Health Benefits of Strategies for Carbon Mitigation in US Transportation, 2017–2050

Neil Maizlish, PhD, MPH, Linda Rudolph, MD, MPH, and Chengsheng Jiang, PhD

Objectives. To quantify health benefits and carbon emissions of 2 transportation scenarios that contrast optimum levels of physical activity from active travel and minimal air pollution from electric cars.

Methods. We used data on burden of disease, travel, and vehicle emissions in the US population and a health impact model to assess health benefits and harms of physical activity from transportation-related walking and cycling, fine particulate pollution from car emissions, and road traffic injuries. We compared baseline travel with walking and cycling a median of 150 weekly minutes for physical activity, and with electric cars that minimized carbon pollution and fine particulates.

Results. In 2050, the target year for carbon neutrality, the active travel scenario avoided 167 000 deaths and gained 2.5 million disability-adjusted life years, monetized at $1.6 trillion using the value of a statistical life. Carbon emissions were reduced by 24% from baseline. Electric cars avoided 1400 deaths and gained 16 400 disability-adjusted life years, monetized at $13 billion.

Conclusions. To achieve carbon neutrality in transportation and maximize health benefits, active travel should have a prominent role along with electric vehicles in national blueprints. (*Am J Public Health*. 2022;112(3):426–433. https://doi.org/10.2105/AJPH.2021.306600)

Achieving carbon neutrality by 2050 is imperative to stem adverse health impacts of climate change.[1] In the United States, adoption of solar and wind power has put the energy sector on a trajectory to meet this goal. However, since 2017, carbon emissions in transportation have eclipsed other sectors and have trended upward.[2] Two strategies to reduce carbon emissions in transportation are (1) electrification of the vehicle fleet and (2) reduction of vehicle miles traveled (VMT). Both have significant health benefits through, respectively, air pollution reduction and increased physical activity associated with walking and cycling.

Although the strategies are complementary, the investments and policies to achieve them are very different. For example, electrification requires charging infrastructure and could include subsidies for electric vehicles or limitations on sales of new internal combustion engine vehicles. VMT reduction requires policies and investments to make land use and built environment changes that increase neighborhood access to the necessities of life and make transit affordable and convenient, automobile travel less attractive, and walking and cycling safer and more attractive.

In considering options, quantification of the health benefits or harms of different strategies provides crucial information to decision-makers. Key questions include how to best optimize simultaneous health and climate benefits and to what extent health benefits potentially offset implementation costs.

To answer these questions, we contrasted idealized transportation scenarios that represent endpoints for health benefits and carbon mitigation: (1) electrification of US light-duty passenger vehicles (LDPVs) and (2) nonmotorized transport to achieve a national population median of up to 150 minutes per week of physical activity in adults—consistent with the guidelines of the 2018 Physical Activity Guidelines Committee.[3] LDPVs include automobiles, light-duty pick-up trucks, passenger vans, and sports utility vehicles, and in 2017 accounted for 71% of greenhouse gas emissions (GHGEs) by US road vehicles.[2] Nonmotorized transport, or "active transport," is walking and cycling for nonrecreational purposes and travel to and from transit stops.

Previous research has identified 3 main health impact pathways in transportation: physical activity from active transport, fine particulate (particulate matter with a diameter of $\leq 2.5\ \mu m$; $PM_{2.5}$) pollution from vehicle emissions, and road traffic injuries.[4] US studies that integrated these pathways have focused on state, regional, or city impacts. Other studies, while national in scope, considered only $PM_{2.5}$ pollution.[5] To our knowledge, this is the first national health impact assessment that considers all 3 pathways and carbon dioxide (CO_2) emissions.

METHODS

The 2017 National Household Travel Survey[6] describes baseline travel times for walking and cycling and baseline travel distances for walking, cycling, LDPVs, and bus and rail passengers. We estimated truck VMT from Federal Highway Administration data,[7] and we derived bus VMT from data on occupancy[8] and bus personal miles traveled from the National Household Travel Survey.

