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Article in Transportation Research Part D Transport and Environment - January 2022
DOI: 10.1016/j.trd.2021.103114

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From strategic noise maps to receiver-centric noise exposure sensitivity mapping

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A R T I C L E I N F O

Keywords:
Noise mapping
Road traffic noise
Population exposure
Road network sensitivity

A B S T R A C T

Road traffic is a major source of environmental noise pollution in urban areas. While strategic noise maps are widely used to identify the critical areas and propose mitigation plans, more specific tools are needed to evaluate the impact from traffic noise such as overall population exposure or anticipated impact from specific vehicles in varying spatiotemporal traffic conditions.

The present contribution proposes a receiver-centric mapping approach, introducing “noise-exposure sensitivity maps”, meant to assess the potential noise exposure impact from a specific vehicle in a given network, quantifying the associated exceedance over the prevailing background noise, under varying spatiotemporal traffic conditions. The resulting maps are thus focused on a representation of the receiver exposure as opposed to considering the noise emission and propagation alone.

The complete methodology, its underlying assumptions, and possible applications such as route optimisation are demonstrated on realistic scenarios.

1. Introduction

Environmental noise has been regarded for decades as a cause of public health concern (of the European Communities, 1996). Its negative impact as an environmental stressor in Europe is increasing in dominance (Organization et al., 2011) with road traffic noise considered as the main contributor (Agency, 2014), therefore remaining today a very active area of research.

As a milestone effort to address this increasing concern, the European Noise Directive (END) of 2002 (Directive, 2002) required European Union Member States to calculate strategic noise maps every five years in order to assess and accordingly plan noise mitigation strategies. These strategic noise maps, though a positive step towards noise pollution control, have several limitations in part associated with their static and source-centric modelling approach. The assumption of traffic noise to be considered as a static source undermines its temporal features. However, noise annoyance from transportation noise has been found to be dependent on these very features (Roberts et al., 2003; De Coensel et al., 2009; Wunderli et al., 2016). Furthermore, contemporary noise mapping methodology is centred around the noise sources, even though the receivers are the intended beneficiaries. The present original article aims at contributing to this issue with a method allowing to generate so-called “noise-exposure sensitivity maps”, which

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https://doi.org/10.1016/j.trd.2021.103114
Received 30 July 2021; Received in revised form 1 October 2021; Accepted 4 November 2021
Available online 1 December 2021
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enable a receiver-centric evaluation of traffic noise exposure from a vehicle of interest while taking into account the spatiotemporal distribution of traffic.

The END’s strategic noise maps were initially calculated using different standardised methods such as HARMONOISE (Vos et al., 2005), NMPB (Besnard et al., 2009) and NORD2000 (Kragh et al., 2001); after the update to Annex II of END (Directive, 2015), a common assessment methodology – CNOSSOS-EU (Kephalopoulos et al., 2012) – was established and its use was encouraged for the subsequent rounds of noise map calculations, becoming mandatory from 2022.

As per the requirement in Annex IV of the END (Directive, 2002), the estimation of the number of people exposed to noise requires considering spatially distributed population data. The extent of population exposure evaluation is however limited by the spatial resolution of the available population data. In the case when only region- or block-level population data is available, post processing with additional details such as building information (Kephalopoulos et al., 2012) or land-type classification (Wang et al., 2018) increases the scope of exposure estimation. The availability of high-resolution population data (Gulliver et al., 2015) or its allocation through trained population models (Cai et al., 2019) allows for a micro-scale exposure assessment (Cai et al., 2019).

The building-level population distribution then needs to be further allocated to receiver points around its façades. Different allocation strategies (der Belastetenzahlen, 2007; Arana et al., 2009; Kephalopoulos et al., 2012) have been comparatively tested. Each approach is concluded to be most relevant in order to capture a particular aspect of noise exposure (Licitra et al., 2010, 2017) and the choice of exposure estimation method is found to be crucial to the outcome of the evaluation (Murphy and Douglas, 2018). As an improvement to exposure assessment, several contributions propose to incorporate dynamics in population distribution (Kaddoura et al., 2017; Ganić et al., 2018; Le Bescond et al., 2021), leading to refinements in the assessment of individual noise exposure (Le Bescond et al., 2021) and policy-making (Kaddoura and Nagel, 2018).

Regarding the temporal aspects of noise exposure assessment, the END strategic noise maps are based on averaged noise indicators such as $L_{DEN}$ and $L_{night}$. While these have been useful to assess the overall noise exposure in the population (Arana et al., 2009; Murphy and King, 2011; Eriksson et al., 2013), they do not take into consideration short-term transients in the sound environment. The efforts made by the community to evaluate noise impact from temporal variations of traffic noise gave rise to several initiatives to shift towards dynamic noise mapping (Szczodrak et al., 2014; Wei et al., 2016; Zambon et al., 2017; Lan et al., 2020; Lan and Cai, 2021; Le Bescond et al., 2021). This involves generating multiple noise maps across the day thus capturing the intraday variations in noise emission levels. Most of these approaches begin with a baseline noise map and use temporal data such as noise measurements, traffic flow rates and traffic speed in order to update the map. The temporal resolution gained in noise exposure evaluation is found to provide noise exposure information beyond the capabilities of static strategic noise maps (Chevallier et al., 2009; Can et al., 2010; Estévez-Mauriz and Forssén, 2018; Benocci et al., 2019; Yang et al., 2020). The increase in time granularity comes at the expense of more computationally costly approaches, which generally require efficient computational methods, especially when large areas and dynamic mapping with short time-steps are considered. Tabulating the noise attenuation between static sources and receiver positions, stored in the form of a noise attenuation matrix evaluated once in a pre-processing step, has thus been introduced as one of such strategies to reduce the computational burden of dynamic assessment (Wei et al., 2016; Cai et al., 2016; Lan et al., 2020).

