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, Beiqing 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$_2.5$ 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.

Funding National Natural Science Foundation of China and FRIEND Project (through the National Research Foundation of Korea, funded by the Ministry of Science and ICT).

Copyright © 2022 The Author(s). Published by Elsevier Ltd. This is an Open Access article under the CC BY-NC-ND 4.0 license.

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. At the same time, urban air pollution from the transport sector has been linked to about 800000 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. The differential impact of air pollution across exposed populations is also widely recognised. 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. From a socioeconomic perspective, the distributional impacts of air pollution are amplified by historical patterns of land use in cities and the ability to afford cleaner technologies. 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. 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. Reductions in each of these factors will have direct and indirect positive impacts on human health. Referred to as health co-benefits, 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
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, CO₂ emissions, PM₂·₅ 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.

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, CO₂ emissions, PM₂·₅ 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.
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.

Scenario description and research scope
Due to data availability from the Beijing Transport Annual Report, 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. 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]: table; appendix pp 4–6).

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). 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. 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. 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. To align with the goals of the Paris Agreement...
and the China Government pledge, we also developed a near zero CO₂ 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).

Modelling air pollutant emissions, scope of travel modes, and PM₂·₅ 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. 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 PM₂·₅ concentrations on the basis of the energy consumption (Eₘᵢᵣₑ) 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 PM₂·₅ 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 PM₂·₅ concentration is presented in the appendix (p 11).

PM₂·₅-related health impact assessment
This study considers the effect of long-term exposure to PM₂·₅ concentration on mortality, which is modelled by a more recent GEMM that incorporates recent epidemiological evidence, including that from a cohort study on outdoor PM₂·₅ pollution in China. 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. PM₂·₅-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 PM₂·₅-related health impact assessment is in the

For the EMEP model see http://webdab.emep.int/
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$_{2.5}$ 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 2015.13

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$_{2.5}$ 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$_{2.5}$ and CO$_2$, for each scenario are shown in the appendix (p 22). Estimates of PM$_{2.5}$ 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$_{2.5}$ 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
Figure 3: PM₂.₅-attributable mortality under five future scenarios, 2020–50
(A) Disease-specific and sex-specific mortality. (B) Total PM₂.₅-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, CO₂ emissions of cars and buses decrease over time, whereas they increase over time in a BAU scenario. Under the MEV scenario, CO₂ emissions increase before 2035, but decline from 2035 onwards.

In 2015, the average population-weighted PM₂·₅ concentration in the central area of Beijing was 79·4 [SD 13·2] μg/m³, according to the GAINS-Asia model. Most of the population in the study area is exposed to more than the average PM₂·₅ concentration, located in the southeast area of Beijing (appendix p 23). A downward trend of PM₂·₅ 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 μg/m³), 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 PM₂·₅ concentrations under each of the four scenarios are lowest with near zero (−0·45% or −0·36 PJ), followed by 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 PM₂·₅ concentrations for a particular scenario is mostly consistent with the trend in PM₂·₅ emissions.

Mortality attributed to PM₂·₅ 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, 72900 deaths [95% CI 66100–79300] 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=12171) 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 (6–137) 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
Articles

(Figure 4 continues on next page)
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
(Figure 5 continues on next page)
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 CO₂ 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 or other countries have focused on a specific outcome, primarily estimates of changes in pollution or CO₂ 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 $255000 (43000–532000) in economic benefits from CO₂ 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 13000 in Delhi). There is previous evidence on the implications of shifting private transport to electric vehicles. 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 23·0%). 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% (3·6%) to 40·5% (7·8%) during 2020–50. Comparing the IGT scenario with the 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, the share of green transport reaches 99·4%. Furthermore, comparing the IGT_MEV scenario with the near zero scenario, the share of green transport reaches 99·4%

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

<table>
<thead>
<tr>
<th>Benefits of reducing carbon emission</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IGT</strong></td>
<td>0 (0–0)</td>
<td>1950 (0–4300)</td>
<td>4470 (0–19300)</td>
<td>8200 (181–37700)</td>
<td>13600 (1970–54700)</td>
<td>21900 (6000–75200)</td>
<td>36300 (15700–96100)</td>
</tr>
<tr>
<td><strong>MEV</strong></td>
<td>3 (0–5)</td>
<td>19 (3–39)</td>
<td>41 (7–86)</td>
<td>72 (12–150)</td>
<td>114 (19–238)</td>
<td>170 (28–354)</td>
<td>244 (41–598)</td>
</tr>
<tr>
<td><strong>IGT_MEV</strong></td>
<td>11 (2–22)</td>
<td>23 (4–49)</td>
<td>56 (9–117)</td>
<td>73 (12–153)</td>
<td>88 (15–184)</td>
<td>102 (17–213)</td>
<td>125 (20–276)</td>
</tr>
</tbody>
</table>

*IGT* = increased green transport. *IGT_MEV* = increase green transport and more electric vehicles. *MEV* = more electric vehicles.

www.thelancet.com/planetary-health Vol 6 June 2022
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.3
In 2016, He and Qiu2 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.19–21

For health outcomes, although studies have found that
women are more at risk for negative health impacts from
air pollution,22 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 incidence
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 differ-
ces 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.23

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.23 This finding is in line with several studies23–26,41
that suggest older populations are particularly affected by
long-term exposure to air pollution23 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 CO2 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.24 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 neigh-
bourhoods and thus meets social and equity goals
through reducing atmospheric pollution loading in
vulnerable communities, particularly for those located
near congested streets and highways.26 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.23
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.23 In addition, another study suggests
that electrification of transport without the replacement
of fossil-fuel power plants leads to an increase in CO2
emission.23 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.25 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
combined 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 compre-
prehensive 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.6 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 CO₂ 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 CO₂ emissions quickly and effectively due to the effectiveness of transport electrification policy.23

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 approach49 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.4 Transport modal shift from cars to walking, cycling, and public transport48 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.53,54

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 revision. CL 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.

**Acknowledgments**

This research received funding from the National Natural Science Foundation of China (71874097; 41921005; 71904007; 72140002; and 71904040) and the Fine Particle Research Initiative in East Asia Considering National Differences (FRIEND) Project (through the National Research Foundation of Korea, which is funded by the Ministry of Science and ICT; project number 2020M3G1A114622).

**References**


41 Sun Z, An X, Tao Y, Hou Q. Assessment of population exposure to PM2.5 for respiratory disease in Lanzhou (China) and its health-related economic costs based on GHS. *BMC Public Health* 2013; 13: 274.