We contrasted baseline travel with 4 alternative scenarios. The first ($AT_{100\%}$) represents ambitious expansion of active travel so that half or more of US adults achieve 150 weekly minutes of moderate-intensity physical activity. We assumed total per-capita travel that is the same as baseline, reciprocal increases in active travel and decreases in LDPV travel, and a per-capita median of 75 minutes per week each for walking and cycling. Based on the US Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES),[9] this scenario assumes that national fuel economy standards[10] for model year 2017 LDPVs are fully implemented by 2025 and extend through 2050. Carbon emissions per mile traveled fall from 405 grams CO_2 in 2015 to 226 grams CO_2 in 2050. MOVES also projects emissions of primary $PM_{2.5}$, tire and brake wear, and secondary constituents such as sulfur dioxide (SO_2) and oxides of nitrogen (NOx) from 2015 to 2050. In the second scenario ($AT_{25\%}$), we estimated health benefits from active transport in which half or more of US adults attain 25% of the physical activity goal by walking and cycling, each for 18.5 minutes per week.

The third scenario is full electrification ($EV_{100\%}$) of LDPVs in which carbon emissions are reduced to zero by 2050, and primary and secondary constituents of $PM_{2.5}$, except for tire and brake wear, are reduced to zero. The fourth scenario ($EV_{50\%}$) is 50% electrification of LDPVs. The scenarios for electrification do not take into account carbon emissions or $PM_{2.5}$ pollution from the generation of electricity that fuels electric LDPVs.

We assumed that all scenarios were implemented by 2050, the year we evaluated health impacts. Projections by the Federal Highway Administration indicate little change in per-capita VMT for light duty vehicles through 2047.[11] Similarly, 3 cycles of National Household Travel surveys (2001, 2009, and 2017) show marginal increases in active travel.[12] Barring significant changes in policy and investments, our baseline reasonably approximates "business as usual" in 2050.

The Integrated Transport and Health Impact Model

The Integrated Transport and Health Impact Model (ITHIM) implements comparative risk assessment for 3 health pathways. The methodology has been described previously[4] and in supplemental materials (https://ithim.org/ithim). The method determines the change in the population burden of disease from the shift in the exposure distribution (or "dose") of physical activity, LDPV emissions, and collision risk. The reference exposure distribution is based on the current travel pattern ("baseline") or the current pattern projected at a future time ("business as usual"). The alternative distribution is given by a future scenario in which travel patterns are altered by policy, systems, and environmental change.

The change in the burden of disease (*BD*) is a function of the annual burden of disease, disease specific dose–response functions (*DRF*), and the change in "*Dose*." The latter 2 elements are expressed as the epidemiological population attributable fraction (*PAF*):

$$\text{(1)}\quad \Delta BD = f(BD,\ DRF,\ \Delta Dose) = BD \times PAF$$

The burden of disease is expressed as deaths and disability adjusted life years (DALYs) for specific diagnostic entities associated with physical activity, $PM_{2.5}$, and road traffic injuries. We downloaded data on age-, sex-, and cause-specific deaths and DALYs for the United States in 2015 from the Global Burden of Disease project.[13] We estimated the 2050 US burden of disease from the projected US population[14] in 2050 and the average annual percent changes in age-, sex-, and cause-specific mortality rates from 2015 to 2050.[15]

Physical Activity

The "dose" of physical activity was the population distribution of hours per week of walking and cycling for transport weighted by energetic intensity.[16] We expressed energetic intensity as marginal metabolic equivalent task (mMET) hours per week (mMHWs) for physical activity beyond a resting state. We derived the distribution from the log-transformed per-capita mean weekly minutes of active travel and its standard deviation. We approximated the distribution in quintiles and stratified by sex and age (0–4, 5–14, 15–29, 30–44, 45–59, 60–69, 70–79, and ≥ 80 years). mMET weights for walking reflected age and sex variation from an average walking speed of 3 miles per hour (~3 mMETs) and we based those for cycling on an average speed of 12 miles per hour (5 mMETs). The change in dose (Δ) reflected changes in the distribution of mMET-weighted walking and cycling times from a baseline, *b*, to the alternative scenario, *s*.

The dose–response function was nonlinear,[3] disease-specific, and, as incorporated into the *PAF*, has the form

$$(2) \qquad PAF = 1 - RR, \text{ where}$$

$$RR = \frac{rr_s}{rr_b} = \frac{\exp(\boldsymbol{\beta} * \Delta mMHW_s)}{\exp(\boldsymbol{\beta} * \Delta mMHW_b)}$$

The *PAF* is calculated from an overall relative risk (*RR*), which incorporates relative risks of baseline (rr_b) and scenario (rr_s) at their respective mMHWs on the dose–response curve. Based on meta-analyses of Garcia et al.,[17] the dose–response decreased linearly up to 10 mMHW. For higher levels, we set the relative risks to those of 10 mMHWs.

