Scenarios of demographic distributional aspects of health co-benefits from decarbonising urban transport

Chenxi Lu, W Neil Adger, Karyn Morrissey, Shaohui Zhang, Sergey Venevsky, Hao Yin, Taochun Sun, Xuanren Song, Chao Wu, Xinyu Dou, Biqing Zhu, Zhu Liu

Summary

Background There is limited knowledge on the distribution of the health co-benefits of reduced air pollutants and carbon emissions in the transport sector across populations.

Methods This Article describes a health impact assessment used to estimate the health co-benefits of alternative land passenger transport scenarios for the city of Beijing, China, testing the effect of five transport-based scenarios from 2020 to 2050 on health outcomes. New potential scenarios range from implementing a green transport infrastructure, to scenarios primarily based on the electrification of vehicle fleets and a deep decarbonisation scenario with near zero carbon emissions by 2050. The health co-benefits are disaggregated by age and sex and estimated in monetary terms.

Findings The results show that all the alternative mitigation scenarios result in reduced PM$_{2\cdot5}$ and CO$_2$ emissions compared to a business-as-usual scenario during 2020–50. The near zero scenario achieves the largest health co-benefits and economic benefits annually relative to the sole mitigation strategy, preventing 300 (95% CI 229–450) deaths, with health co-benefits and CO$_2$ cost-saving an equivalent of 0·01% (0·00–0·03%) of Beijing's Gross domestic product in 2015 by 2050. Given Beijing's ageing population and higher mortality rate, individuals aged 50 years and older experience the greatest benefit from the mitigation scenarios. Regarding sex, the greatest health benefits occur in men.

Interpretation This assessment provides estimates of the demographic distribution of benefits from the effects of combinations of green transport and decarbonising vehicles in transport futures. The results show that there are substantial positive health outcomes from decarbonising transport in Beijing. Policies aimed at encouraging active travel and use of public transport, increasing the safety of active travel, improving public transport infrastructure, and decarbonising vehicles lead to differential benefits. In addition, disaggregation by age and sex shows that the health impacts related to transport pollution disproportionately influence different age cohorts and genders.

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Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing, China (C Lu BS, S Venevsky PhD, T Sun BE, X Song MBA, C Wu PhD, X Dou BS, B Zhu PhD, Z Liu PhD); **Department of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, UK** (C Lu, W N Adger PhD); **Sustainability Division, Department of Technology, Management and Economics, Technical University of Denmark, Lyngby, Denmark** (K Morrissey PhD); **School of Economics and Management, Beihang University, Beijing, China** (S Zhang PhD); **International Institute for Applied Systems Analysis, Laxenburg, Austria** (S Zhang); **School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada** (H Yin PhD); **Department of Economics, University of Southern California, Los Angeles, CA, USA** (H Yin); **Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA** (C Wu)

Correspondence to:
Chenxi Lu, Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing 100084, China
luchenxicc1023@163.com

or

Zhu Liu, Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing 100084, China
zhuliu@tsinghua.edu.cn

Introduction

It is well established that there are considerable benefits of tackling transport pollution for both climate change and more localised pollutant concentrations. Carbon emissions in the transport sector are rising faster than emissions from other sectors and are projected to be 80% higher than current levels by 2030.[1] At the same time, urban air pollution from the transport sector has been linked to about 800 000 deaths per year globally, with a further 1·2 million deaths per year due to road traffic accidents and 1·9 million deaths per year due to physical inactivity.[2] The differential impact of air pollution across exposed populations is also widely recognised.[3,4] For example, children, older people, and those with predisposed respiratory and cardiovascular disease are known to be more susceptible to the health impacts of air pollution due to their increased biological sensitivities and different exposure patterns.[5–7] From a socioeconomic perspective, the distributional impacts of air pollution are amplified by historical patterns of land use in cities[8] and the ability to afford cleaner technologies.[9] Therefore, promoting a transition to low-carbon transport is a priority for climate change mitigation as well as for reducing the disproportionate risks faced by many individuals and communities.

Greenhouse gas mitigation measures in the transport sector include decreased use of motor vehicles, electrification of vehicles, increased levels of active travel (eg, walking and cycling), and increased use of public transport.[5,10] Recent research has examined several mitigation measures or potential mitigation scenarios in the transport sector regarding energy consumption, greenhouse gas emissions, atmospheric pollution, and public health.[11–13] Reductions in each of these factors will have direct and indirect positive impacts on human health.[14] Referred to as health co-benefits,[15] improvements in health outcomes from transport mitigation measures might include a reduction in mortality and morbidity attributable to air pollution exposure; a reduced burden of obesity and chronic, non-communicable diseases

Research in context

Evidence before this study

We searched Web of Science, Google Scholar, and references from relevant articles using the search terms "climate mitigation" (or "mitigation measures" or "decarbonizing"), "scenario study", "health co-benefits", "transport sector" (or "urban transport" or "decarbonizing"), "passenger transport", and "economic benefits" in the title or abstract. We searched for articles published between Jan 1, 2001, and March 1, 2021, in English or Chinese. Most studies on traffic pollution mitigation in China or other countries have assessed benefits solely in terms of their effects on pollutant emissions at the national or local level and a few studies have evaluated the effect of vehicular emissions on air quality in China. There is sparse evidence on the economic benefits of mitigation measures in the transport sector. Moreover, impact assessment on transport mitigation measures on health is still deficient.

Added value of this study

This study builds on previous studies and provides information on multiple outcomes from different urban transport mitigation scenarios, also stratified by age and sex, in the passenger transport sector in Beijing: energy consumption, CO_2 emissions, $PM_{2·5}$ concentrations, and health co-benefits, in 2020–50 compared with a business-as-usual scenario. As such, this study provides evidence showing that a combination of green transport and decarbonising vehicles will have major health benefits.

Implications of all the available evidence

The results show that there are substantial benefits from decarbonising the transport sector in Beijing, especially through the application of more green transport (ie, active travel and public transport). Policies aimed at encouraging active travel and use of public transport, increasing the safety of active travel, improving public transport infrastructure, and decarbonising vehicles lead to differential benefits. In addition, disaggregation by age and sex shows that the health impacts related to transport pollution disproportionately influence different age cohorts and genders.

through increasing physical exercise from active travel; and reduced danger from road traffic.[12,16]

Wang and colleagues, in 2020,[11] studied vehicle emission control measures in China from 2000 to 2015 and found that, without these control measures, vehicular emissions during 1998–2015 would have been 2–3 times larger. Furthermore, in 2015, the average concentration of $PM_{2·5}$ would have been higher by 11·7 μg/m³ and the average concentration of O_3 would have been higher by 8·3 parts per billion; the number of deaths attributable to air pollution in 2015 would have been higher by 500 000 (95% CI 360 000–730 000). Liang and colleagues, in 2019,[17] developed multiple scenarios by considering various penetration levels of electric vehicles in China and found that higher fleet electrification ratios can deliver improved air quality, with resultant climate and health benefits. They estimated that the electrification of 27% of private vehicles could reduce the number of annual premature deaths nationwide by 17 500 (10 656–22 160).

To accommodate the transport needs of the current population of Beijing (22 million),[18] the energy consumption of the transport sector is increasing year on year,[14,18] while rapid socioeconomic development resulted in a 146% increase in personal motor vehicle ownership[19] from 2005 to 2019. The rapid increase of passenger vehicles increases energy consumption and greenhouse gas emissions,[20] as well as exacerbating traffic congestion and air pollution. Particulate pollution, in particular high concentrations of $PM_{2·5}$ pollution, have been the foremost environmental problem for Beijing.[21] In response, the Beijing Government has implemented transport policy packages to tackle these problems (appendix p 1). Most mitigation studies in China to date have assessed benefits solely in terms of their effects on pollutant emissions at the national[13,22] or local level[23,24] and a few studies have evaluated the impact of vehicular emissions on air quality across the country.[25,26] In this Article, we provide comprehensive insights into the impact of transport mitigation measures on population health, and on the distributional impact of such measures on different subpopulations. We also investigate the economic benefits of mitigation measures in the transport sector in China.[27]

See **Online** for appendix

To optimise the social and economic benefits of transport mitigation strategies and address environmental injustice, it is necessary to investigate the health co-benefits of mitigation measures across different populations. Accordingly, the objective of this Article is to explore potential emissions reductions and health co-benefits by age and sex, as well as quantifying the monetary benefits of four urban land passenger mitigation scenarios for Beijing compared with the business-as-usual (BAU) scenario from 2020 to 2050. We apply an integrated assessment model that consists of a grey forecasting model, a low-carbon traffic development model, the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-ASIA model, a global exposure mortality model (GEMM), and a health economic model. We analysed the research results at a spatial resolution of 0·1°0·1° (about 1 km²) across Beijing's central area to provide detailed insights into the potential benefits of transport mitigation strategies in China at the city level. This analysis also enables policy makers to compare different transport mitigation strategies for decarbonisation and health co-benefits. The age–sex distributional analysis provides insights into some of the policy needs of different segments of the population.

