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ARTICLE

Health benefits from cleaner vehicles and increased active transportation in Seattle, Washington

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BACKGROUND: Climate mitigation policies that focus on the transportation sector yield near-term health co-benefits that could motivate policy action.

OBJECTIVE: We quantified CO_2 emission reductions as well as the air pollution and health benefits of urban transportation policies promoting electric vehicles (EV) and walking and bicycling in Seattle, Washington.

METHODS: We compared a business-as-usual scenario projected to 2035 with intervention scenarios in which 35% of gasoline vehicles were switched to EV, and 50% of car trips less than 8 kilometers were replaced by walking or bicycling. We modeled changes in primary traffic-generated oxides of nitrogen (NO_x) and fine particulate matter ($PM_{2.5}$) as well as walking and bicycling activity, CO_2 emissions from traffic, and fatal traffic injuries due to the transportation policy scenarios. We estimated the impacts of these changes on annual cases of asthma and premature mortality in the Seattle population.

RESULTS: Increasing the use of EV, walking, and bicycling is estimated to reduce CO_2 emissions by 744 tons/year (30%) and lower annual average concentrations of primary traffic-generated NO_x and $PM_{2.5}$ by 0.32 ppb (13%) and 0.08 μg/m^3 (19%), respectively. In Seattle, the lower air pollutant concentrations, greater active transportation, and lower fatal traffic injuries would prevent 13 (95% CI: −1, 28), 49 (95% CI: 19, 71), and 5 (95% CI: 0, 14) premature deaths per year, respectively and 20 (95% CI: 8, 27) cases of asthma per year.

SIGNIFICANCE: Moving towards cleaner vehicles and active transportation can reduce CO_2 emissions, improve air quality, and population health. The resulting public health benefits provide important motivation for urban climate action plans.

IMPACT STATEMENT: Using key components of the health impact assessment framework, we quantify the environmental and health benefits of urban transportation policy scenarios that promote electric vehicle use and replace short car trips with walking and bicycling as compared with a business as usual scenario in 2035. Our findings demonstrate that transportation scenarios promoting cleaner vehicles and active transportation can reduce CO_2 emissions, improve air quality, and increase physical activity levels, resulting in significant public health benefits.

Keywords: Health impact assessment; Transportation; Air pollution; Walking; Bicycling; Traffic injuries

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INTRODUCTION

A reliance on private vehicles over public transportation and physically active modes of transportation poses several important challenges to public health. On-road motor vehicles contribute appreciably to greenhouse gas emissions and thus climate change [1]. They also impact public health through air pollution, reduced physical activity, and traffic injuries [2]. In fact, air pollution and injuries from on-road motor vehicles have been estimated to cause 1.5 million deaths globally each year, representing 2.9% of deaths from all causes, placing them as the eighth leading cause of global health lost [3]. The true burdens may be even larger as these estimates ignore the health costs of physical inactivity as people replace active with motorized transportation. Given these large burdens, interest has been growing in designing and implementing transportation policies that promote cleaner vehicles and alternatives to private motor vehicle use [2].

In the United States, more than three-quarters of the population drives alone during their commutes and less than 3% walk or bicycle as a means of transportation [4]. An estimated 32% of the population is fully physically inactive [5]. Such inactivity puts the population at a greater risk of chronic conditions such as ischemic heart disease, ischemic stroke, diabetes, colon cancer, and breast cancer [2, 6]. Given that almost 41% of all car trips in the United States are less than 3.2 kilometers (km), a distance that is often walked or biked in European cities [7], replacing these short car trips with active transportation such as walking and bicycling could translate to substantial health benefits by reducing on-road vehicle emissions and increasing physical activity [2, 8–13]. In

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addition, this could reduce the risk of traffic injuries. As the population of the United States and elsewhere adjusts work and leisure schedules given the COVID-19 pandemic, while concurrently developing climate action plans, it is timely to consider policy measures that can reduce environmental and health burdens from the transportation sector.

