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Urban compactness and the trade-off between air pollution emission and exposure: Lessons from a spatially explicit theoretical model

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A R T I C L E I N F O

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A B S T R A C T

Air pollution is a major concern in urban areas worldwide. The interplay between urban structure and air pollution from an environmental, health and social perspective is the focus of our work: we model how urban structure impacts traffic-induced pollutant emissions and the exposure of residents to those pollutants.

We present a chain of models applied to theoretical monocentric space: a residential choice model with endogenous open-space and road network, a commuting traffic generation and road assignment model and a pollutant emissions, dispersion and exposure model. The theoretical study approach decouples results from location specific characteristics and enables us to analyse how the preference of households for green amenities, a transport tax, the provision of public transport alternatives and local neighbourhood design impact the environment (total emissions) as well as residents' health (population exposure) and utility.

We emphasise that environmental strategies in the form of urban compaction have a strong impact on the exposure of households to pollutants, especially close to the centre, in addition to their reduction of welfare. Our results suggest that more beneficial policy outcomes can be obtained from strategies which preserve green spaces close to the centre or which intend a greater shift from car to public transport. Further, we find indication that different local designs of neighbourhoods have much stronger impacts on the exposure–emission tension than city-wide land use or transport options.

1. Introduction

Despite vast technological improvements and various political control strategies, air pollution is still a major concern in urban areas worldwide. It is not only a hazard to the environment but also to human health. Annually, approximately 1.3 million people worldwide die prematurely due to outdoor air pollution (WHO, 2011), for which car traffic is acknowledged to be a major source. Quantifying those emissions caused by traffic and the subsequent exposure of the population is therefore crucial for potential mitigation of health risks, such as asthma prevalence (HEI, 2010).

Linking pollution to traffic flows questions the reason for and pattern of personal trips, hence the separation of activities in space and the urban form. Urban patterns and densities shape transport infrastructures and affect household modal choices between polluting modes. Urban forms requiring high emissions of transport modes are criticised for their lack of sustainability. Alternatively, evaluating the exposure of citizens to emissions can affect the health and attractiveness of a city and its urban form. Selecting an urban form either reducing emissions or residents' exposure may not necessarily lead to the same urban planning policies. The trade-off between emissions and exposure as resulting from urban form is the central issue investigated in this article. In order to obtain general findings, we opt for a modelling approach in a fully controlled environment: we model a series of urban structures resulting from households' decisions and policy scenarios, from which we derive car traffic and analyse pollution exposure and emissions.

We start with a brief literature review to highlight the contradicting impacts of urban form policies and to position and explain the rationale of our modelling choice.

1.1. On urban form and the emission – exposure tension

Many studies provide evidence for the environmental impacts of automobile traffic and highlight the role of urban forms and land

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use planning for achieving a more sustainable mobility (Banister, Watson, & Wood, 1997) and more environmentally friendly cities. There is now a large body of literature explicitly relating urban forms to transport network growth (Batty, Xie, & Sun, 1999; Rui & Ban, 2011), to mode choices and travel distances (Boarnet & Sarmiento, 1998; Brownstone & Golob, 2009; Camagni, Gibelli, & Rigamonti, 2002; Ewing & Cervero, 2001; Ewing, Pendall, & Chen, 2003; Handy, Cao, & Mokhtarian, 2005; Jabareen, 2006; Levinson, 1998), to energy consumption (Newman & Kenworthy, 1989, 2000) and to pollution emissions (e.g. Manins et al., 1998; Dolney, 2009). In order to meet sustainability challenges, many planners and policy makers argue that a compact city is the desirable urban form, precluding that this form shortens commutes and other trips. In addition, lesser fragmentation of natural habitats and waste of agricultural land or lower infrastructure costs are argued to be benefits of a compact city, in contrast to the trend towards urban sprawl (e.g. European Environment Agency, 2006).

However, whether energy consumption and the emission of pollutants can be shown to be reduced at regional scale with a more compact urban form because of reduced car use, containment policies, densification and anti-sprawl measures are still very much debated (Breheny, 1995; Gordon & Richardson, 1997; Neuman, 2005; Van der Waals, 2000). For example, Echenique, Hargreaves, Mitchell, and Namdeo (2012, p. 121) argue that *compact development should not automatically be associated with the preferred spatial growth strategy* as there is also evidence that compact development with its social and environmental effects has not been examined closely enough.

