the TECL scenario, $PM_{2.5}$ concentrations would decrease noticeably in Hunan (by 1.75 μg/m^3), Jiangxi (by 1.42 μg/m^3), Chongqing (by 1.41 μg/m^3), Anhui (by 1.33 μg/m^3) and Hubei (by 1.32 μg/m^3) in 2030. Moreover, under the TECH scenario, $PM_{2.5}$ concentrations in these provinces could be further reduced by 46.92%,

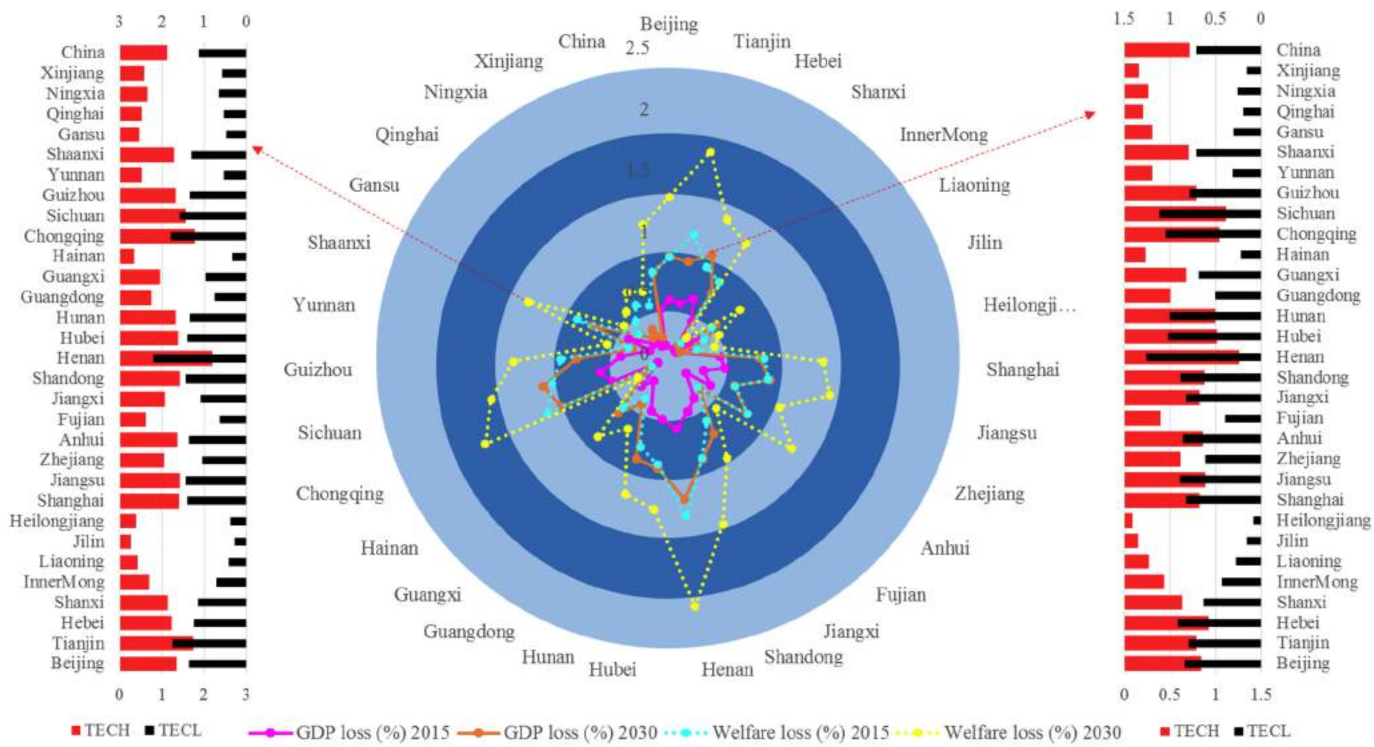

Fig. 5. Macroeconomic impacts from road transport sector.

44.92%, 51.21%, 40.60% and 46.74% in 2030, respectively.