Strategic noise mapping as per the END (Directive, 2002) requires estimating both the noise levels and the distribution of exposed people/dwellings under a chosen noise indicator. These two outputs of the assessment, though based on the same underlying noise calculations, are generally treated as independent objectives delivered in the form of cartographic maps and tabulated data, respectively. Combining the data from environmental noise levels and population exposure to represent it within a single cartographic data set can enable a direct evaluation of trajectories for population exposure. This has been developed for aircraft noise in the form of multi-objective aircraft trajectory optimisation (Wijnen and Visser, 2003; Visser, 2005; Zachary et al., 2010; Prats et al., 2011; Ho-Huu et al., 2019), but due to the 3-dimensional and floating boundaries for aircraft vehicles, the optimisation of routes and visualisation of population exposure maps is not straightforward. The same principle applied to road vehicles would offer more benefits due to the 2-dimensional and fixed road network, but it has not yet been implemented to the best of the authors’ knowledge.

The present contribution aims at filling this gap by proposing a methodology towards noise-exposure assessment which includes spatiotemporal variations and has a direct connection to actual population distribution and exposure. Thereby, given established traffic configurations, the proposed noise mapping enables making an efficient, early evaluation of the impact associated with the introduction of additional vehicles in the road network. The resulting map, offering a visual rendering of susceptibility to negatively affect the population’s exposure to noise, further enables the methodology to provide an early qualitative assessment of spatiotemporal routing possibilities. With the conventional noise maps as a starting point, the mapping methodology proposed here introduces “noise-exposure sensitivity maps”, particularly focusing on the noise exposure of the population rather than environmental noise levels alone, using early impact indicators.

In a first section, the methodological aspects of the approach are detailed, with a particular focus on the input data and the steps involved. Then, the methodology is applied to the cities of Stockholm and Munich in a set of qualitative scenario comparisons as well as a realistic routing problem. Finally, the resulting maps and sensitivity evaluations are discussed and put in perspective with the methodological assumptions and chosen indicators.

2. Methodological aspects

The approach proposed aims at establishing noise maps centred on the impact in terms of expected exposure levels on the population. It involves considering the noise emissions associated with single vehicles, assuming surrounding noise levels to be
primarily dependent on the traffic conditions, and evaluating the impact of the chosen vehicle in terms of the exposure to noise levels exceeding those of the surrounding traffic conditions. In this sense, the generated maps are here referred to as “noise-exposure sensitivity maps”, reflecting an evaluation of the impact related to the addition of a single vehicle in time- and space-specific traffic conditions.

The resulting mapping tool may open for an early comparison of how driving noise emissions from single vehicles may impact the population in urban environments, considering multiple scenarios. These scenarios are dependent on a set of parameters considered to be highly influential in the proposed approach. An overview of the approach is plotted in Fig. 1, with a selection of the influential parameters chosen among the following:

- time of day, e.g. peak hour, nighttime, specific time;
- vehicle route, including speed limitations;
- vehicle noise emission model, associated with a selection of vehicle categories.

2.1. Modelling and input data

Traffic noise modelling consists in the simulation of traffic noise emission and propagation in a given area. The two main steps of such modelling thus consist in the prediction of the vehicle emission levels, and the associated propagation in the area of study, dependent on the layout of the area (buildings, forests...).

In the present contribution, the CNOSSOS-EU framework (Kephalopoulos et al., 2012) is used for both noise emission and propagation models, though the methodology is not limited to this framework. For the traffic noise modelling, an open-source noise mapping tool – NoiseModelling (Bocher et al., 2019) – is chosen, which at the time of simulation is almost compliant with the CNOSSOS-EU standard method (Kephalopoulos et al., 2012). These simulations rely on the following set of inputs: noise sources (position and emission model), the layout of the area of interest (buildings, parks...) and receivers, i.e. locations of interest where the noise levels are calculated.

The receivers may be defined in several ways depending on the objective: as a regular grid of points when assessing the distribution of noise levels, or as points distributed around the perimeter of buildings when assessing population exposure. For the proposed methodology, the latter option is adopted, as it offers a consistent way of aggregating a number of citizens to each receiver point, in connection with their building of residence.

The literature shows that while the choice of receiver placement is crucial for the final outcome (Murphy and Douglas, 2018; Licitra et al., 2010), there are many approaches (Directive, 2002; Group et al., 2006; Furst and Saurat, 2006; Gulliver et al., 2015) which differ in relation with the height of the receiver, distance from the façade and criteria for including a façade in the evaluation. In view of this, since the presented approach is not limited to a particular choice of receiver positions, a distribution that reasonably captures the noise exposure at the different façades of the buildings while reducing computational burden is chosen. The distribution of receiver points is inspired by the alternative approach suggested in CNOSSOS-EU (Kephalopoulos et al., 2012) and is performed according to the following general pattern: an initial façade receiver point is randomly positioned half a metre from an edge of the...
building, subsequently placing the additional receiver points along the edges of the building with a 50-metre separation distance until all edges have been covered. A typical distribution of receiver points around buildings is illustrated in Fig. 2. In the case study considered here, this allocation appears to provide a reasonable trade-off, adequately capturing the noise emitted by vehicles, as it results in at least one receiver point being placed on the façade most exposed to traffic noise for the vast majority of buildings. Many other distributions of receiver points on façades are possible depending on the aim of the mapping; the proposed methodology is considered to be equally applicable for a wide range of these alternative allocation strategies.

