Environmental Research 167 (2018) 499–505

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

System dynamics for predicting the impact of traffic noise on cardiovascular mortality in Madrid

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ARTICLE INFO

Keywords:
Noise abatement
Traffic intensity
Cardiovascular health
System dynamics
Forecasting

ABSTRACT

The impact of road traffic noise on health is an important issue worldwide. In Madrid (Spain), the existing high daily noise levels all year round have been associated with short-term cardiovascular mortality. A system dynamics model is constructed to estimate the evolution of the traffic noise impact on the population older than 65 in Madrid over the upcoming years. This strategy allows to make predictions based on yearly variations in traffic intensity, population at risk, motor vehicle-related technological advances and lifestyles, and urban planning policies. Madrid harbours a persisting noise epidemic since 1980, which would be eradicated in 2040 at the earliest if significant action for noise abatement were taken.

1. Introduction

The impact of urban noise is an important public health issue, owing to the growth of cities and the increasing number of exposed persons worldwide (Recio et al., 2017). The health protection values of 65 dBA-daytime and 55 dBA-nighttime are often exceeded in a number of European cities, and 30% of the population are at risk of noise-induced adverse health outcomes (WHO, 2011). Long- and short-term exposure to road traffic noise have long been associated with increased cardiovascular morbidity (Banerjee et al., 2014; Argalášová-Sobotová et al., 2013; Sørensen et al., 2014; Carmona et al., 2017). In Europe, a 10-dBA increment in mean noise levels is associated with an 8% increased incidence of ischemic heart disease (Kempen et al., 2018). Moreover, in this region, road traffic noise is attributed a loss of 400–1500 healthy life years per million people due to ischemic heart disease (Hänninen et al., 2014).

As regards mortality, the risk of death from myocardial infarction in the long-term increases ~4% per a 10-dBA increase in mean noise levels (Héritier et al., 2017); for those over 65 years of age, the increased risk rises to 10% (Gan et al., 2012). In the short-term, the increased risk of death from myocardial infarction and stroke in the over-65 age group is ~3% per a 1-dBA increase in the equivalent noise levels of the night before, with no substantial change after adjustment for air pollutants (Recio et al., 2016).

The city of Madrid (Spain) features considerably high noise levels all year round, which makes it suitable for the study of the adverse effects of urban noise on health (Recio et al., 2016). Indeed, in the period 2003–2009, nocturnal noise levels were above 60 dBA on average, and it was estimated that nearly 200 annual deaths from cardiovascular causes in the population over 65 years would have been avoided if such mean noise levels had been 1 dBA lower (Recio et al., 2017).

Based on the above results from recent time-series studies conducted in Madrid, we further aimed to estimate the evolution of the road traffic noise impact over time. For this purpose, we chose a system dynamics approach. Systemic analysis is a method widely used in forecasting, resource allocation, and public health management studies focused on topics such as health care planning, transmissible diseases, and chronic illness (Homer and Hirsch, 2006; Yu et al., 2018; De Silva, 2017; Sharareh et al., 2016; Tomaskova et al., 2016).

In this study, the epidemic behaviour of environmental noise effects on the population over 65 years of age in the city of Madrid is examined, through its short-term association with mortality from cardiovascular causes, by means of a system dynamics model. This analysis was conducted only for the over-65 age group and cardiovascular mortality, since risk associations for this population group and such a death cause are strongest and well established. With the help of systemic modelling, we also aimed to forecast the repercussion of a hypothetical shift in the type of automobiles used by Madrid citizens: from traditional combustion automobiles to modern electric vehicles.

Abbreviations: Leq. 24 h, 24-h equivalent noise level; Leqd, diurnal equivalent noise level

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https://doi.org/10.1016/j.envres.2018.07.021
Received 3 May 2018; Received in revised form 16 June 2018; Accepted 12 July 2018
0013-9351/

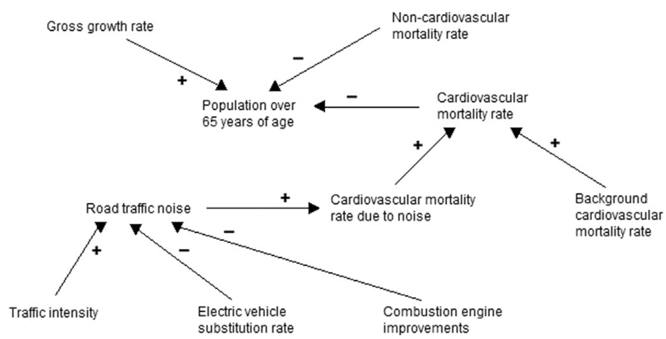

Fig. 1. Causal diagram for the urban noise impact on cardiovascular mortality.

2. Methodology

2.1. Model construction

In order to simulate the impact of traffic noise over time, a dynamic model was constructed (Barber and López-Valcárcel, 2010; Sharareh et al., 2016). First we defined the relationships between the distinct elements of the model in a causal diagram (Fig. 1). The model contains one main stock variable: the stock of people older than 65 in the city of Madrid at time *t*. This is a dynamic variable whose value is the net accumulation of two flows: an inflow of the gross growth of the population over 65 years of age at a given time, and an outflow of the overall mortality for this population, or number of deaths in the same period.

