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Burden of disease from transportation noise and motor vehicle crashes: Analysis of data from Houston, Texas

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ABSTRACT

Background: Transportation systems have an essential role in satisfying individuals' needs for mobility and accessibility. Yet, they have been linked to several adverse health impacts, with a large, but modifiable, burden of disease. Among the several transportation-related health risk factors, this study focused on transportation-related noise as an emerging exposure whose burden of disease remains partially recognized. We compared premature deaths potentially attributable to transportation-related noise with deaths from motor vehicle crashes, a well-researched and widely recognized transportation risk factor.

Method: We employed a standard burden of disease assessment framework to quantify premature cardiovascular diseases mortality attributable to transportation-related (road and aviation) noise at the census tract level ($n = 592$) in Houston, Texas. The results were compared to motor vehicle crash fatalities, which are routinely observed and collected in the study area. We also investigated the distribution of premature deaths across the city and explored the relationship between household median income and premature deaths attributable to transportation-related noise.

Results: We estimated 302 (95% CI: 185–427) premature deaths (adults 30–75 years old) attributable to transportation-related noise in Houston, compared to 330 fatalities from motor vehicle crashes (adults younger than 75 years old). Transportation-related noise and motor vehicle crashes were responsible for 1.7% and 1.9% of all-cause premature deaths in Houston, respectively. Households with lower median income had a higher risk of adverse exposure and premature deaths potentially attributable to transportation-related noise. A larger number of premature deaths was associated with living in the central business district and the vicinity of highways and airports.

Conclusion: This study highlighted the significant contribution of transportation-related noise and motor vehicle crashes to premature deaths in the city of Houston. The analogy between the estimated premature deaths attributable to transportation-related noise and motor vehicle crashes showed that the health impacts of transportation-related noise were as significant as motor vehicle crashes. The estimated premature death rate attributable to transportation-related noise was also comparable to the death rate caused by suicide, influenza, or pneumonia in the US. There is an urgent need for imposing policies to reduce transportation noise emissions and human exposures and to equip health impact assessment tools with a noise burden of disease analysis function.

Abbreviations: AEDT, Aviation Environmental Design Tool; CBD, Central Business District; CDC, Centers of Disease Control and Prevention; CI, Confidence Interval; CVD, Cardiovascular Diseases; DALY, Disability-Adjusted Life Year; ERFs, Exposure-Response Functions; FAA, Federal Aviation Administration; FARS, Fatality Analysis Reporting System; FHWA, Federal Highway Administration; HEAT, Health Economic Assessment Tool; HF, Heart Failure; HIA, Health Impact Assessment; HR, Hazard Ratio; INM, Integrated Noise Map; ITHIM, Integrated Transport and Health Impact Model; MI, Myocardial Infarction; NTNMT, National Transportation Noise Mapping Tool; NO_2, Nitrogen Dioxide; $PM_{2.5}$, Particulate Matter with a Diameter Equal or Less than 2.5 μm; PAF, Population Attributable Fraction; RR, Relative Risk; PAF, Population Attributable Fraction; TNM, Traffic Noise Model; WHO, World Health Organization

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1. Introduction

Alongside the important role of transportation systems to satisfy individuals' needs of mobility, several adverse health impacts are linked to transportation. Previous studies showed that transportation-related air pollution is a significant cause of premature death where transportation-related air pollution alone is responsible for one-fifth of premature deaths attributable to Ozone and Particulate Matter with a diameter equal or less than 2.5 µm ($PM_{2.5}$), in the UK, US, and Germany (Lelieveld et al., 2015). Motor vehicle crashes are ranked as the 8th leading cause of deaths in the world and the leading cause of deaths amongst those aged 15–29 where, in the year 2016 alone, motor vehicle crashes were responsible for 1.4 million global deaths (WHO, 2018b). Noise pollution is a growing health concern, while road traffic noise is the most dominant contributor to environmental noise (European Environment Agency, 2014). On the other hand, transportation can benefit public health by encouraging users to undertake routine physical activities such as walking and cycling (Woodcock et al., 2010). The potential detrimental and beneficial impacts of transportation on public health in urban areas have been discussed extensively in the literature (Khreis et al., 2016). Most recently, 14 transportation-related pathways to health have been identified (Andrew Glazener, Not published).

The burden of disease attributable to different transportation-related exposures in urban areas was quantified in several studies, e.g., noise (Stassen et al., 2008; Tobías et al., 2015; Tainio, 2015; Mueller et al., 2016, 2017), air pollution (Tainio, 2015; Holnicki et al., 2017; de Sá et al., 2017), motor vehicle crashes (Bhalla et al., 2014; Tainio, 2015; de Sá et al., 2017), and physical activity (Woodcock et al., 2014; Tainio, 2015; Rojas-Rueda et al., 2016; de Sá et al., 2017). Quantifying the burden of transportation exposures may prompt transportation planners to enact health-promoting transportation policies such as investing in public transit, and encouraging active transportation - i.e., cycling and walking. Also, safer and environmentally-friendly infrastructure designs may be expected after considering the health impacts of transportation infrastructures in design and planning. The quantified health impacts of emerging technologies (e.g., electric, connected and automated vehicles) may encourage the automotive industry to invest more in developing safer and zero-emission vehicle designs. Health professionals can also use this information to detect high-risk spots in cities and plan interventions accordingly. Finally, such exercises can raise public awareness of the health impacts associated with transportation and promote dialogue with policymakers and other stakeholders, especially when it comes to less acknowledged exposures, such as transportation noise. In this context, several Health Impact Assessment (HIA) tools have been developed to facilitate the HIA analysis of plans, projects, and policies. These tools allow to quantify the burden of disease attributable to transportation exposures (e.g., Health Economic Assessment Tool (HEAT) by WHO (WHO, 2017), and Integrated Transport and Health Impact Model (ITHIM) (Woodcock et al., 2009)).

In this study, we focus on quantifying and analyzing the burden of disease attributable to transportation noise and motor vehicle crashes, in the form of premature death. We selected noise as an emerging exposure which receives less attention in burden of disease assessments and transportation planning and policy, and whose burden of disease remains partially recognized. The WHO has recently reviewed its noise guidelines for Europe after a series of systematic reviews which established that noise contributes to serious health outcomes such as cardiovascular disease, adverse birth outcomes, cognitive impairment, metabolic outcomes, mental health, annoyance, effects on sleep, hearing impairment and tinnitus (WHO, 2018a). However, in the context of burden of disease assessments, studies mainly quantified cardiovascular diseases and deaths from cardiovascular causes attributable to noise (Tobías et al., 2015; Briggs et al., 2015; Mueller et al., 2018). In contrast, motor vehicle crashes have been recognized as a key transportation-related health issue, decades ago, and have received substantial policy attention and investments (Khreis et al., 2016).

