Burden of Disease from Transportation Noise and Motor Vehicle Crashes: Analysis of Data from Houston, Texas

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Highlights

- In 2016, 302 premature deaths in Houston (adults 30 to 75 years old) were attributable to the transportation noise compared to 345 deaths in motor vehicle crashes.
- 4% of premature mortality in Houston is attributable to transportation noise and motor vehicle crashes.
- Residents of lower economic neighborhoods had the highest risks for adverse exposure and premature death.
- The estimated premature death rate attributable to transportation noise is comparable to the death rate caused by suicide, influenza, or pneumonia in the US.

ABSTRACT

Background: Transportation systems have an essential role in satisfying individuals' needs for mobility. 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 noise as an emerging exposure whose burden of disease remains partially recognized. We compared premature deaths potentially attributable to transportation noise with deaths from motor vehicle crashes, a well-researched and widely recognized transportation risk factor.

Method: We employed a standard burden of disease analysis framework to quantify premature cardiovascular diseases mortality attributable to transportation (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 collected in the study area. We also investigated the distribution of premature mortality burden across the city and explored the relationship between household income and premature mortality attributable to transportation noise.

Results: We estimated 302 (95% CI: 185-427) premature deaths (adults 30 to 75 years old) attributable to transportation noise in Houston, compared to 345 fatalities from motor vehicle crashes. Transportation noise and motor vehicle crashes were responsible for 4% all-cause premature deaths while 2% of all-cause premature deaths are attributable to transportation noise. Households with lower income had a higher risk of adverse exposure and premature death attributable to transportation noise. A larger number of premature deaths was associated with living in the central business district and the vicinity of highways and airport.

Conclusion: This study highlighted the significant contribution of transportation noise and motor vehicle crashes to premature mortality in the city of Houston. The analogy between the estimated premature death attributable to transportation noise and motor vehicle crashes shows that the health impacts of transportation noise were as significant as motor vehicle crashes. The estimated premature death rate attributable to transportation 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 exposures and to equip health impact assessment tools with a noise burden of disease analysis function.

Keywords: Burden of disease; Transportation noise; Premature mortality; Attributable deaths; Motor vehicle crashes

Abbreviations: AEDT, Aviation Environmental Design Tool; CBD, Central Business District; CDC, Centers of Disease Control and Prevention; CI, Confidence Interval; CVD, Cardiovascular Diseases; ERF, Exposure-Response Functions; FAA, Federal Aviation Administration; 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; $PM_{2.5}$, Particulate Matter with a diameter equal or less than 2.5 micrometers; Population Attributable Fraction; RR, Relative Risk; PAF, TNM, Traffic Noise Model; WHO, World Health Organization

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 mortality where traffic emissions alone are responsible for one-fifth of premature deaths attributable to Ozone and Particulate Matter with a diameter equal or less than 2.5 micrometers ($PM_{2.5}$), in the UK, US, and Germany (Lelieveld et al., 2015). Motor vehicle crashes are ranked as the 8th leading cause of death in the world and the leading cause of death amongst those aged 15-29 where, in the year 2016 alone, motor vehicle crashes were responsible for 1.4 million global deaths (World Health Organization, 2018b). Noise pollution is a growing health concern, while road 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 (Khreis et al., 2019).

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), 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 the dialogue with policymakers and other stakeholders, especially when it comes to less acknowledged exposures, such as transportation noise. To facilitate the Health Impact Assessment (HIA) of plans, projects, and policies, several tools have been developed in the literature. These tools allow to quantify the burden of disease attributable to transportation exposures (e.g., Health Economic Assessment Tool (HEAT) by WHO (World Health Organization, 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 mortality. 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 (World Health Organization, 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. Generally, 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 using Exposure-Response Functions (ERF) extracted from the literature (Mueller et al., 2016, Tobías et al., 2015). 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 previous studies, the burden of disease from both ambient environmental noise (Mueller et al., 2016, Mueller et al., 2017, Mueller et al., 2018, Tobías et al., 2015) and transportation noise (Tainio, 2015, Briggs et al., 2015) 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 mortalities (Tobías et al., 2015), premature mortalities (Mueller et al., 2016), disability-adjusted life year (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, Mueller et al., 2017) to city (Stassen et al., 2008, Tainio et al., 2016), national (Hänninen et al., 2014, Briggs et al., 2015, Bhalla et al., 2014) and continental levels (World Health Organization, 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. The finer the spatial resolution of the analysis, the better the insight one can gain into health equity issues and high-risk spots which can be effectively targeted by policies. This study contributes to the literature by specifying the transportation component of the exposure (i.e., using transportation noise as opposed to ambient environmental noise exposure) and estimating the burden of disease attributable to transportation noise and crashes at the census tract level with further analyses by socio-economic status and geography. As a case study, we quantify and analyze the premature mortality attributable to transportation noise (from roads and aviation) and motor vehicle crashes in the city of Houston, Texas; the fourth most populated city in the United States (US).

2 Material 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 2,303,482 residents in 2016 (US Census Bureau, 2016). It 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 twofold. First, some variables (e.g., mortality) were only available at the county level and so approximations are 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. Second, because of limitations in the availability of motor vehicle crashes data and the simplifying assumptions in the crashes spatial analysis (discussed in subsequent sections), the census tract level was selected as the basis of the spatial burden of disease analyses. Consequently, 592 census tracts were included in this study which was fully or partially located within the city's boundaries.

We quantify the health impacts in the form of attributable premature mortality. Premature mortality is 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 mortality in this study.

We estimated the premature mortality attributable to aviation and road noise for the cardiovascular class of diseases. The risk cardiovascular diseases (CVD) mortality in association with transportation noise were estimated using results from an epidemiological study for individuals older than 30 years old (details are provided in subsequent sections). Hereafter, the term premature mortality refers to the death of individuals aged 30 to 75 years old. The motor vehicle crashes deaths had no age assigned to them, and as such, they were all considered premature, and in theory, preventable.

2.2 Input data

The data used in this study were collected from multiple sources–namely, US census bureau, Centers of 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 households' median income in the city of Houston, in 2016, was 60,784 dollars while the lowest and highest household median income at the census tract level were 10,128 and 246,058 dollars, respectively (see Figure S1 for the spatial distribution of the median household income across the city). City of Houston geographical limits was sourced from the city's open data portal which was used to identify the census tracts within the city's boundaries (retrieved from https://cohgis-mycity.opendata.arcgis.com/datasets/houston-city-limit).