Methods

Integrated assessment model

This study applies an integrated assessment model that combines a grey forecasting model, a low-carbon traffic development model, the GAINS-ASIA model, a health assessment model (ie, GEMM), and a health economic model (figure 1).

The grey forecasting model is used to forecast resident trips in the central area of Beijing per year, from 2020 to 2050 (appendix p 2). The low-carbon traffic development model is applied to calculate travel distances and energy consumption of different travel modes. The GAINS-ASIA model estimates future air pollutant emissions using data on energy consumption, industrial production, and proposed environmental regulations under different scenarios. The GEMM model is used to examine $PM_{2.5}$-related mortality and avoided deaths attributable to ambient $PM_{2.5}$ related to regional production and consumption activities. Finally, the health economic model is used to evaluate the economic benefits from saving lives because of mitigation measures in transport.

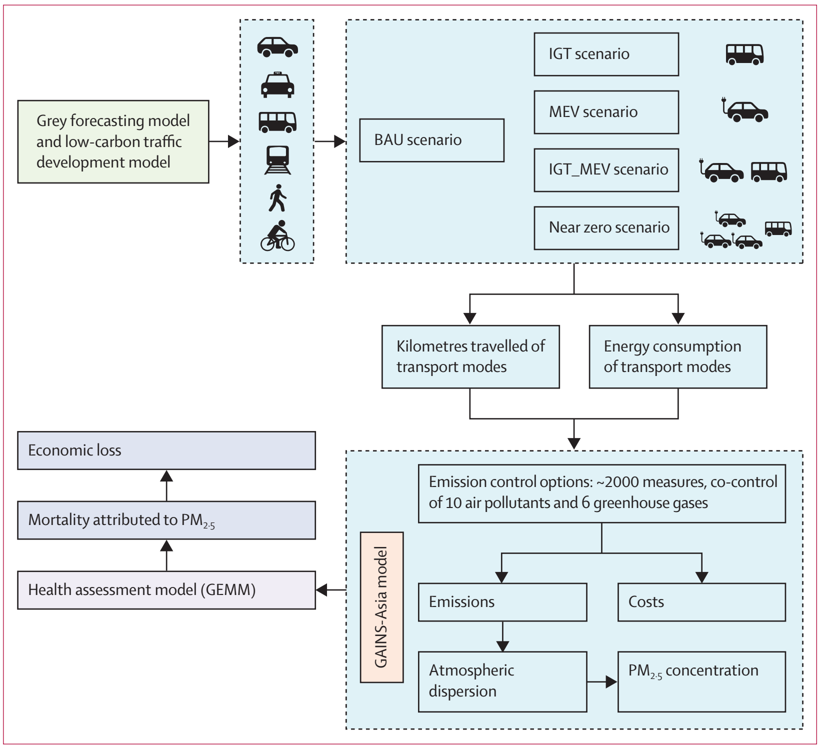


Figure 1: **Research framework for assessment of health and economic outcomes of different transport scenarios for Beijing**

BAU=business as usual. GAINS=Greenhouse Gas and Air Pollution Interactions and Synergies. GEMM=global exposure mortality model. IGT=increased green transport. IGT_MEV=increase green transport and more electric vehicles. MEV=more electric vehicles.

Scenario description and research scope

Due to data availability from the Beijing Transport Annual Report,[19] the research area for this study is the central area of Beijing, China, including the Dongcheng, Xicheng, Chaoyang, Haidian, Shijingshan, and Fengtai districts (appendix p 3). The transport sector was divided into freight, intercity passenger, and urban passenger transport according to the classification of national statistical systems.[28] Data were used on urban land passenger transport, which was defined as public passenger transport (ie, buses, subway, walking, and cycling) and private passenger transport (ie, private cars and taxis). The year 2015 was selected as the base year for this study.

A BAU scenario is used as the reference scenario, with four alternative mitigation scenarios proposed: increased green transport (IGT), more electric vehicles (MEV), both IGT and MEV scenarios (IGT_MEV), and near zero CO_2 emissions (we set scenarios according to climate mitigation measures for the transport sector from the Beijing City Master Plan [2016–35];[29] table; appendix pp 4–6).

	Description
BAU	Improve transport and energy infrastructure; increase the share of green transport (including walking, cycling, subway, and buses) in the central area of Beijing to 75% by 2020 (per the 2020 Beijing Transport Annual Report[19]); reduce share of passenger cars and taxis
IGT	Increase share of green transport in the central area of Beijing, to more than 75% by 2020 and not less than 80% by 2035 (per the Beijing City Master Plan 2016–35[29])
MEV	Based on BAU, focus on decarbonising motor vehicles; increase diffusion of electric cars according to Beijing Municipality regulations on quantifying the number of passenger cars and restricting usage of gasoline cars (per the Beijing City Master Plan 2016–35[29])
IGT_MEV	A scenario that aggregates the IGT and MEV scenarios
Near zero	Based on the IGT_MEV scenario, achieve 100% electrification of passenger vehicles in Beijing by 2050; eliminate gasoline cars over time, reducing their total number and the number of total passenger vehicles

BAU=business as usual. IGT=increase green transport. MEV=more electric vehicles. IGT_MEV=increase green transport and more electric vehicles.

Table: **Principal features of different transport scenarios for Beijing**

The BAU scenario takes account of transport structure improvement over time as well as any energy structure improvements in the transport sector. The historical share of different land passenger travel modes in Beijing from 2007 to 2019 is shown in the appendix (p 7). The IGT and MEV scenarios refer to policies associated with Beijing's transport development, outlined in the Beijing City Master Plan (2016–35).[29] The IGT scenario emphasises increasing the share of green transport (ie, walking, cycling, and public transport) in Beijing, to more than 75% by 2020 and not less than 80% by 2035.[29] The MEV scenario emphasises the decarbonisation of vehicles, which will affect their fuel consumption. In this study, two types of passenger cars are considered—gasoline cars and electric cars. There are three major types of electric car used by consumers in Beijing—battery electric vehicles, plug-in hybrid electric vehicles, and range-extended electric vehicles.[30] In this study, we assume all electric vehicles are carbon-free electric vehicles, such as battery electric vehicles and range-extended electric vehicles, under the five relevant scenarios (appendix p 8). The IGT_MEV scenario aggregates the IGT and MEV scenarios.

