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AGENT-BASED TRANSPORT SYSTEMS AND THE REPRESENTATION OF MICROENVIRONMENTS FOR ASSESSING INDIVIDUAL EXPOSURE TO NOISE POLLUTION

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ABSTRACT

Conventional methods for modelling noise impacts of urban transport traffic are often limited to the static spatial estimation of noise levels and their relationship with populations in their place of residence. Including an assessment of individuals' exposure would improve the evaluation of transport scenarios. Accordingly, for the last decades, few agent-based transport models were coupled with environmental models in order to enhance spatially, temporally and socially the noise exposure assessment. However, transport models are not originally designed for this purpose, which reinforces the need to understand their validity domain for modeling the exposure phenomenon. Given this context, in this paper, the representation of activity places and their associated microenvironments are addressed in detail to analyse how they influence noise exposure modelling. Based on the Nantes, France, scenario methodological guidelines are proposed. The results show that the biases of spaces conceptualization and exposure estimation can limit the noise exposure model sensibility to urban acoustic mitigation strategies.

Keywords: *noise exposure assessment, noise modelling, agent-based transport systems, urban environment*

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1. INTRODUCTION

The acoustic degradation of urban environments due to noise pollution has a significant impact on human health and is still a major problem to be confronted in cities [1–3]. Among the sound sources that compose urban environments, transport sources are the primary contributors to noise pollution [4]. Accordingly, common noise assessment methods in Europe were determined based on transport-related emissions. In the standard European approach, CNOSSOS-EU [5], people's noise exposure is estimated in terms of daily noise averages, often expressed by the number of people exposed to pollution level thresholds. These results are obtained by crossing population counts data from residential surveys with noise level data from standard noise models.

Some criticism has been addressed to standard approaches. Urban mobility is not integrated into the exposure assessment. Noise exposure estimation considers that people stay at home all day long. The fixed-point activity approach is limited to residential density and individual within-day exposure dynamics are neglected [6–8]. That static statement may be a reasonable hypothesis for exposure during night periods, but not for day periods.

Considering the current state of noise exposure assessment, agent-based transport systems coupled with noise models represent a promising approach. Due to their individual-centered structure, these models propose an innovative representation of agents' choice behavior with a finer spatial, temporal, and social simulation of the urban mobility dynamics [9]. In the last decade, few studies have implemented a noise exposure assessment framework using agent-based models [7, 10, 11]. Since transport models are not originally designed for environmental impact evaluation, more work is necessary to investigate their validity range in assessing noise exposure.

In this paper, the representation of activity places and their associated microenvironments are addressed in detail to analyse how they influence noise exposure modelling. The analysis is conducted with reference to an dynamic agent-based exposure model which is representative of the state-of-the-art models. The Nantes transport scenario is used to illustrate the exposure assessment framework. The software platforms that integrate the framework are MATSim [9], EQASim [12] and NoiseModelling [13, 14]. This research is part of the SYMEXPO project, which aims to understand and model the links between mobility and exposure to air pollution and noise [15, 16].

The paper is structured as follows. In Section 2 a definition for microenvironments is presented. The agent-based framework used for the exposure assessment is presented in Section 3. The results are presented in Section 4 and the discussion is presented in Section 5.

2. SPACE AND MICROENVIRONMENTS

The quality of urban environments is spatially heterogeneous and evolves throughout the day. There are places that favor and others that mitigate noise pollution. Therefore, when assessing the noise exposure of an individual, it is of high relevance to know which places he frequented, what were the places' characteristics, and why he was present there.

In this context, the concept of microenvironment is introduced. According to the International Society for Exposure Analysis (ISEA) [17], microenvironments are surroundings defined as homogeneous or well characterized in terms of pollutants concentrations. Thus, the microenvironment represents a space delimitation from the point of view of the pollutant, being the smallest spatial subdivision where the exposure of an individual occurs. Two individuals in the same microenvironment are subjected to equal levels of pollution.

In reality, noise levels are extremely sensitive to space and can differ by a distance of meters. This being so, defining microenvironments depends on the context of the study and there is no consensus on how to represent pollution exposure places. If the study aims to understand noise exposure in housing environments, the granularity of microenvironments should be high and different rooms, e.g. the kitchen, the bedroom, and the living room, are relevant. But, if the study is at the urban scale, the house may represent a single exposure microenvironment.

A space is composed of microenvironments and in different spaces there might be microenvironments with similar pollutant exposure profiles. In an attempt to identify regularities of exposure to noise pollution, studies use different approaches to measure noise, and to describe and classify microenvironments. Thus, it is necessary to analyze how microenvironments are represented in direct and indirect exposure assessment approaches.