2.2.2 Crashes

The motor vehicle crashes fatality data were collected from the Fatality Analysis Reporting System (known as FARS) 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, the information of the physical address of the individuals involved in the crash was not available, nor was the age of the individuals.

To explore the exposure of the city's residents to fatal motor vehicle crashes, we divided the crashes into two groups: local crashes and highway crashes. The motor vehicle crashes were assigned into these two groups based on their locations of occurrence. The highways' map, sourced from the Texas roadway inventory data by Texas Department of Transportation from 2016 (retrieved from https://www.txdot.gov/inside-txdot/division/transportation-planning/roadway-inventory.html), was used to identify crashes located in highways. The fatalities from highway crashes were assigned to the city. The remaining crashes (not included in highway crashes) were assigned to the census tract where they were located and were labeled as local crashes. As such, we assumed that local crashes within a census tract were attributable to residents of that census tracts, and that highway crashes were attributable to individuals living within the city.

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 rate[1] at the county level with 95% Confidence Interval (CI). For quantifying the premature mortality attributable to noise, the number of deaths from CVD for people aged 30 to 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

[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.

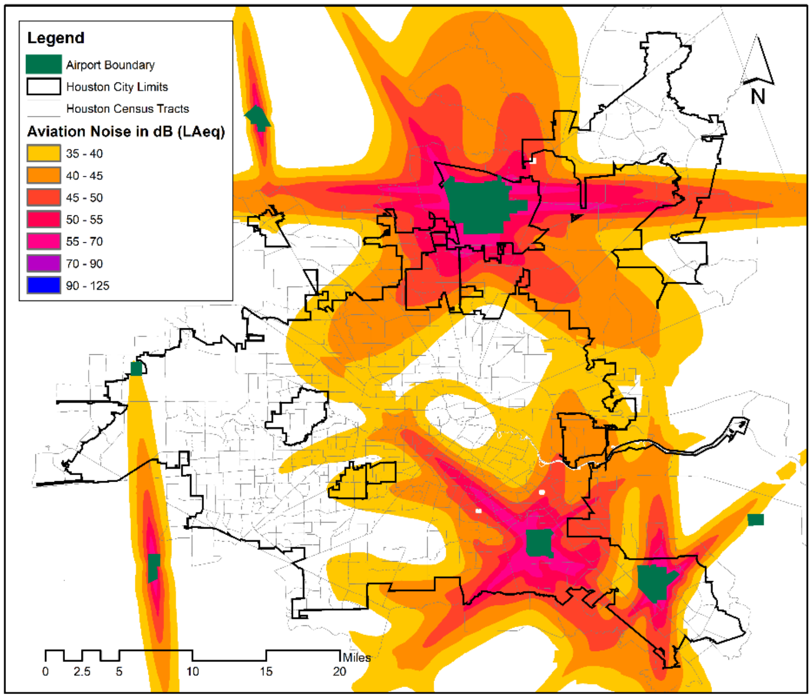
cases (available at the county level) across census tracts proportionally based on their population size. In 2016, a total number of 17,704 all-cause premature deaths were reported in the city of Houston (30 to 75 years old) where 5,384 deaths were caused by CVD, 465 deaths were caused by Heart Failure (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 Tables S1.

2.2.4 Noise

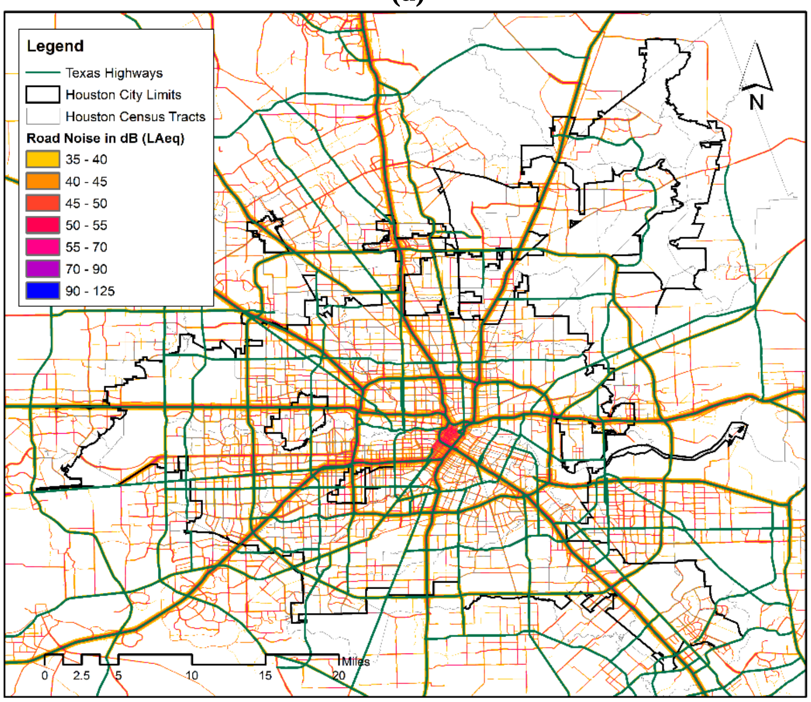
Road traffic and aviation noise data were collected from the National Transportation Noise Mapping Tool (NTNMT) generated by the US Department of Transportation's Bureau of Transportation Statistics (retrieved from http://osav-usdot.opendata.arcgis.com/datasets?q=noise&sort_by=relevance). The noise map 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 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 hours (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 hours of traffic noise at 17 sites verifies the accuracy of TNM where the average difference between predicted and measured sound level is as low as 1.0 dB for all wind condition 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 aircrafts with narrow-body, 6.2 dB difference for two engine aircrafts with narrow-body, 3.3 dB difference for two and three engine aircrafts with wide-body, and 3.4 dB difference for four engine aircrafts 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 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 hours 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 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 Figure 1, the distribution of the averaged daily aviation and road noise across the city of Houston is depicted. The noise map was developed for noise level higher than 35 dB (L_{Aeq}).