In 2020, China pledged to become carbon neutral by 2060.[31] To align with the goals of the Paris Agreement

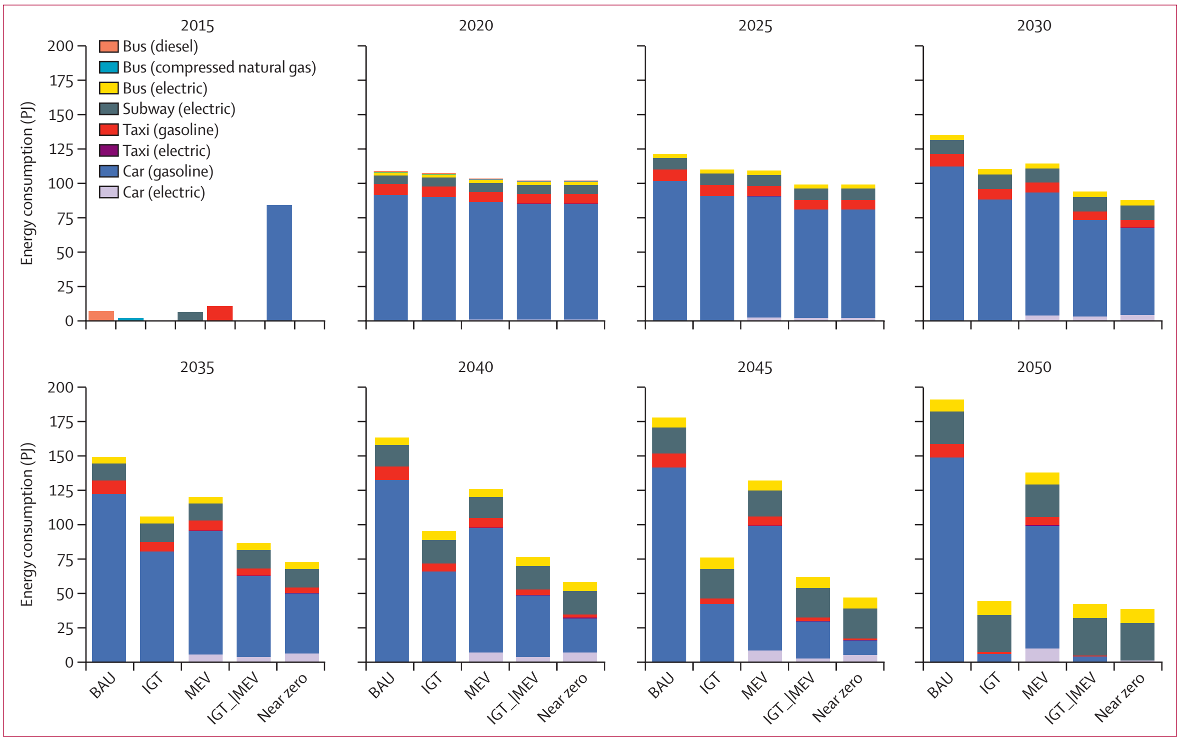


Figure 2: **Energy consumption of passenger land travel modes in Beijing in 2015 and in the future under five scenarios**
BAU=business as usual. IGT=increased green transport. IGT_MEV=increase green transport and more electric vehicles. MEV=more electric vehicles.

and the China Government pledge, we also developed a near zero CO_2 emissions scenario. This scenario is based on the IGT_MEV scenario, but it goes further by promoting 100% electrification of Beijing's passenger transport, including passenger cars, taxis, and buses by 2050. To compare results between different scenarios, five common assumptions are used (appendix p 10).

For the **EMEP model** see http://webdab.emep.int/

Modelling air pollutant emissions, scope of travel modes, and $PM_{2·5}$ concentration

The low-carbon traffic development model is used to calculate the travel distance of each travel mode under the five scenarios, multiplying the energy intensity of different fuel vehicles. We used the bottom-up approach of the Intergovernmental Panel on Climate Change (2006) for calculating greenhouse gas emissions.[32] The equation for calculating the energy consumption of different travel modes is in the appendix (p 11).

The GAINS-ASIA model is applied for estimating air pollutants, greenhouse gas emissions, and $PM_{2·5}$ concentrations on the basis of the energy consumption ($E_{i,t,s,f}$) of different fuels (in PJ). Additional pollutants, such as particulate matter from tyre wear and braking of vehicles during driving, are not considered in these estimates, which might therefore be conservative and lower-bound estimates of actual pollution levels. Emissions are calculated through a combination of three data categories: activity pathways, emission vectors, and control strategies and associated costs. On the basis of the detailed spatial and sectoral GAINS emissions inventory, the GAINS model computes fields of ambient $PM_{2·5}$ concentrations with the help of source–receptor associations derived from an atmospheric chemistry transport model called EMEP. The EMEP model runs on a 0·1°0·1° grid. The $PM_{2·5}$ concentration is presented in the appendix (p 11).

$PM_{2·5}$-related health impact assessment

This study considers the effect of long-term exposure to $PM_{2·5}$ concentration on mortality, which is modelled by a more recent GEMM that incorporates recent epidemiological evidence, including that from a cohort study on outdoor $PM_{2·5}$ pollution in China.[4] There are two versions of GEMM: one is GEMM NCD+LRI, which covers risks from non-accidental non-communicable diseases and lower respiratory infections; and another one is GEMM 5-COD, which comprises five causes of mortality: ischaemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections. In this study, we apply these two versions to assess the mortality of different scenarios; we define deaths from additional non-accidental, non-communicable diseases via subtracting the five causes of mortality in GEMM 5-COD from GEMM NCD+LRI. $PM_{2·5}$-attributable mortality under different scenarios are measured by sex (female and male) and age group (25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, and 80+). The equation for the $PM_{2·5}$-related health impact assessment is in the appendix (p 16). The uncertainty analysis and sensitivity test can be found in the appendix (pp 20–21).

Benefits from decarbonising urban land passenger transport

To better understand and compare different mitigation scenarios, we calculated two types of benefits for the four mitigation scenarios compared with the BAU scenario. These benefits are health co-benefits related to $PM_{2\cdot5}$ pollution and benefits of reducing CO_2 emissions (appendix p 19). It was estimated that the social cost of carbon in China was US$24 (4–50) per tCO_2 in 2015.[33]

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

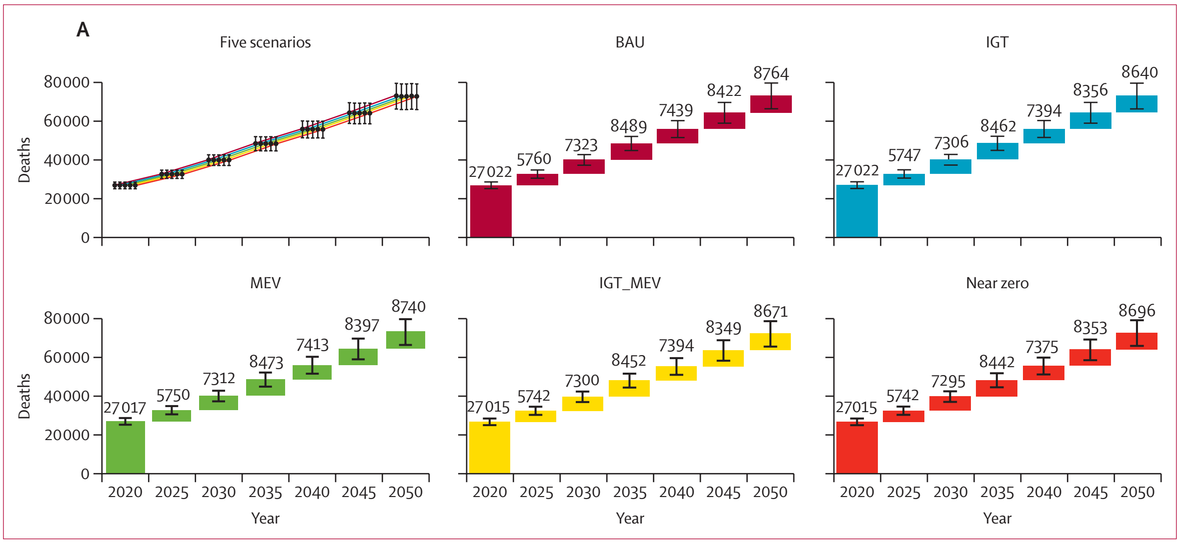
Results

Energy consumption, air pollution emissions, and $PM_{2\cdot5}$ concentration

In 2015, the total energy consumption of eight fuel types of vehicle was 110 PJ (figure 2). Energy consumption for privately owned gasoline cars is much higher than that of other vehicles, accounting for 76% (84 PJ) of the total energy consumed, followed by gasoline taxis. In general, less energy is consumed for different scenarios than for BAU during study years; the near zero scenario consumes the least amount of energy annually.

