Simulating the impact of urban transport infrastructure design on local air quality in Beijing

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Abstract

Urban transport infrastructure can result in the physical, psychological and environmental separation of neighborhoods, public space and pedestrian network, leading to negative impacts on citizens' daily commutes, social activities and health. In this paper, we simulate the impacts of road network design on individual activity patterns, travel mode choices and air pollution using an agent-based model. The simulation model is applied to a case study in Beijing and the air pollution heat maps are produced for road network designs comparing with the real-time pollution data. This illustrates the potential value of such simulation models which generate activities for a given urban layout and transport network, and shows how human behavior can impact air quality.

Keywords

urban transport infrastructure, human behavior, environmental evaluation, agent-based modeling, policy-making support

1. Introduction

After the Industrial Revolution, patterns of cities changed prominently as result of urban explosion. The urban transport infrastructure (e.g., road, railway and light rail) has been shaping urban spaces. In developing countries, governments invested in infrastructure to meet the need of rapid urbanization accompanied by horizontal sprawl. However, because transportation development was prioritized over public realm design in many cities, the transport infrastructure is sometimes represented as a linear separating component that cuts the urban fabric into fractured, inaccessible and unfriendly pieces of public space. These pieces of "lost space", named by Carmona (2003) as Space Leftover After Planning (SLOAP), are in lack of meaningful purpose. The SLOAPs have low visual aesthetic quality and minimal physical equipment for outdoor activity. Therefore, they are less used by citizens which is a significant element of improving public health.

Furthermore, the construction of transport infrastructures cuts the urban ecosystem into separate natural habitats, thereby influencing the system's ecological resilience and leaving it vulnerable to shifts in climate change (Alberti & Marzluff 2004). The unconnected blocks in urban fabric raise individual's dependence on motorized transportation, which generates a considerable amount of air pollution compared to walking and cycling. The bad air quality in return impacts human behavior and results in reduction of physical activity (e.g. staying for a while and attending social events) and active travel (i.e. walking and cycling) in public spaces.

This paper focuses on the problem of public space separation and social segregation result from transport network design. Here, we show how a simulation model can be used to visualize the negative impacts of road network design on individual activity patterns, travel mode choices and air pollution. This platform is vital for the current society to involve civic participatory into the policy-making process, along with to achieve the human needs-based construction, which offers the possibility of sustainable development and "good life" in present-day society (Jackson, Jager, & Stagl 2004). A case study in Beijing is used to demonstrate to the relationship between human activity and air pollution compared by the real-time data.

2. Literature Review

In the domain of urban design, an integration of urban transport infrastructure and built environment is widely recognized as an essential precondition for sustainable development (Varnelis 2008). To achieve the goal of integration, the traditional urban design method of "survey-analysis-plan" has been gradually combined with mathematical and digital modeling, involving planners, modelers and other designers. According to urban dynamics theory, city is regarded as a complex system consisting of interconnected parts -- two of which are transport and land-use sub-systems. These two systems are usually combined and holistically planned through land-use transport models. Other urbanist theorists got inspirations from nature, leading to a concept of Bio-inspired Urbanism, which regards city as an evolving organism Geddes (1915). At the present time, the self-organization in biological systems has been introduced into urban systems study, leading to wide discussions and practices in exploring the analogues between built environment & social unit and biological & ecological processes.

A group of research focuses on the reciprocal relationship between active travel policy, which encourages walking and cycling, and public health. In the relation loop, transport and planning policies previously impact on human behavior (in terms of travel mode, route choices and physical activity) and environmental quality, which jointly influence human exposure to environment (e.g. air pollution, heat and traffic injuries) (De Nazelle et al. 2011).

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The policy-making process evolved gradually which was initially described by Axelrod (1976), focusing on an individual's causal assertions. In the democratic society, however, policy-making shifts to an integrated analysis approach involving scientists, policy-makers and the public (Zellner 2008). Researchers pointed out that models take a role of mediation and platform for participation. Moreover, because major infrastructure and policy decisions need to be based on sound evidence, computer modeling (with advantages of real-time data validation and prediction) is an efficient way that could facilitate the evaluation of different scenarios which would then supplement decision-making. Among others, agent-based modeling (ABM) has been markedly applied to provide qualitative insights and quantitative results for the cooperation of decision makers (Axelrod 1997).

3. Methodology

In order to integrate transport planning, human behavior and environmental quality, this paper initially analyzed the interactive mechanism underlying the urban infrastructure development, human needs (including personal, social and environmental aspects) and ecology needs (e.g. biodiversity, networked green and water system). Analogues in biology was adapted in creating a conceptual model. DNA, as a molecule of the self-organized biological system, is similar to the urban system. Inspired by the double helix structure of DNA, a prototype of self-organized urban system was found (see Figure 1). Corresponding to the two helical chains in DNA, human and ecology needs form the backbone of urban organization, since human demands drive the development and functioning of a city, and the ecology quality restricts urban growth.