From a methodological standpoint, previous studies share similar methods for quantifying the burden of disease attributable to noise. Typically, the baseline exposure level is compared with either level of exposures recommended by health authorities or a no-exposure scenario, and the burden of disease for the health outcome of interest is quantified employing exposure-response functions (ERFs) extracted from the literature (Tobías et al., 2015; Mueller et al., 2016). Previous studies on burden of disease attributable to noise vary based on the source of noise exposure considered as the input to the analysis. In the literature, the burden of disease from both ambient environmental noise (Tobías et al., 2015) and transportation noise (Tainio, 2015; Briggs et al., 2015; Mueller et al., 2016, 2017) was estimated. Health impacts from crashes, however, are directly extracted from motor vehicle crash datasets (Briggs et al., 2015; Götschi et al., 2015). In previous studies, the transportation noise and motor vehicle crashes burden of disease was measured using the number of deaths (Tobías et al., 2015), premature deaths (Mueller et al., 2016), disability-adjusted life years (DALYs) (Mueller et al., 2018), and health care costs (not in the context of noise-related burden of disease) (Ling-Yun and Lu-Yi, 2016). The spatial resolution of previous burden of disease assessments and analysis varied from census-tract level (Mueller et al., 2016, 2017) to city (Stassen et al., 2008; Tainio et al., 2016), national (Hänninen et al., 2014; Bhalla et al., 2014; Briggs et al., 2015) and continental levels (WHO, 2018a).

The input data needed for assessing transportation-related risk factors and their impact on health is a key component of the burden of disease analysis and the HIA process (Nieuwenhuijsen et al., 2017). In addition to the quality and reliability of data, exposure data with explicit transportation sources should be used for quantifying impacts of *transportation* on public health, instead of ambient exposures originating from multiple sources. The spatial level of the analysis is usually dependent on the availability of data. A finer spatial resolution could help decision-makers to gain a better insight into health equity issues within cities and identify high-risk spots more precisely. However, downscaling data inappropriately can result in increased uncertainty and/or error in the burden of disease estimations. This study contributes to the literature by specifying the transportation component of the exposure (i.e., using two sources of transportation noise as opposed to ambient environmental noise exposure), estimating the burden of disease attributable to transportation noise at the census tract level with further analyses by socioeconomic status and its spatial variation across the city, and comparing the estimated burden of disease from noise to motor vehicle crashes fatalities. As a case study, we quantify and analyze the premature deaths attributable to transportation noise (from road traffic and aviation) and motor vehicle crashes in the city of Houston, Texas; the fourth most populated city in the US.

2. Materials and methods

2.1. Study setting and definitions

The burden of disease attributable to transportation noise and motor vehicle crashes were assessed in the city of Houston. The city of Houston had 2303482 residents in 2016 (US Census Bureau, 2016). Houston is the largest city in Texas with 636.5 square miles (1646 square km) land area (World Population Review, 2019), located in three US counties; Harris, Fort Bend, and Montgomery. The burden of disease analysis was conducted at the finest reasonable spatial resolution: the census tract level. The rationale behind analyzing the burden of disease at the census tract level is that mortality data was only available at the county level and so approximations were required to assign them to a finer spatial level. To minimize the error of approximations, and yet investigate the spatial distribution of health outcomes, we chose to limit the spatial resolution of this study to the census tracts level. Consequently, 592 census tracts were included in this study which were fully or partially located within the city's boundaries.

We quantify the health impacts in the form of attributable premature deaths. Premature deaths are defined as a measure of unfulfilled life expectancy (Doughty, 1951), which is considered as the number of deaths before reaching the expected age. The life expectancy in the US was 78.6 years old in 2016 (Xu et al., 2018). Given that and according to the availability of the baseline mortality data (in 5-years intervals), the deaths of individuals aged less than 75 years old were considered as premature deaths in this study. We estimated the premature deaths attributable to aviation and road traffic noise for the cardiovascular class of diseases. Since the risk of mortality from cardiovascular diseases (CVD) is associated with transportation noise for individuals older than 30 years old (details are provided in subsequent sections), hereafter, the term premature death refers to the death of individuals aged 30–75 years old, and in theory, preventable. For motor vehicle crashes, the deaths of individuals younger than 75 years old were considered as premature deaths.

2.2. Input data

The data used in this study were collected from multiple sources, namely, US census bureau, Centers for Disease Control and Prevention, Texas Department of Transportation and US Department of Transportation, as described in the following sections.

2.2.1. Population, economic and geographic data

Population and economic data were collected from the US Census Bureau for 2016 at the census tract level. We analyzed the burden of disease by household economy using the median household income at the census tract level, as sourced from the US Census Bureau. The average of median household income in the city of Houston, in 2016, was 60,784 dollars while the lowest and highest median household income at the census tract level were 10,128 and 246,058 dollars, respectively (see Fig. S1 for the spatial distribution of the median household income across the city). The geographical limits of the city of Houston were sourced from the city's open data portal, which was used to identify census tracts within the city's boundaries (retrieved from https://cohgis-mycity.opendata.arcgis.com/datasets/houston-city-limit).

2.2.2. Motor vehicle crashes data

Premature deaths from motor vehicle crashes were defined as the fatalities of individuals younger than 75 years old. Fatalities from motor vehicle crashes were collected from the Fatality Analysis Reporting System, known as FARS, and provided by the National Highway Traffic Safety Administration for the year 2016. The location of motor vehicle crashes' occurrence along with the number of fatalities was publicly available from https://www.nhtsa.gov/research-data/fatality-analysis-reporting-system-fars. However, information on the physical address of the individual(s) involved in the crash was not available.

We conducted a supplementary analysis of the crashes data to explore the spatial distribution of premature deaths from motor vehicle crashes. To this end, we categorized the crashes into two categories: (1) local crashes and (2) highway crashes. Highway crashes refer to crashes that occurred on highways. The remainder of crashes were assigned to the census tract where they occurred. For the supplementary comparison between premature deaths attributable to transportation-related noise and motor vehicle crashes, we assumed that local crashes occurring within a census tract can be attributable to residents of that census tract. The highways' map, sourced from the Texas roadway inventory data by the from 2016 (retrieved from https://www.txdot.gov/inside-txdot/division/transportation-planning/roadway-inventory.html), was used to identify crashes which occurred on highways.

2.2.3. Mortality data

The baseline mortality data for Texas was sourced from the Centers for Disease Control and Prevention (CDC) (https://wonder.cdc.gov/mcd.html). The mortality data was available both in the form of the number of deaths and crude mortality rates[1] at the county level with 95% Confidence Interval (CI). For quantifying the premature deaths attributable to noise, the number of deaths from CVD for people aged 30–75 years old was used in this study. Given that the city of Houston is located in three counties: Harris, Fort Bend, and Montgomery, the mortality data for these three counties was collected. As of the time of inquiry (January 2019), the mortality data were available for the year 2016. We distributed the number of mortality cases (available at the county level) across census tracts proportionally based on their population size, assuming constant mortality rate for census tracts located within a county. To keep the consistency with premature death data, the population aged 30–75 years old was used for assigning mortalities to census tracts. In 2016, a total number of 17,704 all-cause premature deaths were reported in the city of Houston (30–75 years old), where 5,384 deaths were caused by CVD, 465 deaths were caused by Heart Failure (HF), and 569 were caused by Myocardial Infarction (MI) (representing 30.5%, 2.5% and 3.2% of all-cause premature deaths, respectively). The summary statistics of the mortality data at the census tract level are reported in Table S1.

2.2.4. Noise data

Road traffic and aviation noise data were collected from the National Transportation Noise Mapping Tool (NTNMT) generated by the US Department of Transportation's Bureau of Transportation Statistics (retrieved from http://osav-usdot.opendata.arcgis.com/datasets?q = noise&sort_by = relevance). The noise map was generated by implementing the Aviation Environmental Design Tool version 2b (AEDT 2b) developed by Federal Aviation Administration (FAA) and the acoustic algorithms from the Traffic Noise Model 2.5 (TNM) proposed by the Federal Highway Administration (FHWA). The transportation noise map was generated utilizing traffic data, roadway inventory, aircraft flight operation data along with simplifying assumptions–namely, atmospheric absorption for aviation noise, non-homogenous atmospheric effects in road traffic noise modeling and TNM's default temperature and humidity levels (68 degrees F, 50% relative humidity), acoustically soft ground, average pavement material and texture of the road, and even distribution of average annual daily traffic data across 24 h (see (US Department of Transportation, 2017) for more information).