Under the BAU and MEV scenarios, the energy consumption of passenger vehicles increases compared with the three other scenarios. In comparison with BAU (191 PJ), energy consumption decreases by 77% (–146 PJ) with IGT, 28% (–53 PJ) with MEV, 78% (–149 PJ) with IGT_MEV, and 80% (–152 PJ) with near zero by 2050; and the difference in energy consumption between BAU and the other scenarios gets larger each year. Under all scenarios, energy consumption from gasoline cars is projected to decrease; for the IGT, IGT_MEV, and near zero scenarios, energy consumption from gasoline cars no longer dominates, ranging from 65% (89 PJ) in 2020 to 0% in 2050. Only under the MEV scenario does the energy consumption of gasoline cars become dominant (65% [89 PJ] in 2050). Starting in 2030, the energy consumption of electric cars becomes more pronounced under MEV, IGT_MEV, and near zero (when the percentage of kilometres travelled by electric cars takes up more than 20% of the total distance travelled by cars in the central area of Beijing [appendix p 14]); for example, from 2030 to 2050, the percentage of energy consumed by electric cars rises from 3% (3 PJ) to 5% (4 PJ) under IGT_MEV. But under IGT_MEV and near zero, the percentage of energy consumption of electric cars is less in 2050 than in the previous year due to the increasing share of public buses and subway transit. At the same time, the percentage of energy consumed by public buses and the subway (green transport) gradually increases under all scenarios. By 2050, the energy consumption of public buses and the subway is the top consumer for each travel mode under IGT, IGT_MEV, and near zero.

Emissions, including $PM_{2\cdot5}$ and CO_2, for each scenario are shown in the appendix (p 22). Estimates of $PM_{2\cdot5}$ emissions range from 0·8 kt to 0·9 kt (+13%) under BAU; from 0·8 kt to 0·6 kt under IGT (–29%); from 0·8 kt to 0·7 kt (–4%) under MEV; from 0·8 kt to 0·5 kt (–29%) under IGT_MEV; and from 0·8 kt to 0·5 kt (–29%) under near zero, during the 2020–50 period. In 2050, the ranking of $PM_{2\cdot5}$ emissions under different scenarios is BAU with the highest emissions, followed by MEV, then IGT, then IGT_MEV, which is equal, in terms of emissions, with near zero. Compared with the BAU scenario, CO_2 emissions from buses and cars decrease by



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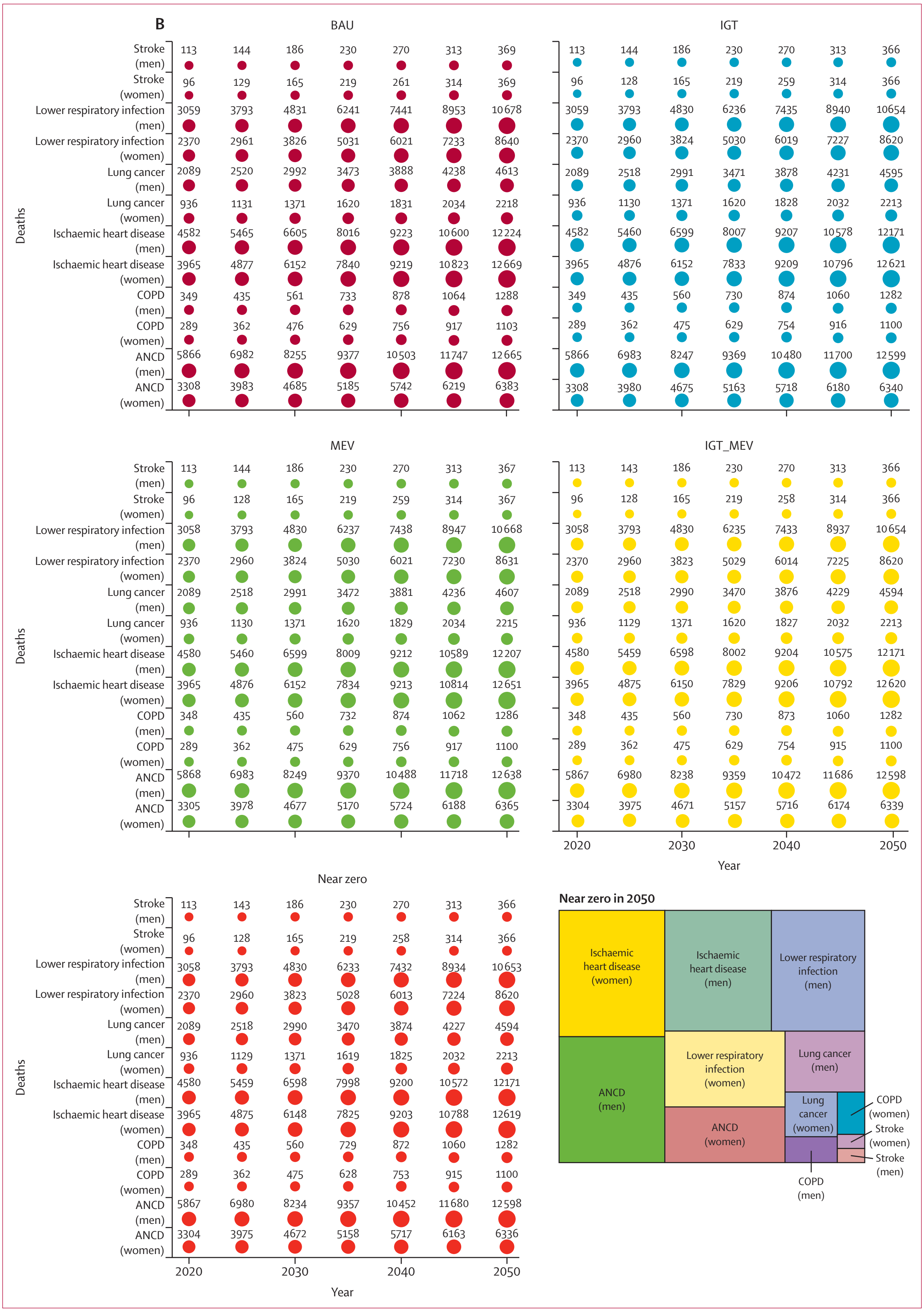


***Figure 3:* PM$_{2.5}$-attributable mortality under five future scenarios, 2020–50**
(A) Disease-specific and sex-specific mortality. (B) Total PM$_{2.5}$-attributable mortality under different scenarios; the panel at the bottom right shows the percentage of deaths by sex and cause under the near zero scenario by 2050. ANCD=additional, non-accidental, non-communicable diseases. BAU=business as usual. COPD=chronic obstructive pulmonary disease. IGT=increased green transport. IGT_MEV=increase green transport and more electric vehicles. MEV=more electric vehicles.

96% (–10·2 PJ) with IGT, 40% (–4·3 PJ) with MEV, 97% (–10·4 PJ) with IGT_MEV, and 100% (–10·6 PJ) with near zero in 2050, which means the near zero scenario achieves zero carbon emissions regarding urban passenger transport. Under the IGT, IGT_MEV, and near zero scenarios, CO_2 emissions of cars and buses decrease over time, whereas they increase over time in a BAU scenario. Under the MEV scenario, CO_2 emissions increase before 2035, but decline from 2035 onwards.

In 2015, the average population-weighted $PM_{2.5}$ concentration in the central area of Beijing was 79·4 [SD 13·2] $\mu g/m^3$, according to the GAINS-Asia model. Most of the population in the study area is exposed to more than the average $PM_{2.5}$ concentration, located in the southeast area of Beijing (appendix p 23). A downward trend of $PM_{2.5}$ concentrations exists under all scenarios except for the BAU scenario (appendix p 23). However, none of the scenarios meet China's Ambient Air Quality Standard level II (35 $\mu g/m^3$),[34] if other sectors (ie, not urban passenger transport) keep the same structure as they have in 2015 (as assumed in this study). Compared with the BAU scenario, annual $PM_{2.5}$ concentrations under each of the four scenarios are lowest with near zero (–0·45% or –0·36 PJ]), followed by IGT (–0·45% or –0·35 PJ), then IGT_MEV (–0·43% or –0·34 PJ), and then finally MEV (–0·01% or –0·01 PJ) from 2020 to 2050. In general, the trend in $PM_{2.5}$ concentrations for a particular scenario is mostly consistent with the trend in $PM_{2.5}$ emissions.