Dose–response gradients, e^{β} (ΔRR per mMHW), were as follows: ischemic heart disease (0.9764), hypertensive heart disease (0.9764), stroke (0.9697), dementia (0.9666), diabetes (0.9666), depression (0.9695), colon cancer (0.9940), breast cancer (0.9813), and lung cancer (0.9771). We based the relative risk–physical activity gradient on active travel and leisure time. We estimated age- and sex-specific leisure physical activity times at quintiles of active transport times from National Health and Nutrition Examination Survey data that reported breakdowns of physical activity for leisure activities apart from walking and cycling for transport.[18]

Fine Particulate Matter

For comparative risk assessment, the dose–response function was

$$(3) \qquad PAF = 1 - \exp\left(\boldsymbol{\beta} * \Delta PM_{2.5}\right).$$

For cardio-respiratory diseases, which include ischemic heart disease, hypertensive heart disease, stroke, asthma, chronic obstructive pulmonary disease, and respiratory tract infections, the RR/$PM_{2.5}$ gradient, e^{β}, was 1.0146 based on the meta-analysis of prospective cohort studies by Vodonos et al.[19] For lung cancer, the RR/$PM_{2.5}$ gradient was 1.0122.

We derived the change in national ambient $PM_{2.5}$ concentration attributable to a change in VMT by LDPVs from changes in LDPV emissions of the baseline and the scenario. MOVES[9] modeled the US vehicle fleet and generated primary and secondary constituents of $PM_{2.5}$ in tons per year. LDPV emissions for $PM_{2.5}$, tire and brake wear, NO_x, and SO_2 were obtained between 2015 and 2050 in 5-year increments.

The US Environmental Protection Agency (USEPA) publishes coefficients, c_i, for US mortality per ton per year (TPY) of emissions of $PM_{2.5}$, NO_x, and SO_2 emissions for road vehicles.[20] Annual mortality is estimated by multiplying the coefficients by annual emissions for each precursor (*i*) and then summing. We derived ratios for each $PM_{2.5}$ precursor relating change in ambient levels of $PM_{2.5}$ to tons of emissions by equating annual deaths from the previously mentioned dose–response formula and USEPA's incidence per ton coefficients from 2015 to 2050.

$$(4) \qquad Ratio_i = \frac{PM_{2.5(i)}}{TPY_i} = \frac{\frac{\ln\left(1 - \frac{1}{BD}\right)}{\boldsymbol{\beta}}}{\frac{1}{c_i}}$$

The change in ambient $PM_{2.5}$ was given by multiplying the ratios by annual tons of $PM_{2.5}$ precursors and summing.

$$(5) \qquad \Delta PM_{2.5} = \sum_{i}^{n} Ratio_i \times \Delta TPY_i$$

We assumed proportionality between emissions and VMT of LDPVs, yielding a change of −0.57 nanograms per cubic meter $PM_{2.5}$ per percent reduction in VMT by LDPVs. For the $EV_{100\%}$ scenario, we assumed 100% reduction in LDPV emissions of CO_2 and precursors of ambient $PM_{2.5}$, except for tire and brake wear.

Carbon Emissions

MOVES estimated carbon dioxide emitted per mile (emissions factor [*EF*]) by vehicle and fuel type. Aggregate emissions are given by

$$(6) \qquad Aggregate\ CO_2\ Emissions = EF \times per\ capita\ mean\ LDPV\ VMT \times Population.$$

CO_2 emission factors were VMT-weighted by fuel type (gas, diesel, and electric hybrid) of LDPVs at 5-year intervals from 2015 to 2050. Carbon emissions in the $EV_{100\%}$ scenario were zero in 2050.

Road Traffic Injuries

Traffic collisions occur when a pedestrian, cyclist, or victim's vehicle is struck by another vehicle, and the risk of injury depends on both personal miles traveled (*PMT*) by the victim and VMT by the striking vehicle. The risk of injury is considered for every pairwise combination of victim mode (*i*) and striking vehicle (*j*) for baseline (*B*) and scenario (*S*) travel, where the modes are walking, cycling, LDPV, motorcycle, bus, and truck. Injury risk is nonlinear[21] and has the functional form

$$(7) \qquad RR_{i,j} = \sqrt{\frac{PMT_{Si} \times VMT_{Sj}}{PMT_{Bi} \times VMT_{Bj}}}$$

The risk function integrated into the expression for the *PAF* was

$$(8) \qquad PAF = 1 - \left(\frac{\sum (RR_{i,j} \times B_{i,j})}{\sum B_{i,j}}\right)$$

$$= 1 - \frac{\sum Injuries_S}{\sum Injuries_B}$$

where $B_{i,j}$ is the number of baseline injuries for combinations of victim and striking vehicle.