The modeling engines of the NTNMT, AEDT 2b and FHWA's TNM models, were validated before. The validation of FHWA's TNM models for 100 h of traffic noise at 17 sites across the US verifies the accuracy of TNM, where the average difference between predicted and measured sound levels were as low as 1.0 dB for all wind conditions, and 0.5 dB after removing strong winds (Rochat and Fleming, 2002). The AEDT 2b is introduced as a replacement of the Integrated Noise Map (INM) previously developed by FAA. The comparison of AEDT 2b and INM in terms of the predicted noise contour area shows consistency between the two models (Federal Aviation Administration, 2017). The INM model was validated by FAA comparing the model results to observed noise data showing that average sound exposure level can be estimated with up to 2.0 dB difference for three-engine aircraft with narrow-body, 6.2 dB difference for two-engine aircraft with narrow-body, 3.3 dB difference for two and three-engine aircraft with wide-body, and 3.4 dB difference for four-engine aircraft with wide-body while take-off, cutback, climb and approach (Flathers, 1982). Also, the national transportation noise map (including both road and aviation noise) has been evaluated by subject matter experts who confirmed that levels were within a reasonable order of magnitude (US Department of

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[1] Crude mortality rate is the total number of deaths to residents in a county divided by the total population for the county (for a calendar year) and multiplied by 100,000.

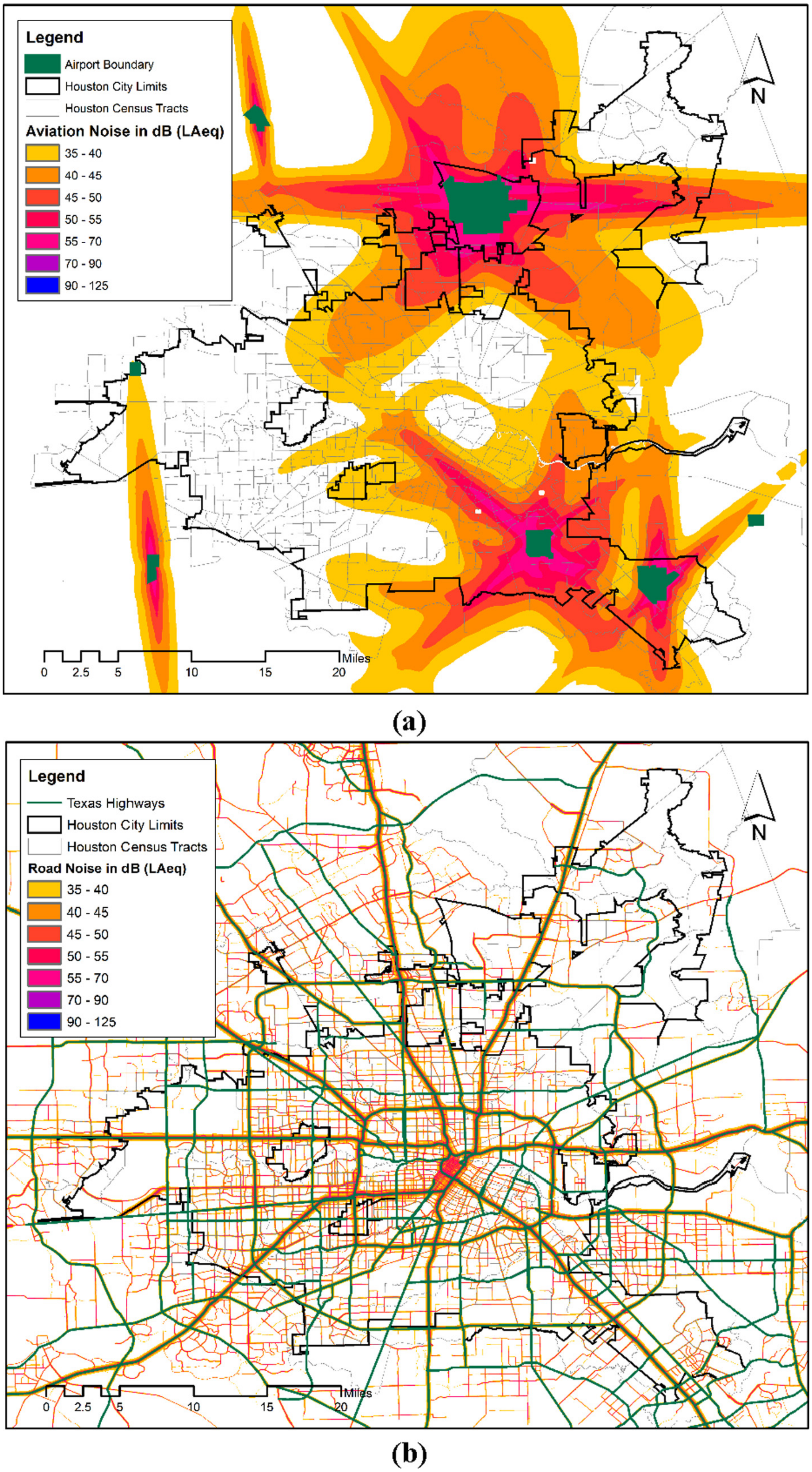

Fig. 1. (a) Aviation, and (b) Road traffic noise maps in Houston.

Transportation, 2017).

The transportation noise inventory was developed using a-weighted 24-hr equivalent sound level noise metric (denoted by L_{Aeq}) which represents the approximate average noise energy due to transportation noise sources over the 24 h at defined receptors. The aviation noise was captured at a gird of receptors with distances that varied between 0.005

and 0.250 nautical miles (9.26 and 463.00 m), depending on the size of the airport and the distance to the airport. The road traffic noise receptors were located on a uniform grid with a resolution of 98.4 feet (30 m). Each receptor was modeled at a height of 4.92 feet (1.5 m) above ground level. Noise levels were adjusted to account for ground effects and free-field divergence differences between the source reference location and the receptor location. In Fig. 1, the distribution of the averaged daily aviation and road traffic noise across the city of Houston is depicted. The noise map was developed for noise level higher than 35 dB L_{Aeq}.

2.3. Burden of disease assessment model

We used a standard burden of disease assessment framework previously developed and used in the literature (Mueller et al., 2016). This framework is employed to estimate the premature deaths attributable to transportation noise. In brief, the inputs to the burden of disease assessment model include the noise exposure levels, as well as the baseline mortality rate from CVD in the studied region. Next, the relative risk (RR) of CVD deaths in association with the difference between current transportation noise exposure levels and the counterfactual transportation noise exposure level is estimated using ERFs sourced from the best available and most relevant epidemiological study (Section 2.3.1). Then, the population attributable fraction (PAF) can be calculated using Eq. (1). The PAF represents the ratio of CVD deaths attributable to transportation noise from all CVD deaths for the difference between current noise exposure level and the counterfactual exposure level.

$$PAF = \frac{RR_{diff} - 1}{RR_{diff}} \tag{1}$$

where RR_{diff} is the relative risk of CVD deaths in association with the difference between current transportation noise exposure levels and the counterfactual transportation noise exposure level.