In the following sections, key input data are detailed further.

2.1.1. Geographical data

Multiple categories of geographical data describing the area of interest are necessary in order to model the propagation of noise. This data is stored in the shapefile data format, suited to be processed using a Geographic Information System (GIS) application.

The first category of geographical data of interest is the physical layout of the area, which includes:

- the road network;
- buildings, as two-dimensional shapes with the height of each building as an attribute;
- green areas, including parks and forests, i.e. spaces with high sound absorption properties.

The second category of necessary geographical data is population data. It should be as spatially detailed as possible, ideally distributed at the level of each building (Kephalopoulos et al., 2012). In this contribution, population is added as an attribute of each building. As a reasonable approximation, the population of a building is equally distributed among all of the receiver points associated with its façades. This population distribution serves as a basis for the estimation of noise exposure. In case the population distribution is not available on a per-building level but rather on a block level, the population may be distributed in a way compliant with the CNOSSOS-EU recommendations.

2.1.2. Reference traffic-related noise levels

In the approach proposed here to establish maps which reflect the impact of adding a vehicle to an existing network, reference noise levels associated with the surrounding traffic are necessary. In order to establish those, two different approaches may be considered, depending on the type of input data available. If microscopic traffic (or micro-traffic) data is available, it may be aggregated to chosen time intervals (typically in the range of a few minutes to an hour), in order to produce time-dependent average traffic per road segment.

If micro-traffic data is not available for the area, then existing strategic noise maps or traffic flow data may be used instead as a starting point as done for instance in Zambon et al. (2017). The advantage of this latter option lies in the fact that such strategic noise maps are suitable datasets in order to assess noise exposure (Eriksson et al., 2013) and are virtually available for all major cities in Europe, following the END 2002/49/EC (Directive, 2002). These may either be used as is if hourly variations in traffic flow are not lost in the averaging step, or post-processed with interpolation (e.g. based on complementary measurements) for coarser granularity.

For the sake of focusing on the methodology and its practicality as an early assessment tool, it is chosen here to establish the test cases on the basis of existing strategic noise maps, whose levels are modulated to finer time granularity based on typical noise level fluctuation patterns obtained from measurements, as detailed in Section 2.2.1.
2.1.3. Vehicle-specific noise emission model

In the present contribution, the chosen emission model is based on the source model of road vehicles as defined in CNOSSOS-EU (Kephalopoulos et al., 2012). This model calculates the source strength of a vehicle rolling noise and propulsion (engine) noise separately, as introduced in Eqs. (1) and (2) below, respectively,

\[
L_{WR,i,m} = A_{WR,i,m} + B_{WR,i,m} \log \left( \frac{v_m}{v_{ref}} \right) + \Delta L_{WR,i,m},
\]

\[
L_{WP,i,m} = A_{WP,i,m} + B_{WP,i,m} \left( \frac{v_m - v_{ref}}{v_{ref}} \right) + \Delta L_{WP,i,m}.
\]

The total source strength, \( L_W \), is subsequently evaluated as the logarithmic sum of the rolling and propulsion noise contributions, such that

\[
L_{W,i,m} = 10 \cdot \log_{10} \left( 10^{L_{WR,i,m}/10} + 10^{L_{WP,i,m}/10} \right).
\]

In Eqs. (1) and (2), the coefficients \( A \) and \( B \) are dependent on the vehicle category \( m \) and frequency band \( i \), and are defined for a reference speed of \( v_{ref} = 70 \text{ km h}^{-1} \). The term \( \Delta L \) incorporates effects of the road surface, road gradients, acceleration, etc. In this investigation focusing on the methodology, all secondary effects are neglected implying that the correction terms \( \Delta L \) are set to 0.

For the forthcoming applications and discussions in Section 3, two types of heavy-duty vehicles are more specifically considered, primarily differing in the type of motorisation: a diesel-powered internal combustion engine (ICE) and a battery-powered electric motor. The \( A \) and \( B \) coefficients in Eqs. (1) and (2) are taken from the recommended amendments of the CNOSSOS-EU source parameters database (Kok and van Beek, 2019), with the ICE vehicle modelled by the category 3 values defined for a representative ICE heavy-duty vehicle. For the electric vehicle, a corresponding vehicle category was not defined within CNOSSOS-EU at the time of simulation. To overcome this, an ad-hoc differential correction of the source strength based on noise measurements conducted close to the position of the engine of a hybrid truck when running in ICE vs. electric mode, is extracted and applied (the interested reader is referred to Venkataraman and Rumpler (2020) by the authors for further details on these measurements). These corrections in effect provide an interim source model for the battery-powered equivalent of the heavy-duty vehicle. This allows for estimating the impact of noise emissions when switching from a diesel- to a battery-powered heavy-duty vehicle. The relationship between total source strength and vehicle speed considered for the case study is shown in Fig. 3.

2.1.4. Vehicle route

If one wishes to use the present methodology to assess or compare the anticipated impact of a vehicle following specific routes, the routes followed by the vehicle whose impact is studied must be available for each scenario. This implies a collection of successive positions of the vehicle and associated timestamps. This data may be either retrieved from measurements (e.g. GPS receiver) or simulated (e.g. with Eclipse SUMO (Lopez et al., 2018)). If this data is measured from a GPS receiver, it may need to be pre-processed in order to correct positioning errors such that every source position is snapped to the closest position on a road of the considered network.

Finally, the vehicle positions may need to be interpolated to ensure that the distance between successive positions is comparable to the distance between adjacent receiver positions.
2.2. Generation of noise-exposure sensitivity maps

In the present contribution, a noise-exposure sensitivity map (henceforth referred to as “sensitivity map” for the sake of conciseness) is defined as a map of the road network where each road segment is associated with a measure of the noise impact on the population, originating from a vehicle of choice driving on this segment at a given time of the day.