Depending on the human-natural need strands, urban transport infrastructure is constructed to meet and connect the two needs, functioning in the same way as the base pairs in DNA. This prototype could support decision makers by considering the human-natural needs as vital intervening variables that shape and constrain their actions; moreover, the need-strands are beneficial for establishing boundaries within which the land-use transport planning, traffic proposal, public health initiative and environmental policies are made.

Depending on the conceptual model of decision-making, this paper proposed an integrated methodology, shown in Figure 2. In the loop of scenario design, after the physical transport and public space planning (see Figure 2. step (a)), scenarios were set into the model to simulate human behavior (i.e. physical activity pattern and choice of travel mode & route & destination), and air quality. In this way, we monitored the population's exposure to air pollution, which is a vital metric of evaluating transport scenarios (see Figure 2. step (b)); then comparisons with real time air pollution distribution were carried out in order to validate the modeling. In this methodology, public participation appeared in the stage of urban context survey, the stage of decision-making (i.e. the public is involved by observing the modeling process and providing suggestions) and finally in the long-term monitoring after implementing one of the transport plans. It is worth noting that this method is more than a linear process, but an iteractive progress that feedback getting from monitoring a designed transport and public system in 1, 5, or 10 years will yield redesigns of the system.

As for simulation tools, Agent-based modeling provides a possibility of simulating agent's needs and behavior by generating a synthetic population from the given statistics, by which the emergence of social behavior could be witnessed. To establish the model's environment, gravity model and travel mode choice model were adopted to simulate the interaction of human behavior and built environment (here refers to public space affiliated with transport infrastructure); linear functions between land-use (density and mix) and physical activity & traffic choice were applied based on the research of De Nazelle et al (2009).

In this paper, a synthetic population was generated for the built environment, according to the population statistics, spatial information and individual activity pattern of the area based on the methodology proposed in (Bustos-Turu, van Dam and Shah 2017). Using socio-demographic data (density, household size, ratio of worker and non-worker, and car ownership), and geographical data (landuse, activity distribution), agents were generated randomly based on number of people living in each area. Then, agents were following an activity schedule which is different for included agent types (e.g. workers, residents those who are not economically active, and visitors), as well as for weekdays and weekends. Each activity was linked to a specific location based on the land-use file. A road network provided access to the different buildings and agents travel along the roads to the location of their next activity. During their trips, agents produced air pollution (CO_2 and NO_x) along the roads they use. The model kept track of the generated pollution which can then be used to visualize the impact of infrastructure change as well as behavior change on the city's air quality.

4. Case study and results

Beijing, the capital of China, is one of world's most global, dense and ancient cities. The Beijing-Zhangjiakou railway currently cuts through the center of Beijing, but the out-of-date rail track is being demolished and will be transformed to an electrical railway underground. Figure 3 shows a representative fractured urban area lying around a 10-kilometer section of the Beijing-Zhangjiakou railway, which was the very first urban rail constructed in Beijing. Facing a detrimental problem of the heavy air pollution, environmental impacts are essential metrics for redesigning the transport infrastructure and public space in Beijing. Being able to compare various design proposals by metrics such as environmental quality, human behavior and human exposure, helps the decision-making process of policy-making. In this paper, we demonstrate how our methodology can be used to test proposals.

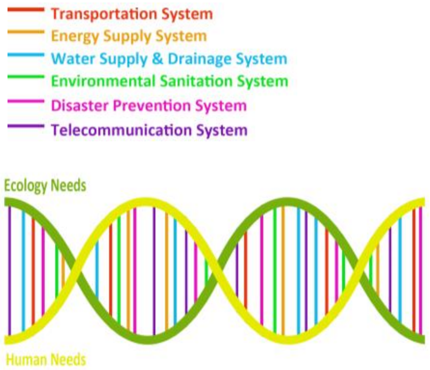

Figure 1. The DNA form of urban development.