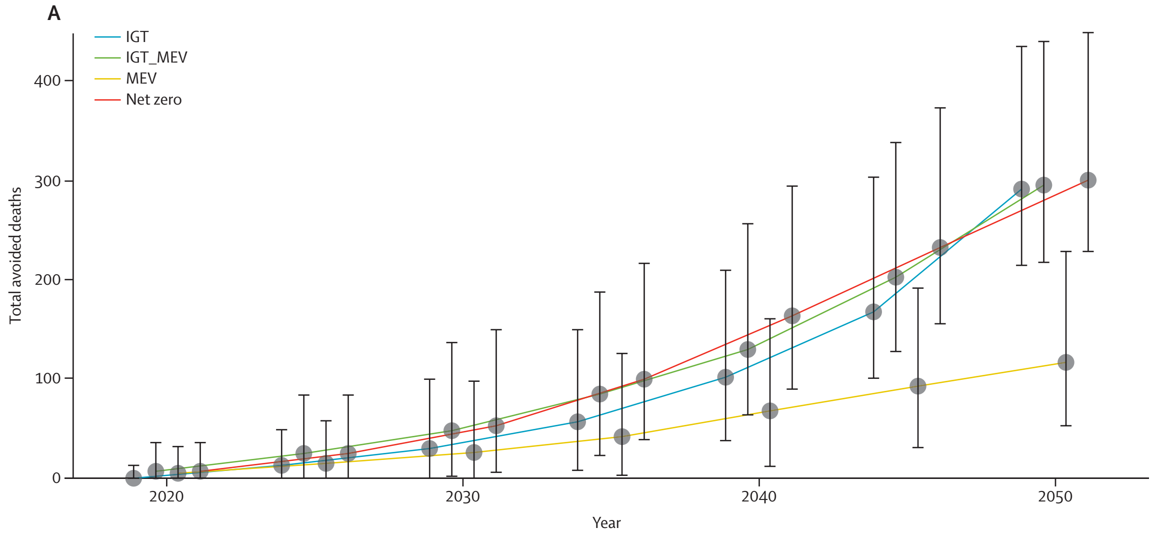
Mortality attributed to $PM_{2.5}$ exposure

Under all scenarios, total mortality increases annually (figure 3A). However, there are fewer deaths under the four mitigation scenarios from 2020 to 2050 than with the BAU scenario, with near zero recording the lowest number of deaths annually (eg, 72 900 deaths [95% CI 66 100–79 300] in 2050). The MEV scenario has the most deaths among the four mitigation scenarios from 2030 onwards.

Ischaemic heart disease represents around 32·5% (95% CI 31·5–34·0) and additional non-accidental, non-communicable diseases represent around 32·5% (26·0–34·0) of the total annual deaths, followed by lower respiratory infections (23·0% [20·1–26·4]), lung cancer (10·4% [9·3–11·2]), and stroke (0·9% [0·8–1·0]; figure 3B). However, mortality caused by lower respiratory infection (19·3–30·2%) increased fastest among all five specific causes annually, followed by stroke (17·0–31·0%). Men with chronic obstructive pulmonary disease, lung cancer, lower respiratory infection, stroke, or additional non-accidental, non-communicable diseases have a greater mortality than women, but women with ischaemic heart disease (after 2040) have a greater mortality than men (figure 3B). For example, under the near zero scenario in 2050, men with ischaemic heart disease account for 17% (n=12 171) of the total deaths, while men and women with stroke each account for 0·5% (n=366).

Economic benefits under mitigation scenarios

Compared with the BAU scenario, 0 (95% CI 0–13) deaths are estimated to be avoided with the IGT scenario, 5 (0–32) with the MEV scenario, 7 (0–36) with IGT_MEV, and 7 (0–36) with near zero by 2020; 30 (0–100) deaths with IGT, 26 (0–98) with MEV, 48 (2–137) with IGT_MEV, and 53 (6–150) with near zero by 2030; 102 (38–210) with IGT, 68 (12–161) with MEV, 130 (64–257) with IGT_MEV, and 164 (90–295) with near zero by 2040; and 292 (215–436) with IGT, 117 (53–229) with MEV, 296 (218–441) with IGT_MEV, and 301 (229–450) with near zero by 2050 (figure 4A). Among the four mitigation scenarios, IGT_MEV and near zero save the most lives over time; the effect of the IGT scenario on saving lives gets more pronounced while the effect of the MEV



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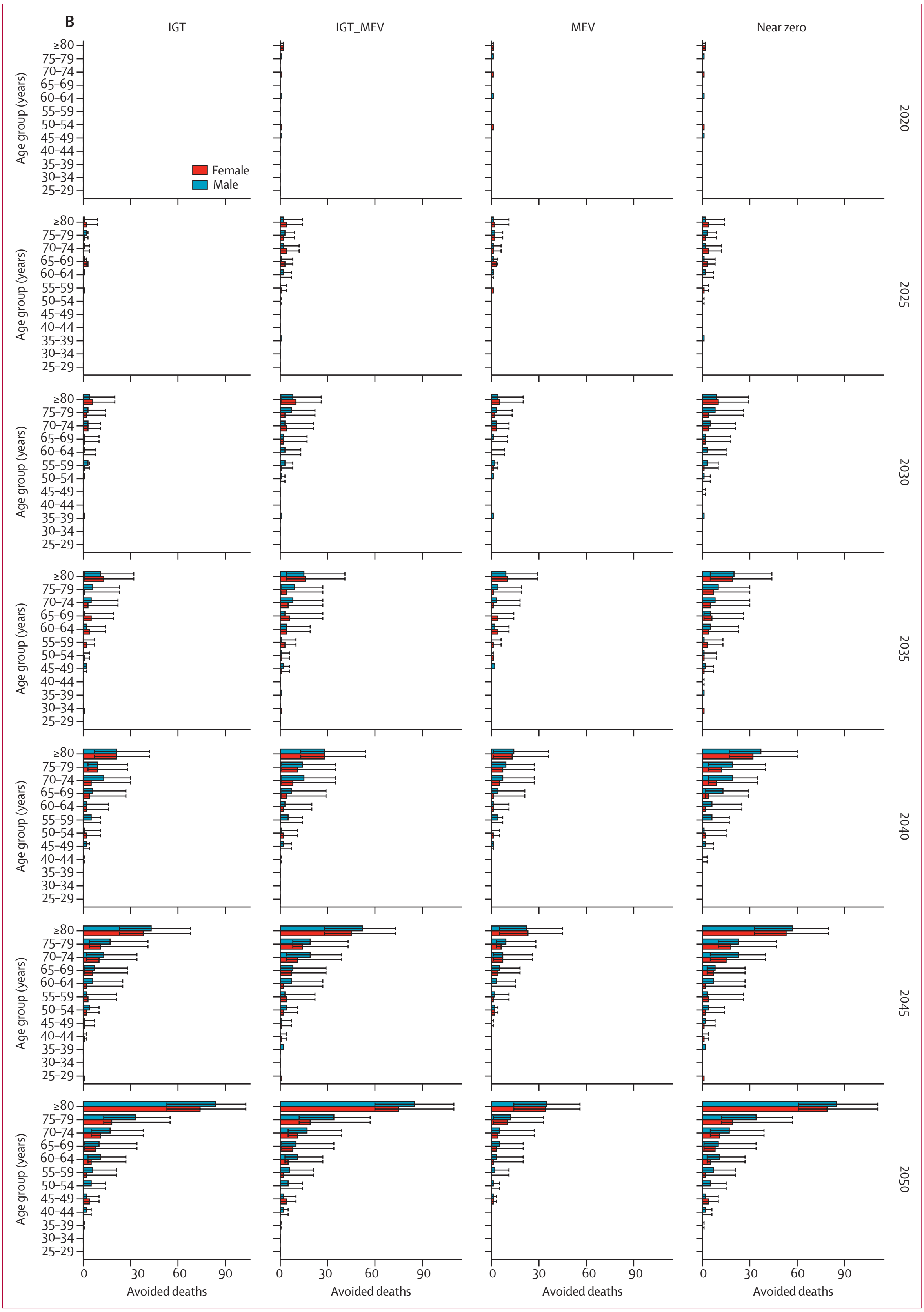