Finally, the attributable deaths are estimated using the mortality rate and population counts for people aged 30–75 years old, and the estimated PAF (Eq. (2)). The motor vehicle crash data, however, translated directly into mortality as these were observations of deaths from crashes. The employed burden of disease assessment framework is presented in Fig. 2. This procedure was used for each disease category across each of the 592 included census tracts.

$$Attributabl\ \ Mortality = PAF \times Mortality\ \ rate \times Population\ \ counts \tag{2}$$

2.3.1. Exposure-response functions

We extracted the ERFs linking transportation-related noise and CVD mortality from a previously published epidemiological study. We sourced the ERFs from the study by Héritier et al. (2017), after considering several epidemiological and meta-analysis studies which have been used (or discussed) in previous noise burden of disease assessments (Beelen et al., 2009; Huss et al., 2010; Sørensen et al., 2011; Gan et al., 2012; Babisch, 2014; Halonen et al., 2015; Héritier et al., 2017; van Kempen et al., 2018). The selection of the ERF in this study was based on three criteria. First, the selected ERF needed to associate noise with mortality, and not morbidity as in Sørensen et al. (2011). Second, since we are investigating the detrimental health impacts of two transportation-related noise sources: road traffic and aviation, studies reporting ERFs for both sources were prioritized (Héritier et al., 2017; van Kempen et al., 2018). Considering the first and second criteria, we excluded the studies that have not associated transportation-related noise to mortality and have not estimated ERFs for both aviation and road traffic noise (Beelen et al., 2009; Huss et al., 2010; Sørensen et al., 2011; Gan et al., 2012; Babisch, 2014; Halonen et al., 2015). Among the studies that met the first and second criteria, Héritier et al. (2017) estimated ERFs for both aviation and road traffic noise using a mutual database. Also, van Kempen et al. (2018) synthesized ERFs from previous studies and estimated ERFs for different sources of noise. Third, the selected ERF needed to be compatible with the classification for the causes of death data, as sourced from the CDC. To avoid underestimating the health outcomes of transportation-related noise, we selected the study which associated noise to mortality from a wide range of CVDs. Héritier et al. (2017) associated road traffic and aviation noise with mortality from a wide range of CVD, with international classification of disease (ICD 10) codes ranging from I00 to I99 for road traffic noise, and I21, I22, and I50 for aviation noise, and in line with the CDC definitions (Centers for Disease Control and Prevention, 2017). On the contrary, the study by van Kempen et al. (2018) only proposed ERFs for some CVDs, offering a smaller range of health outcomes which included ischemic heart disease (I120-I125) and stroke (did not code by ICD 10). Finally, we selected the ERFs from the Héritier et al. (2017) study which meets all three selection criteria: investigating noise and the risk of mortality, estimating ERFs for road traffic *and* aviation noise, and covering the widest range of CVD mortality, in association with noise exposures.

Héritier et al. (2017) found statistically significant associations between exposure to road traffic and aviation noise and CVD mortality. Multi-pollutant models were used for estimating the ERFs including linear terms for each noise source which controls for effect of the other source of noise. This study was a population-based cohort study conducted in 4.4 million adults, older than 30, in Switzerland, and for road traffic noise and aviation noise levels higher than 35 dB and 30 dB, penalized for the evening and nighttime (L_{den}[2]). The estimated ERFs were adjusted for a comprehensive set of potential confounders: sex, neighborhood index of socioeconomic position (low, medium, high), civil status (single, married, widowed, divorced), education level (compulsory education or less, upper secondary level education, tertiary level education, not known), annual average nitrogen dioxide (NO_2) concentration, mother tongue, and nationality. Based on the estimated ERFs for road traffic noise and CVD mortality, the RR was 1.025 (95% CI = 1.018–1.032) for each 10 dB increase in L_{den}. Respectively, the RR of MI and HF mortality for aviation noise were 1.027 (95% CI = 1.006–1.049), and 1.056 (95% CI = 1.028–1.085) for 10 dB increase in L_{den}. The study did not find a statistically significant associations between aviation noise and CVD mortality and as such, we only investigated the burden of HF and MI attributable to aviation noise. RRs are reported in Table 1.

2.3.2. Overlap of attributable health impacts

Road traffic and aviation noise were both associated with MI and HF. Therefore, the estimated premature deaths from HF and MI attributable to road traffic and aviation noise may overlap. This overlap will result in double-counting premature deaths attributable to transportation-related noise in the studied area. In this study, we ran a supplementary analysis and examined the overlap between the MI and HF outcomes, based on probability theory. Given that we do not have information about the target population of the diseases, we approximated the double-counted premature deaths using addition rules in probability. This analysis and the methodology behind it are reported in the supplementary material (Section S.1).

2.3.3. Noise exposure calculation and conversion

To assign noise exposures to the population living in each census tract, it was assumed that:

- The population was distributed evenly within each census tract since no information was available on the specific residential

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[2] 2: The average sound level over a 24-hour period, with a penalty of 5 dB added for the evening hours (19:00 to 22:00) and a penalty of 10 dB added for the night time hours (22:00 to 7:00).

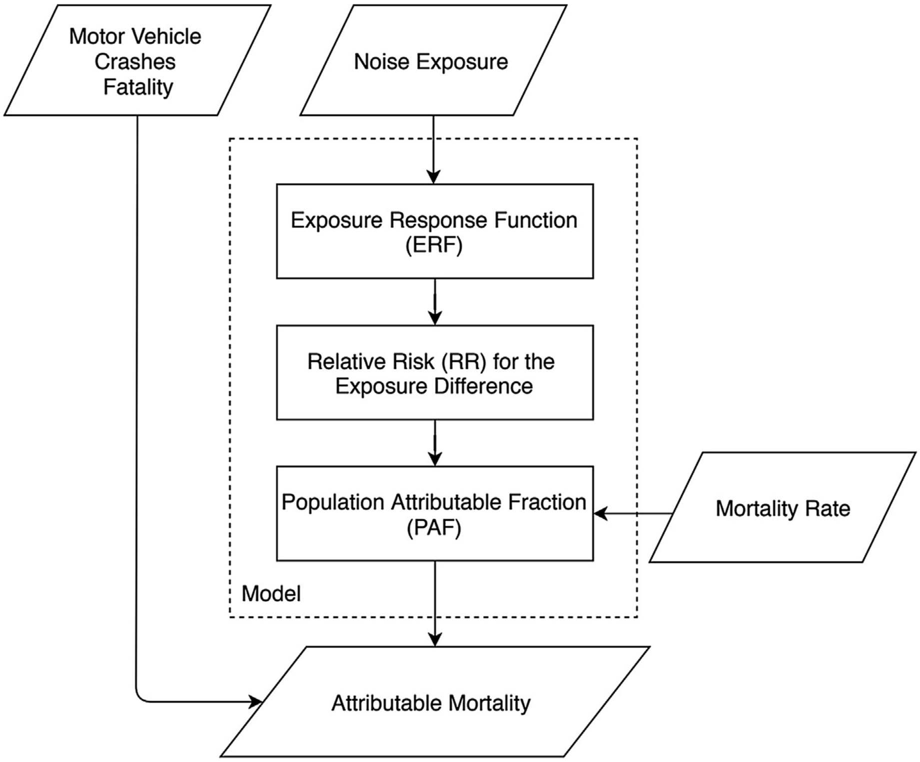

Fig. 2. Burden of disease assessment framework.