Both inflow and outflow are flow variables determined by certain parameters or constants and by other auxiliary dynamic variables. In our case, the inflow is determined by the over-65 population growth rate, that we consider constant over the study period. Since we are concerned with cardiovascular (CV) mortality, only deaths from CV causes were considered, discarding from the model the outflow due to other death causes –which had to be subtracted from the inflow such that the net flow produced the actual population for every time interval–. Further, total CV deaths were split into two branches: background CV deaths and CV deaths due to noise; the former being determined by a constant parameter (background CV mortality rate), while the latter depends on an auxiliary variable (CV mortality rate attributed to noise). Since noise levels change over time as a function of various dynamic parameters, CV mortality rate attributed to noise for a time-period *t* depends on another auxiliary variable: the average 24-h equivalent noise level (Leq. 24 h) for that period, which in turn depends on another stock variable: traffic intensity.

Causal relationships between variables can be either positive or negative, as shown in the causal diagram (Fig. 1). Positive links indicate an influence in the same direction, whereas negative links indicate an influence in the opposite direction. Thus, opposed to the gross growth of the population older than 65 is the number of deaths from CV causes –among others–, and this number increases when noise levels rise; further, noise levels rise when so does traffic intensity, but decrease with the advent of combustion engine improvements and the gradual substitution of traditional automobiles by electric vehicles. There are no loops in our causal diagram, for we considered that the increase in the over-65 population did not significantly contribute to the increase in road traffic volume. Last, traffic intensity was mathematically modelled to accommodate the observed values for the period 2003–2009.

Table 1 summarizes the main variables of the dynamic system. Considering all relevant variables and constant parameters, we obtained the stock and flow model of Fig. 2. In this diagram, the bottom part shows the process of generation of urban noise levels with potential adverse effects on CV health, while the top part presents the dynamics of road traffic noise impact on the study population.

2.2. Population growth

Data for the population older than 65 with residence in the municipality of Madrid between 1996 and 2013 were supplied by the INE (National Statistics Institute/*Instituto Nacional de Estadística*). For that period, assuming that the population underwent the typical exponential increase, net growth rate was estimated as follows. In 17 years, the study population increased by a factor of

$$\frac{\mathrm{Pop}(2013)}{\mathrm{Pop}(1996)} = \frac{631,\,900}{516,\,300} = 1.2239$$

Then, for each year of the period, the growth factor was

$$\textit{Annual growth factor} = \sqrt{1.2239} = 1.012$$

Each year the population multiplies by 1.012, which means a 1.2% increase:

$\textit{Net growth rate} = 0.012\ \mathrm{year}^{-1}$

Thus, for any year *t* the population older than 65 in Madrid was estimated as

$$\textit{Population}\,(t) = 516,\,300 \times 1.012^{t-1996}$$

This estimate provides reliable figures for the years next to the period 1996–2013, but as we set farther the rate value or the trend itself may undergo variations. However, in our simulation we considered the net growth rate constant since 1920, when the number of automobiles in Madrid exceeded 1000 units.

The over-65 population net growth rate is the gross growth rate minus the overall mortality rate with respect to this population. Additionally, the overall mortality rate is the CV mortality rate plus the non-CV mortality rate. Since we want to disregard the non-CV deaths from the outset, the growth rate chosen as the input (i.e. inflow) for our model must be the gross growth rate minus the non-CV mortality rate, such that

Table 1
Main variables of the model.

Variable	Definition	Value	Type–units
Population over 65 years of age(t)	Mean population aged 65 years and older in the city of Madrid in year *t*	___	Stock–persons
Traffic intensity(t)	Average traffic volume (per day) in year *t*	___	Stock–motor vehicles (modelled)
Population growth(t)	Incoming population aged 65 minus deaths from non-cardiovascular causes in those over 65, per year	___	Flow–persons year^{-1}
Background cardiovascular deaths(t)	Deaths from cardiovascular causes not attributed to noise per year	___	Flow–persons year^{-1}
Cardiovascular deaths due to noise(t)	Deaths from cardiovascular causes attributed to noise per year	___	Flow–persons year^{-1}
Growth rate	Proportion of incoming population aged 65 minus deaths from non-cardiovascular causes in those over 65, per year	0.0221	Constant–year^{-1}
Background cardiovascular mortality rate	Proportion of deaths from cardiovascular causes not attributed to noise per year	0.0087	Constant–year^{-1}
RR	Relative risk for a 1-dBA increase in mean daily (24-h equivalent) noise levels	1.033	Constant–No units
Cardiovascular mortality rate due to noise	Proportion of deaths from cardiovascular causes attributed to noise per year	___	Auxiliary–year^{-1}
Leq. 24 h(t)	Mean daily (24-h equivalent) noise level in year *t*	___	Auxiliary–dBA