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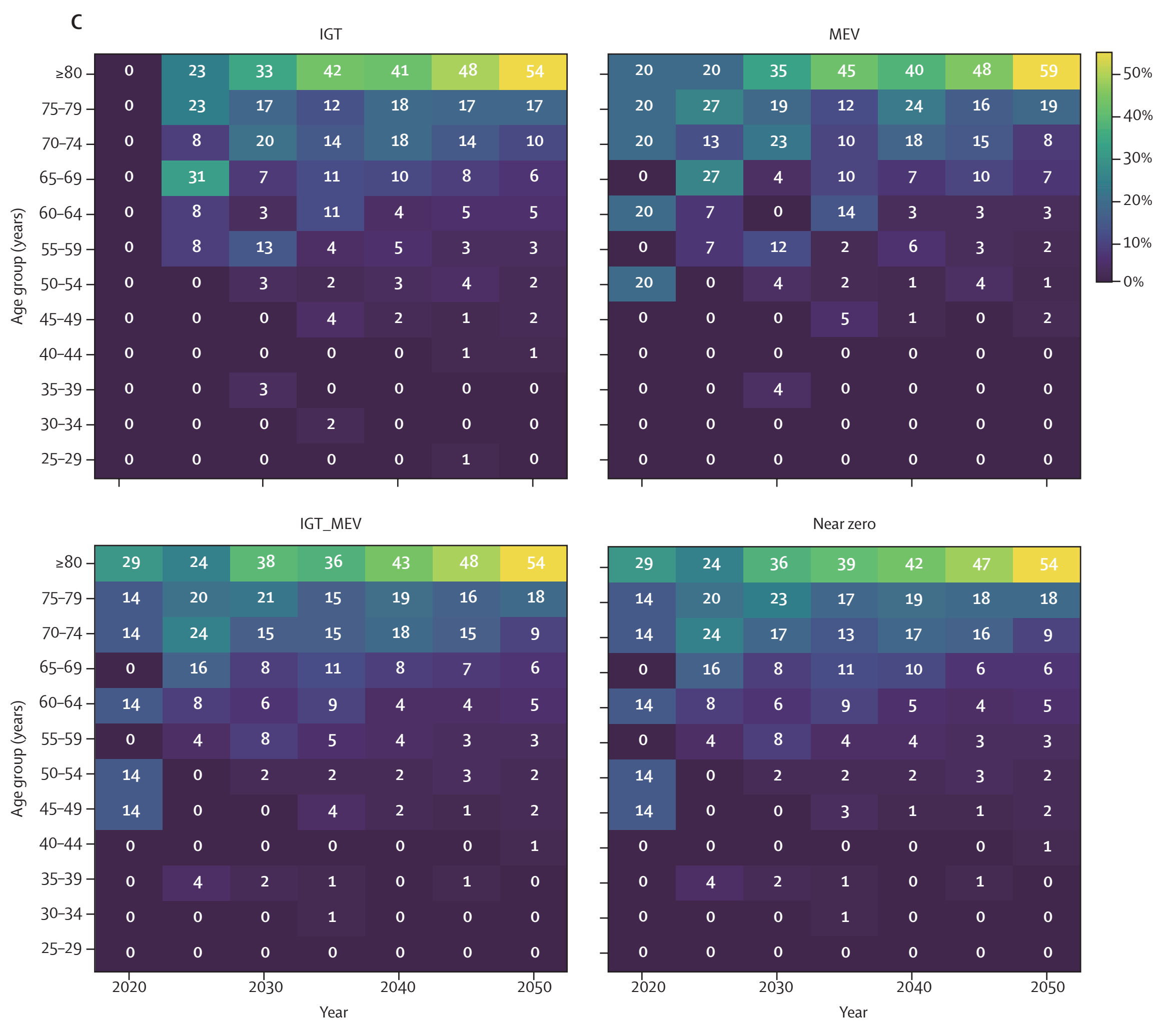


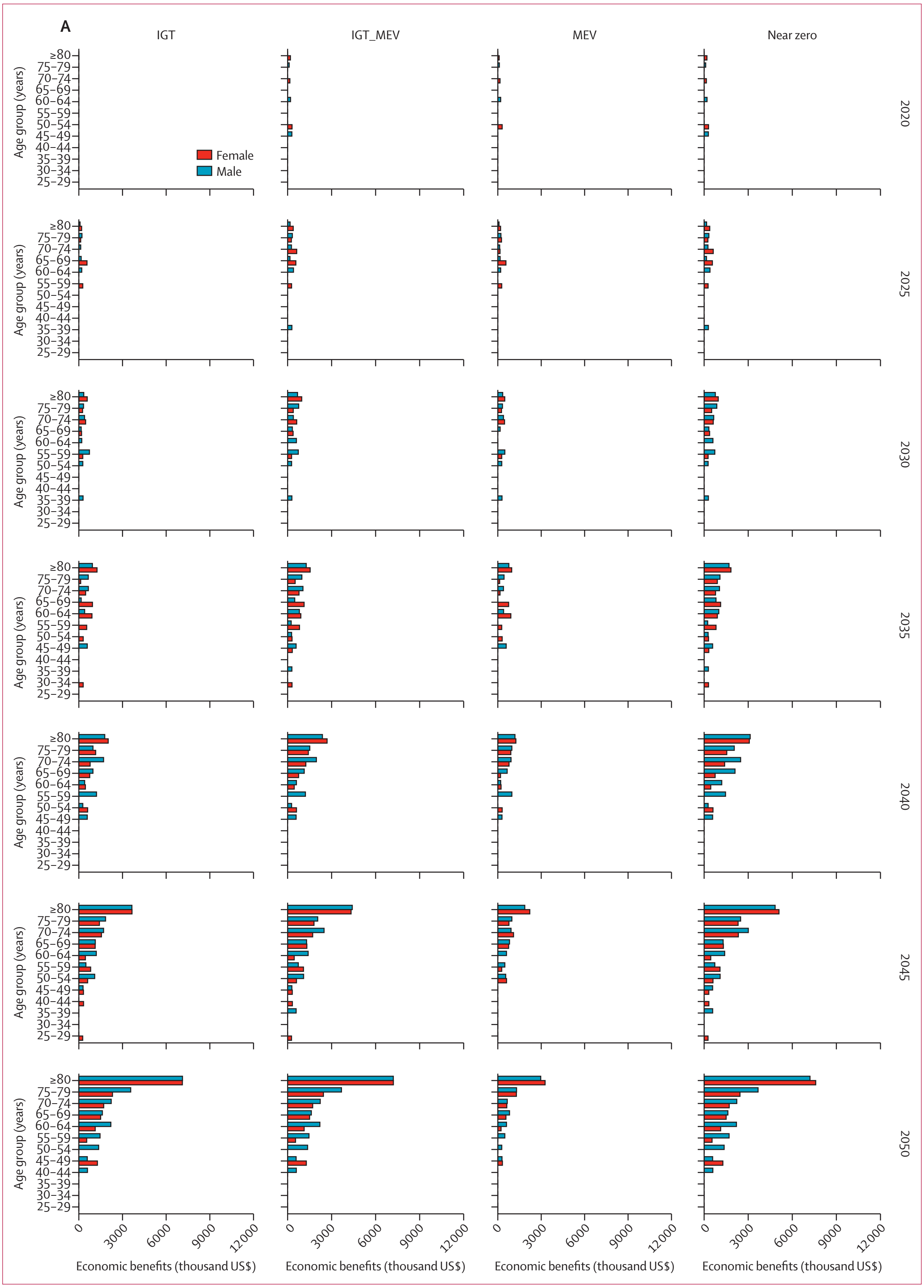
***Figure 4:* Avoided deaths attributable to PM$_{2.5}$, measured by sex and age under mitigation scenarios compared with the BAU scenario, 2020–50**
(A) Total avoided deaths under different scenarios. (B) Detailed avoided deaths measured by sex and age under different scenarios. (C) Percentage of avoided deaths for different population age groups under different scenarios. BAU=business as usual. IGT=increased green transport. IGT_MEV=increase green transport and more electric vehicles. MEV=more electric vehicles.

scenario on saving lives gets less pronounced than the other three scenarios (figure 4A).