We categorized injury severity as fatal or serious, and we stratified injuries by roadway type (highway, arterial, or local), which is a surrogate for traffic speed and volume. We downloaded data on fatal injuries for 2016 from the Fatality Analysis Reporting System[22] and on serious injuries from the Crash Report Sampling System.[23]

Monetization of Health Outcomes

The health benefits and harms attributable to the change in burden of disease and injury were monetized based on the value of a statistical life. We multiplied the change in the number of deaths by the 2019 value of a statistical life, $9.8 million.[24]

Modeling Platform and Analysis

ITHIM estimates health impacts' order of magnitude and direction. To avoid conveying undue precision, we rounded model estimates. We created an interactive Web site with decision-support and educational materials (https://ithim.org/ithim).

RESULTS

Per-capita median active travel time increased 10-fold in the $AT_{100\%}$ scenario compared with baseline (Table 1). The $AT_{100\%}$ scenario demonstrated large annual health benefits for physical activity and modest benefits for $PM_{2.5}$ reduction, but increased deaths and decreased DALYs for road traffic injuries. $EV_{100\%}$ did not change baseline levels of active transport and was associated with a modest reduction in annual deaths and gain in DALYs (1400 and 16 400, respectively) from $PM_{2.5}$ reduction. The annual net benefit for $AT_{100\%}$ was the avoidance of 167 000 deaths and the gain of 2.5 million DALYs. The annual monetized net benefits of $AT_{100\%}$ greatly exceeded that of $EV_{100\%}$. In the $AT_{100\%}$ scenario, carbon emissions were lowered by 150 million metric tons per year, 24%, from the 2050 baseline of 630 million metric tons per year. By design, the $EV_{100\%}$ scenario had no carbon emissions. The less ambitious scenarios for $AT_{25\%}$ and $EV_{50\%}$ generated fewer health benefits and carbon reductions. However, the health benefits of meeting 25% of the AT goal greatly exceeded those of full electrification.

DISCUSSION

We found trade-offs in health benefits and carbon mitigation in idealized scenarios to achieve carbon neutrality in the transportation sector. Ambitious expansion of active travel had the potential for orders of magnitude greater health benefits than electrification of LDPVs. Benefits were attributable to increases in physical activity and reduction in $PM_{2.5}$ pollution, which were moderated by increases in road traffic injuries, likely because of LDPVs striking pedestrians and cyclists.[4] This is consistent with other health impact assessments.[25] However, because a large percentage of VMT by LDPVs in the United States (87%)[6] occurs in trips exceeding 5 miles, which are less amenable to active travel, even large increases in active travel cannot achieve necessary transportation GHGE reductions. Strategies that complement electrification and support active transportation are also important. Land-use and housing changes to increase access to jobs and essential services within short distances, including in rural areas, and significant investments in high-quality electric transit (and its supporting walk and cycling infrastructure) can address longer trips while increasing physical activity and reducing traffic injuries, carbon emissions, and traffic congestion.

Light-duty fleet electrification had greater potential for carbon mitigation and generated health benefits from reduced $PM_{2.5}$ pollution. Our estimates of avoided $PM_{2.5}$-related mortality are similar to studies that accounted for geographic variation of air pollution and that included health impacts of other pollutants such as ozone.[5,26] The greater health impact of

TABLE 1— Per-Capita Median Active Travel Time, Annual Avoided and Incurred Deaths and Disability Adjusted Life Years (DALYs), Monetized Health Costs, and Carbon Emissions by Pathway and Scenario: United States, 2050

Scenario	Median Travel Time (min/p/w)		Physical Activity Pathway		$PM_{2.5}$ Pathway		Road Traffic Injury[a] Pathway		Costs, Billion, $, ΔVSL[b]	Carbon Emissions, MMTY
	Walk	Cycle	ΔDeaths	ΔDALYs	ΔDeaths	ΔDALYs	ΔDeaths	ΔDALYs		
Baseline	14	1								630
Active transport										
100%	75	75	178 000	2 900 000	330	3 800	−11 000	−442 000	1 600	480
25%	19	19	52 000	988 000	80	950	−4 000	−217 000	470	600
Electrification of light-duty passenger vehicles										
100%	14	1	0	0	1 400	16 400	0	0	13	0
50%	14	1	0	0	700	8 200	0	0	7	315

Note. DALY = disability adjusted life year; min/p/w = minutes per person per week; MMTY = million metric tons per year; $PM_{2.5}$ = fine particulate matter with a diameter of ≤ 2.5 µm; VSL = value of a statistical life. Figures in table are rounded.