(a)



(b)

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

2.3 Burden of disease model

We used a standard burden of disease estimation framework previously developed in the literature (Mueller et al., 2016). This framework is employed to estimate the premature mortalities attributable to transportation noise. In brief, the inputs to the burden of disease 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 exposure level is estimated using ERFs obtained from epidemiological studies. Then, the Population Attributable Fraction (PAF) can be calculated using Equation 1. The PAF represents the ratio of CVD deaths attributable to noise to all CVD deaths for the difference between current noise exposure and the counterfactual exposure level.

$$PAF = \frac{RR_{diff} - 1}{RR_{diff}} \qquad \text{Equation 1}$$

where RR_{diff} is the relative risk of CVD deaths in association with the difference between current transportation noise exposure levels and the counterfactual exposure level. Finally, the attributable mortality is estimated using the mortality rate and population counts for people aged 30 to 75 years old, and the estimated PAF (Equation 2). The motor vehicle crash data, however, translated directly into mortality as these were observations of deaths from crashes. The employed burden of disease estimation framework is presented in Figure 2. This procedure was used for each disease category across each of the 592 census tracts.

$$Attributabl\ Mortality = PAF \times Mortality\ rate\ \times Population\ counts \qquad \text{Equation 2}$$

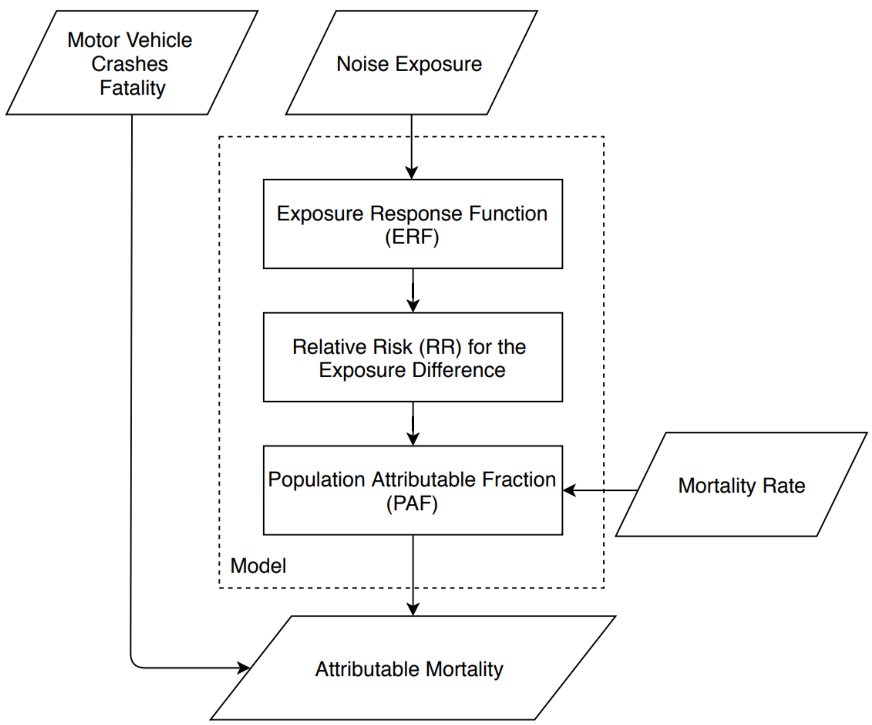


Figure 2. Burden of disease quantification framework

2.3.1 Exposure-response functions

We extracted the ERFs of traffic noise and CVD mortality from published epidemiological studies. The selection of the ERF in this study was based on four criteria. First, the selected study needed to associate the noise with mortality (as opposed to morbidity). Second, the selected ERF should be compatible with the available mortality data and corresponding classification in term of the cause of death, as sourced from the CDC. Third, since we are investigating noise from two transportation sources, road and aviation, studies reporting ERFs for both sources were prioritized. The sample size of the epidemiological study/meta-analysis was the fourth criteria where we preferred the largest sample sized study as we expect a larger sample size to result in more precise ERFs.

Based on these criteria, the ERFs were sourced from an epidemiological study by Héritier et al. (2017) among several epidemiology and meta-analysis studies–namely (Gan et al., 2012, Beelen et al., 2009, Héritier et al., 2017, Halonen et al., 2015, Huss et al., 2010, van Kempen et al., 2018). Héritier et al. (2017) found statistically significant associations between road and aviation noise exposures and CVD mortality using a multi-pollutant model, including linear terms for each noise source. This study was a cohort study conducted in 4.4 million adults (older than 30) in Switzerland, and for exposure levels higher than 35 dB for road noise and 30 dB for aviation noise. The estimated ERFs were 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. The ERF for road noise and CVD mortality was a Hazard Ratio (HR) of 1.025 (95% CI=1.018–1.032) for each 10 dB increase in noise exposure penalized for the evening and nighttime (L_{den}[2]). Respectively, the ERFs for aviation noise and MI and HF mortality 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 found no statistically significant associations between aviation noise and all CVD deaths and as such, we only investigated the burden of HF and MI attributable to aviation noise. These ERFs are reported in Table 1.

2.3.2 Noise exposure calculation and conversion

To assign noise exposure 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 locations of the population within each census tract), and
- the mortality rate was constant within each census tract (the mortality rate available at the county level was assigned to census tracts proportionally based on their population size).

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 Figure 3, the population living in areas A^1_{N35} and A^2_{N35} are exposed to aviation noise levels equal to 35 dB. The population living in the area A^1_{N30}, A^1_{N40} and A^1_{N45} are exposed to 30, 40, and 45 dB aviation noise, respectively. The population exposed to the 35 dB aviation noise can be estimated by:

$$P^{Ci}_{N35} = \frac{\sum_{n=1}^{N} A^n_{N35}}{A_{Ci}} . P^{Ci} \qquad \text{Equation 3}$$

where P^{Ci}_{N35} represents the population at census tract i (C_i) exposed to the noise level 35 dB. A^n_{N35} is the nth area exposed to 35 dB noise 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 Equation 2. 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 (the white areas in Figure 3).

Based on the constant mortality rate within a census tract assumption, the number of deaths can be calculated for each area. Note that, the RR is not consistent across the exposed areas within each census tract (based on differences in noise exposure levels) and therefore, the attributable mortality needs to be

L_{den}[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).

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.