1. The direct exposure assessment: The individual monitoring approach for assessing noise exposure is highly detailed in terms of microenvironments. This approach is based on the use of individual monitoring embedded systems that record in real-time the spatial location and the exposure level to pollutants along with activity-travel diaries. Thus, the capability to represent microenvironments depends fundamentally on the quality of the sensor and the measure. The experimental campaign of Kou et al. [6, 18] illustrates the richness of the data from an individual monitoring campaign. Held in December 2017 to February 2018, the inhabitants of Meiheyuan community, Beijing, China were studied. This study collected data on individuals' daily movement, noise exposure, and self-reported noise perception and psychological stress. As a result, different activity, travel, social and temporal contexts of exposure were investigated;

2. The indirect exposure assessment: The modelling approach for estimating noise exposure is concerned with the difficulty in defining and limiting the microenvironments modelled. Often, rather than using the real noise exposure microenvironments of individuals moving along their daily trajectories, noise levels at the facades of the dwellings are used as a first approximation [19]. But this simplification is not a fixed rule, as can be seen in the agent-based transport framework of Kaddoura et al. [7]. In this study, the model is implemented to analyze Berlin, Germany, population exposure to road traffic noise. Their study investigates the need to account for the spatio-temporal variation in the population's daily activity trajectories to avoid an overestimation of residential noise damages. It is interesting to note that the locations used for the exposure calculation are defined by a grid of receivers and the agents' activity places are associated with the nearest noise receiver of the

grid.

3. METHODS

The assessment of pollution exposure is accomplished through the use of an urban numerical modeling framework, requiring its modules breakdown. As depicted in Figure 1, the exposure framework consists of three modules: i) the transport module; ii) the noise environmental module; and iii) the noise exposure model.

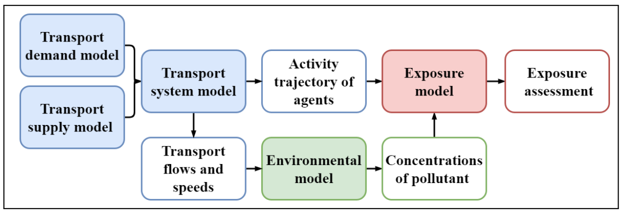

Figure 1. Pollution exposure framework scheme

The transport module is the starting point of the framework. It is composed of a transport supply model, a transport demand model and a transport system model. These models interact to simulate an agent-based transport scenario to then provide traffic flows data for the environmental model and agents' spatio-temporal locations data for the exposure model. As an open-source transport software platform, the Multi-Agents Transport Simulation (MATSim) [9] is used for the implementation of our large-scale agent-based simulation and the scenario input data, including the synthetic population, are treated and generated by EQASim [12].

In MATSim, the transport demand is represented by a population, the synthetic population, composed of individuals, the agents, with their intended activities, the activities plan, to be performed throughout the simulation period, commonly a typical work weekday. The agents' activities plans are simulated in a transport network with limited transport services. During the simulation agents compete to perform their daily trajectories and, after the simulation, a score is associated with their executed plans. According to their score and previous simulation conditions, executed plans are modified (e.g. modes, itinerary and travel departure time choice) at the re-planning stage to then be simulated again. The system equilibrium is achieved by the cyclic co-evolutionary algorithm that aims to maximize the score of the entire synthetic population

Second, the environmental module is responsible for performing noise calculations of environmental acoustics. It aims to dynamically estimate the different noise levels in space based on the previous simulated transport noise sources. As an open-source physical acoustics platform, NoiseModelling [13, 14] is used to produce environmental noise maps of large-scale urban areas according to European standards.

Finally, the exposure module integrates the spatio-temporal agents' activities trajectories and the spatio-temporal evolution of pollutant concentrations in order to assess noise exposure. The assessment is performed by estimating agents' noise exposure doses throughout the simulation. In this final module, the synthetic population exposure to transport noise sources caused by their own mobility demand is evaluated, completing the cause-and-effect chain of the pollution exposure phenomenon. Here, the exposure model is a NoiseModelling extension.

3.1 Example of the city of Nantes

The Nantes city counts more than 300,000 inhabitants and has a surface of approximately 65 km². Our corresponding exposure framework of Nantes is implemented with a representative mobility scenario of the year 2015. The synthetic population is simulated base on a 20% sampling rate. This means that 20% of the population of the study area is simulated in an adapted scale transport model [20], and then the results are extrapolated to the total population.