[a] Negative sign indicates increase in deaths and DALYs.
[b] VSL = \$9.8 million (2019 dollars).

physical activity compared with $PM_{2.5}$ pollution is similar to other studies in which active travel replaces conventional car travel.[25] The EV scenarios showed smaller benefits than some health impact studies of vehicle electrification. This may reflect differences in baseline year (e.g., 2015 vs 2050), defining health outcomes based on cause-specific mortality rather than all-causes mortality, and different health impact tools (HEAT,[27] BenMAP[28]), which vary from ITHIM in age restrictions, dose–response functions, and methods for monetizing health outcomes. Nonetheless, replacing fossil fuels with electricity does not change current car-centric transportation associated with long and sedentary commuting, noise, urban sprawl, community severance, and traffic injuries. Electrification will not entirely eliminate health risks because tire and brake wear will contribute to $PM_{2.5}$.

Both electrification and active travel scenarios pose significant implementation and policy challenges.[29] Technology for electric vehicles must be developed, deployed, and financed that addresses battery charging, vehicle range, and cost. Only 1.5% of new car sales were fully electric vehicles in 2019. Electrification is stimulated by voluntary pledges of vehicle manufacturers to phase out sales of gasoline-powered cars by 2050, rebates and tax incentives for electric car purchases, and the California gubernatorial executive order that bans sales of new gasoline-powered cars by 2035. By contrast, active travel does not require a change in technology, but significant financial investment in pedestrian, bicycle, and transit infrastructure and changes in land use that equilibrate future demand for housing and job growth. Several European countries with a broad portfolio of such investments have already exceeded the $AT_{25\%}$ scenario goals for transport-related cycling (Netherlands) and walking (Switzerland), signaling that ambitious active travel is attainable.[30]

California legislation in 2008 required regional transportation plans to reduce GHGEs, but a 2018 report found VMT still increasing and that a reduction of single-occupancy vehicle travel is necessary to achieve statewide GHGE reduction goals.[31] This suggests that carbon neutrality in US transportation will not likely be achieved by 2050 without significant changes to how communities and transportation systems are planned, funded, and built. To promote additional housing, several US cities have upended traditional land use by abolishing single family zoning. These initial steps will have to be followed by larger systemic changes to elevate active travel to a dominant travel mode.

The 2 strategies highlight potentially divergent interests. For example, affordable housing or transit advocates may prioritize policies that reduce VMT, while some vehicle manufacturers prioritize policies that support electrification. The scenarios also contrast in that active travel investments (sidewalks, bike lanes, transit systems) are largely public, and electrification builds on private vehicle ownership. Recent national blueprints to achieve carbon neutrality clearly favor vehicle electrification and understate the role of active travel.[26] These documents do not question the hegemony of car-centric transportation or the impacts of their plans on the social determinants of health, and existing health and racial inequities.

Limitations

Our scenarios had important assumptions and limitations. We assumed that the 2015 baseline per-capita VMT and active travel would fairly represent travel patterns in 2050. We did not alter per-capita transit distances. An ambitious expansion of transit would add to active travel and be a source of additional health benefits. Our active travel scenarios accounted for safety in numbers in estimating the health burden of road traffic injuries, but we did not model walking and cycling infrastructure (e.g., separated lanes) that could significantly reduce collisions between active travelers and motorized vehicles.[32]

Our LDPV electrification scenarios did not consider additional health benefits from electricity generated from renewable sources, which, in one study, was nearly double that of vehicle emissions.[5] We did not assess the air pollution benefits of electrifying heavy-duty trucks, whose $PM_{2.5}$ emissions substantially contribute to premature deaths. We did not incorporate potential changes in active travel or vehicle emissions associated with newer technologies such as ebikes, cargo bicycles, and autonomous vehicles.