Potential applications for the use of such sensitivity maps may include:

- estimating quickly the approximate noise impact of a vehicle depending on its route;
- optimising traffic routing and delivery scheduling in order to reduce the noise impact of a specific vehicle;
- determining geofencing areas where, for instance, hybrid vehicles may be required to switch to electric mode;
- changing the speed limit dynamically or permanently in the most sensitive areas.

The methodology leading to the generation of these sensitivity maps revolves around the following three main steps:

1. the first step consists in establishing an average background noise map for the area of study, which is meant to serve as a noise level baseline;
2. the second step consists in placing the vehicle of interest at each possible position on the discretised road network and simulating the propagation of the noise emitted by the vehicle from each of these positions;
3. the final step consists in evaluating the impact of this individual vehicle at each of these positions with an indicator reflecting the increase in noise levels that citizens are exposed to, compared to the otherwise established baseline level. The resulting indicator value is subsequently associated with the originating source noise position on the road network.

2.2.1. Baseline: background noise maps

This first step of the methodology consists in generating a reference noise map for each of the targeted time segments of the day. As previously mentioned in Section 2.1.2, the choice made here is to establish this baseline from existing strategic noise maps.

Strategic noise maps are available for daytime ($L_d$), evening ($L_e$) and nighttime ($L_n$) for the cities of Stockholm and Munich. However, this granularity is insufficient to assess the evolution of the noise impact of a vehicle on an hourly basis. In order to introduce a finer time granularity, an interpolation of the $L_d$ ($L_e$) strategic noise maps was made, using noise levels measured continuously on weekdays in the centre of Stockholm, taken from Rumpler et al. (2020) (also in use in Rumpler et al., 2021). This measured data was averaged on an hourly basis using a centred moving average. Then, the daytime ($L_d$) and nighttime ($L_n$) strategic noise maps were interpolated to generate a new background noise map $L_i$ for each given time of day $t$, such that

$$L_i = \frac{m_t - \bar{m}_{[22;06]}}{\bar{m}_{[06;19]} - \bar{m}_{[22;06]}} \cdot (L_d - L_n) + L_n,$$

where $m_t$ corresponds to the noise level measured at time $t$, $\bar{m}_{[22;06]}$ is the average noise level measured over the period 22:00–06:00 (nighttime), and $\bar{m}_{[06;19]}$ is the average noise level measured over the period 06:00–19:00 (daytime).

2.2.2. Vehicle noise simulation on the discretised road network

In order to evaluate the impact of a specific vehicle at each possible position on the road network, the road network is first discretised. This may be done by placing equally spaced points on every road segment of the network. The distance between two consecutive points is chosen such that all receiver positions are exposed to significant contributions from vehicle source positions in the network. Following preliminary testing, steps of 1–5 m seem to offer a good compromise between computational cost and accuracy. It should be noted that the points are not required to be equally spaced; the distance between two points may vary on a per-road basis (e.g. with larger steps if no buildings are in the vicinity of some roads, in order to reduce the computational cost), although this might increase the complexity of this pre-processing step.

Then, a sound source corresponding to the vehicle driving at the maximum speed allowed on each road segment is assigned to every point of the discrete road network. Another speed may be chosen, e.g. if the vehicle is limited to lower speeds than the maximum speed allowed, or if a measure of speed fluctuation associated with traffic density is taken into account. On the basis of each position and the associated velocity attribute, the corresponding sound power level may be calculated. This emitted sound power level in each octane band is based on the specific noise emission model of the studied vehicle, which in this case is based on the CNOSSOS-EU emission model as described in Section 2.1.3.

Finally, the noise propagation is simulated from all positions of the vehicle to the receivers. The outcome is stored as $L_{A_{eq}}$ levels for each source-receiver pair.

2.2.3. Noise impact and sensitivity evaluation via an exceedance indicator

The noise impact of an individual vehicle varies depending on the time of day or the neighbourhood in consideration, given that ambient noise can play an important role in the discomfort caused by a vehicle (De Coensel et al., 2009). In order to evaluate that impact in connection with a baseline level associated with ambient noise, it is assumed here that this impact may be directly linked to the level at the receiver points exceeding the baseline set by the rest of the traffic. Such an approach of impact assessment has been attempted in Zachary et al. (2010) and Cai et al. (2019). This assumption initially disregards the impact that may be associated with
the baseline level itself, a point which obviously may be further refined (Nygren et al., 2020). Under these assumptions, a simple exceedance level metric $ΔL^+_i$ (in dB) may be calculated for each position of the vehicle $j$ at each receiver point $i$, and defined as

$$ΔL^+_i = 10 \cdot \log_{10} \left( \frac{10^{L_{eq,i,j}/10} + 10^{L_{bg,i}/10}}{L_{bg,i}} \right) - L_{bg,i}, \tag{5}$$

where $L_{eq,i,j}$ corresponds to the A-weighted noise level at receiver point $i$ induced by the vehicle at position $j$ (without background noise), and $L_{bg,i}$ is the average background noise level at receiver point $i$ at the given time of day. This indicator therefore reflects the increase in sound energy received due to the passing of the vehicle.

Subsequently, local indicators associated with the impact of the vehicle on the population may be derived from this exceedance metric. In the case studies of this contribution, a choice is made to evaluate the impact at receiver point $i$ from the vehicle at position $j$ using indicators of the form

$$I_{i,j} = \text{cost}(ΔL^+_i) \cdot NP_i \tag{6}$$

where cost is a function characterising the impact of exceedance levels, $ΔL^+_i$ is the exceedance at receiver point $i$ caused by the vehicle at position $j$ from Eq. (5), and $NP_i$ is the number of citizens associated with this receiver.