Health impact assessment (HIA) is an approach that uses an array of data sources, analytic methods, and inputs from stakeholders to ensure that public health is taken into consideration in policy decisions such as those related to transportation [14]. Past studies from Europe have used HIAs to show that shifting private car use to walking and bicycling should translate into positive net health benefits by reducing all-cause mortality and chronic diseases [10, 15, 16]. Several HIA studies have similarly documented potential health benefits of transportation policies in the United States, yet few have focused on evaluating the health benefits of promoting active transportation, reducing car trips, and increasing electric vehicle (EV) use [8, 9, 16]. Therefore, more research is needed to fully understand the impact of transportation policies that include these scenarios. Furthermore, studies are needed that examine the impact of transportation scenarios on pollutants other than just fine particulate matter ($PM_{2.5}$) since motor vehicle emissions contribute a large fraction of pollutants such as oxides of nitrogen (NO_x), which directly influences health and leads to secondary ozone formation, and greenhouse gases such as CO_2.

In this study, we utilize key components of the HIA framework to quantify the public health benefits of urban transportation policies that promote EV use and replace short car trips with walking and bicycling, focusing on two air pollutants that are harmful to health (NO_x and $PM_{2.5}$) as well as physical activity, traffic injuries, and estimates of CO_2 emission reductions. Specifically, we compare the impacts of these interventions to a business-as-usual scenario (BAU), which assumes no additional efforts to increase the percentage of EVs or active transportation. We evaluated these policies in the urban area of Seattle, Washington, where regional and local agencies have developed transportation plans to increase active transportation and improve infrastructure to support EV use.

METHODS

Study design

We constrained the scope of this study to the assessment phase of the HIA framework [14] since our transportation policy scenarios are based on the Washington Transportation Plan 2035 (WTP-2035) [17] and the Drive Clean Seattle Strategy [18], which incorporated screening and scoping work conducted by the Seattle Office of Sustainability and Environment. We used the comparative risk assessment (CRA) model proposed by the World Health Organization (WHO) [19] and the approach proposed by Woodcock et al. [10] to estimate the expected change in disease burden caused by shifts in the distribution of air pollution, physical activity, and traffic accidents between a baseline (BAU) and alternative scenarios. We predicted concentrations of primary NO_x and $PM_{2.5}$ as well as CO_2 emissions from on-road vehicles, the amount of physical activity, and the number of fatal traffic injuries for the population of Seattle in 2035 under three different urban transportation policy scenarios. We then projected the expected changes in mortality and incident asthma cases for the Seattle population between scenarios using more EVs and active transportation as compared to a BAU scenario.

Scenarios of urban transportation

We examined three transportation policy scenarios based at least in part on the WTP-2035 [17] and the Drive Clean Seattle Strategy from the Seattle Office of Sustainability and Environment [18]. For all scenarios, we used traffic conditions in 2010 in Seattle reported by the Washington State Department of Transportation (WSDOT) and projected them to 2035 [17, 20].

Under the BAU scenario, we used the WSDOT forecast of overall motor vehicle usage, which projects that the vehicle kilometers traveled (VKT) in Washington for 2035 will increase 19%, concurrent with the projected trends in population and economic growth for the area [17, 20]. While EV growth is increasing, the number of EVs is limited at present, well under 1% in most areas. Thus, for simplicity, the base case assumed 0% EVs [18]. In addition, under the BAU scenario we assumed no changes in the percentage of trips using active modes of transportation (i.e.; 59% of trips less than 2.4 km are walked and less than 5% of trips between 2.4 and 8 km are bicycled at baseline). In Scenario 2, we assumed the same VKT and active transportation as the BAU but assumed that by 2035 35% of the gasoline passenger cars and light-duty tracks will be replaced by EVs. In Scenario 3, we assumed the same improvements in the vehicle fleet technology as described in Scenario 2 but also assumed that 50% of car trips less than 2.4 km will be replaced by walking and 50% of car trips between 2.4–8 km will be replaced by bicycling [9]. For all scenarios, including the BAU, we assumed improved fuel economy for the fleet based on the Joint National Standards (2017–2025) of the USEPA and the National Highway Traffic Safety Administration [21]. These standards, which were developed to reduce greenhouse gas emissions and improve fuel economy of passenger cars and light-duty trucks, are the most recent available standards for motor vehicles.