locations of the population within each census tract nor did we have a detailed population grid
- The mortality rate was constant within each census tract as the mortality rate which was only available at the county level was assigned to census tracts proportionally based on their population size (section 2.2.3)

Given these assumptions, the population exposed to a given level of noise could be calculated by finding the area within a census tract which corresponds to each exposure level. For example, in Fig. 3, the population living in areas A_{N35}^{1} and A_{N35}^{2} are exposed to aviation noise levels equal to 35 dB L_{Aeq}. The population living in the area A_{N30}^{1}, A_{N40}^{1} and A_{N45}^{1} are exposed to 30, 40, and 45 dB L_{Aeq}, respectively. The population exposed to the 35 dB L_{Aeq}aviation noise can be estimated by:

$$P_{N35}^{Ci} = \frac{\sum_{n=1}^{N} A_{N35}^{n}}{A_{Ci}}.\ P^{Ci} \tag{3}$$

where P_{N35}^{Ci} represents the population at census tract i (C_i) exposed to the noise level 35 dB L_{Aeq}. A_{N35}^{n} is the n$^{\text{th}}$ area exposed to 35 dB L_{Aeq} while n can vary from 1 to N. A_{Ci} and P^{Ci} represent the area and the population of the census tract i. The population exposed to other levels of noise can be estimated similarly, using Eq. (3). Since the noise data was only available for levels higher than 30 dB L_{Aeq}, noise exposures could not be estimated for the noise levels less than 30 dB L_{Aeq} (the white areas in Fig. 3).

Based on the constant mortality rate within a census tract assumption, the number of deaths can be estimated for each area. Note that, the RR_{diff} is not consistent across the exposed areas within each census tract (given the differences in noise exposure levels), and therefore, the attributable mortality needs to be estimated separately for the areas with the different noise exposures, even within a census tract. ArcMap spatial analysis tools were used to determine the exposure levels and areas.

The NTNMT reports noise exposure with L_{Aeq}. However, the ERFs we selected in this study associated CVD mortality with L_{den}. To convert L_{Aeq} to L_{den} *before* calculating the noise exposure, we used a suggested conversion guideline between noise indicators proposed by Brink et al. (2018). In this context, the aviation and road traffic noise in L_{Aeq} were converted to L_{den} as follows:

$$L_{den}^{aviation} = L_{Aeq}^{aviation} + 3.5(95\%\text{CI} = 0.1 - 6.9) \tag{4}$$

$$L_{den}^{road} = L_{Aeq}^{road} + 3.6(95\%\text{CI} = 2.2 - 5.0) \tag{5}$$

2.3.4. Contrafactual scenario

Given that the ERFs were originally estimated for exposures greater than 35 dB $L_{den}$for road traffic noise and 30 dB $L_{den}$for aviation noise, the counterfactual noise levels were selected accordingly. Therefore, the contrafactual scenarios were defined as:

- The daily average of road traffic noise level did not exceed 35 dB L_{den}
- The daily average of aviation noise level did not exceed 30 dB L_{den}

In this context, the attributable premature deaths were estimated for the difference between the current and counterfactual noise level of 35 dB $L_{den}$for road traffic noise and 30 dB $L_{den}$for aviation noise. In other words, we assume that the population exposed to noise levels less than 35 dB and 30 dB L_{den} (road traffic and aviation noise, respectively) had no increased risk of death from CVD.

2.4. Sensitivity analysis

Uncertainties are inherited in variables incorporated in the burden of disease assessment studies, mainly arising from uncertainty in the baseline health data, the exposure model predictions, and the selected ERFs, among others. To explore the range of uncertainties from the variables included in our analysis, including (1) the baseline mortality rates, (2) the ERFs, and (3) the conversion of the noise metrics, we ran two uncertainty analyses. First, we estimated the most conservative and most extreme burden of disease scenarios using the combinations of the lower and upper 95% CI for each of the three variables named above

Table 1
The number of premature deaths attributable to transportation noise in Houston.

Exposure source	Age group	Contrafactual scenario	Cause of death (ICD-10[I])	Adjusted RR[II] associated with 10 dB increase in L_{den} (95% CI)	L_{Aeq} to L_{den} Conversion (95% CI)	Premature death cases (95% CI)	Attributable premature deaths (95% CI)[III]
Road traffic noise	> 30 y	Reduction to 35 dB where in exceedance	CVD (I00-I99)	1.025 (1.018–1.032)	+3.6 (2.2–5.0)	5,384 (5,251–5,517)	215 (153–279)
Aviation noise	> 30 y	Reduction to 30 dB where in exceedance	MI (I21-I22) HF (I50)	1.027 (1.006–1.049) 1.056 (1.028–1.085)	+3.5 (0.1–6.9)	569 (525–611) 464 (427–504)	52 (20–96) 35 (12–52)
Total =							302 (185–427)

[I] The 10th revision of the International Statistical Classification of Diseases and Related Health Problems (Centers for Disease Control and Prevention, 2017)

[II] Adjusted for sex, neighborhood index of socioeconomic position (low, medium, high), civil status (single, married, widowed, divorced), education level (compulsory education or less, upper secondary level education, tertiary level education, not known), annual average nitrogen dioxide (NO_2) concentration, mother tongue and nationality and controlled for the other noise source exposure

[III] Refers to the most conservative and extreme estimations using the combinations of the lower and upper 95% CI for variables

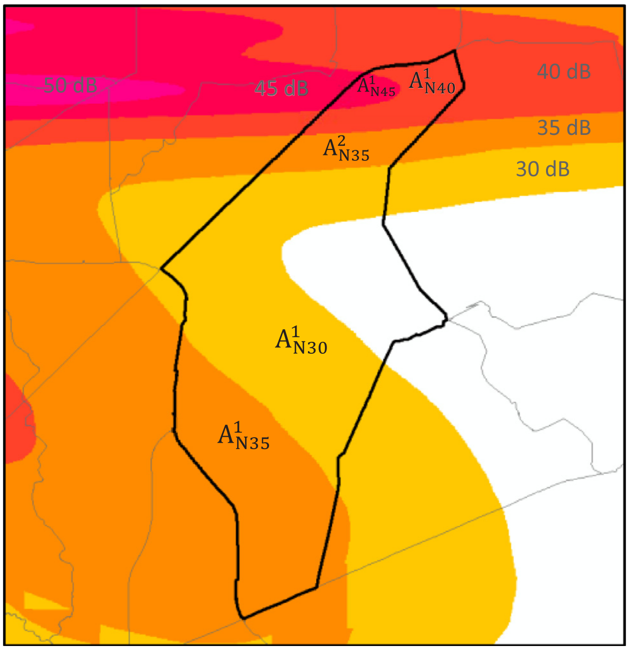

Fig. 3. Aviation noise exposure levels in a given census tract (C_i).

(Table 1). Second, we reran the analysis for each variable *individually*. In this context, the burden of disease for the upper and lower 95% CI of each variable was estimated (Fig. 6).

In addition to the above-mentioned uncertainty analyses, a sensitivity analysis was run to better understand the relation between inputs and outputs of the burden of disease assessment. To this end, we examined the changes in the estimated attributable premature deaths using a 10% marginal change in exposure values of noise, baseline mortality rate, noise conversion, and the ERFs (Fig. 7).