The mode categories simulated are private car, public transport, bike and walk. The activity categories simulated are work, study, leisure, home, shop and others. Agents are mainly described by their age, sex, socio-professional category, ongoing employment and education status, and possession of a driver's licence and a public transport subscription. Three vehicle noise source categories are distinguished : light-duty motor, medium heavy-duty and heavy-duty. Noise from air and rail transports are not considered.

The scenario input data sources are: a) French population census of 2015 (INSEE); b) Population work and education commute data of 2015 (INSEE): c) Open-Street-Map networks and buildings data; c) Public transport lines GTFS data from different sources (TAN Nantes, Aléop Loire Atlantique, SNCF and others) ; d) National address database of 2015 (IGN); e) National service and facility database of 2019 (INSEE); f) National enterprise census (INSEE), and; g) Loire-Atlantique household travel survey of 2015 (Data Loire-Atlantique). The data treatment approach to generate input data to the transport system simulation is described in Hörl and Balac [21].

In the agent-based simulation, the distinction between place of activity and place of exposure must be specified. The activities performed by the agents are located at a fixed point in space. These points are defined using addresses from the National address database (BD-TOPO). The addresses can be understood as a set of facilities, being also a set of possible places to be experienced. An activity is performed at a facility and at a facility different activities can be performed. Then, in order to calculate noise exposure, the facility-activity points are spatially associated with the nearest standard noise receiver in a maximum range of 50 meters. Standard noise receivers are placed 2 meters from a building facade, 4 meters from the ground and 5 meters from each other around the building footprint. The building geometry data is obtained from Open-Street-Map. The step by step of the exposure model is described in Le Bescond et al. [10].

In summary, the places of exposure correspond to the standard receivers derived from the facility locations. Thus, the set of microenvironments depends not only on the approach of spatialization of activities, but also on the approach of association between activities and noise exposure receivers. The construction of microenvironments in the model implies several biases that are presented and discussed below.

4. RESULTS

During the simulation, agents experience numerous exposure contexts along their trajectories. These contexts can be divided into two broad categories : the activity microenvironments and the transport microenvironments.

First, regarding noise exposure at transport, the framework in question neglects agents' exposure during travel. In the model, travelling is strictly considered as a pollution emissions period, while performing activity is strictly considered as an exposure period. To the best of our knowledge, there are no agent-based models that estimate exposure during travel.

Second, regarding noise exposure at activity microenvironments, the exposure model can be analysed in two scales, the facility scale and the urban scale.

4.1 Facility scale

At the facility scale, the vertical and horizontal spatialization of noise receivers and the acoustic attributes of facilities provide limits for the exposure estimation. First, the height of the buildings are not considered during receivers placement and the exposure is restricted to 4 meters height. Further, facility locations registered in the National address database correspond approximately to the entrance door of buildings. Therefore, with the nearest standard receiver affectation approach, facility exposure receivers are more likely to be placed at the street-oriented facade of a building. Consequently, building footprints and courtyards are underrepresented. Finally, relevant building attributes, as age of construction, that could be used to estimate acoustic parameters, as insulation rate, are neglected in the construction of the exposure model.

In order to illustrate activity microenvironments at the facility level, the Figure 2 shows the noise map of Nantes Canclaux at 08h15 a.m. and the spatialization of exposure receivers. The noise map is calculated based on traffic flows means simulated between 08h00 and 08h15. The black points are the facility standard receivers for all activities, that is, more than one type of activity can be performed in one point location. Due to the acoustic building shielding effect, internal courtyard facades can be significantly less exposed depending on the urban morphology. However, these protected microenvironments are spatially poorly represented. A similar effect occurs with vertical spatialization. The highest floors of a building tend to be less exposed to noise pollution, however all the receivers are placed 4 meters from the ground.

4.2 Urban scale

At the urban scale, the set of activity exposure places is defined based on the facility-building approach, which limits the representation of outdoor urban spaces. There is no specific data treatment for outdoor activities, either for their generation as activity places or for their association with noise receivers. In addition, the association algorithm between the place of activity and the place of exposure constrains the microenvironments to building facades. Thus, it results in a lack of spatial representation of outdoor spaces relevant to the city life, such as green areas, parks, and historical and cultural open public spaces.