Changes in air pollution

To quantify differences in concentrations of primary traffic-generated NO_x and $PM_{2.5}$ for each scenario, we conducted air quality dispersion modeling using an approach we used previously for modeling current day conditions in the Central Puget Sound Region; this has been described in detail elsewhere [22]. Briefly, we used the Motor Vehicle Emissions Simulator (MOVES, version 2014) and the Research Line-Source Dispersion Model (RLINE v1.2) with inputs representing conditions for each transportation scenario. (Supplementary methods) We then predicted concentrations of primary traffic-generated NO_x and $PM_{2.5}$ at 3140 locations throughout the Seattle urban area. These locations were randomly selected from residential parcels in each census tract to generate a population-weighted exposure.

To compare pollution levels across scenarios, we calculated annual average concentrations for each scenario at all receptor locations and estimated a percentage change as compared to the BAU scenario. For inclusion in our health analyses, we averaged pollutant concentrations of all receptor locations within census tracts and weighted these estimates by the age and sex distribution of the population to develop a population-weighted annual average concentration for each scenario. We also converted NO_x concentrations to NO_2 for consistency with the epidemiological literature, applying a ratio of 0.75 based on previous findings in the study area [22].

Changes in physical activity

The amount of physical activity due to active transportation was assessed using metabolic equivalents (METs). To obtain transportation-related METs, we used data from the Puget Sound Travel Survey [23] to estimate age- and sex-specific travel distances by mode of active transportation for the BAU scenario. To convert distances walked or bicycled into travel times we used the mean of age- and sex-specific walking and bicycling speeds from published studies [10]. Then shifting 50% of short car trips to active transportation we obtained mean travel time distributions by distance, age, and sex for walking and bicycling in Scenario 3.

These travel time distributions were converted into METs using tabulated data for specific activities and speeds (i.e., 6.8 METs are assigned to bicycling and 3.5 METs to walking) [24]. Given the log-normal distribution of METs, we calculated the geometric mean of MET-hours per week by age and sex due to active transportation.

Changes in fatal traffic injuries

Since the shift in active transportation and VKT under Scenario 3 may alter the risk of fatal traffic injuries, we estimated the expected number of fatal traffic injuries for each transportation scenario. We quantified the risk of fatal traffic injuries at baseline (R_0) (2010) per km traveled for the pairwise combination of victim and striking vehicle mode and road type (i.e., highway, principal and minor arterial), which is an indicator of vehicle speed, road features, and traffic volume [9, 10]. The victim and striking mode included are pedestrian, bicycle, motorcycle, car, bus, and truck. For collisions involving more than two modes, we assigned the largest vehicle other than the one used by the victim as the striking vehicle. Data for 2010 on fatal traffic injuries by mode and road type were obtained from the WSDOT, and data on the distance (km) traveled by road type and travel mode were obtained from the WSDOT.

Health impacts for each exposure and transportation scenario

We quantified the projected health impacts due to the alternate transportation scenarios for all non-accidental, cardiovascular or cardiopulmonary mortality in the general population of 15 years and older attributable to changes in air pollution. All-cause and cardiovascular mortality were included as health impacts attributable to changes in transportation-related physical activity in the general population aged 15–64 years [15, 25]. Fatal traffic injuries in the general population were included as health impacts due to traffic collisions. Furthermore, we assessed the impacts on incident asthma cases in children 14 years and younger; while numerous additional mortality outcomes could be included, we chose incident asthma as well as mortality given the best available evidence and the salience of these outcomes for monetized benefits and community stakeholders.

As in previous HIA [9, 10, 15], we estimated the public health benefits using the Population Attributable Fraction (PAF) to reflect the fraction of the deaths in a population that are due to each exposure. This calculation includes the concentration-response function expressed as risk ratios (RRs) and the population distribution of exposure under the BAU and each policy scenario. (Supplementary methods) Since we focused on health and not the economic impacts of our transportation scenarios, we did not include any discounting [19].

Although previous studies conducted in the Seattle area have quantified associations between exposure to traffic-related air pollution and health outcomes [26], we used concentration-response functions derived from a wider body of scientific literature [27–31], reflecting HIA best practice and increasing comparability with other HIAs. (Supplementary Table S.1) For mortality, to avoid double counting, we used reported associations of $PM_{2.5}$ adjusted by NO_2 and NO_2 adjusted by $PM_{2.5}$. Following the literature, we assumed a linear concentration-response function for the association of exposure to NO_2 and $PM_{2.5}$ with our health endpoints in the range of exposures observed in Seattle [31–33].