3. Results

3.1. Premature deaths attributable to noise

Table 1 summarizes the estimated premature deaths attributable to road traffic and aviation noise in the city of Houston. 215 (95% CI: 153–279) premature deaths from CVD for the age group between 30 and 75 years old were attributable to road traffic noise. Respectively, 52 (95% CI: 20–96) and 35 (95% CI: 12–52) premature deaths from MI and HF were attributable to aviation noise. The total number of deaths attributable to transportation noise was therefore estimated as 302 (95% CI: 185–427) premature deaths in 2016. Analyzing the overlap of the estimated premature deaths attributable to MI and HF from road traffic and aviation noise showed that 2 (95% CI: 0–3) premature deaths may be double-counted in this study (see section S.1 in the supplementary materials). Given the uncertainties in calculating this overlap and the small number of potentially double-counted premature deaths as compared to the uncertainties inherited in the burden of disease analyses, we did not consider the double-counted premature deaths in reporting the health outcomes attributable to transportation-related noise in this study.

The spatial distribution of premature deaths attributable to transportation noise is shown in Fig. 4, in the form of percentage from all-cause premature deaths. The percentage of premature deaths attributable to transportation noise was higher in the census tracts located in the central business district (CBD), and in the vicinity of Houston's airports and highways. In more than 40% of census tracts, transportation noise was responsible for more than 2% of all-cause premature deaths in the city, with a more significant role of road traffic noise (Fig. S2).

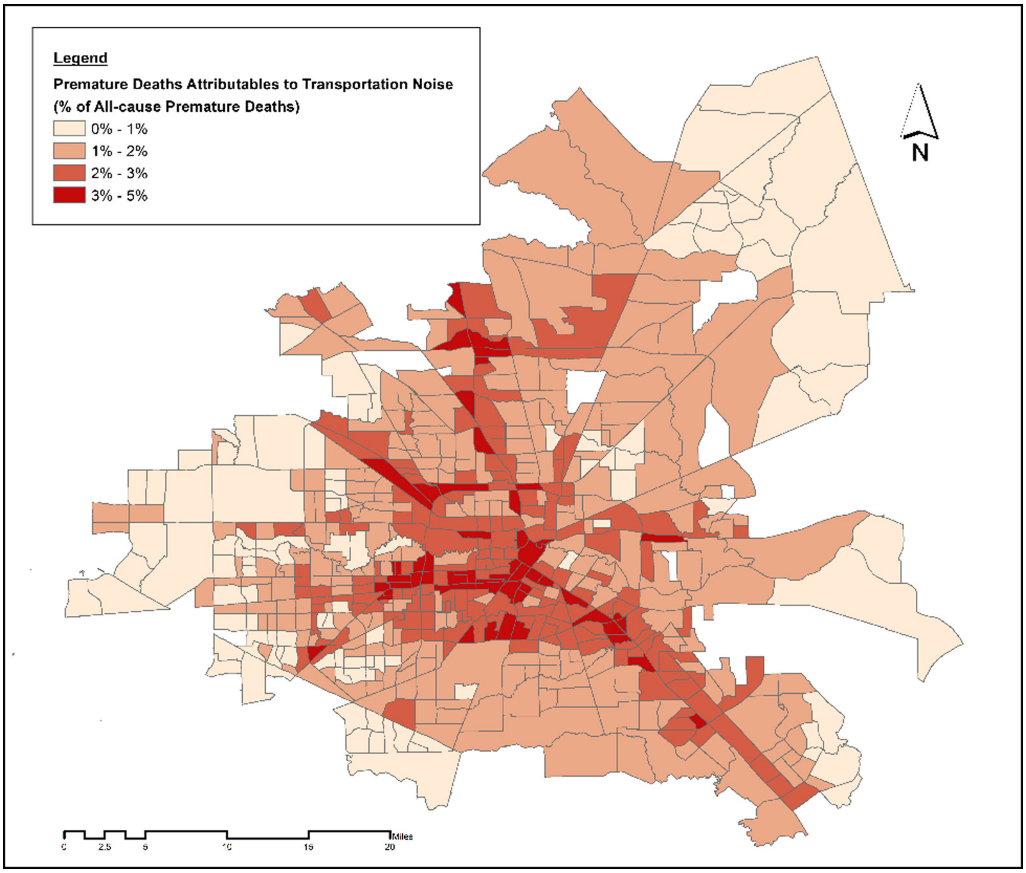

Fig. 4. Spatial distribution of the ratio of premature deaths attributable to transportation noise (road traffic and aviation) to all-cause premature deaths.

3.1.1. Premature deaths attributable to transportation noise by household income

The relation between median household income at each census tract and the premature deaths from transportation noise was further explored. The comparison revealed an inverse correlation between the median household income at the census tract level and the ratio of premature deaths attributable to transportation noise from all-cause premature deaths (the average line in Fig. 5). In other words, it is expected that the ratio of attributable deaths reduces with an increase in household income until the $75,000 income level from 2.3% to 1.7% (Table S4). For households with income higher than $75,000, an inverse relation is observed. A closer look at the health impacts of noise exposure sources shows that this relation is mainly from premature deaths attributable to aviation noise. The ratio of premature deaths from aviation noise to all-cause deaths mortality varies from 0.8% for households with a median income lower than $20,000 to 0.4% for households with a median income more than $75,000.

3.1.2. Sensitivity analysis

The most conservative estimation of premature deaths attributable to road traffic noise resulted in 153 deaths while the most extreme estimation resulted in 279 deaths (reported in Table 1). The most conservative and most extreme estimations for premature deaths attributable to aviation noise resulted in 32 and 148 deaths. Overall, the estimated premature deaths attributable to transportation noise in the city of Houston varied between 185 and 427, given the uncertainties in variables used for the analysis.

Results of the sensitivity analysis of lower and upper 95th CI of each variable is depicted in Fig. 6. The uncertainty in the ERFs had the largest role in the results' uncertainty where the estimated attributable premature deaths to aviation and road traffic noise could be changed by up to 56.8% and 25.5%, respectively. The uncertainties in the MI and HF mortality rates resulted in up to 8.0% deviation in the estimated attributable premature deaths due to aviation noise. The uncertainty in the noise conversions was up to 6.2% for both road traffic and aviation noise (see Table S2 for more details). Overall, a higher level of uncertainty was associated with premature deaths attributable to aviation noise compared to road traffic noise.

The relation between inputs and outputs of the attributable premature deaths estimation was examined by running a sensitivity analysis to find the marginal effect of inputs. The results of this analysis are depicted in Fig. 7. It is shown that 10% marginal changes in the mortality rate, ERF and noise exposure will result in up to 10%, 8.8% and 8.2% change in the estimated mortality (controlling for other variables), respectively. The noise conversion had the lowest marginal effect with a 2.3% change in the estimated premature deaths associated with a 10% change in the noise conversion variable (see Table S3 for more details).

3.2. Premature deaths from crashes

A total number of 330 premature deaths from motor vehicle crashes were reported for individuals younger than 75 years old in Houston in the year 2016. The distribution of premature deaths from motor vehicle crashes across the city in 2016, as the percentage of crash fatalities from all-cause premature deaths, is shown in Fig. S3. From the figure, the ratio of deaths attributable to crashes was higher in suburban areas as opposed to the CBD.