We were not able to provide geographically resolved estimates of health impacts because statistically reliable calibration data on active travel were not available at the state or county level.[6] For air pollution, we only modeled background levels and not those experienced by active travelers, whose exposure may be higher because of higher ventilation rates and proximity to busy roadways, warehouses, and truck depots. Systematic reviews of potential exposures of active travelers indicate that the benefits of physical activity far outweigh potential adverse outcomes from inhalation of $PM_{2.5}$.[33]

We acknowledge uncertainties in ITHIM model parameters, which have been examined in Monte Carlo simulations[34] and sensitivity analyses iterating plausible but extreme values for individual parameters and combinations.[4,32] Although estimates varied, the health benefits of ambitious active travel scenarios exceed those of ambitious adoption of electric vehicles. Several recent publications[19,35] suggest a range of values for the slope of the concentration response function for $PM_{2.5}$-related health outcomes. Our estimates of annual deaths are based on a slope in the middle of the range.

We did not apply a discount rate to our monetization; even after discounting, the monetized value of health benefits in the AT scenarios would be substantial. Monetizing the social cost of carbon generates even larger potential benefits for both the $EV_{100\%}$ and $AT_{100\%}$ scenarios—\$43 billion and \$10 billion in 2050 (assuming a cost of \$69 in 2007 dollars per ton of CO_2 and a discount rate of 3%).[34]

We could not address racial and health equity because of gaps in calibration data and the lack of geographic resolution of our version of the ITHIM model. Researchers are developing versions of ITHIM that simulate travel patterns of individuals in synthetic populations so that health impacts can be aggregated over race/ethnicity, income, and other dimensions of equity and geospatial variation in air pollution.

We did not have the resources to model other transportation–health pathways, including emissions from ozone, elemental carbon, and nitrogen dioxide; noise; community severance; and access to goods and services, jobs, educational opportunities, health care, recreation, and social networks. We did not consider the health benefits of mitigating carbon emissions linked to heat waves, storms and sea level rise, and other climate disruption. We also did not address a post–COVID-19 transportation landscape, which has contradictory tendencies for active travel: increased bicycle ownership, closure of streets to cars, increased telecommuting, decreased retail destinations, and financially stressed transit systems with diminished ridership.

Public Health Implications

Although we presented the scenarios as contrasting visions, together they maximize carbon reductions and health benefits. To succeed together, policies and plans must substantially increase options to allow people to choose active transportation. This means the level of service to reach a wide array of destinations by walking, cycling, transit, and driving an electric car must be comparably time-efficient, affordable, and convenient. As we recover from a pandemic and venture out again, a heightened emphasis on active travel will also make major contributions to public health and carbon mitigation. Additional attention must be focused on safety and racial and health equity. The urgent imperative to rapidly reduce greenhouse gas emissions offers an opportunity to simultaneously and significantly reduce the burden of chronic disease and related health inequities and enormous health care costs.

ABOUT THE AUTHORS

Neil Maizlish is an independent epidemiologist based in Berkeley, CA. Linda Rudolph is with the Public Health Institute, Oakland, CA. Chengsheng Jiang is with the School of Public Health, University of Maryland, College Park.

CORRESPONDENCE

Correspondence should be sent to Neil Maizlish, Public Health Institute, 555 12th St, 10th Floor, Oakland, CA 94607 (e-mail: neil3971@comcast.net). Reprints can be ordered at http://www.ajph.org by clicking the “Reprints” link.

PUBLICATION INFORMATION

Full Citation: Maizlish N, Rudolph L, Jiang C. Health benefits of strategies for carbon mitigation in US transportation, 2017–2050. *Am J Public Health*. 2022;112(3):426–433.

Acceptance Date: October 15, 2021.

DOI: https://doi.org/10.2105/AJPH.2021.306600

CONTRIBUTORS

N. Maizlish was responsible for the concept, methodology, interpretation of the results, and drafting the article. L. Rudolph reviewed and edited the article. C. Jiang implemented the methodology and reviewed the article.

ACKNOWLEDGMENTS

The authors acknowledge the California Air Resources Board, which, in a contract with the University of California, Davis, supported the development of an R/shiny version of the Integrated Transport and Health Impact Model (ITHIM) that served as the template for ITHIM USA.

Bart Ostro, James Woodcock, and Ali Abbas assisted with dose–response functions.

CONFLICTS OF INTEREST

The authors declare they have no actual or potential competing financial interests.

HUMAN PARTICIPANT PROTECTION

Data were public and nonconfidential and did not require human participants protection institutional review.