For associations between physical activity (METs) and all-cause and cardiovascular mortality, we used exposure-response function derived from the literature [34, 35]. Because the relationship between physical activity and these outcomes is curvilinear with the greatest benefits for moving from low to moderate levels of activity [34], we added our estimates of physical activity from active transportation to data for non-transportation related physical activity. (Supplementary methods) We assumed that the non-transportation related physical activity was constant across all scenarios. We also used a 0.25 power transformation of total physical activity with all-cause mortality and a 0.5 power transformation with cardiovascular mortality following recommendations by Woodcock et al. [34, 36]

With the PAF for traffic fatalities, we used a different approach. First, we estimated the expected number of fatal traffic injuries (I_s) for the BAU scenario and Scenario 3 as the product between the baseline risk (R_0) of fatal injuries and the change in the distance (km) traveled by victims and striking mode in each scenario stratified by road type as described above. We applied a square root distribution to the km traveled for the victim and striking mode to account for decreased risk of pedestrians and bicyclist fatal injuries as mode shares increase (known as the safety-in-numbers effects) [37]. Then, the PAF was obtained as the ratio between the estimated fatal traffic injuries for each intervention scenario (I_s) and the injuries for the BAU scenario (I_0) [9]. Supplementary Table S.2 shows the estimated PAF for each exposure and transportation intervention scenario.

Modeling and sensitivity analysis

We quantified the health impacts of air pollution, physical activity, and traffic injuries for the three scenarios using Stata statistical software version 15.1 (StataCorp LLC, College Station, TX). We also included uncertainty analyses around the parameter estimates using Monte Carlo simulations, providing for credible confidence intervals based on 95% of the model runs (CI 95%). Using a lognormal distribution of the population-weighted annual average concentrations of $PM_{2.5}$ and NO_2 at each census tract, METs h/week, and the concentration-response functions with their corresponding standard errors, we generated exposure levels for air pollution and physical activity, and health impacts in 10,000 simulations for a random sample of 10,000 subjects. Similarly, we used a Poisson distribution to generate simulations of fatal traffic injuries from each scenario. Then, from these simulated runs we obtained the 95% confidence intervals for our estimates.

Finally, we ran sensitivity analyses to evaluate the robustness of our results, including the consideration of different concentration-response functions for $PM_{2.5}$ and NO_2 such as those reported in the EPA's Integrated Science Assessment [38]. For active transportation, we performed sensitivity analyses using a linear exposure-response function between transportation-related physical activity and mortality. We also evaluated shorter travel times for our scenario with active transportation.

RESULTS

As shown in Table 1, we estimated that Scenario 2 and Scenario 3 would result in reductions in atmospheric CO_2 emissions from on-road traffic by 26% and 30%, respectively, as compared with the BAU. Both proposed transportation intervention scenarios (Scenarios 2 and 3) resulted in an overall reduction in vehicle emissions of NO_x and $PM_{2.5}$. Under Scenario 2, there was an 8% reduction in NO_x and 11% reduction in $PM_{2.5}$ while under Scenario 3 there was a 9% reduction in NO_x and 19% reduction in $PM_{2.5}$, all compared with the BAU scenario. This was related to the added reduction in annual VKT of 9% for Scenario 3 as compared with the BAU scenario and Scenario 2. Similarly, Scenario 3 resulted in 52% and 242% increases in the annual person km traveled for walking and bicycling, respectively.

We also estimated that switching to EVs in Scenario 2 would reduce the annual average NO_x and $PM_{2.5}$ concentrations from on-road traffic across the Seattle urban area by an average of 0.30 ppb (11%) and 0.04 $\mu g/m^3$ (9%), respectively, as compared to the BAU scenario. Adding a shift of 50% of car trips less than 2.4 km to walking and 2.4 to 8 km to bicycling under Scenario 3 increased NO_x and $PM_{2.5}$ reductions to 0.32 ppb (13%) and 0.08 $\mu g/m^3$ (19%) as compared to the BAU.