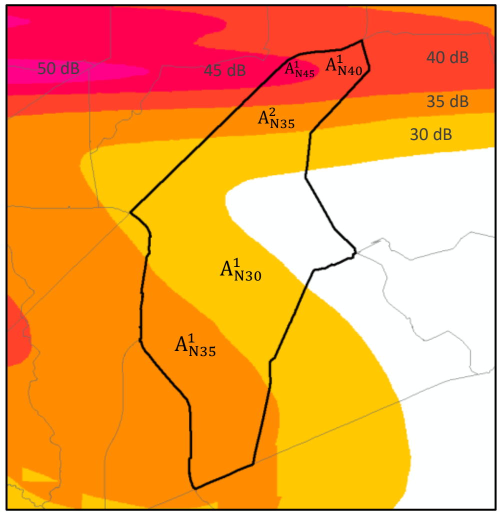


Figure 3. Aviation noise exposure level in a given census tract (Ci)

The NTNMT reports noise exposure with L_{Aeq} measurement. However, the selected ERFs in this study associated CVD mortality with noise measured with L_{den} measurement. We used the suggested conversion guideline between noise indicators proposed by Brink et al. (2018) to convert L_{Aeq} to L_{den}. In this context, the aviation and road noise measured with L_{Aeq} can be converted to L_{den} by:

$$L_{den}^{aviation} = L_{Aeq}^{aviation} + 3.5 \;\; (95\% \text{ CI} = 0.1\text{–}6.9) \qquad \text{Equation 4}$$

$$L_{den}^{road} = L_{Aeq}^{road} + 3.6 \;\; (95\% \text{ CI} = 2.2\text{–}5.0) \qquad \text{Equation 5}$$

2.3.3 Contrafactual scenario

Given that the ERFs were originally estimated for exposures greater than 35 dB for road noise and 30 dB for aviation noise, the counterfactual noise levels were selected accordingly. Therefore, the contrafactual scenario was defined as:

- The daily average of road 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 mortality was estimated for the difference between the current and counterfactual noise level of 35 dB for road noise and 30 dB for aviation noise. In other words, we assume that the population exposed to noise levels less than 35 dB and 30 dB (road and aviation noise, respectively) had no increased risk of death from CVD.

2.4 Sensitivity analysis

Uncertainties are inherited in variables incorporated in burden of disease assessment studies, mainly arising from the 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 the baseline mortality, the ERFs, and the conversion of the noise metrics, we run two uncertainty analysis. 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 variables above (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 (Figure 4). In addition, a sensitivity analysis was run to understand the relation between inputs and output better. We examined the changes in the estimated attributable premature mortality using a 10% marginal change in exposure values of noise, baseline mortality rate, noise conversion, and the ERF.

3 Results

3.1 Premature mortality attributable to noise

Table 1 summarizes the estimated premature mortality attributable to road and aviation noise in the city of Houston. 215 (95% CI: 153-279) premature deaths from CVD for the age group between 30 to 75 years old were attributable to road 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. The spatial distribution of premature deaths attributable to transportation noise is shown in Figure 7 (a), in the form of percentage from all-cause premature mortality. 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 airports and highways. The percentage of premature mortality attributable to transportation noise from all-cause premature mortality was higher than 2% in more than 40% of the census tracts, and this was mainly related to road noise (Figure S2).

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 mortality cases (95% CI)**	**Attributable premature deaths (95% CI)[III]**
Road 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)	1.027 (1.006-1.049)	+3.5 (0.1-6.9)	569 (525-611)	52 (20-96)
			HF (I50)	1.056 (1.028-1.085)		464 (427-504)	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

[III] Refers to the most conservative and extreme estimations

3.1.1 Premature mortality attributable to transportation noise by household income

The relation between median household income at each census tract and the premature mortality burden 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 mortality attributable to transportation noise from all-cause premature mortality (the average line in Figure 4). In other words, it is expected that the ratio of attributable mortality 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 noise exposure sources shows that this relation is mainly from premature mortality attributable to aviation noise. The ratio of premature mortality from aviation noise to all-cause premature 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.

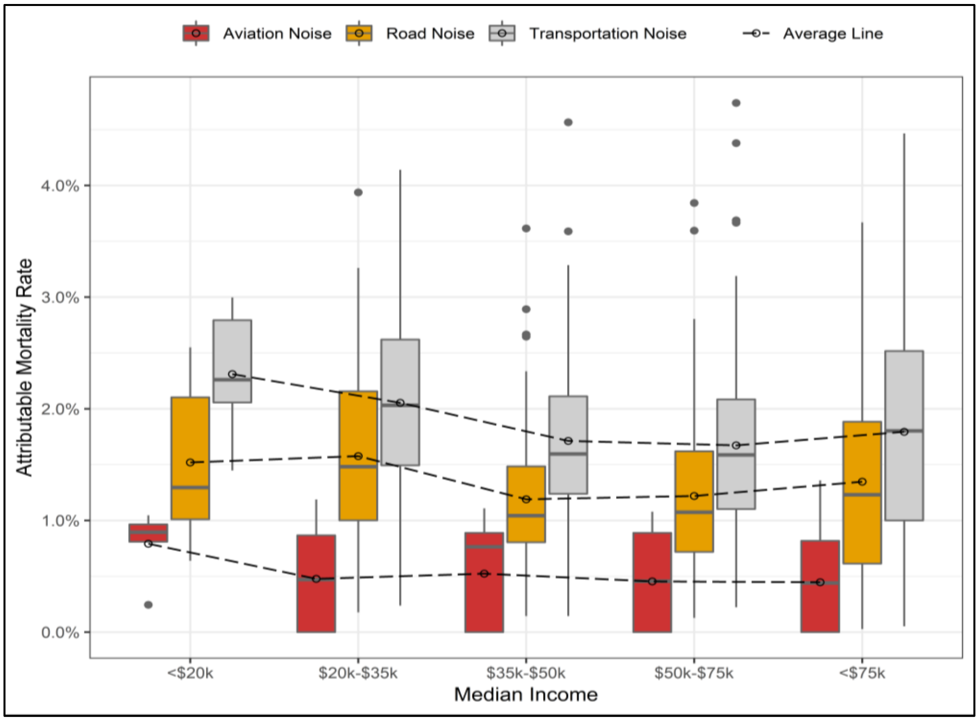


Figure 4. Variation of premature deaths ratio attributable to transportation noise by household median income

3.1.2 Sensitivity analysis

The most conservative estimation of premature mortality attributable to road 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 mortality attributable to aviation noise resulted in 32 and 148 deaths. Overall, the estimated premature mortality attributable to transportation noise in the city of Houston varied between 185 to 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 Figure 5. The uncertainty in the ERFs had the largest role in the results' uncertainty where the estimated attributable premature mortality to aviation and road 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 mortality due to aviation noise. The uncertainty in the noise conversions was up to 6.2% for both road and aviation noise (see Table S2 for more details). Overall, a higher level of uncertainty was associated with premature mortality attributable to aviation noise compared to road noise.