For this purpose, Figure 3 illustrates the noise map of Nantes Coulmiers - Jardin des Plantes at 08h15 a.m. and the spatialization of leisure exposure receivers. On the map, it is possible to identify green spaces, such as the Jardin des Plantes park (left bottom) and the Parc de la Moutonerie (right center). However, in these areas, there is a low density of exposure receivers of leisure activities when compared to densely urbanized areas. The few ac-

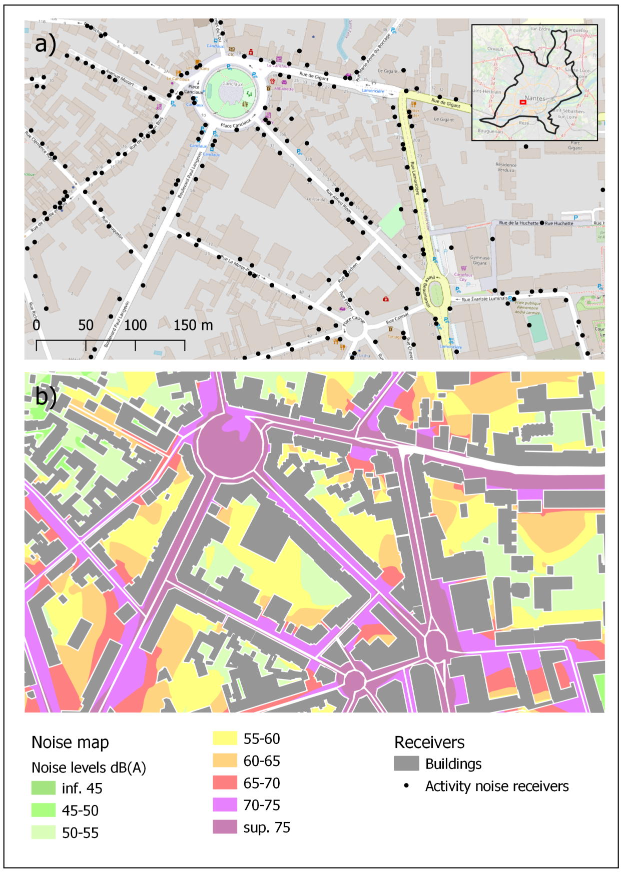

Figure 2. Nantes Canclaux urban blocks: Exposure receivers of all activities (a) and noise map at 08h15 a.m. (b)

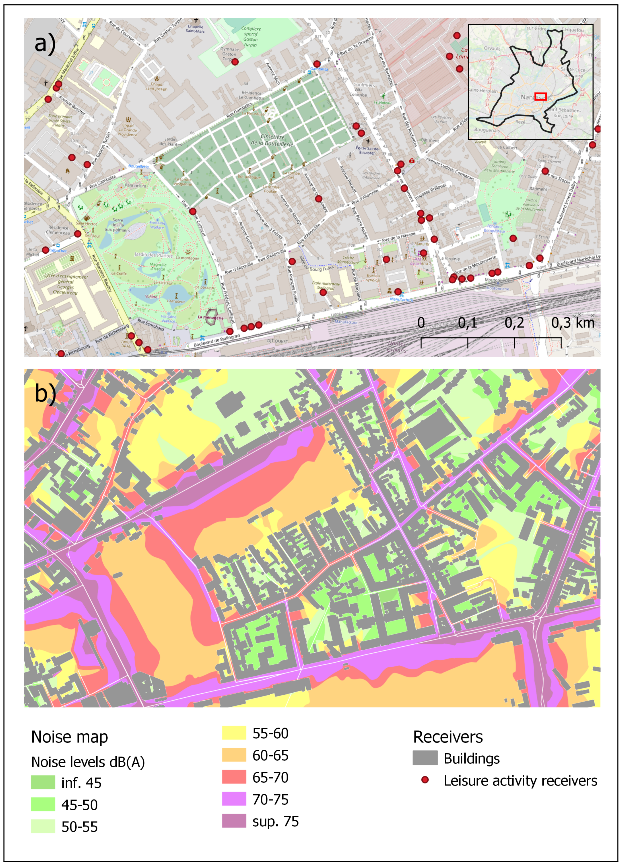

Figure 3. Nantes Coulmiers - Jardin des Plantes green areas: Exposure receivers for leisure activities (a) and noise map at 08h15 a.m. (b)

tivity receivers present in green areas are generated due to the presence of a building on-site registered in the address database. Furthermore, with respect to leisure activities, it should be noted that in-motion activities are not represented due to the static nature of the activity points.