Two more specific indicators were derived from the general form of Eq. (6):

- a “linear impact indicator”, directly proportional to the exceedance, defined as
  $$I^{(l)}_{i,j} = ΔL^+_i \cdot NP_i \tag{7}$$

- an “exponential impact indicator”, which weights exceedance levels exponentially, defined as
  $$I^{(e)}_{i,j} = \left(2^{ΔL^+_i/3} - 1\right) \cdot NP_i \tag{8}$$

In comparison to the linear impact indicator, the exponential indicator penalises high exceedance levels more. With this indicator, a greater emphasis is placed on exposure to extremely high exceedance levels rather than larger groups of population being exposed to lower exceedance levels. Note that this impact indicator may be to a degree aligned with regulations associated with occupational noise exposure (Franks, 1996).

Unless specified otherwise, the linear impact indicator is used throughout this contribution, although these indicators are also meant to be tested and compared in the applications considered in Section 3. Apart from the impact indicators considered here, more specific indicators may be derived from the data, which is in itself a topic of interest beyond the scope of the present contribution (Can et al., 2016; Nygren et al., 2020).

In summary of the noise impact evaluation procedure, for each vehicle source position $j$, the following steps are thus implemented:

1. the impact value (linear or exponential impact indicator) is calculated for each receiver $i$ affected by this vehicle position;
2. the impact values of all receivers impacted by the considered vehicle source position are summed into a “noise-exposure sensitivity” value associated with this source position;
3. the sensitivity values of all vehicle positions are averaged per road segment and assigned to each road segment.

The outcome of this last step is a sensitivity map where each road segment is assigned an average sensitivity value, which is independent of the length of the road segment. Note that a choice was made to average the sensitivity per road segment instead of keeping the raw values associated with each source point on the discrete road network in order to make the resulting maps easier to read, and to ensure that the “total sensitivity” calculated from the sensitivity maps for a vehicle following a specific route throughout the city is not dependent on the choice of discrete source points selected for the calculation — thus ensuring more consistent results between scenarios. However, this last step is not necessary per se, and choosing to keep the raw values per source point remains an alternative for other applications, e.g. involving idling vehicles.

### 2.3. Computational time reduction with a pre-processed attenuation matrix

In order to speed up the generation of multiple sensitivity maps for a given area (e.g. for multiple times of the day, multiple types of vehicles, etc.), an attenuation matrix is introduced. This matrix contains the attenuation in each octave band (in dB) associated with the propagation between the sound power level of each possible vehicle position on the discrete road network and the resulting sound pressure level of each receiver position.

This pre-processing step makes it possible to update the emission levels of a vehicle and calculate the resulting noise levels at the receiver points without the need to run a new simulation, as the attenuation between a source and a receiver only depends on the physical layout and acoustic properties of the area. Similar strategies have been previously introduced in the literature (Wei et al., 2016; Cai et al., 2016) when repeated evaluations are to be considered, as is the case in the present contribution.

The attenuation matrix is meant to contain the attenuation for each possible source-receiver pair. The order of magnitude of the number of receiver points and the number of possible source positions being respectively of $10^5$ and $10^6$ in the chosen application on the city of Munich, this matrix should contain in the order of $10^{11}$ elements, which would require prohibitive storage, memory and processing time. However, in practice, it is not relevant to store the attenuation between all source-receiver pairs. Indeed, when the attenuation between a source and a receiver is very high, e.g. when they are separated by a great distance or multiple buildings,
the resulting noise level at this receiver point is masked by the background noise level and may therefore be neglected. Thus, the simulation parameters used to generate this matrix are chosen such that the propagation of the sound emitted by a vehicle is limited to a maximum range of 200 metres from this source. This distance results in a sound pressure level $L_P$ at the receiver that is 54 dB lower than the emitted sound power level $L_W$, when assuming hemispherical sound propagation.

Limiting the simulation to the pairs within such boundaries results in a drastic reduction in simulation times and a sparse storage of the attenuation matrix, which requires much less memory resources to process and store (a reduction of about two orders of magnitude in the number of elements to be stored in the considered test cases) as the propagation between most pairs is assumed to be irrelevant. In addition to this truncation in propagation range, all the attenuation values exceeding a defined threshold (e.g. greater than 60 dB of attenuation) may be further neglected as also considered to be irrelevant for the proposed methodology.

This attenuation matrix is then used to calculate the noise levels at each receiver point depending on the positions and power levels of the sources. The sound pressure level $L_{P,i,j}$ received at receiver point $i$ from the vehicle at position $j$ which emits a sound power level $L_{W,j}$, is evaluated as

$$L_{P,i,j} = L_{W,j} - A_{i,j},$$  \hspace{1cm} (9)

where $A_{i,j}$ is the attenuation entry between source point $j$ and receiver point $i$.

3. Applications and discussion

The proposed methodology for the generation of noise-exposure sensitivity maps is applied to the road network of two major European cities: Stockholm and Munich.

Strategic noise maps, provided by local authorities, are chosen here as the baselines for both cities. The results obtained in each of these cities may not at this stage be directly compared, given that the strategic noise maps established for each city were not generated by the same organisation, and might thus not use the same input parameters. This is a point opening for future prospects as more uniform practices are gradually adopted among major European cities as per the update to Annex II of the European Noise Directive 2002 (Directive, 2015), but also highlights the potential of generating these maps from inputs in terms of micro-traffic data as part of the methodology.