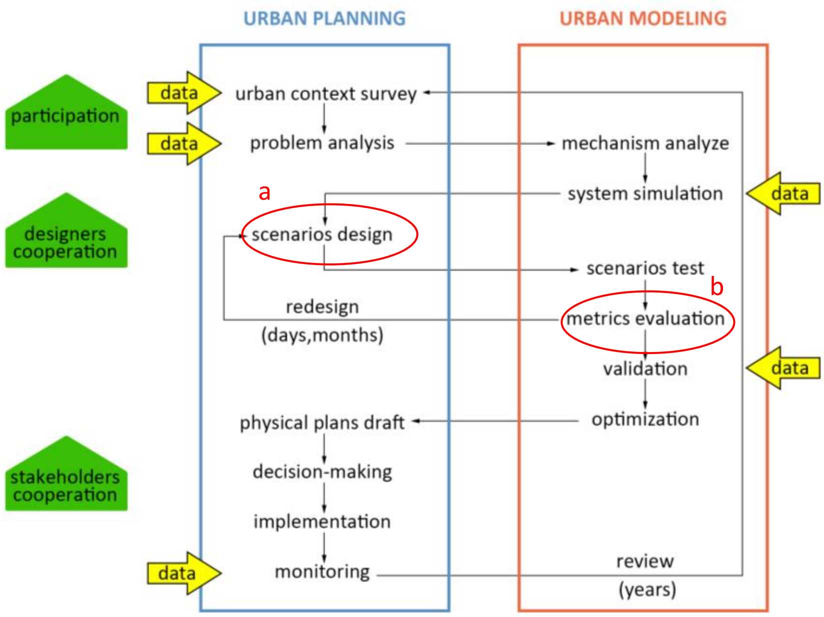

Figure 2. The proposed integrated methodology to evaluate designs and support stake holders.

4.1. Socio-demographic data input

The 6th population census of Beijing (2010), which provides demographic distribution at the district level, is used to generate the agent population. Since our case study is located in Haidian district, a number of density (people/ha^2) is assigned to residential areas by taking into account the statistics of permanent residents and the ratio of residential landuse in Haidian district. Furthermore, the synthetic population is categorized by a scale of worker: non-worker: visitor, which is 5:4:1 in this case. The number of households according to household (hh) size in Haidian district (2.46 people/hh) is also considered. Finally, vehicles are generated in each household with a number of 0.6 car/hh.

4.2. Geographical data input

The connectivity of a street network influences the patterns of pedestrian movement and travel mode choices in the area. In order to study the potential effects of various street networks on walking and driving behaviors, an area with the radius of 800m around the railway track with a buffer of 2500m-3000m away from the railway is considered as the case study area. Activity locations are defined based on two open source maps: parcel map of Beijing (2013) and POIs (points of interest) map of China-latest-free GIS data. Based on the Smart-City Model (van Dam, Bustos-Turu and Shah 2017), five types of human activity are considered in this paper: residential activity, industrial activity, commercial activity, cultural activity, and leisure activity.

In addition, two types of road networks are loaded into the model namely a street network for pedestrian movement and a road network for vehicles. There are nearly 7000 segments in the road networks and each of them hold a quantity of pollutants. In order to count the total pollutants, the emission standard for cars (Category M*) is given to vehicles, which is 80 g/m NOx (Beijing introduced the Euro IV standard and most of the Chinese private cars consume petrol).

4.3. Activity pattern input

The final input is activity pattern created from the 2008 Time Use Survey (TUS) in China, which was carried out for relevant policy-making and reflecting the Chinese life style. Results in this survey represent 7 kinds of human activities in weekdays and weekends, with differences between male and female, urban and rural. Based on this data, an activity schedule is defined for the urban area in Beijing in a typical weekday and a weekend.

4.4. Results & Discussion

After initialization, agents depart from home to workplace etc., by taking the given route choice method (i.e. choosing the shortest path). To calculate air pollution emitted by vehicles, car agents are created based on car-ownerships of the population, which plan their routes only on the layer of motorized roads. Every vehicle's travel distance is calculated and multiplied by emission standards, specifically, NO_2 g/km is chosen as the key. Furthermore, the emission is assigned to each road segment and visualized in heatmap (see Figure 4). As a validation, we compare our result with the real time NO_2 data from an online data source, shown in Figure 5. For the next step, different urban design scenarios will be simulated and compared by means of changing the input spatial data (i.e. the connectivity of road network, land-use, and public space distribution).

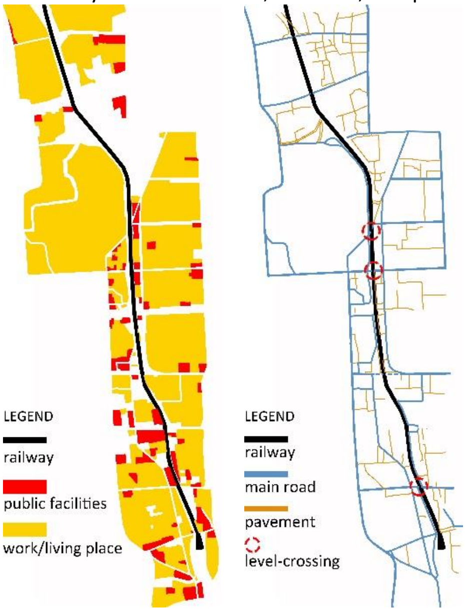

Figure 3. Visual and physical disconnect of the fragmentation around Beijing-Zhangjiakou railway.