The arguments in favour of urban compactness might also change if one considers not only the environmental pillar of sustainability in terms of emission of green house gases, but also human exposure to pollutants, which is key to assessing the risk of adverse health effects and thus a component of social well-being. This perspective is usually not considered in planning practice, while exposure might indeed increase with urban compactness because of the joined concentration of traffic flows, population and shorter trips, meaning colder and thus more polluting engines. As emissions disperse and react, even low emissions can produce high concentrations of first and secondary pollutants in specific locations (Schweitzer & Zhou, 2010). In addition to triggering health problems, the compact city might therefore well reduce the attractiveness of more central areas in favour of exurban residential choices, in contradiction to an anti-sprawl policy. Cervero (2001), Kenworthy and Laube (2002) and Marshall, Mckone, Deakin, and Nazaroff (2005) have highlighted this health effect and this particular dilemma between compact and sprawl cities.

Beyond the compactness–sprawl tension at the scale of a city-region, different aspects of the local morphology of built-up areas – not intrinsic to density – also come into play for assessing pollution emissions and impacts. In particular, the relative spatial distribution of open spaces with respect to residences (De Ridder et al., 2004) or the local street design (Chan, So, & Samad, 2001; Weber, Kuttler, & Weber, 2006) are shown to affect air flows, thus pollution dispersion and exposure. We know from 2D urban economic models with local effects (Caruso, Peeters, Cavailhes, & Rounsevell, 2007; Lee & Fujita, 1997; Wu & Platinga, 2003) that this local arrangement of green and built-up surfaces, i.e. the scatteredness of the urban footprint, can result from agents' preferences, especially on how households trade-off open-space amenities and transport costs. The structure of the road network can also be seen as the result of this trade-off between local goods demand and commuting accessibility. Caruso et al. (2011) show that more linear and connected network structures emerge when the preference for neighbourhood density is high, while more dead-end road structures emerge when local open spaces are highly valued. Residential preferences are not without effect on the relative arrangement of built-up land, green spaces and roads, and this arrangement itself is likely to impact on pollution generation and exposure levels.

1.2. Modelling urban form and pollution exposure

Modelling the link between urban structure and exposure to air pollutants has been the aim of only a few researches so far. Moreover, to our knowledge, none have explicitly linked air pollution to the components of residential choice that lead to different urban structures. We believe this to be an important extra step since the design of land use or transport policy can then be related to residential choice, and further, the impacts on utility (well-being) contrasted with environmental gains.

Marquez and Smith (1999) presented a general framework connecting urban form with first and secondary pollutants. Marshall et al. (2005) proposed an analytical single compartment model where the link between urban growth forms and pollution inhaled is made via a density–emissions elasticity. Using observed and calculated elasticity of density with respect to vehicle kilometres travelled (VKT) by car as a proxy for elasticity of density with respect to emissions, the authors show that increasing population density via infill is unlikely to reduce travelled distances in a way that would reduce pollutants inhaled per capita. Urban sprawl then stands as a better strategy. Yet, the aggregate approach taken by Marshall et al. (2005) does not allow for distinguishing spatial heterogeneities in exposure within the city region, in particular differentiated effects at varying distance from the city center.

Intra-urban spatial heterogeneity is considered explicitly in a series of applied case studies where pollutant flows are modelled in detail, but at the expense of obtaining general rules due to location specific features. De Ridder et al. (2008) and Martins (2012), for instance, used numerical simulations of urban growth patterns and their impact on air quality exposure in the Rhur (Germany) and the Porto (Portugal) area respectively. Both find that the population in the core city is exposed to more pollutants than the population living in the outskirts.

Borrego et al. (2006) offered a comparative approach by using three imaginary cities with different degrees of compactness (compact, corridor and dispersed cities) as input to an air quality simulation model. Although their imaginary cities are rather *ad hoc* from an urban economic point of view and the calibration of traffic and emissions (calibrated on existing cities) are not made as explicit as in Marshall et al. (2005), the authors point out substantial variations of exposure between the city centre and outskirts and emphasise the need for further investigation of local scale effects. They also showed strong differences for different pollutants: the compact city results in fewer people exposed to high levels of ozone (O_3) but more people exposed to nitrate oxides (NO_2) in comparison to the dispersed city.

Empirical and modelling research shows evidence that disaggregate impacts within the city tend to raise equity effects that add up to the aggregate dilemma between emissions per capita and average exposure to pollutants. Aspiring equity between centrally located and exurban households further actuates the compactness policy agenda.

Beyond distance effects, one can finally also consider (hyper-) local or neighbourhood effects. First, Marshall et al. (2005) suggested that local design is key to resolving the compact city contradiction. Second, from a methodological view, Mensink, De Ridder, Deutsch, Lefebre, and Van De Vel (2008) have identified aggregation biases and scale interactions between the various components of urban pollution models. Third, we also know that neighbourhood effects matter in terms of residential location choice: local density can be seen as a congestion externality impacting the urban equilibrium (see model with congestion externalities in Fujita