Some resulting sensitivity maps comparing different times of the day (i.e. 5:00 a.m., corresponding to a very quiet segment of the day, and 5:00 p.m., corresponding to dense traffic conditions) for the city of Stockholm are shown in Fig. 4 for the sake of illustration. Notice qualitatively the sharp decrease in sensitivity from 5:00 a.m. to 5:00 p.m., highlighted by a shift from dark red areas to light red or white areas in densely populated neighbourhoods of the city centre. The analysis in the following is more particularly focused on the city of Munich.

The following sections intend to illustrate a range of qualitative scenario comparisons on the basis of such sensitivity maps, and to showcase a quantitative comparison on an illustrative routing example in Section 3.6. Unless specified otherwise, the indicator for sensitivity is calculated according to the “linear impact indicator” in Eq. (7).
3.1. From strategic noise maps to noise-exposure sensitivity maps

Strategic noise maps, though useful in the early process of the definition of mitigation plans, do not readily reflect the actual population exposure to noise. The contrast between the information provided by strategic noise maps versus the proposed noise-exposure sensitivity maps is shown in Fig. 5 for the same area of Munich. The contrast is obvious: while the strategic noise map highlights sound sources – main roads –, the sensitivity map calls attention to the areas with high potential impact in terms of population exposure to noise in case of increased traffic. As a result, the proposed sensitivity maps are readily suited to highlight areas to be avoided in order to limit disturbance, i.e. areas of high sensitivity to additional noise sources.

3.2. Impact of time on sensitivity

Background noise levels vary significantly throughout the day, which in turn influences noise-exposure sensitivity. It is thus interesting to compare sensitivity maps at two different times of the day for the exact same vehicle. This is done at two contrasting times in the city of Munich, on a weekday: 5:00 a.m. (off-peak hour, very low traffic and background noise levels) and 5:00 p.m. (peak hour, dense traffic and high background noise levels). The resulting sensitivity maps for the city of Munich are shown in Figs. 6a and 6b for 5:00 a.m. and 5:00 p.m., respectively, both using the same colour scale.

In a similar way to the illustration introduced for the city of Stockholm in Fig. 4, the overall sensitivity is qualitatively much lower at 5:00 p.m., during rush hours, than it is at 5:00 a.m.: some areas of high sensitivity (red) at 5:00 a.m. have a medium sensitivity (white) at 5:00 p.m., while some areas of medium sensitivity (white) become marginally sensitive (blue), which indicates an overall reduction of the impact of the considered vehicle (diesel truck in this case) when driving at 5:00 p.m. compared to 5:00 a.m.
a.m. However, some areas are still dark red during rush hours, thus indicating that the risk of highly affecting noise exposure at 5:00 p.m. may remain quite high for a truck passing through these areas.

These observations are of course to be contrasted with the following limitations of the proposed early assessment methodology:

- The vehicle is assumed to drive at the speed limit on every road. However, in a situation of dense traffic, such as at 5:00 p.m., it is unlikely that the vehicle would be able to maintain a driving speed at the actual speed limit, even if it may be argued that this assumption is not overly unrealistic given the fact that the sound power level associated with the source noise model of a truck has a relatively low dependency on speed for low speeds (see Fig. 3, where variations in the order of 1–2 dB(A) per 10 km.h$^{-1}$ are reported).
- The input population data does not account for population and density dynamics, assuming only permanent residents, assigned to their place of residence at all times of the day. Taking into account a dynamic distribution of the population during the day may provide yet another refinement of the methodology with substantial changes in the results, and increased potential for analysis and mitigation measures.

3.3. Impact of motorisation on sensitivity

In the context of urban environments, where vehicles are limited in speed due to regulations or traffic conditions, the engine-related noise emissions account for a significant share of the impact of a vehicle. The gradual transition to an electrified transport system is thus expected to enable a significant reduction of noise emissions, though the contribution associated with rolling noise will become increasingly in focus. Here a case is presented for these two types of motorisation: internal combustion engine (ICE) or electric vehicle.

In order to evaluate the difference in terms of noise exposure sensitivity as proposed here, two trucks are compared on the roads of Munich in otherwise identical conditions: one using a hybrid engine in electric mode while the other one features a diesel engine. Their noise emission levels are calculated according to the models in Section 2.1.3. The resulting sensitivity maps are displayed in Fig. 7, keeping a comparison between the two contrasting time segments previously introduced, namely 5:00 a.m. and 5:00 p.m.
Fig. 8. Noise-exposure sensitivity maps for two trucks on the road network at 5 p.m. in two neighbourhoods of Munich. In a densely populated area: (a) with a diesel engine, (b) with a hybrid engine in electric mode; in a sparsely populated area: (c) with a diesel engine, (d) with a hybrid engine in electric mode. The colour scale is continuous, from blue (low sensitivity) to white (medium sensitivity) to red (high sensitivity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The difference between these two sets of sensitivity maps is not obvious with the given colour-scale, but nevertheless visible at both time segments: Figs. 7b and 7d highlight an increased share of areas with sensitivity values classified as low (blue) or medium (white) with a hybrid engine compared to a diesel engine in Figs. 7a and 7c. This reduction in sensitivity by switching to the electric mode is particularly visible on the 5:00 p.m. maps, where only very few areas remain highly sensitive after that switch (see Fig. 7d). A better assessment may obviously be obtained with a quantified rather than visual evaluation (see Section 3.6).

3.4. Impact of neighbourhood on sensitivity

As observed in Figs. 6 and 7, some areas have very high noise-exposure sensitivity values regardless of the time of day or type of engine of the vehicle, while others always have lower sensitivity values, despite the truck driving at the speed limit in all areas. This difference is obviously associated with population density: a truck driving in a densely populated area will expose more people to noise pollution than in a sparsely populated area, resulting in higher impact and associated sensitivity values, according to the definitions in Section 2.2.3.