The population older than 50 years gains the greatest health benefits (>84%) annually under the four mitigation scenarios (figure 4B–C). Moreover, with time, the older population gains more health benefits than the younger population. For example, in 2025, the group aged 80 years and older accounts for 23% (3/13; showing 3 people aged 80 or older saved from the death of 13 total avoided deaths) of the total health benefits under IGT, 20% (3/15) under MEV, 24% (6/25) under IGT_MEV, and 24% (6/25) under near zero individually; while in 2050, the same age group accounts for 54% (158/292) under IGT, 59% (69/117) under MEV, 54% (160/296) under IGT_MEV, and 54% (164/301) under near zero individually (figure 4C). On the other hand, younger groups (ie, those younger than 50 years) gradually avoid more deaths with time (figure 4B–C).

Men obtain more health co-benefits than women across the study timeframe under each scenario and cumulatively, with men avoiding more deaths than women under the four scenarios. However, in the group aged 80 years and older, women would sometimes gain more health co-benefits under the four mitigation scenarios from 2020 to 2050, due to the effect of demographic changes (ie, more women than men in this age group; appendix p 18) outperforming mortality rates (figure 4B; appendix p 17).

The economic benefits measured by sex and age show the same trend as avoided deaths. Economic benefits will get larger annually and the near zero scenario provides the largest economic benefits compared with the other three. People older than 50 years and men gain the most



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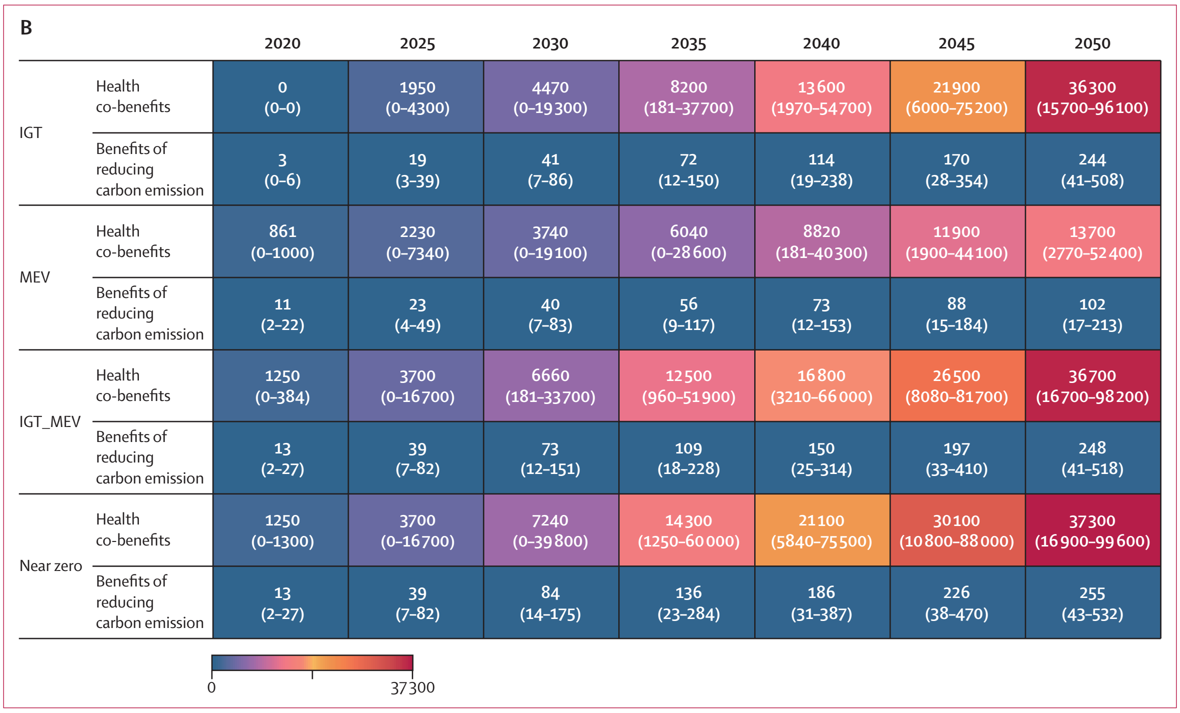

		2020	2025	2030	2035	2040	2045	2050
IGT	Health co-benefits	0 (0–0)	1950 (0–4300)	4470 (0–19300)	8200 (181–37700)	13600 (1970–54700)	21900 (6000–75200)	36300 (15700–96100)
	Benefits of reducing carbon emission	3 (0–6)	19 (3–39)	41 (7–86)	72 (12–150)	114 (19–238)	170 (28–354)	244 (41–508)
MEV	Health co-benefits	861 (0–1000)	2230 (0–7340)	3740 (0–19100)	6040 (0–28600)	8820 (181–40300)	11900 (1900–44100)	13700 (2770–52400)
	Benefits of reducing carbon emission	11 (2–22)	23 (4–49)	40 (7–83)	56 (9–117)	73 (12–153)	88 (15–184)	102 (17–213)
IGT_MEV	Health co-benefits	1250 (0–384)	3700 (0–16700)	6660 (181–33700)	12500 (960–51900)	16800 (3210–66000)	26500 (8080–81700)	36700 (16700–98200)
	Benefits of reducing carbon emission	13 (2–27)	39 (7–82)	73 (12–151)	109 (18–228)	150 (25–314)	197 (33–410)	248 (41–518)
Near zero	Health co-benefits	1250 (0–1300)	3700 (0–16700)	7240 (0–39800)	14300 (1250–60000)	21100 (5840–75500)	30100 (10800–88000)	37300 (16900–99600)
	Benefits of reducing carbon emission	13 (2–27)	39 (7–82)	84 (14–175)	136 (23–284)	186 (31–387)	226 (38–470)	255 (43–532)

***Figure 5:* Economic benefits of mitigation scenarios, 2020–50**

(A) Economic benefits measured by sex and age under mitigation scenarios. (B) Total value of benefits under different mitigation scenarios (thousand US$). IGT=increased green transport. IGT_MEV=increase green transport and more electric vehicles. MEV=more electric vehicles.

benefit (figure 5A). For instance, under the near zero scenario, men would cumulatively gain $4970 more than women through avoided mortality during 2020–50. Figure 5B lists two types of benefits under the four mitigation scenarios. Monetary health co-benefits contribute the most to the total benefits. Although the CO_2 reduction value is small, it increases annually (figure 5B). In 2050, under the near zero scenario, the total value from mitigation is equal to 0·01% (0–0·03%) of Beijing's Gross domestic product in 2015 ($369 billion). Under the IGT, IGT_MEV, and near zero scenarios, economic benefits rise annually.

Discussion

Previous transport mitigation studies for China[13,14,22–26] or other countries[12,16] have focused on a specific outcome, primarily estimates of changes in pollution or CO_2 emissions. This study builds on those and provides information on multiple outcomes, according to sex and age, for different urban transport mitigation scenarios in the passenger transport sector in Beijing. Hence, this study shows that a combination of green transport and decarbonising vehicles could have substantial positive benefits, with implications for policy to realise these benefits. The near zero scenario achieves the largest health co-benefits and economic benefits annually relative to other mitigation scenarios; in 2050, an estimated 300 (95% CI 229–450) deaths are averted, with $37 million (17–100) in economic benefits from better health outcomes and $255 000 (43 000–532 000) in economic benefits from CO_2 cost savings. This study indicates cumulative benefits from combining actions, such as electrifying vehicles, reducing motor vehicle use, and achieving aggressive reductions in carbon emissions by the middle of this century in the transport sector. This finding is consistent with scenarios for other cities, such as London (UK) and Delhi (India), which showed that a combination of active travel and lower-emission motor vehicles result in the largest benefits (7500 disability-adjusted life-years in London and 13 000 in Delhi).[12]

There is previous evidence on the implications of shifting private transport to electric vehicles.[17,35,36] This study indicates that increasing the share of green public transport and active travel can provide more benefits compared with electrification of private vehicles alone. The IGT scenario saves an estimated zero lives (95% CI 0–13) in 2020 and 292 lives (215–436) in 2050, with the share of green transport increasing from 75·4% in 2020 to 99·4% in 2050 (increase of 32%). The MEV scenario, by contrast, is estimated to save five lives (0–32) in 2020 and 117 lives (53–229) in 2050, with the percentage of cars that are electric rising from 0·7% (36·7) to 40·5% (326·7) during 2020–50. Comparing the IGT scenario with the IGT_MEV scenario, the effects of increasing electric cars are most visible before 2050, with avoided mortality from the swap to electric cars decreasing when the share of green transport reaches 99·4%. Furthermore, comparing the IGT_MEV scenario with the near zero scenario, we find that, by 2050, when the share of green transport has reached 99·4%, only five additional lives are saved under the near zero scenario with 100% electrification in private passenger cars compared with 40·5% electrification under the IGT_MEV scenario.