5. DISCUSSION

Agents are not exposed to noise during their travels, which represents the first source of bias in the estimation of daily pollution doses. The construction of an exposure model for transport microenvironments is necessary. Technically, agent-based simulation provides detailed data about the events that compose an agent' travel. In MATSim, for example, the simulation events for a car travel contain the time and location of the agent's departure from an activity, the agent's entering a vehicle, the agent's entering and leaving road links, agent's leaving a vehicle and agent's arrival at an activity. All these steps could be integrated into the conception of an exposure model. However, it is important to state that these details may vary according to the mode simulated. The presented framework does not model a walking network and walk travels are simulated by agents' teleportation from one activity to the next based on an average speed and a straight-line distance, thus without itinerary and space-time travel traceability.

Individual monitory studies show that noise exposure in transport is of extreme relevance as their microenvironments can be acoustically highly polluted. In Kou et al. [6] the results of the noise monitoring campaign are presented for transport and activity contexts. Public transport travels have significantly higher measured noise levels averages than any other activity and the proportion of reporting moderate or serious levels of perceived noise and psychological stress in public transport are also high.

The scientific understanding of noise exposure in transport needs further study. A recent research review of environmental exposure studies during travel shows that air quality studies lead the research in the domain, while other exposures, including noise, deserve more scholarly attention [22]. This gap is also reflected in the exposure model domain. For air pollution, there are already models such as EXPLUME [23] which integrates the estimation of exposure during travel using an agent-based approach.

Another bias in the estimation of daily pollution exposure doses is in the relationship between activity places and their associated microenvironments. First, the integration of vertical and horizontal spatialization of noise receivers around facilities could better represent its soundings noise microenvironments. Second, facility and building attributes could integrate the microenvironments context description, notoriously with the use of acoustic insulation rate. Third, the use of the agent's characteristics and momentary contexts, such as activity purpose and day period, could compose an approach to a coherent association between activity places and the most likely microenvironment to be experienced. Therefore, the exposure model could differentiate a commercial activity that is performed on the ground floor on the street side from a protected residential activity in an acoustic planned courtyard.

More broadly, given the limitations in representing activity microenvironments, the sensitivity of the exposure model to noise mitigation strategies can be questioned. Some urban planning practices are already widely used and can significantly promote noise mitigation in an urban block: the definition of a buffer zone and a safe separation distance between transport infrastructures and facilities; the use of screen buildings and building continuity to protect facilities that are located inside the urban block; the reinforcement of the acoustic insulation of the most exposed buildings; and the strategic positioning of noise-sensitive activities, such as dwelling, in noise-protected areas. In addition, these noise mitigation strategies are part of major urban challenges, such as urban consolidation and neighborhood mixed-use, being extremely important to be evaluated from the point of view of noise exposure.

At the urban scale, it is possible to identify the biases of microenvironment conceptualization. First, it is essential to expand the concept of facility locations to the concept of places of activity, whether indoor or outdoor. This would require the diversification of territorial data and dedicated treatments to extend the presence of agents to places that are essential for the city life. In parallel, the categories of activities and transport modes simulated should be thought of since their conception in order to facilitate the identification of the microenvironment contexts that are of interest to the study.

In urban acoustics, the case of green areas represents a highly relevant subject. Their maintenance and expansion can provide multiple environmental and social benefits [24,25]. However, their acoustic environments are not always preserved [26], which implies the need for identification of the quiet areas and areas to be protected. With due caution, exposure modeling using agent-based models could integrate the exposure that occurs in these contexts to improve the environmental evaluation.

In summary, transport models and the way they represent places of activity must be adapted and extended to the noise exposure problem. The simplifications of the mobility for a pure transport model can limit and bias the pollution exposure estimation calculations. It is of utmost importance to harmonize the design assumptions in order not to restrict the representativeness of microenvironments.

6. CONCLUSION

The use of transport models based on multi-agent systems for environmental evaluation is a recent and promising application. Since transport models are not originally designed for this purpose, an understanding of their validity domain for exposure assessment is necessary. To model is also to simplify reality, and it is of prime importance to understand how design biases can influence the subsequent environmental assessment.

In this article, the problem of microenvironments is defined and addressed in detail. The biases of exposure estimation and urban space conceptualization are analyzed based on an dynamic agent-based exposure model which is representative of the state-of-the-art models. The microenvironment representativeness is dependent on the activity and transport places input data diversity, the activity and modes categories simulated in the transport model, the richness of microenvironment context attributes, and the relationship between agent locations and exposure places, translated in the association approach between facility places and noise receivers.

The structure harmonization between the transport and the exposure model can render the dynamic agent-based assessment of noise exposure more sensitive to the good and bad practices of acoustical territorial planning, providing a better transport scenario environmental evaluation.

7. ACKNOWLEDGMENTS

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