The relation between inputs and outputs of the attributable premature mortality estimation was examined by running a sensitivity analysis to find the marginal effect of inputs. The results of this analysis are depicted in Figure 6 which show 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 2.3% change in the estimated premature attributable mortality associated with a 10% change in the noise conversion variable (see Table S3 for more details).

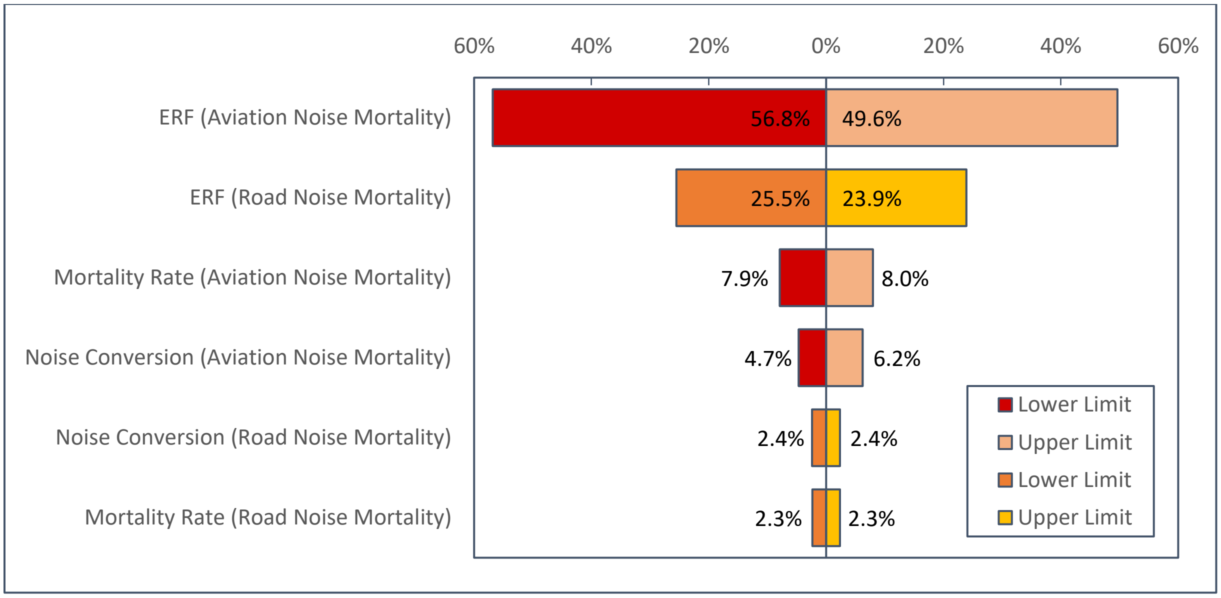


Figure 5. Sensitivity analysis of estimated premature mortality to variables varying from lower and upper 95th CI

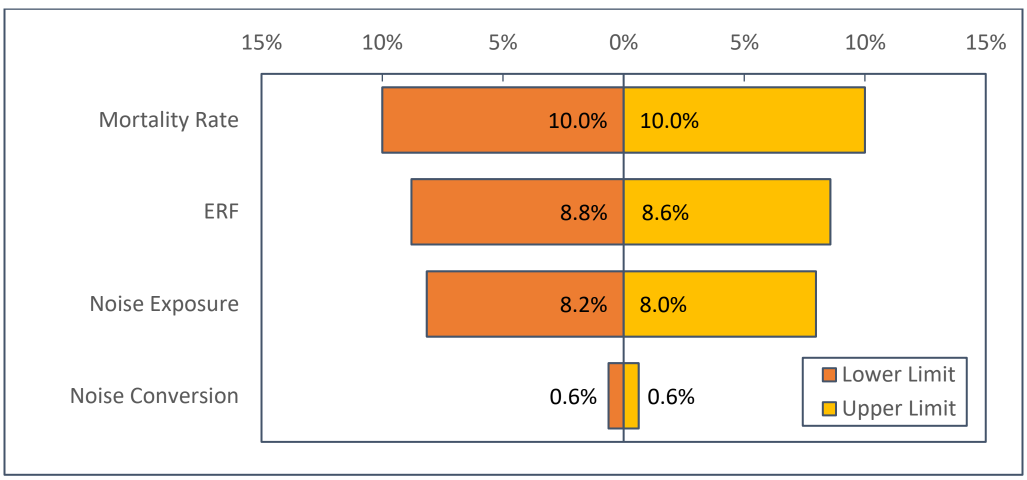
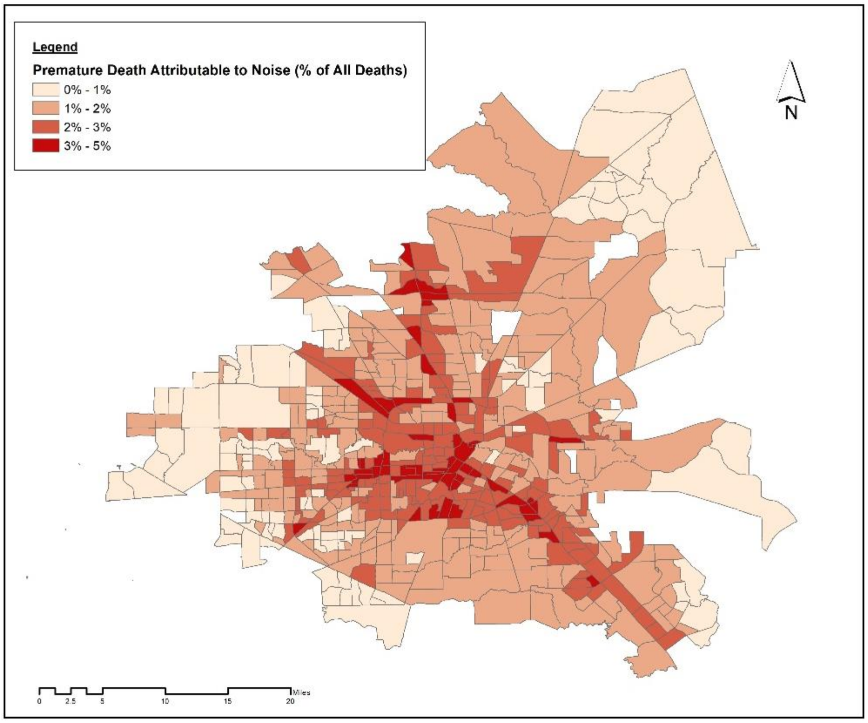