Fig. 8 shows sensitivity maps in two equally sized areas where the population densities differ significantly: a “dense” neighbourhood, in the city centre, with a population density of 25,561 inhabitants per km², and a suburban, “sparse” neighbourhood, with a population density of 1995 inhabitants per km². Fig. 9 further details the distribution of the population per building in each of these two areas, for the sake of illustration of the underlying population distribution data. This distribution was derived from block-level population data.

The sharp contrast in population density results in the dense area displaying almost exclusively extremely high sensitivity values (see Figs. 8a and 8b), while the sparse area is nearly uniformly blue, which represents much lower sensitivity values (see Figs. 8c and 8d). For these cases, at the extremes of the sensitivity scale, the difference between the two types of engine in each neighbourhood, while visible, is naturally less striking. In order to better assess this difference, Table 1 presents the median sensitivity values in those neighbourhoods depending on the type of motorisation.

The noise-exposure sensitivity mapping proposed here as highlighted by the figures in Table 1, is thus well-suited to capture the following anticipated observations:

- Having a truck navigate through a sparsely populated area instead of a densely populated area has a much higher impact on the reduction of noise exposure than switching from a diesel to a hybrid truck in a densely populated area, under the assumption of a linear impact indicator (reduction of over 30,000 in median sensitivity by switching from the dense area to the sparse area compared to a reduction of less than 10,000 by a change of motorisation in the dense area).
3.5. Impact of the indicator on sensitivity

As introduced in Section 2.2.3, the choice of indicator for the sensitivity metric may in itself be a topic for further, dedicated consideration beyond the scope of the present contribution, given its potential impact on the resulting quantification. Several additional aspects may be taken into account in order to propose different ways of weighting noise pollution by exposure, e.g. depending on the type of sources, adding thresholds to ignore or strongly penalise certain noise levels, taking into account the duration of exposure, etc.

In this section, the so-called “exponential impact indicator”, defined in Eq. (8), is compared to the “linear impact indicator”, defined in Eq. (7) and used in previous sections. The resulting sensitivity maps for the city of Munich are shown in Fig. 10, to be compared with Fig. 7 reflecting the “linear impact indicator”, although the values associated with the colour scales are not identical, for obvious scaling reasons.

The exponential impact indicator appears to generate noticeably sharper contrasts in sensitivity, in line with the heavy weight put on large exceedance levels in this metric. The comparison between these indicators is further detailed on a quantified routing problem in the following section.

3.6. Application to a realistic routing problem

In order to illustrate the potential of the proposed methodology for the early assessment of the routing of individual vehicles and estimate of the associated impact, two routes are chosen for an indicator comparison using the sensitivity maps. These two routes are plotted in Fig. 11. Both have the same departure and destination points, namely the intersection between European route E52 and the boundary of Munich, and a hypothetical delivery destination on Heideckstraße. For the sake of representing the underlying population distribution associated with the part where the two routes diverge, Fig. 12 details the distribution of the population per building, derived from block-level population data. The chosen colour-coding allows to identify particularly three types of buildings: those assumed to be associated with individual houses or business buildings (i.e. low residential density), those of intermediate to large size, arbitrarily chosen to be counting up to 100 residents per building, and those with a very large number of residents, exceeding 100 persons.

---

**Table 1**

Median (linear) sensitivity of a truck in two neighbourhoods of Munich depending on the truck’s motorisation.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>Engine</th>
<th>Median sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>Diesel</td>
<td>34 883</td>
</tr>
<tr>
<td>Dense</td>
<td>Hybrid</td>
<td>24 987</td>
</tr>
<tr>
<td>Sparse</td>
<td>Diesel</td>
<td>3393</td>
</tr>
<tr>
<td>Sparse</td>
<td>Hybrid</td>
<td>2021</td>
</tr>
</tbody>
</table>

- Switching from a diesel truck to a hybrid truck has a more significant impact in densely populated areas than in sparsely populated areas (reduction of about 10,000 in median sensitivity in the dense area compared to less than 1400 in the sparse area).
Fig. 10. Noise-exposure sensitivity maps (exponential indicator) for two trucks on the road network of Munich at two times of the day, at 5 a.m.: (a) with a diesel engine, (b) with a hybrid engine in electric mode; at 5 p.m.: (c) with a diesel engine, (d) with a hybrid engine in electric mode; the colour scale is continuous, from blue (low sensitivity) to white (medium sensitivity) to red (high sensitivity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. Two routes with identical start and destination points chosen for comparison. The light blue route is referred to as the "short route" while the dark blue route is referred to as the "long route".

The first route, referred to as the “short route” is 11.0 km long. The second route, referred to as the “long route”, is slightly longer with 12.2 km and follows the motorway for as long as possible instead of the more direct route through the city.

For the calculation of the aggregated sensitivity associated with each route, a truck is assumed to drive at the maximum speed allowed on each road. A source-point is generated along the route at each second for the duration of the journey, and assigned with the sensitivity value of the road segment it belongs to. The total sensitivity of the route is then calculated by summing the sensitivity values of all source points.

The results are presented in Table 2 for the linear sensitivity indicator, and in Table 3 for the exponential indicator, as defined in Eqs. (7) and (8), respectively. According to these results, for both indicators and each time/motorisation pair (i.e. each row in the
Fig. 12. Population distribution per building in the area where the two chosen routes (light blue and dark blue) differ. The buildings are colour-coded from blue to red, according to the legend (b), to represent the number of citizens associated to each of them. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Total sensitivity (linear indicator). Each row presents the sensitivity values for a given route/motorisation pair.