3.3. Overall impacts

Table 2 summarizes the estimated number of premature death cases attributable to transportation noise and motor vehicle crashes in the city of Houston in 2016. 632 premature deaths were attributable to

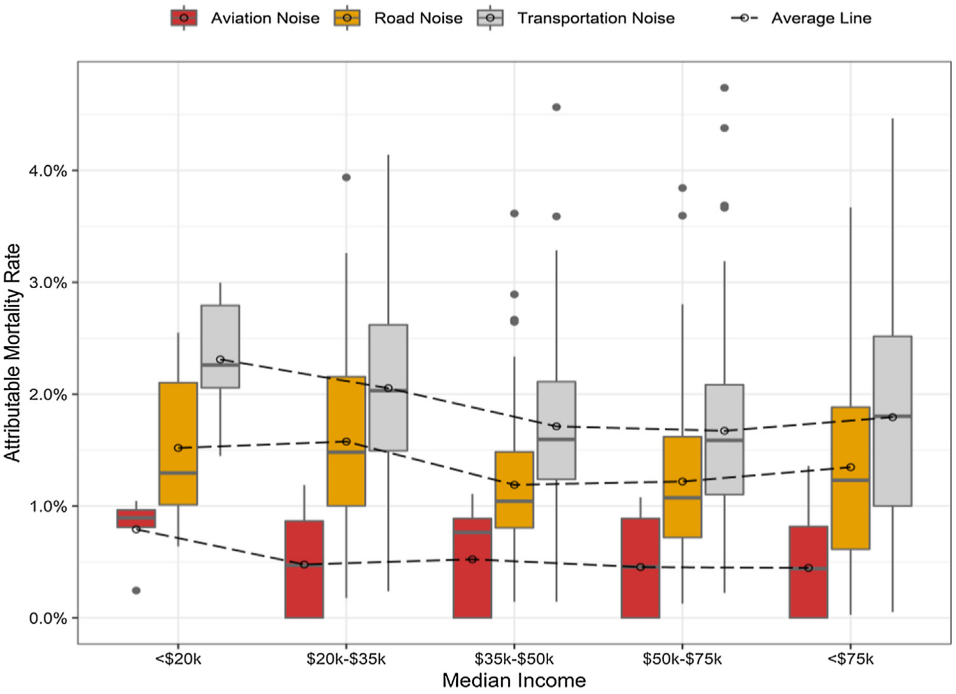

Fig. 5. Variation of the ratio of the premature death attributable to transportation noise (road traffic and aviation noise) by household median income.

transportation noise and crashes which represents 3.6% of all-cause premature deaths in the city. Transportation noise and crashes were responsible for 1.7% and 1.9% of all-cause premature deaths, respectively.

4. Discussion

This study sheds light on the health burden attributable to transportation noise and motor vehicle crashes in the city of Houston, Texas, in the form of premature deaths. The results showed that, in 2016, 302 (95% CI: 185–427) premature deaths were attributable to the noise from road traffic and aviation, which accounts for 1.7% of all-cause premature deaths in Houston. 330 deaths from motor vehicle crash for individuals younger than 75 years old were reported in 2016, which accounts for 1.9% of all-cause premature deaths. These findings, therefore, highlight a significant role of transportation noise in the public health burden in Houston, where the estimated premature death cases attributable to noise were comparable to motor vehicle crash fatalities. Overall, 632 premature deaths per year were attributed to transportation noise and crashes. This can be translated into 3.6% of premature deaths in the city, which is higher than the death rate caused by diabetes in the US (2.9% in 2016 according to (Xu et al., 2018)), and is comparable with the death rate from Alzheimer's disease (4.2% in 2016 (Xu et al., 2018)). Also, the estimated premature death rate attributable to transportation noise is higher than the death rate caused by influenza and pneumonia or suicide, in the US (Xu et al., 2018).

The ERFs employed in this study were responsible for the largest range of uncertainty in the estimated health impacts. Also, we showed that the estimated premature deaths were more sensitive to the following inputs in this order: mortality rate, ERF and noise exposure level. We found that the burden of premature death from transportation noise was higher in the census tracts located in the CBD, and in the vicinity of the highways and near the airports. We demonstrated the inverse correlation between the median household income and the ratio of premature deaths attributable to aviation noise, while a more complex relationship was observed between median household income and detrimental health outcomes form road traffic noise. The findings of this study not only can directly provide decision-makers and engineers

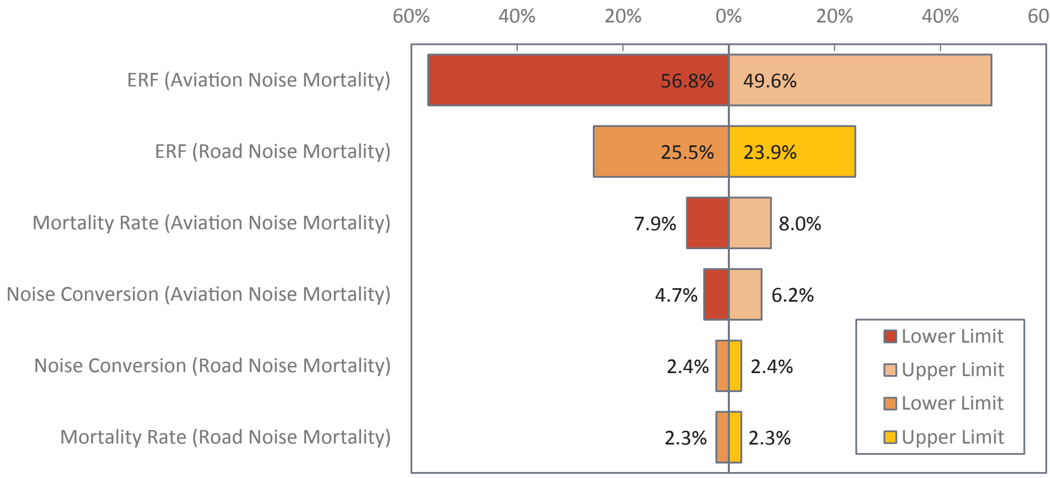

Fig. 6. Analysis of the sensitivity of estimated premature deaths to variables varying from lower and upper 95th CI.

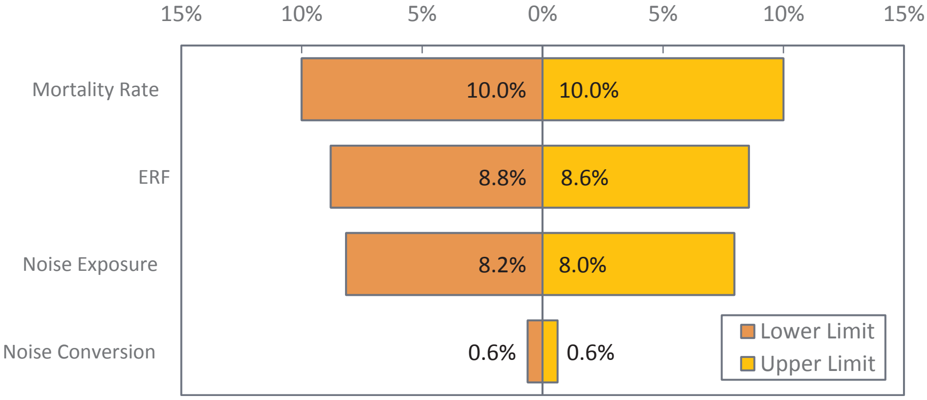

Fig. 7. Analysis of the sensitivity of estimated premature deaths to 10% change in variables.

Table 2
The number of premature deaths attributable to noise and motor vehicle crashes.