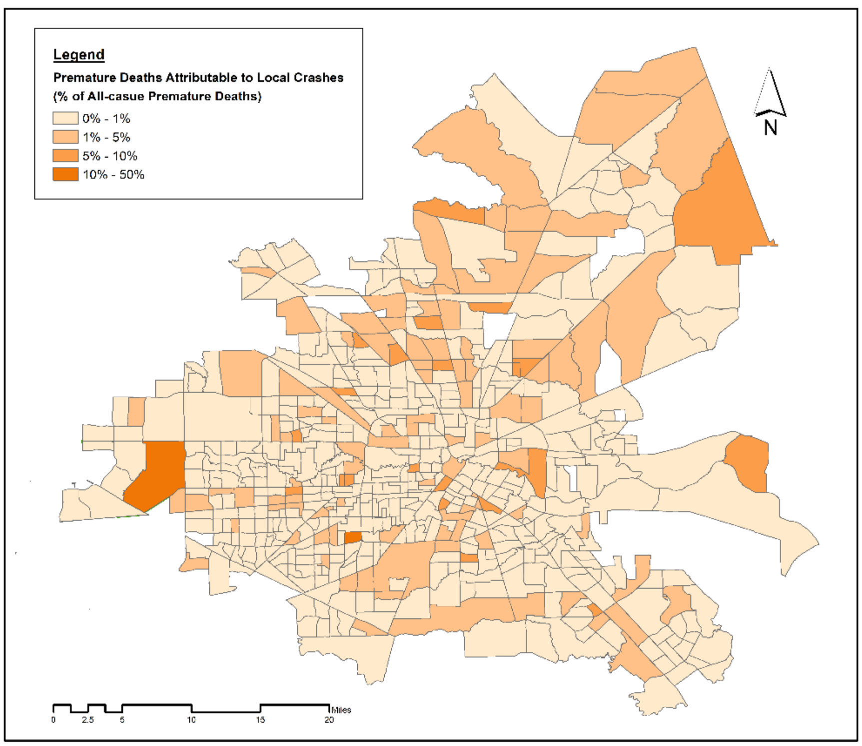
Figure 6. Sensitivity analysis of estimated premature mortality to 10% change in variables

3.2 Premature mortality attributable to crashes

A total number of 345 deaths from motor vehicle crashes were reported in the city in the year 2016. 206 of these deaths occurred on highways and 139 death were considered as local crashes. The distribution of premature mortality attributable to motor vehicle crashes across the city, as the percentage of crash fatalities from all-cause premature mortalities, is shown in Figure 7 (b). From the figure, the ratio of deaths attributable to crashes was higher in suburban areas as opposed to the CBD.



(a)



(b)

Figure 7. (a) Spatial distribution of the ratio of the premature death attributable to noise, and (b) Spatial distribution of the ratio of the premature death attributable to local roadway crashes to all-cause premature deaths

3.3 Overall impacts

Table 2 summarizes the estimated number of premature mortality cases attributable to transportation noise and motor vehicle crashes in the city of Houston in 2016. 644 premature deaths were attributable to transportation noise and crashes. Transportation noise and crashes were responsible for 1.7% and 1.9% of all-cause premature deaths, respectively.

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

Exposure source		Attributable premature mortality (95% CI)	% of all-cause premature deaths[II]
Noise	Aviation	87 (32-148)	0.5%
	Road	215 (153-279)	1.2%
Crash	Highways	206[I]	1.1%
	Local	139[I]	0.8%
Total		644 (528-759)	3.6%

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

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 mortality. The results showed that, in 2016, 302 (95% CI: 185-427) premature deaths were attributable to noise from road traffic and aviation, which accounts for 1.7% of all-cause premature deaths in Houston. 345 deaths from motor vehicle crashes 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 mortality cases attributable to noise were comparable to motor vehicle crash fatalities. Overall, 644 premature deaths per year were attributed to transportation noise and crashes. This can be translated into 4% 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 comparable with the death rate caused by suicide, influenza or pneumonia 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 attributable premature mortality estimates were more sensitive to the following inputs in this order: mortality rate, ERF and noise exposure level. We found that the burden of premature mortality 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 household median income and the ratio of premature deaths attributable to aviation noise, while the relationship with the road and total transportation noise were more complex. The findings of this study not only can directly provide decision makers and engineers with more detailed information about the health outcome attributable to transportation noise and crashes but can also be implemented to update existing or new HIA tools.

4.1 Strengths and limitations

In this study, we used transportation noise, as opposed to ambient environmental noise estimates (Mueller et al., 2016, Mueller et al., 2017), to specifically quantify the potential contribution of transportation noise to premature mortality. As a result, 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. We estimated the exposed population, and their transportation noise exposure levels, separately for different noise levels within each census tract, instead of averaging the noise exposures at the level of the census tract and assigning that exposure estimate to the whole tract population, as is usually practiced (Mueller et al., 2016). This may result in a more accurate estimation of the attributable mortality since the magnitude of RR is dependent on the level of exposure. The deaths from motor vehicle crashes were compared with the deaths attributable to transportation noise at the census tract level to investigate the spatial variation of health impacts related to different transportation risk factors. We showed clear differences in the locations most sensitive to transportation noise versus those most sensitive to motor vehicle crashes. The mortality attributable to transportation noise by household income was analyzed and the results were in agreement with the burden of childhood asthma attributable to air pollution by median household income in the US (Alotaibi et al., 2019).