Implementation of moderate air mitigation technology measures would reduce negative health impacts substantially (Fig. S4 in SI). Annual mortality would be reduced by 60.44 thousand deaths (95% CI: 4.53–120.88) in 2030. The risk of morbidity would decrease by 0.10% (95% CI: 0.05%–0.20%). Total health care related expenditures would be reduced by 1.39 BilYuan (95% CI: 0.53–1.96). VSL loss would be reduced by 133.05 BilYuan (95% CI: 9.98–266.10). Work time loss would be reduced by 0.77 h/capita (95% CI: 0.66–0.89). The health benefits are more pronounced with stricter measures (TECH scenario). The above health effect indicators would be reduced by 74.80 (95% CI: 5.61–149.61) thousand people, 0.16% (95% CI: 0.06%–0.22%) of morbidity risk, 1.73 (95% CI: 0.66–2.44) BilYuan of health care expenditure, 328.25 (95% CI: 24.62–656.50) BilYuan of VSL loss, 0.95 (95% CI: 0.81–1.09) hour/capita of work loss under the TECH scenario. Of the two scenarios, those stricter measures (TECH scenario) will be the most-effective. The above health effect indicators would be decreased by 42.14%, 42.14%, 41.94%, 26.22% and 42.65% compared to no control measure in 2030.

At a provincial level, emissions reductions under the TECH scenario will lead to health outcomes for all provinces in 2030. Annual mortality would decrease most in Hunan, Henan, Guangdong, Sichuan, and Anhui, which are projected to decrease by 5.09 thousand people, 4.43 thousand people, 4.34 thousand people, 4.23 thousand people, and 3.59 thousand people, respectively. The risk of morbidity would decrease most in Hunan, Chongqing, Hubei, Jiangxi, and Anhui. Health care expenditures would be reduced most in Sichuan, Hunan, Hubei, Anhui, and Jiangxi, with reduced figures of 0.145 BilYuan, 0.131 BilYuan, 0.092 BilYuan, 0.089 BilYuan, and 0.084 BilYuan, respectively. For VSL loss, Guangdong, Hunan, Henan, Sichuan and Hubei will have significant reductions, with save figures of 21.58 BilYuan, 20.70 BilYuan, 16.92 BilYuan, 16.23 BilYuan, and 14.60 BilYuan, respectively. In addition, Hunan (1.24 h/capita), Chongqing (1.04 h/capita), Jiangxi (0.99 h/capita), Hubei (0.99 h/capita), and Anhui (0.94 h/capita) will have the most reduction effects with regard to work time loss.

Table 2 shows GDP loss and welfare loss from the road transport sector at the national level under different control scenarios compared with the BaU scenario. At a national level, strict technology measures (TECH scenario) would reduce GDP loss and welfare loss to 0.708% (95% CI: 0.345%–1.097%) and 1.124% (95% CI: 0.547%–1.743%) respectively. At a provincial level (Fig. 5), GDP loss and welfare loss would be reduced in all provinces. For GDP loss, Henan, Sichuan, Chongqing, Hubei and Hunan are provinces with relatively higher losses under all scenarios, while for welfare loss, Henan, Tianjin, Chongqing, Sichuan, and Jiangsu will have relatively higher losses under all scenarios.

Table 2
National GDP loss and welfare loss in 2030.

Scenario	GDP loss (%)			Welfare loss (%)		
	Lower	Medium	Upper	Lower	Medium	Upper
REF	0.354	0.722	1.117	0.562	1.149	1.776
TECL	0.346	0.710	1.100	0.550	1.128	1.747
TECH	0.345	0.708	1.097	0.547	1.124	1.743

Since control measures are costly, the corresponding impacts are also province-specific. The cost-benefits to the road transport sector with the implementation of control measures at national and provincial levels are shown in Fig. 6. In addition, Fig. 6 also presents that how much GDP loss, expenditure and the VSL loss can be avoided after the implementation of these control measures. The total national costs under the TECL and TECH scenarios would be 0.90 trillion yuan (1.41% of GDP) and 0.95 trillion yuan (1.49% of GDP), respectively. At a provincial level, Shanghai (0.50%–0.52% of GDP), Beijing (0.73%–0.77% of GDP), Tianjin (0.74%–0.77% of GDP), Zhejiang (1.03%–1.07% of GDP) and Liaoning (1.05%–1.10% of GDP) are low-cost provinces under all the scenarios. However, Guizhou (3.54%–3.78% of GDP), Jiangxi (2.56%–2.74% of GDP), Sichuan (2.34%–2.49% of GDP), Guangxi (1.96%–2.09% of GDP) and Hebei (1.94%–2.03% of GDP) are high-cost provinces under all the scenarios.