We found that switching to active transportation in Scenario 3 would increase transport-related physical activity. In particular, we estimated that shifting 50% of short car trips to active transportation would increase the daily average transport-related walking and bicycling times from 8 and 2 min in the BAU scenario to 14 and 21 min under Scenario 3, respectively (Table 2). In addition, the mean daily traveled distance for transport-related walking and bicycling will increase from 0.5 and 0.6 km in the BAU scenario to 0.9 and 4.7 km under Scenario 3, respectively (Table 2).

These reductions in exposure to air pollution and increases in physical activity would translate to improved health outcomes in the population of the Seattle urban area (Table 3). Specifically, we estimated that for the 691,000 people aged 15 years and older in 2035, reductions in NO_2 from on-road traffic would prevent 10 (95% CI: −1, 21) and 11 (95% CI: −1, 25) premature deaths per year for all non-accidental mortality in Scenario 2 and Scenario 3, respectively, compared with the BAU. Of these reductions, these NO_2 reductions would prevent 4 (95% CI: −2, 10) and 5 (95% CI: −2, 11) premature deaths per year for cardiovascular mortality in Scenario 2 and Scenario 3, respectively, as compared with the BAU. Fewer health benefits were estimated for reductions in primary $PM_{2.5}$ from on-road traffic, with 1 (95% CI: −1, 3) and 2 (95% CI: −2, 7) premature deaths avoided per year for all non-accidental mortality for Scenario 2 and Scenario 3 as compared to the BAU, respectively. The reductions in all non-accidental premature mortality were primarily driven by reductions in cardiopulmonary deaths for both scenarios (Table 3).

Increments in active transportation would result in 49 (95% CI: 19, 71) premature deaths avoided per year for all-cause mortality, of which 11 (95% CI: 5, 14) were attributable to reductions in cardiovascular mortality (Table 3). Due to the lower VKT for passenger cars, we estimated that switching to active transportation would reduce premature deaths from traffic injuries by an average of 5 (95% CI 0, 14) premature deaths per year in Scenario 3 as compared with the BAU. The total health gain estimated for Scenario 3, which includes active transportation, was 67 (95% CI: 35, 93) avoided deaths as compared to 11 (95% CI: 0, 22) for Scenario 2.

In addition, we also found that for the 95,000 children in the region aged 14 years and younger in 2035, reductions in NO_2 from on-road traffic would prevent 3 (95% CI: −1, 7) and 4 (95% CI: −2, 8)

Table 1. Modeled daily miles traveled, CO_2 emissions, and NO_x and $PM_{2.5}$ emissions and annual average concentrations, by transportation scenario.

Variable	Scenario 1: Business as Usual (BAU)	Scenario 2: Electric Vehicles	Scenario 3: Electric Vehicles and Active Transport
		Value (% change from BAU)	
Emissions of Atmospheric CO_2			
Emissions, thousands of tons/year[a]	1,068.7	793.4 (−25.7)	744.1 (−30.2)
Emissions of Air Pollutants			
NO_x			
Emissions, tons/year[a]	372.2	342.6 (−7.9)	337.5 (−9.3)
$PM_{2.5}$			
Emissions, tons/year[a]	29.8	26.6 (−10.7)	24.1 (−19.3)
Annual Daily Vehicle km Traveled	18,668,000	18,668,000 (0.0)	16,952,000 (-9.2)
Annual Daily Person km Traveled by Mode			
Walking	409,000	409,000 (0.0)	619,000 (51.6)
Bicycling	356,000	356,000 (0.0)	1,215,000 (241.6)
Motorcycle	64,000	64,000 (0.0)	64,000 (0.0)
Car	27,192,000	27,192,000 (0.0)	25,358,000 (-6.7)
Bus	356,000	356,000 (0.0)	356,000 (0.0)
Truck	870,000	870,000 (0.0)	870,000 (0.0)
Total	29,247,000	29,247,000 (0.0)	27,742,000 (-5.1)
Average Concentrations in Population			
NO_x, ppb			
Mean concentration (SD)	2.5 (1.2)	2.2 (1.1)	2.1 (1.1)
Mean reduction from BAU		0.30 (−10.9)	0.32 (−12.9)
$PM_{2.5}$, μg/m^3			
Mean concentration (SD)	0.4 (0.2)	0.4 (0.2)	0.3 (0.2)
Mean reduction from BAU		0.04 (−9.3)	0.08 (−18.6)

[a] Metric tons.

incident asthma cases per year in Scenario 2 and Scenario 3, respectively, compared with the BAU. Reductions in $PM_{2.5}$ provided larger reductions in incident asthma, preventing 8 (95% CI: 3, 11) and 16 (95% CI: 6, 23) incident asthma cases per year in Scenario 2 and Scenario 3, respectively, as compared with the BAU.