This study has certain limitations which are mainly related to the input data. The health impacts of noise are mainly discussed through CVD (Mueller et al., 2017) and so this study focused on estimating CVD premature deaths attributable to transportation noise. 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 may, therefore, result in underestimating the impacts of transportation noise in Houston. We also assumed that the victims of motor vehicle crashes were younger than 75 years old, as the age of individuals involved in the fatal crashes was not available, and as such the deaths attributable to motor vehicle crashes were considered as premature mortality only for comparison purposes. This assumption may conclude in a higher number of premature mortality cases from crashes. 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 for 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 the acoustically hard ground (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. The ERFs selected for the burden of disease analysis were estimated for road noise exposures above 35 dB and aviation noise exposures above 30 dB. Likewise, the NTNMT model only predicted noise exposure levels above 35 dB L_{Aeq}. Therefore, the estimated premature mortality is attributable to noise exposures above 30 dB and 35 dB for road and aviation noise, respectively. Eliminating a lower level of noise may result in underestimating the attributable premature mortality in the city of Houston.

4.2 Research and policy recommendations

The estimated premature deaths can be considered preventable by enacting policies and implementing efficient urban and transportation designs to improve traffic safety and control noise emissions and exposures. Decreasing traffic flow, 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). Reducing 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 in cities. Distancing people from noise sources (Moudon, 2009, Ögren et al., 2018), implementing noise barriers including acoustic walls (Moudon, 2009), and increasing vegetation (Peng et al., 2014, Jang et al., 2015) are some of the noise exposure abatement strategies.

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 mortality burden, we suggest equipping HIA tools with a noise burden of disease analysis function.

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 avoid, or mitigate, adverse impacts. Transportation impacts on health have been quantified through various burden of disease assessment studies and HIA tools. In this study, we quantified the health impacts of transportation noise and motor vehicle crashes in the form of premature mortality, at the census tract level in the city of Houston, Texas. The results of this study highlighted a significant role of transportation noise in public health, where the premature mortality attributable to transportation noise was comparable to that due to motor vehicle crash fatalities (302 deaths attributable to transportation noise versus 345 deaths from crashes). Our analysis showed that 2% of all-cause premature deaths in Houston (between 30 to 75 years old) 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 in those living in the city's CBD, and in the vicinity of highways and airports. Also, we found that premature mortality attributable to aviation 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 that prevent, and mitigate, these adverse health impacts.

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Competing financial interests

The authors declare they have no competing interests.

Appendix. Supplementary material

See the below tables/figures.

Table S1. Summary statistics of the data and estimated results at the census tract level

Variable	Sample Size (# of Census Tracts)	Min	Median	Mean	Max
All-cause Premature Mortality (persons)	592	0.198	27.109	29.390	134.650
CVD[1] Premature Mortality (persons)	592	0.062	9.095	10.689	78.001
MI[2] Premature Mortality (persons)	592	0.006	0.978	1.194	15.039
HF[3] Premature Mortality (persons)	592	0.005	0.799	0.986	8.701
Aviation Noise Premature Mortality Ratio	398	0.0%	0.6%	0.5%	1.4%
Road Noise Premature Mortality Ratio	592	0.0%	1.2%	1.3%	3.9%
Transportation Noise Premature Mortality Ratio	592	0.1%	1.7%	1.8%	4.7%
Crash Fatality Ratio	119	0.0%	0.0%	0.9%	59.9%
Median Income (dollar)	592	10,128	48,587	60,784	246,058

[1] CVD: Cardiovascular Disease
[2] MI: Myocardial Infarction
[3] HF: Heart Failure

Table S2. Sensitivity analysis of variables varying from 5th to 95th CI

Source	Variable	Estimated mortality	Lower limit	Difference from central estimate	Upper limit	Difference from central estimate
Road Noise	Mortality rate	215	210	5	220	5
	Noise Conversion	215	210	5	220	5
	ERF	215	160	55	266	51
Aviation Noise	Mortality rate	87	80	7	93	7
	Noise Conversion	87	82	4	92	5
	ERF	87	37	49	129	43

Tables S3. Sensitivity analysis of 10% change in variables

Variable	Estimated mortality	Lower limit	Difference from central estimate	Upper limit	Difference from central estimate
Noise Exposure	302	277	25	325	23
Mortality Rate	302	271	31	331	29
Noise Conversion	302	299	3	303	1
ERF	302	275	27	327	25

Tables S4. Variation of ratio of premature mortality attributable to transportation noise by household income

Median Income Groups	Transportation Noise	Road Noise	Aviation Noise
<$20k	2.3%	1.5%	0.8%
$20k - $35k	2.1%	1.6%	0.5%
$35k - $50k	1.7%	1.2%	0.5%
$50k - $75k	1.7%	1.2%	0.5%
$75k<	1.8%	1.3%	0.4%