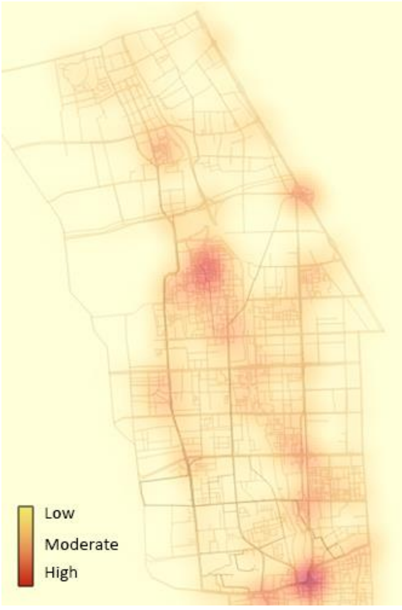

Figure 4. Visualization of NO_2 pollution in one workday (in midnight).

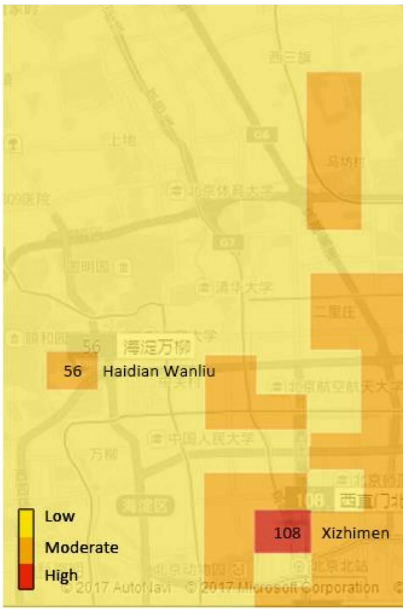

Figure 5. NO_2 pollution data at 22:00, Aug 9, 2017. (Source: UrbanAir)

5. Conclusion

This paper demonstrated a bottom-up and human-needs driven design and quantitative evaluation methodology, with respect to the demands of the ecosystem. Since policy-making is an interconnected network involving distinct stakeholders, this paper introduced a transparent platform by ABM for integrating urban transport infrastructure and public space design with human behavior and environmental quality analysis. The main part of this methodology was then applied in a case study in Beijing to test the effects of transport design scenarios on air quality, leading to policy-making supports.

References

Alberti, M., & Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. *Urban Ecosystems, 7*(3), 241-265.

Axelrod, R. M. (1976). *Structure of decision: The cognitive maps of political elites*. Princeton, US: Princeton university press.

Axelrod, R. M. (1997). *The complexity of cooperation: Agent-based models of competition and collaboration*: Princeton University Press.

Bustos-Turu, Acha, van Dam and Shah (under review) Electric vehicle smart charging strategies in urban energy systems: An integrated agent-based and multi-objective modelling approach, currently under review for Applied Energy Journal.

Carmona, M. (2003). *Public places, urban spaces: the dimensions of urban design* (1st ed. ed.). Oxford: Architectural Press.

De Nazelle, A., Rodríguez, D. A., & Crawford-Brown, D. (2009). The built environment and health: impacts of pedestrian-friendly designs on air pollution exposure. Science of the Total Environment, 407(8), 2525-2535.

De Nazelle, A., Nieuwenhuijsen, M. J., Antó, J. M., Brauer, M., Briggs, D., Braun-Fahrlander, C., ... & Hoek, G. (2011). Improving health through policies that promote active travel: a review of evidence to support integrated health impact assessment. Environment international, 37(4), 766-777.

Geddes, S. P. (1915). *Cities in evolution: an introduction to the town planning movement and to the study of civics*. London, UK: Williams & Norgate London.

Jackson, T., Jager, W., & Stagl, S. (2004). Beyond insatiability: needs theory, consumption and sustainability. *ESRC Sustainable Technologies Programme Working Paper Series, 2*.

UrbanAir. http://urbanair.msra.cn/

Varnelis, K. (2008). *The infrastructural city: Networked ecologies in Los Angeles*. Barcelona: Actar.

Zellner, M. L. (2008). Embracing complexity and uncertainty: the potential of agent-based modeling for environmental planning and policy. Planning theory & practice, 9(4), 437-457.