In sensitivity analyses, we found that our results were largely robust to different concentration-response functions for air pollution-related premature deaths for all-cause non-accidental mortality that were within the range of our initial findings (e.g., 1–2 prevented deaths for Scenario 2 and 2–4 prevented deaths for Scenario 3). In contrast, results for physical activity were sensitive to the exposure-response function. In particular, using a linear exposure-response function for walking and bicycling related-physical activity resulted in overall benefits that were up to 3 times greater than those we estimated using a non-linear exposure-response function (e.g.; avoided deaths for all-cause mortality in Scenario 3: 153, 95% CI: 83, 176). In contrast, assuming shorter travel times, especially for bicycling (e.g.; 11 min and a distance of 2.6 km) resulted in smaller health benefits (avoided premature deaths: 32, 95% CI: 19, 45), though these values were within the range of our results assuming longer travel times. In addition, assuming a linear association between person km traveled and fatal traffic injuries resulted in more avoided premature deaths with 5 (95% CI: 0, 14) premature deaths avoided in Scenario 3 compared with the BAU.

DISCUSSION

Transportation interventions involving shifting to cleaner vehicle technologies and/or increased active transit translate to health benefits for the general population. We estimated that switching 35% of all gasoline cars and passenger trucks to electricity and shifting 50% of car trips less than 8 km to walking and bicycling would result in 67 fewer premature deaths each year due to impacts on a subset of primary traffic-generated air pollutants, mortality associated with physical activity, and fatal traffic injuries, as well as 20 fewer incident asthma cases due to reduced air pollution levels from traffic. In addition to local health benefits, these transportation scenarios demonstrated their contribution to achieving local goals to reduce carbon emissions, with approximately 30% less transportation-related CO_2 emissions under both scenarios, which are largely due to switching to cleaner vehicles.

Our results are consistent with previous research that documented health benefits of replacing car use by active transportation and reducing vehicle emissions that have mostly found larger health benefits of increased physical activity as compared to improved air quality [8–10, 15, 16]. For example, Grabow et al conducted a HIA in 11 metropolitan areas of the midwestern United States and found that shifting 50% of short car trips to active transportation resulted in 0.01–0.05 μg/m^3 lower $PM_{2.5}$ levels, which was very similar to our estimate (0.04 μg/m^3). Grabow M et al. also found declines in all-cause mortality from the air pollution and physical activity benefits of about 1295 (41.4 deaths/million) fewer deaths per year [8]. Larger estimates were reported by the study by Maizlish et al. for the San Francisco Bay area where they found overall net health benefits of 2413 (265.2 deaths/million) avoided premature deaths per year [9].

Our estimate of 67 fewer deaths per year (96.7 deaths/million) is bounded by the literature values, likely related in part to geographic differences in traffic patterns and population density. For example, the annual VKT per person in the San Francisco Bay

Table 2. Travel times and distances for active transportation.

Variable	Scenario 1: Business as Usual (BAU)	Scenario 3: Electric Vehicles and Active Transportation
Mean Daily Travel Times[a] (SD), minutes		
Walking	7.7 (5.5)	13.9 (4.2)
Bicycling	2.0 (5.2)	21.4 (8.2)
Mean distance traveled, km		
Walking	0.5 (0.5)	0.9 (0.6)
Bicycling	0.6 (1.9)	4.7 (1.4)
Average speed, km/hour[b]		
Walking	4.5	4.5
Bicycling	12.7	12.7

[a]Geometric mean of weekly physical activity.

[b]Mean speed data taken from previous studies.

Table 3. Estimated air pollution, mortality, and morbidity changes per year among adults and children of the general population due to transportation intervention scenarios as compared with the BAU scenario.