Exposure source		Attributable premature deaths (95% CI)	% of all-cause premature deaths[II]
Noise	Aviation	87 (32–148)	0.5%
	Road traffic	215 (153–279)	1.2%
Motor Vehicle Crash		330[I]	1.9%
Total		632 (528–759)	3.6%

[I] No uncertainty is associated with the crash fatalities.
[II] > 30 and < 75 years old.

with more detailed information about the health outcome attributable to transportation noise and crashes but also underscores the need for implementing noise burden of disease assessments in HIA tools.

4.1. Strengths and limitations

In this study, we used aviation and road traffic noise, as opposed to focusing on one source of noise (Mueller et al., 2016, 2017), to quantify and compare the potential contribution of transportation noise to premature deaths. We also quantified the burden of disease from transportation noise as opposed to ambient environmental noise (Tobías et al., 2015). Therefore, the health impacts of transportation noise exposure can be compared to the health impacts attributable to other transportation risk factors in the future, such as traffic-related air pollution and transportation-related physical activity. To be able to account for the non-linear ERFs in the burden of disease assessment of noise, we estimated RR_{diff} for exposure to different levels of noise within a census tract. This would result in a more accurate burden of disease analysis compared to estimating the health outcomes attributable to the averaged noise across the census tracts which is usually used (Mueller et al., 2016). We compared the deaths from motor vehicle crashes with the deaths attributable to transportation noise to show the significance of transportation-related noise burden of disease in an urban area. We also specifically explored the relationship between the median household income and the estimated attributable burden. The U-shaped relationship between the estimated premature deaths attributable to transportation noise and median household income was consistent with the recent finding of Alotaibi et al. (2019) who also showed a U-shaped relation between childhood asthma attributable to air pollution and median household income across the contiguous US.

This study has certain limitations that are mainly related to the input data. We aimed to show a clear and easy-to-grasp contrast between an exposure that received significant policy attention and financial mitigation resources: motor vehicle crashes, and one whose health impacts are only emerging: transportation noise. To do that, we employed an easy-to-grasp metric: premature death. This metric, however, does not account for the number of years lost due to premature death, nor does it measure the time lived with disability, as opposed to DALYs. Quantifying the health impacts of noise and motor vehicle crashes using DALYs can provide better insight, for example by considering the effect of youngsters' deaths from motor vehicle crashes, but is more difficult to interpret by professionals outside public health. Future work would benefit from using DALYs in similar burden of disease comparisons. This study also focused on estimating CVD premature deaths attributable to transportation noise and other detrimental health impacts of noise were not quantified. Although a contrast observed in the spatial distribution of premature deaths from motor vehicle crashes and premature deaths attributable to transportation-related noise, further analysis is required before drawing any conclusions from this contrast, given the uncertainties in assigning local crashes. The extracted ERFs were estimated for adults older than 30 years, and so the potential mortality in the younger population was not quantified. Our approach is, therefore, likely to result in underestimating the overall impacts of transportation noise in Houston. The noise exposure data was deployed from the transportation noise modeling tools developed by the US Department of Transportation, the only available transportation noise map thus far. The map was produced in 2014, and we assumed that the noise estimations were applicable to this study's time period which was the year 2016. Similar to any model, the transportation noise models were based on several simplifying assumptions (discussed in Section 2.2.4). Assuming soft ground for modeling noise will result in under-predicting sound levels for large areas with acoustically hard grounds (e.g., water or pavement). Also, assuming average road pavement material and texture may under/over-predict the sound levels, depending on the road pavement type in place. The ERFs selected for the burden of disease analysis were estimated for road traffic noise exposures above 35 dB$L_{den}$and aviation noise exposures above 30 dBL_{den}. The NTNMT only predicted noise exposure levels above 35 dBL_{Aeq}, which is equal to 38.6 dBL_{den} according to Brink et al. (2018). Therefore, the number of premature deaths was only possible to estimate for noise exposures above 38.6 dB L_{den}, for both road traffic and aviation noise. Consequently, the premature deaths attributable to noise in the studied area are likely underestimated. The number of mortalities at the census tract level was approximated based on the variation of population counts across the census tracts located within a county. In short, we weighted the number of mortalities based on the population size of each census tract assuming constant mortality rates across the county. However, the rates of mortality were shown to be higher in communities with lower socioeconomic characteristics (Anderson et al., 1997; Wilkinson and Pickett, 2008; Pickett and Wilkinson, 2015). Unfortunately, we had no other source of mortality data with a finer spatial resolution, and this is a common limitation that is often seen in the health impact and burden of disease assessment studies, like ours. Consequently, our approximation may result in underestimating the number of premature deaths attributable to noise at census tracts with lower households' median income. We also assumed homogeneous distribution of the population across census tracts. Although this assumption may be valid in a dense urban area, it may lead to underestimating the burden of disease in suburban areas, especially for road traffic noise as higher population densities and levels of exposure may occur in the vicinity of high speed roads.

4.2. Research and policy recommendations

Further studies are needed to examine the assumptions and limitations of this study, including the ERF limitations, transportation noise exposure uncertainties, and limitations in the availability and spatial assignment of motor vehicle crashes. Given the significant contribution of transportation noise to Houston's premature death burden, we suggest equipping HIA tools with a noise burden of disease analysis function. Quantifying the health impacts of transportation-related air pollution and comparing its spatial distribution with the health impacts of transportation-related noise can also be an interesting future study which provides greater comparibility.

The estimated premature deaths can be considered preventable by enacting policies and implementing efficient urban and transportation designs to improve traffic safety and control transportation noise emissions and exposures. Decreasing traffic flows, improving the roadway design, equipping vehicles with safety features and incorporating new technologies (e.g., connected and automated vehicles) are some of the strategies that have been suggested to improve traffic safety (Goniewicz et al., 2016). Decreasing traffic volumes and speeds (Ögren et al., 2018), using low-noise tires (Heutschi et al., 2016), electric motors (Tobollik et al., 2016), and quite pavements (Praticò and Anfosso-Lédée, 2012) are some of the strategies that have been suggested to reduce transportation noise emissions. Distancing people further away from noise sources (Moudon, 2009; Ögren et al., 2018), implementing noise barriers including acoustic walls (Moudon, 2009), and increasing vegetation including green walls (Peng et al., 2014; Jang et al., 2015; Khreis et al., 2020) are some of the noise exposure abatement strategies.

4.3. Summary and conclusion

Quantifying the health impacts of transportation may support decision makers, transportation engineers, urban planners, and health practitioners to better account for the health burden from transportation and make more informed decisions to prevent adverse impacts. Transportation impacts on health have been quantified using burden of disease assessment methodology and HIA tools. In this study, we quantified the health impacts of transportation in the form of premature deaths, at the census tract level in the city of Houston, Texas, and compared it with deaths resulting from motor vehicle crashes. The results of this study highlighted a significant role of transportation noise in public health, where the premature deaths attributable to transportation noise was comparable to that due to motor vehicle crash fatalities (302 deaths attributable to transportation noise versus 330 deaths from crashes). Our analysis showed that 2% of all-cause premature deaths (between 30 and 75 years old) in Houston were associated with transportation noise; a burden that is equal to the suicide, influenza, or pneumonia death rate in the US. Deaths attributable to transportation noise were higher for those living in the city's CBD, and in the vicinity of highways and airports. Also, we found that the burden of premature deaths from transportation noise was higher in households with lower income. The findings of this study underline the necessity of imposing policies and implementing efficient urban and transportation designs to mitigate transportation noise emissions and exposures and their adverse health impacts.

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6. Disclaimer

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CRediT authorship contribution statement

Soheil Sohrabi: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing - original draft, Writing - review & editing. **Haneen Khreis:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105520.

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