Results indicate that the Chinese provinces would benefit

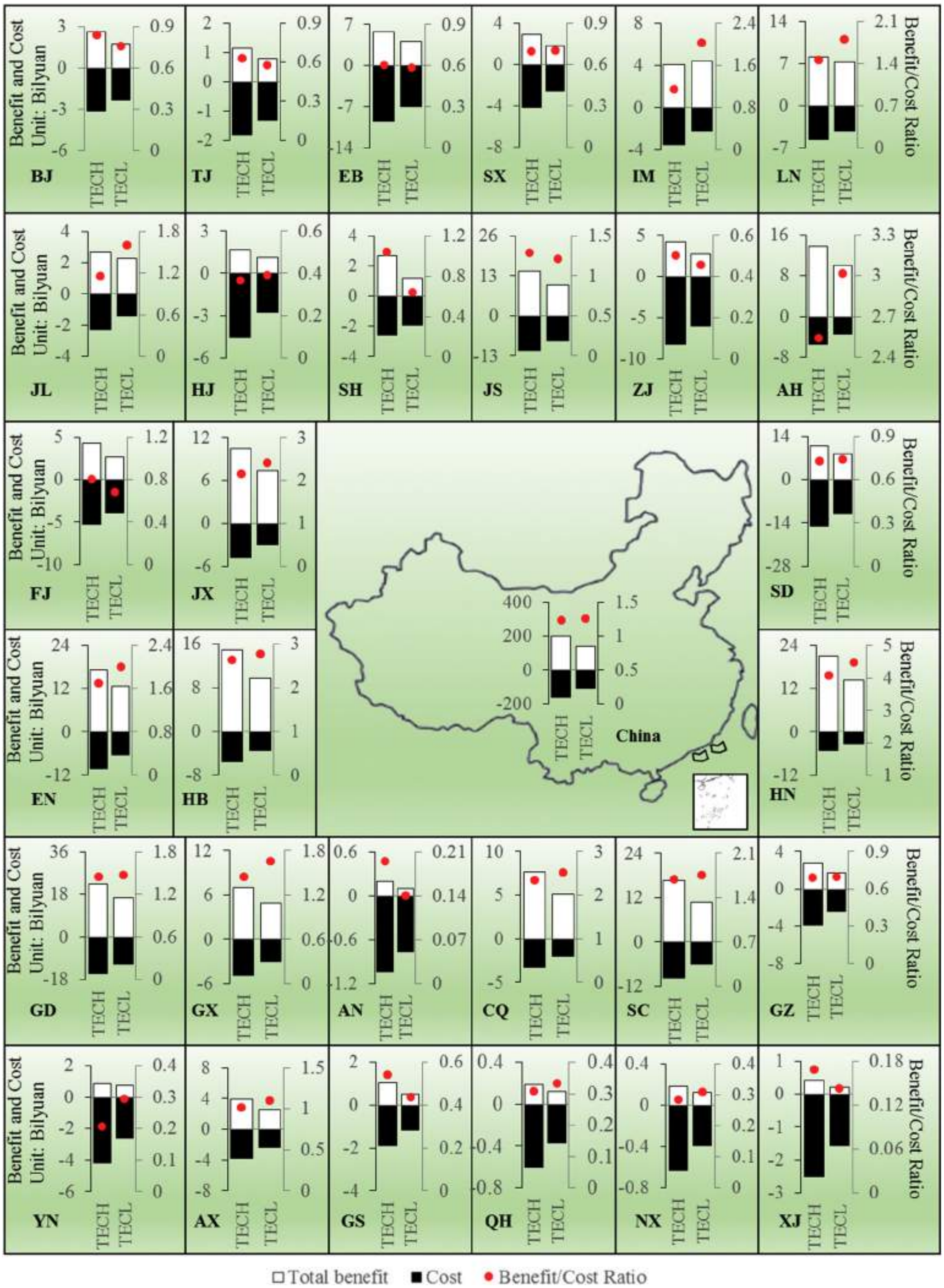

Fig. 6. Cost-benefits of control measures to the road transport sector in 2030.

substantially with strict measures (TECH scenario). Particularly, provinces with higher health impacts attributed to air pollutants from the road transport sector (such as Henan and Sichuan) would benefit most from the implementation of control measures. Such results confirm the necessity of control measures on the road transport sector.