Benefits	Scenario 2: Electric Vehicles	Scenario 3: Electric Vehicles and Active Transport
Air pollution		
NO_2, ppb[a]		
Reduction in concentration[b] (SD)	0.21 (0.10)	0.24 (0.12)
$PM_{2.5}$, μg/m^3		
Reduction in concentration[b] (SD)	0.04 (0.02)	0.08 (0.04)
Mortality[c]		
NO_2, ppb[a]		
Premature deaths avoided (95% CI)		
All non-accidental	10 (−1, 21)	11 (−1, 25)
Cardiovascular	4 (−2, 10)	5 (−2, 11)
$PM_{2.5}$, μg/m^3		
Premature deaths avoided (95% CI)		
All non-accidental	1 (−1, 3)	2 (−2, 7)
Cardiopulmonary	1 (0, 2)	2 (−1, 4)
Total non-accidental deaths avoided due to reductions in air pollution	11 (0, 22)	13 (−1, 28)
Physical Activity[d]		
Minutes increased in physical activity[e]		25
Premature deaths avoided		
All-cause		49 (19, 71)
Cardiovascular		11 (5, 14)
Fatal traffic injuries		
Premature deaths avoided		5 (0, 14)
Total deaths avoided		
Air pollution, physical activity and injuries	11 (0, 22)	67 (35, 93)
Morbidity[f]		
NO_2, ppb[a]		
Incident asthma cases	3 (−1, 7)	4 (−2, 8)
$PM_{2.5}$, μg/m^3		
Incident asthma cases	8 (3, 11)	16 (6, 23)
Total incident asthma cases avoided due to reductions in air pollution	11(4, 16)	20 (8, 27)

[a]NO_2 concentrations were obtained applying a ratio of 0.75 to NO_x concentrations,

[b]Mean reduction in the annual average concentration of NO_x (ppb) or $PM_{2.5}$ (μg/m^3) in each intervention transportation scenario as compared with the BAU across census tracts,

[c]Population aged 15 years and older,

[d]Population aged 15–64 years,

[e]Mean increased minutes in physical activity per person,

[f]Children 14 years and younger.

area is twice the Seattle annual VKT [9]. Differences in the baseline levels of walking and cycling across these areas might also explain dissimilarities since 28% of the population in Seattle already walks as means of transportation as compared to only 8.3% in the San Francisco Bay area. Other possible explanations for differences across studies might be the assumptions such as the percentage of car trips replaced by active transportation, the inclusion of cleaner vehicles, and the amount of physical activity assumed under the different scenarios. In addition, we used concentration-response functions of $PM_{2.5}$ and NO_2 that were adjusted by co-pollutants to avoid double counting, whereas some older studies used estimates from single pollutant studies. Furthermore, we estimated incident childhood asthma as opposed to the occurrence of respiratory symptoms in subjects with asthma of the general population, included in the study by Grabow and colleagues, making comparability challenging. In general, numerous morbidity outcomes have been associated with $PM_{2.5}$ and NO_2, and our selection was intended to show impacts for a health outcome with a high burden of disease. Nonetheless, our estimates likely represent and underestimate of health impacts and costs due to omitted morbidity outcomes, like asthma aggravation.

Unlike some [9, 10] but not all previous studies [15, 36], we found a net decrease in the risk of fatal traffic injuries in our active transportation scenario. Although increasing the km traveled by pedestrians and bicyclists slightly increased fatal traffic injuries for these modes, the overall benefits of reducing VKT for passengers in cars overcome the risk of car-pedestrian and car-bicycle fatal collisions. This suggests that the strong health benefits outweigh the drawbacks when switching to active transportation. However, since motorist culture, inadequate infrastructure for active transit, and crime may discourage walking and bicycling [39–41], additional work needs to be done on cultural norms, education, and infrastructure investments to obtain greater shifts to active transit in a large proportion of the population.