REFERENCES

1. Masson-Delmotte V, Zhai P, Pörtner H-O, et al. Global warming of 1.5°C. Intergovernmental Panel on Climate Change. 2018. Available at: https://www.ipcc.ch/sr15. Accessed December 14, 2020.
2. US Environmental Protection Agency. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2017. EPA 430-R-19-001. 2019. Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017. Accessed February 7, 2021.
3. Physical Activity Guidelines Advisory Committee. *2018 Physical Activity Guidelines Advisory Committee Scientific Report*. US Department of Health and Human Services. 2018. Available at: https://health.gov/paguidelines/second-edition/report. Accessed February 7, 2021.
4. Maizlish N, Woodcock J, Co S, Ostro B, Fairley D, Fanai A. Health cobenefits and transportation-related reductions in greenhouse gas emissions in the San Francisco Bay Area. *Am J Public Health*. 2013;103(4):703–709. https://doi.org/10.2105/AJPH.2012.300939
5. Peters DR, Schnell JL, Kinney PL, Naik V, Horton DE. Public health and climate benefits and trade-offs of US vehicle electrification. *GeoHealth*. 2020;4:e2020GH000275. https://doi.org/10.1029/2020GH000275
6. US Department of Transportation. 2017 National Household Travel Survey. Version 1.1. 2017. Available at: https://nhts.ornl.gov. Accessed February 7, 2021.
7. Office of Policy Information. Annual vehicle distance traveled in miles and related data—2015. Table VM1. Federal Highway Administration. 2018. Available at: https://www.fhwa.dot.gov/policyinformation/statistics/2015/pdf/vm1.pdf. Accessed March 11, 2020.
8. Federal Transit Administration. Exhibit A 39: Load factor by mode. National transit summaries & trends 2016. Appendix. 2016. Available at: https://www.transit.dot.gov/ntd/annual-national-transit-summaries-and-trends. Accessed March 11, 2020.
9. Assessment and Standards Division, Office of Transportation and Air Quality. *MOVES2014a User Guide*. US Environmental Protection Agency. 2014. Available at: https://19january2017snapshot.epa.gov/moves/moves2014a-latest-version-motor-vehicle-emission-simulator-moves_.html#manuals. Accessed February 7, 2021.
10. US Environmental Protection Agency. 2017 and later model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards. *Fed Regist*. 2012;77(199):62623–63200. Available at: https://www.govinfo.gov/content/pkg/FR-2012-10-15/html/2012-21972.htm. Accessed February 7, 2021.
11. Office of Highway Policy Information. FHWA forecasts of vehicle miles traveled (VMT): spring 2019. Special tabulations. Federal Highway Administration. 2019. Available at: https://www.fhwa.dot.gov/policyinformation/tables/vmt/vmt_forecast_sum.cfm. Accessed December 18, 2020.
12. Buehler R, Pucher J, Bauman A. Physical activity from walking and cycling for daily travel in the United States, 2001–2017: demographic, socioeconomic, and geographic variation. *J Transp Health*. 2020;16:100811. https://doi.org/10.1016/j.jth.2019.100811
13. Institute for Health Metrics and Evaluation. Global Burden of Disease (GBD). University of Washington. 2015. Available at: http://www.healthdata.org/gbd. Accessed February 7, 2021.
14. US Census Bureau, Population Division. National population projections datasets: projected population by age, sex, race, and Hispanic origin: 2014 to 2060. NP2014_D1. 2014. Available at: https://www.census.gov/data/datasets/2014/demo/popproj/2014-popproj.html. Accessed March 7, 2020.
15. Canudas-Romo V, DuGoff E, Wu AW, Ahmed S, Anderson G. Life expectancy in 2040: what do clinical experts expect? *N Am Actuar J*. 2016;20(3):276–285. https://doi.org/10.1080/10920277.2016.1179123
16. Ainsworth BE, Haskell W, Herrmann S, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. *Med Sci Sports Exerc*. 2011;43(8):1575–1581. https://doi.org/10.1249/MSS.0b013e31821ece12
17. Garcia L, Strain T, Abbas A, et al. Physical activity and risk of cardiovascular disease, cancer, and mortality: a dose–response meta-analysis of prospective studies. PROSPERO 2018 CRD42018095481. National Institute for Health Research. 2021. Available at: https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=95481. Accessed July 1, 2021.
18. National Center for Health Statistics. NHANES Physical Activity and Physical Fitness Questionnaire

(PAQ). Centers for Disease Control and Prevention. 2015. Available at: https://wwwn.cdc.gov/nchs/data/nhanes/2015-2016/questionnaires/PAQ_I.pdf. Accessed March 11, 2020.