With regard to the benefit/cost ratio (Fig. 6), the national benefit is higher than the national cost after the implementation of control measures, with figures of 1.26 and 1.24 under the TECL and TECH scenarios, respectively. At a provincial level, 15 out of 30 Chinese provinces have benefit/cost ratios higher than 1 under the TECH scenario, while, 14 out of 30 provinces have benefits/cost ratios higher than 1 under the TECL scenario. Moreover, compared to Xinjiang, Hainan and Yunnan, provinces such as Hunan, Anhui, Hubei, Chongqing and Jiangxi with higher associated health impacts present higher benefit/cost ratios under both scenarios in 2030. Overall, in more developed provinces such as Shanghai and Jiangsu, the benefit/cost ratios under the TECH scenario are higher than those under the TECL scenario. However, results in western and central provinces are inverse. Take Shanghai and Henan provinces as an example, their benefit/cost ratios are 0.64 and 2.01 under the TECL scenario, whereas 1.03 and 1.70 under the TECH scenario, respectively.

4. Discussions

4.1. Policy implications

Health impacts of $PM_{2.5}$ pollution from the road transport sector vary in different provinces in China. Our results reveal that provinces such as Henan, Sichuan and Jiangxi have high health impacts, while provinces such as Shanghai and Jiangsu have lower health impacts attributable to air pollutants from the road transport sector. The reasons are complicated and diverse. High $PM_{2.5}$ concentration leads to higher health impacts. Therefore, air pollutants reduction plays a key role in reducing health impacts (Cifuentes et al., 2001). Provinces such as Henan and Jiangxi have the highest levels of NO_X and $PM_{2.5}$ emissions from the road transport sector (M. Song et al., 2016, Y. Song et al., 2016). Therefore, health impacts are also highest in these provinces. Long-range atmospheric transport and chemistry of $PM_{2.5}$ pollution are important factors as well (M. Song et al., 2016, Y. Song et al., 2016). For instance, in Sichuan province, which locates in the Sichuan Basin where pollution does not disperse easily due to its geographical location, more emissions are accumulated locally and may cause more severe health impacts.

Our results clearly show that reduction of $PM_{2.5}$ emissions from road transport sector can significantly help reduce the health impacts. Also, compared with moderate control measures, the strict implementation with high vehicle standards can help further reduce the emissions and health impacts. In China, gasoline vehicles are still the major vehicles. Consequently, it will be crucial to promote new energy vehicles in all the provinces. In this regard, government should play a leading role by releasing more appropriate policies. Recently, the Ministry of Industry and Information Technology (MIIT) of China announced that China will phase out the sale of traditional fossil fuel-based vehicles. Such a plan could not only guide the vehicles selections of consumers, but also accelerate the technology upgrade of vehicle manufacturers. In addition, the Chinese government should fully consider the heterogeneity of regional development. In the past time, implementation of vehicle standards is province-specific. While large municipalities such as Shanghai and Beijing have actively updated their vehicle standards, those central and western provinces are still observing such changes and do not take any effective actions (Wu et al., 2016). Under such a circumstance, it would be necessary for the central government to encourage these provinces to learn the experiences from those more advanced regions. Moreover, it would be rational for these central and western provinces to set up more economic drivers to encourage their consumers to purchase new energy vehicles, such as financial subsidies, cheaper vehicle plates and insurance fees. Capacity-building activities are needed so that consumers can improve their environmental awareness and accept such innovative vehicles, such as TV, radio, billboards and internet promotions. Besides, large cities should actively promote public transit systems so that their citizens can easily access public transit systems and reduce their private drives. Other measures, such as shared scooters and bicycles, carpooling, and walking, can further reduce the overall emissions from the road transport sector. Finally, it is critical to improve the oil quality, particularly in those less developed Chinese provinces where oil quality is not stable.