These findings suggest that when green transport already accounts for a large share of resident trips, then further electrification of vehicle fleets provides a small marginal reduction in pollution and its associated health burden. Other scenario studies in Beijing also conclude that public transport development should be given priority over new energy and clean energy vehicles.[37] In 2016, He and Qiu[27] concluded that the largest reduction of pollution emission would occur by increasing the use of both public buses and cycling. Several studies have noted that a shift from private vehicle use to active transport is a key intervention for improving public health, physically and psychologically.[38–40]

For health outcomes, although studies have found that women are more at risk for negative health impacts from air pollution,[41] in our study, the health co-benefits are marginally greater for men than for women across all scenarios. This finding is explained by the higher male population in Beijing and the relatively higher incident rates of each of the five disease categories for men compared with women (appendix pp 17–18). Proposed explanations for the so-called male–female health-survival paradox include biological differences, behavioural differences such as risk-taking and reluctance to seek and comply with medical treatment, methodological challenges such as selective non-participation and under-reporting of health problems, and delayed seeking of treatment.[42]

The results show that populations aged 50 years and older and women aged 80 years and older in Beijing benefit more from transport mitigation owing to the structure of the ageing population and the vulnerability and increased risk of older groups exposed to air pollution.[6] This finding is in line with several studies[5,21,41,43] that suggest older populations are particularly affected by long-term exposure to air pollution[41] so that they gain more health co-benefits when making mitigation changes. This study also finds that, as well as obtaining health co-benefits via decarbonising the transport sector in Beijing, there could be substantial benefits through a reduction in CO_2 mitigation costs. This finding is in line with a study finding that stringent penetration of electric vehicles can reduce the carbon mitigation cost generated by the 2 °C climate stabilisation target.[35] It also implies that transport-based mitigation also has an overall positive economic impact.

Previous research suggests that the electrification of vehicles improves air quality for disadvantaged neighbourhoods and thus meets social and equity goals through reducing atmospheric pollution loading in vulnerable communities, particularly for those located near congested streets and highways.[44] However, fossil fuel-powered plants are normally far from urban areas, which means that increased usage of electric vehicles disproportionally benefits city dwellers (as cities contain the highest concentration of electric vehicles). On the other hand, those who are exposed to pollution from electricity generation predominantly reside in rural areas, which are downwind of fossil fuel power plants.[44] In 2015, Ji and colleagues found that electric vehicles could increase inequality in terms of the health impacts of pollution in China; around 77% (41–96%) of emission inhalation attributable to urban electric vehicles is distributed to rural communities whose incomes are on average lower than those for city residents who use urban electric vehicles.[45] In addition, another study suggests that electrification of transport without the replacement of fossil-fuel power plants leads to an increase in CO_2 emission.[35] These previous studies suggest that a scenario for city transport based primarily on electrification does not address the fundamental issue of pollution generation; rather it displaces the pollution exposure to other areas, often outside the city. Hence, low-carbon power as a means to decarbonise power generation has a key role in electrifying the transport sector.[35] In China, the percentage of renewable generation (including hydropower, nuclear, wind, and solar power) was 32·1% of the total power generation in 2020, and the annual rate of increase of low-carbon power was around 10% during 2015–20 (appendix p 24). These figures suggest that there is a major challenge to achieve 100% low-carbon power generation by 2060 for China.

There are uncertainties in our assessment. Through our uncertainty and sensitivity analysis, we found that health assessments using an integrated exposure–response model might underestimate the $PM_{2·5}$-related health co-benefits without considering additional non-accidental non-communicable diseases, which can be around two-fold or three-fold less than the results from GEMM in this study. Furthermore, the monetarised avoided deaths of mitigation scenarios could be around 1·8–2·8 times larger if using the invariant value per statistical life. If different segments of the population were reduced by 50%, under the near zero scenario, $PM_{2·5}$-related mortality can reduce by 50% in 2050, showing that the population size is proportional to mortality in this integrated assessment and that $PM_{2·5}$-related deaths are sensitive to the distribution of future subpopulations.

The integrated method used in this study can be easily applied to similar or broader research in different research areas and can be compatible with setting different future transport mitigation scenarios. This research has limitations common to many scenario studies: data availability, underestimation of comprehensive health impacts, and various sources of uncertainty: (1) health impacts from increasing physical activity are not considered; (2) other sources of air pollution aside from $PM_{2·5}$ are not considered; and (3) technology improvement and innovation in the future. More details and results of the sensitivity analysis can be found in the appendix (pp 25–29). Regardless of these limitations, the findings obtained in this study can be used to inform sustainable transport planning for Beijing as well as for other megacities (appendix p 30) if they vigorously adopt sustainable transport.

Conclusion and policy implication

Comparing different pollution mitigation measures in the urban land passenger sector, this study shows that a combination of green transport and the adoption of electric vehicles generate the largest health co-benefits. The study also provides evidence that developing green transport measures outperforms the electrification of passenger transport. Increases in green transport are progressive and are consistent with environmental justice: they improve access and increase health benefits for disadvantaged populations and those who have more limited travel options.[46] Examining the impact of transport-based mitigation on health across different age and sex groups, this study reveals some of the ways in which the benefits of decarbonising Beijing's transport system would be distributed across society. This study shows that, in the context of Beijing's geography and demographic make-up, men benefit more across all mitigation strategies. Although older people receive the greatest benefits from decarbonisation in terms of avoidance of premature death, younger groups have a higher relative risk when exposed to air pollution. Our research also shows a reduction in CO_2 mitigation costs via transport electrification, restricted vehicle using, and phasing out internal combustion engine vehicles. The comprehensive results suggest that stakeholders, including transport planners, energy experts, policy makers, and economists, should develop a joint strategy for transport electrification to reduce CO_2 emissions quickly and effectively due to the effectiveness of transport electrification policy.[35]

There are substantial benefits to Beijing authorities prioritising green transport development policies as outlined in the 13th Five-Year Plan.[47] However, the effectiveness of these green transport strategies partly depends on the demand for green and public transport. An avoid–shift–improve approach[48,49] could focus on reducing the need to travel, which can be achieved by refocusing urban planning: the so-called 15-min city concept, for example, seeks to increase active travel by locating services and employment within active travel distance of where people live,[50,51] as well as promoting teleworking.[48] Transport modal shift from cars to walking, cycling, and public transport[48] can be promoted by cultivating citizens' travel habits to adopt more green transport, through providing incentives and information on the health benefits.[52] Such incentives are widely implemented in cities throughout the world to increase car ownership costs, limit car access in city centres, and increase investment for walking and cycling infrastructure.[53–55]

The sensitivity analysis suggests that the geographical distribution of the population has a fundamental effect on health burden: radical interventions, such as relocating vulnerable groups to less polluted areas, could therefore potentially reduce aggregate exposure. The results also suggest that relying solely on mitigation in passenger transport cannot achieve air quality standards within China's Ambient Air Quality Standard level II (35 μg/m³),[34] even with deep decarbonisation measures. Consequently, comprehensive mitigation actions across all polluting sectors are urgently required.

Contributors

CL, WNA, and KM contributed to study conceptualisation and design. CL did the data collection, data analysis, data interpretation, and visualisation, and wrote the first draft. WNA, KM, and ZL supervised the research, and SZ and HY supervised the methodology. WNA, KM, and ZL critically revised the manuscript. TS, XS, XD, and BZ helped analyse part of the data. SV, HY, and CW contributed to revising ideas. CL, WNA, KM, and ZL accessed and verified the data underlying this study. All authors had full access to all the data in the study, approved the final version, and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Urban passenger transport data for projection is from the Beijing Statistical Yearbook (2015–19) and the Beijing Transport Annual Report (2012–20). Mortality data used in this research is from the China Health Statistics Yearbook (2016). The air pollution exposure used in this research are available from the authors on request. Some data might not be available to external investigators because of data confidentiality agreements.

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