19. Vodonos A, Awad YA, Schwartz J. The concentration-response between long-term $PM_{2.5}$ exposure and mortality; a meta-regression approach. *Environ Res.* 2018;166:677–689. https://doi.org/10.1016/j.envres.2018.06.021
20. Office of Air Quality Planning and Standards. Technical support document: estimating the benefit per ton of reducing PM2.5 precursors from 17 sectors. US Environmental Protection Agency. 2018. Available at: https://www.epa.gov/sites/production/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf. Accessed March 9, 2019.
21. Elvik R, Bjørnskau T. Safety-in-numbers: a systematic review and meta-analysis of evidence. *Saf Sci.* 2015;92:274–282. https://doi.org/10.1016/j.ssci.2015.07.017
22. National Highway Traffic Safety Administration. Fatality Analysis Reporting System (FARS). US Department of Transportation. 2017. Available at: http://www.nhtsa.gov/FARS. Accessed February 7, 2021.
23. National Center for Analysis and Statistics. *Crash Report Sampling System CRSS Analytical User's Manual 2016–2018.* Report no. DOT HS 812 846. National Highway Traffic Safety Administration. 2019. Available at: https://www.nhtsa.gov/crash-data-systems/crash-report-sampling-system-crss. Accessed February 7, 2021.
24. US Environmental Protection Agency. Regulatory impact analysis for the final revisions to the National Ambient Air Quality Standards for Particulate Matter. Appendix 3.A. EPA-452/R-12-005. 2013. Available at: https://www3.epa.gov/ttn/ecas/regdata/RIAs/finalria.pdf. Accessed April 12, 2019.
25. Mueller N, David Rojas-Rueda D, Cole-Hunter T, et al. Health impact assessment of active transportation: a systematic review. *Prev Med.* 2015;76:103–114. https://doi.org/10.1016/j.ypmed.2015.04.010
26. Larson E, Greig C, Jenkins J, et al. Net-zero America: potential pathways, infrastructure, and impacts: interim report. Princeton University. 2020. Available at: https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf. Accessed December 16, 2020.
27. Kahlmeier S, Götschi T, Cavill N, et al. Health Economic Assessment Tool (HEAT) for walking and for cycling. Methods and user guide on physical activity, air pollution, injuries and carbon impact assessments. World Health Organization. 2017. Available at: https://www.heatwalkingcycling.org/#homepage. Accessed August 20, 2021.
28. Davidson K, Fann N, Zawacki M, Fulcher C, Baker K. The recent and future health burden of the US mobile sector apportioned by source. *Environ Res Lett.* 2020;15(7):075009. https://doi.org/10.1088/1748-9326/ab83a8
29. National Research Council. *Overcoming Barriers to Electric-Vehicle Deployment: Interim Report.* Washington, DC: The National Academies Press; 2013. https://doi.org/10.17226/18320.
30. Götschi T, Tainio M, Maizlish N, Schwanen T, Goodman A, Woodcock J. Contrasts in active transport behaviour across four countries: how do they translate into public health benefits? *Prev Med.* 2015;74:42–48. https://doi.org/10.1016/j.ypmed.2015.02.009
31. California Air Resources Board. 2018 progress report: California's Sustainable Communities and Climate Protection Act. 2018. Available at: https://ww2.arb.ca.gov/sites/default/files/2018-11/Final2018Report_SB150_112618_02_Report.pdf. Accessed November 30, 2019.
32. Stevenson M, Thompson J, Hérick de Sá T, et al. Land use, transport, and population health: estimating the health benefits of compact cities. *Lancet.* 2016;388(10062):2925–2935. https://doi.org/10.1016/S0140-6736(16)30067-8
33. Cepeda M, Schoufour J, Freak-Poli R, et al. Levels of ambient air pollution according to mode of transport: a systematic review. *Lancet Public Health.* 2017;2(1):e23–e34. https://doi.org/10.1016/S2468-2667(16)30021-4
34. US Environmental Protection Agency. Social cost of carbon fact sheet. 2016. Available at: https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf. Accessed August 14, 2021.
35. Chen J, Hoek G. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. *Environ Int.* 2020;143:105974. https://doi.org/10.1016/j.envint.2020.105974