While our transportation policy scenarios yielded climate and public health benefits, they would clearly incur some costs and have other tradeoffs. First, some investments are required to facilitate electricity charging technology and support pedestrians and bicycle traffic. For example, the Seattle master plan for bicycles projected that the addition of nearly 161 km of protected bicycle lanes, 402 km of neighborhood greenways, and bicycle parking facilities would cost the city nearly $72.6 million for the first five years (2017–2021) [42]. Second, electricity used to power EVs could be derived from power plants utilizing fossil fuels, which would increase emissions from the power sector. However, as cleaner technologies are used for electricity generation, the air pollution emissions from EVs are expected to decline [43]. In fact, a recent analysis estimated that the air pollution impacts of EVs in the near future will be 60% lower than the EVs driven today [43, 44]. In addition, Seattle has relied largely on clean energy with 88% of its electricity from hydroelectric sources since 2016. Finally, it may be that people reduce their leisure-time physical activity as they increase their active transit [45]. This is not definite, however, as some studies have found that more active transportation is associated with more physical activity due to active commuting [46]. Despite these potential limitations, the resulting health benefits of these policies likely outweigh their costs. For example, similar policies promoting active transportation in the midwestern United States estimated (net) health cost savings of around $212 million for an area with a comparable population as Seattle [8].

As with all HIAs, our estimates are sensitive to key assumptions. We used air pollution concentration-response functions for the United States from the American Cancer Study even though previous epidemiological studies in Seattle have largely found weaker associations between exposures to air pollution and mortality [26, 47]. Additionally, we did not include adverse health outcomes for those individuals walking and bicycling next to traffic. That said, we expect that the overall benefits observed would be robust, as this work and other studies have shown that the benefits of increased physical activity, even near traffic, far exceed the adverse health impacts of air pollution [48]. In contrast, we may have underestimated our health benefits by not including the health impacts of secondary pollutants (i.e., O_3 or secondary aerosols). In addition, the EPA projections for fuel formulations and vehicle fleet distribution for 2035 based on existing standards and rules [49, 50] may be overly optimistic. We do not expect this to influence our estimates, however, since these assumptions apply to both our intervention and BAU scenarios. While we used local traffic injury data by road type, we did not assume any improvements in walking and biking infrastructure for Scenario 3 in our analysis. If there were improvements over time then our estimates might overestimate traffic injuries due to active transportation. Although this study is focused only on the urban area of Seattle, which has relatively good air quality and has a mid-sized population, Seattle is also known for being highly traffic congested. With more than 200,000 daily vehicles at some locations, highways in the area have been shown to importantly contribute to population exposures to traffic-generated air pollution. [22]. We expect that the health impacts would be larger in more polluted cities and in locations with drier or milder winters that might further promote active transit. Finally, there might be socioeconomic and racial/ethnic differences in exposure changes and the health impacts that lead to disproportionate outcomes that were not explored in this study. These factors may need further study to confirm the health and equity benefits of active transportation.

In spite of these limitations, our study makes some important contributions to the HIA literature. Instead of assuming uniform reductions of VKT due to shifting car trips to active transportation, as most studies have done, we used information on the census tracts of origin and destination of all car trips in Seattle from the Puget Sound Travel Survey to estimate local impacts [23]. In addition, by modeling residential locations throughout the city, we were able to estimate exposures that were representative and population-based.

In conclusion, this study demonstrates that moving towards cleaner vehicles and active transportation can help to not only reduce greenhouse gas emissions but also improve population health through improved air quality, increased physical activity, and reduced traffic injuries. Our findings also suggest that policies involving active transportation will be the most effective since most health benefits were attributed to increased physical activity, though coupling these measures with strategies such as EVs will be important in meeting climate targets.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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AUTHOR CONTRIBUTIONS

The authors specific contributions to this work are as follows: PF made substantial contributions to conceive and design the study, acquisition of data, analyzed and interpreted data, drafted the article, including the version to be published. JL contributed to the design and implementation of the study and the health impact assessment approach, made important contributions to analyze and interpret the data, critically revised the draft for important intellectual content and gave final approval of the version to be published. JG contributed to the acquisition of data, structured analytical datasets, reviewed several drafts and gave approval of the version to be submitted; SB made substantial contributions to the study design, especially the air quality modeling approach, critically revised the draft for important intellectual content, and gave final approval of the version to be submitted. SA made substantial contributions to conceive and design the study, provided intellectual insights to analyze and interpret data, acquisition of data, revised draft for important intellectual content and gave final approval of the version to be submitted.

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COMPETING INTERESTS

The authors declare no competing interests.

ETHICAL APPROVAL

Given the nature of the data and information used in this study, ethics approval was not required.

ADDITIONAL INFORMATION

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