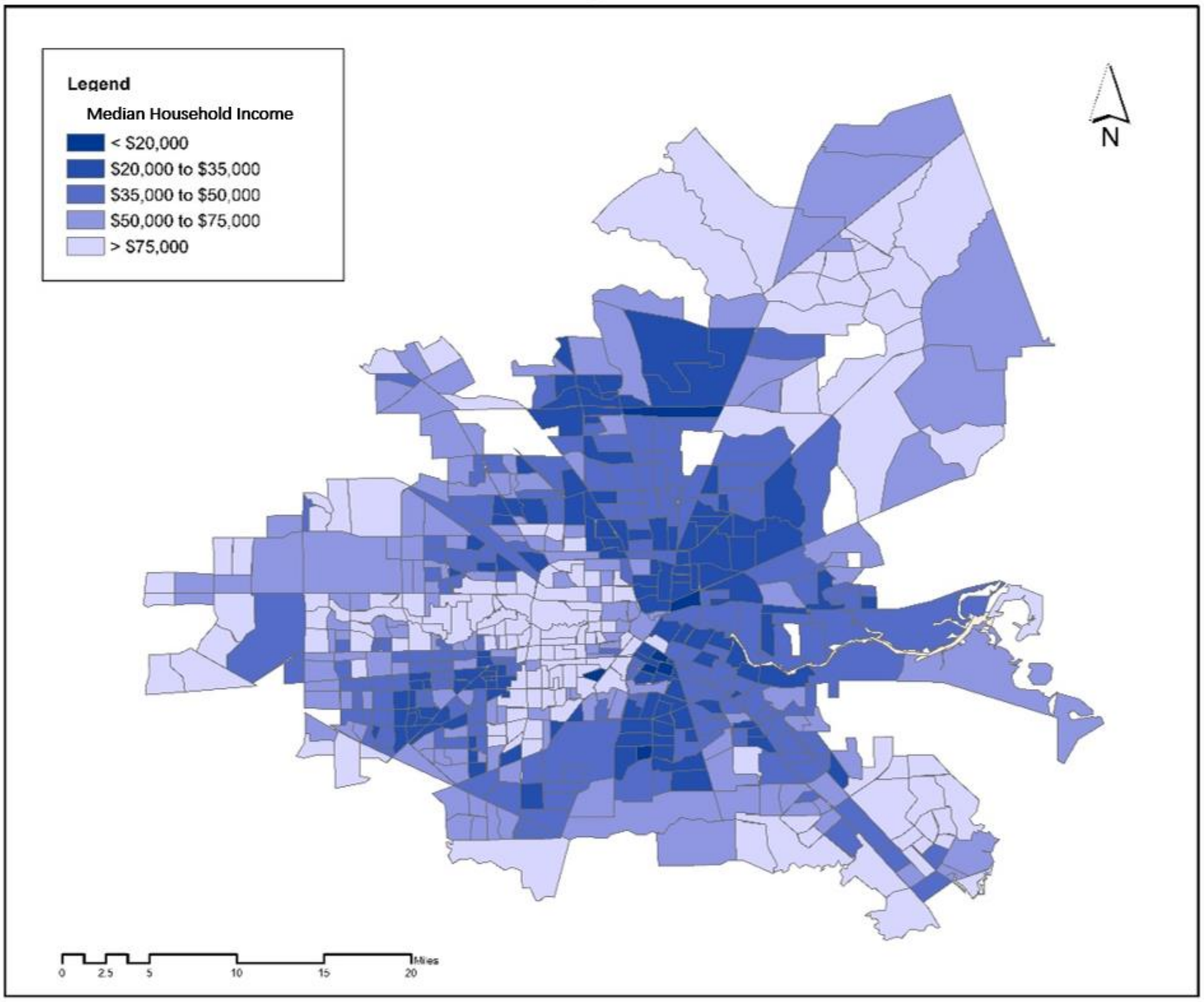

Figure S1. Spatial distribution of median household income at the census tract level

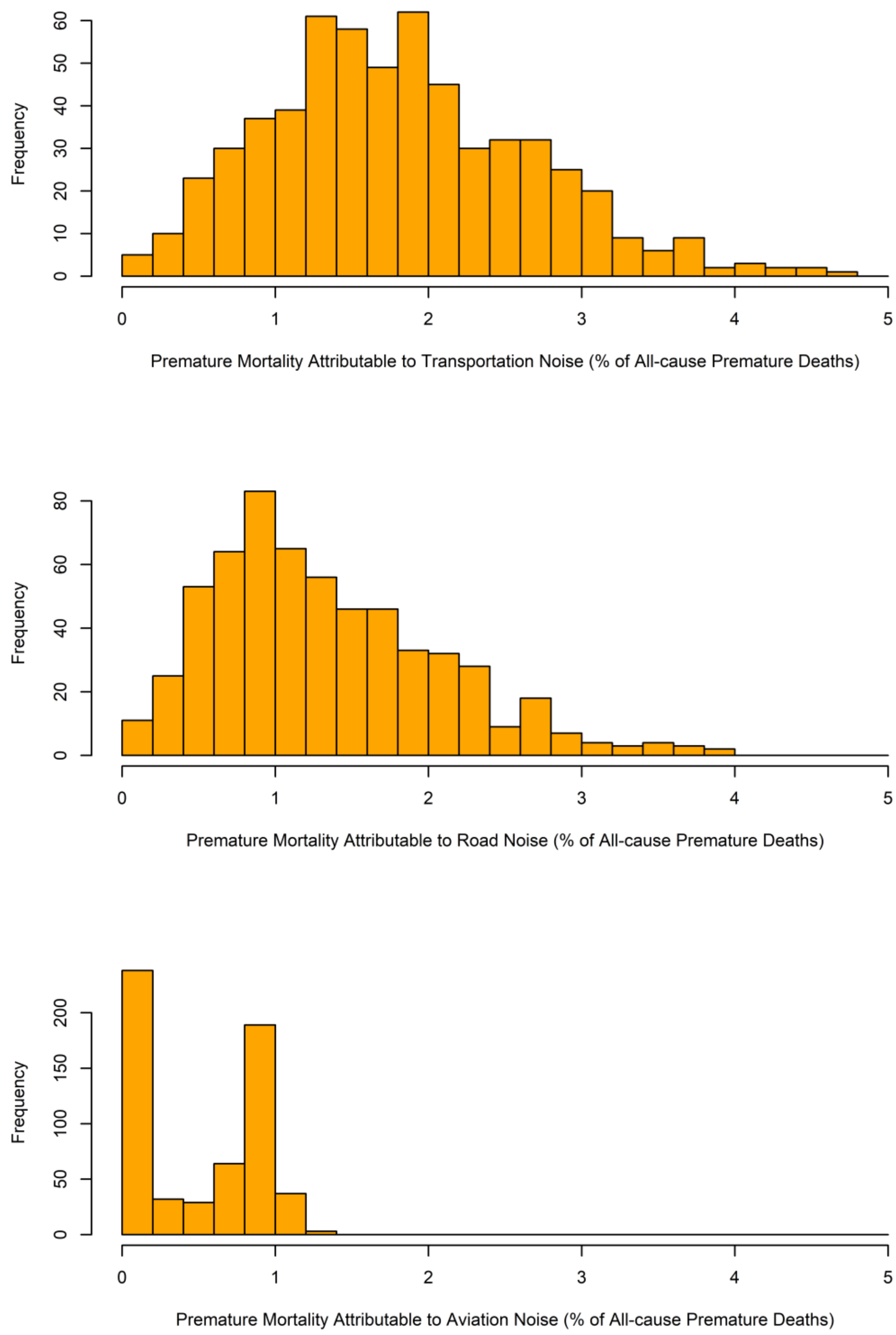

Figure S2. Distribution of ratio of premature mortality attributable to noise from all-cause premature deaths across 592 census tracts

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