<table>
<thead>
<tr>
<th>Route</th>
<th>Engine</th>
<th>00:00</th>
<th>05:00</th>
<th>08:00</th>
<th>17:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>Diesel</td>
<td>5,768,470</td>
<td>7,816,073</td>
<td>3,614,430</td>
<td>3,576,524</td>
</tr>
<tr>
<td>Short</td>
<td>Hybrid</td>
<td>4,030,810</td>
<td>5,825,912</td>
<td>2,279,201</td>
<td>2,249,617</td>
</tr>
<tr>
<td>Long</td>
<td>Diesel</td>
<td>2,892,544</td>
<td>3,818,455</td>
<td>1,894,980</td>
<td>1,875,835</td>
</tr>
<tr>
<td>Long</td>
<td>Hybrid</td>
<td>2,030,008</td>
<td>2,846,694</td>
<td>1,205,749</td>
<td>1,190,586</td>
</tr>
</tbody>
</table>

tables), the long route has a lower overall impact than the short route, from a noise-exposure point of view, despite being longer both in terms of distance and duration. This is an interesting observation to potentially put in perspective with other environmental and sustainability factors.

However, comparing the results for the short and long routes using different propulsion systems highlights the impact of the choice of indicator. A comparison of the two tables for instance provides diverging conclusions: according to the linear indicator (Table 2), the hybrid truck on the short route has a significantly larger impact than the diesel truck on the long route, while according to the exponential indicator (Table 3), the hybrid truck on the short route has a lower impact than the diesel truck on the long route.
Table 3

<table>
<thead>
<tr>
<th>Route</th>
<th>Engine</th>
<th>00:00</th>
<th>05:00</th>
<th>08:00</th>
<th>17:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>Diesel</td>
<td>43,343,741</td>
<td>129,983,496</td>
<td>11,244,697</td>
<td>10,931,620</td>
</tr>
<tr>
<td>Short</td>
<td>Hybrid</td>
<td>14,178,707</td>
<td>42,537,376</td>
<td>3,682,022</td>
<td>3,579,425</td>
</tr>
<tr>
<td>Long</td>
<td>Diesel</td>
<td>21,463,252</td>
<td>60,011,495</td>
<td>6,043,041</td>
<td>5,884,000</td>
</tr>
<tr>
<td>Long</td>
<td>Hybrid</td>
<td>6,945,188</td>
<td>19,431,687</td>
<td>1,958,358</td>
<td>1,906,518</td>
</tr>
</tbody>
</table>

These differences may be explained by the difference in population density of the areas surrounding each route, the difference in exceedance level from the choice of motorisation, and the choice of indicator (weighting of the exceedance level): on the long route, the truck mainly crosses low density areas, while on the short route, it goes through very densely populated areas, see Fig. 12. As a result, a diesel truck on the long route tends to have an impact on fewer citizens but with higher noise levels than the hybrid truck on the short route, which results in higher sensitivity values using the exponential impact indicator. Determining which of these two scenarios is preferable and a better reflection of the reality is at the heart of the questions associated with the choice of indicator: to which degree is it preferable to disturb fewer citizens with higher noise levels, or many more citizens with lower noise levels?

These results also highlight the importance of the time of day: rescheduling a delivery may at times have a higher impact on the disturbance it causes than switching propulsion system, thus highlighting the importance of planning as a mitigation measure, complementing the transition to an electrified transportation system. As an example, rescheduling the considered delivery route from 05:00 to 00:00 may allow to switch from an electrified vehicle to a diesel vehicle without significant change of overall noise exposure impact, regardless of the metric used in this case.

Conclusion

The present contribution proposes a method which enables the assessment of the noise-exposure sensitivity associated with a vehicle of interest on each road segment of an urban area. The novelty of this method lies in its receiver-centric approach, focusing on the exposure of citizens to noise aggregated at the level of the point of emission. This approach allows for the generation of noise-exposure sensitivity maps which readily allow to identify a range of issues and opportunities for noise mitigation by several stakeholders. It may for instance be used as a qualitative tool to evaluate the most sensitive areas of a city, where mitigation measures might be very effectively applied in order to limit or reduce the noise impact of vehicles – e.g. through geo-fencing or lower speed limits –, as well as a quantitative tool to optimise traffic allocation and delivery scheduling with marginal impact on noise exposure. In particular, the introduced case study highlights an interesting dependency of the noise impact on timing and routing, at times more relevant than the question of motorisation.

While population is a static input data in the present application, it is a very natural extension to also consider its time-dependency in a way similar to the fluctuating background reference noise levels. The choice of indicators for the quantification of noise exposure impact of a vehicle is also a natural perspective of ongoing consideration by the authors.

CRediT authorship contribution statement

Sacha Baclet: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing. Siddharth Venkataraman: Conceptualisation, Data curation, Investigation, Methodology, Writing – review & editing. Romain Rumpler: Conceptualisation, Investigation, Funding acquisition, Methodology, Supervision, Writing – review & editing. Robin Billsjö: Resources, Writing – review & editing. Johannes Horvath: Resources, Writing – review & editing. Per Erik Österlund: Resources, 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.

Acknowledgements

The authors would like to thank the Centre for ECO2 Vehicle Design, which is funded by the Swedish Innovation Agency Vinnova (Grant Number 2016-05195). The funding from the EIT Urban Mobility project “Zero Emission off-peak Urban Deliveries (ZEUS)” (GA 20035), and from the J. Gustaf Richert foundation (Grant Number 2021-00697) are also gratefully acknowledged.