The air pollution from the road transport sector causes a substantial fraction of economic impacts. Z. H. Zhang et al., (2017) found that China's $PM_{2.5}$ associated health costs are equivalent to 3.1% of national GDP in 2015, while our study shows China's GDP loss is about 0.37% attributed to the road transport sector in 2015. In addition, our previous study shows that $PM_{2.5}$ pollution from all the sectors will cause 2.00% GDP loss in 2030 (Xie et al., 2016). By contrast, this study shows that $PM_{2.5}$ pollution from the road transport sector causes 0.68% GDP loss, indicating that approximately 34% of the national GDP loss from $PM_{2.5}$ pollution could be attributed to the road transport sector in 2030. As for the total benefit-cost ratio, from a national perspective, China would benefit substantially from implementing control measures on the road transport sector. 15 out of 30 Chinese provinces have higher benefits than costs. Another implication of our results is that although air pollutants and health impacts could be reduced significantly with strict control measures, it is at the expense of economic development, especially in those central and western provinces. Nevertheless, these provinces which suffer more health impacts from the road transport sector (such as Henan and Sichuan) would gain more benefits after the implementation of control measures, which further confirms that strict control measures will function in these provinces.

4.2. Sensitivity analysis

Sensitivity analysis of ERFs used in the health model is carried out in this study, the error bars in Fig. 4 show 95% CI of ERFs and risk of morbidity ranges between −62.9% and 36.2%, mortality between −92.5% and 100.0%, expenditure between −61.9% and 41.1%, VSL between −92.5% and 100.0%, and work time loss between −14.98% and 14.98%, indicating that chronic mortality and VSL caused by ambient air pollution are sensitive to ERFs. Nonetheless, only 2% of work time loss results from mortality so that the sensitive variable mortality is not likely to influence the economic results considerably. Table 2 shows that the GDP and welfare losses range between −51.3% and 54.9% under the TECL scenario, between −51.3% and 55.1% under the TECH scenario, both of which correspond to 95% CI of ERFs.

5. Conclusions

Economic impacts from $PM_{2.5}$ pollution-related health effects in China's road transport sector at both national and provincial levels are evaluated in this study by combining three integrated GAINS, health and CGE models. Three innovation aspects are identified in this study. The first one is to evaluate the $PM_{2.5}$ pollution-related health effects in China's road transport sector at both national and provincial levels from 2015 to 2030. Our results show that without additional control measures, the mortality, morbidity risk, health expenditures, VSL loss and work time loss attributable to road transport sector would increase by 8.47%, 7.11%, 113.83%, 66.44% and 6.90% from 2015 to 2030 at the national level, respectively. The second aspect is to evaluate economic impacts from $PM_{2.5}$ pollution-related health effects in China's road transport sector. The major finding is that $PM_{2.5}$ pollution from the road transport sector causes 0.37% of GDP loss due to work time loss at the national level in 2015. The third aspect is to evaluate the effects of air pollutants control measures on reducing $PM_{2.5}$ pollution-related health and economic effects from China's road transport sector. The major finding is that with the implementation of stricter technology vehicle standards, the above health indicators would be decreased by 42.14%, 42.14%, 41.94%, 26.22% and 42.65% in 2030, respectively, while strict technology measures would reduce GDP loss to 0.708% in 2030, indicating that China would benefit substantially from implementing control measures within the road transport sector. Particularly, those provinces which suffer more health impacts from the road transport sector (such as Henan and Sichuan) would gain more benefits after implementing control measures. In addition, this study highlights that in order to decrease $PM_{2.5}$ pollution-related health and economic effects from China's road transport, government, producer and consumers should work together to transit towards a low-carbon transport system that can bring significant environmental and health co-benefits.

There are several research limitations that deserve future studies. This study only focuses on the road transport sector due to limited data availability in the shipping and air transport sectors. It also does not distinguish the different types of vehicles. In addition, the work time loss could be underestimated as this study does not consider the time spent caring for family members and others with health-related problems caused by $PM_{2.5}$ pollution. These questions should be further answered in the future research work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.03.030.

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