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Urban Interventions to Reduce Pollution Exposure and Improve Spatial Equity

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Air pollution is of increasing concern to urban residents and urban planners are struggling to find interventions which tackle the trade-off between environmental, health, and economic impacts arising from this. We analyze within a spatially explicit theoretical residential choice model how different urban interventions can reduce exposure to endogenous traffic-induced air pollution at residential locations. We model a city of fixed population size, where households are averse to localized pollution and examine how a flat commuting tax, an urban growth boundary, a cordon toll, and the optimal distance-based tax compare to an urban scenario without any planner's intervention. We find that an urban intervention to optimally address exposure concerns needs to achieve steep density gradients near the urban fringe and flat gradients near the center. We show the deficiencies of the alternative interventions to achieve optimal population distributions within the city and in a scenario where peoples' aversion to pollution increases. We then discuss these interventions in light of resulting spatial patterns of exposure and spatial equity that is households' assessment of their own exposure to air pollution relative to their responsibility for the exposure of others depending on their spatial location within the city. Our results show that, when equity is also a concern, compensations are needed from households who live in the periphery and our simulations suggest that a cordon toll can then achieve a more balanced outcome.

Introduction

Urban air pollution is a prominent feature of our urbanized world and causes environmental and health problems. The pollution arising from traffic is the main source of intra-urban spatial variations in the concentration of air pollutants in many cities (HEI 2010). Depending on where households live within a city, they are responsible or affected by traffic pollution differently. If households value local air quality and want to reduce their own exposure to pollution, the intra-urban distribution of the population will be more dispersed (e.g., Robson 1976; Schindler, Caruso, and Picard 2017). Conversely, the increased environmental consciousness of households

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(or of policy makers) may lead to further concentration around central locations in order to reduce commuting trips, hence own emissions (e.g., Schindler and Caruso 2018) and their impact on others. It is particularly intriguing for a household that environmental or equity concerns oppose to its health concern and willingness to reduce its own exposure to pollutants. Likewise, the juggling of this is difficult for a policy maker and the result of a particular intervention, such as a per km tax or a cordon toll, may remain unclear.

In the present work, we contend that these questions underpin a problem of spatial equity, which is largely overlooked in the literature. It is indeed a spatial equity concern in the sense of how much each household, given its residential location within the city, causes other residents to be exposed to pollution, compared to how much each household is itself affected by the location choice of others. This relative spatial assessment could in turn influence the perception of risk associated with air pollution by households (Gatersleben and Uzzell 2000) at their residential location.

Our goal here is to identify the effect that typical urban interventions, which attempt to reduce exposure at the residential location, have on urban structure and urban welfare and then to discuss these interventions in light of increased awareness about pollution and equity.

We pursue this goal within a spatially explicit theoretical residential choice model where endogenous local pollution externalities arise from passing traffic as in Schindler, Caruso, and Picard (2017). This article extends work by Schindler, Caruso, and Picard (2017) who studied the equilibrium city structure (without planner's intervention) and conditions for a planner's optimum achieved through a distance-based tax in an open city framework (i.e., endogenous population size). Instead, population here is fixed in order to focus on comparing planner's interventions: a flat commuting tax, an urban growth boundary, an optimal distance-based tax, and a cordon toll (closed city framework as of Fujita 1989). We contribute to the literature which attempts to identify practical urban interventions in comparison to optimal strategies in the presence of negative endogenous urban externalities. More generally, we contribute to the geographical and urban economics literature on urban structure and air pollution, where exposure (i.e., the health perspective) is still understudied despite it recently receiving increased attention (e.g., De Ridder et al. 2008b; Schweitzer and Zhou 2010; Schindler and Caruso 2014, 2018; Hankey and Marshall 2017; Gao et al. 2018) compared to emissions (i.e., the environmental perspective) and where intra-urban variations are often ignored. In particular, our geographical perspective adds discussions of spatially differentiated effects of the various interventions to literature studying the relationship between urban structure and health implications due to localized air pollution.

Urban structure and air pollution

Every now and then for about 50 years, urban air pollution received some theoretical attention from geography, urban, and environmental economics. Early models with intra-urban variations of pollution can be found in Henderson (1977), who considered dispersion from firm production sources, and in Fisch (1975), Robson (1976), McConnell and Straszheim (1982), who considered pollution stemming from traffic specifically. More recent theoretical endeavors with intra-urban variations include Verhoef and Nijkamp (2003), Arnott, Hochman, and Rausser (2008), Rauscher (2009), Kyriakopoulou and Xepapadeas (2013), Schindler and Caruso (2014), Borck and Brueckner (2018), Larson, Liu, and Yezer (2012), Schindler and Caruso (2018), Schindler, Caruso, and Picard (2017) with either more explicit treatment and analysis of spatial components or environmental externalities.

Among these recent models, only Schindler and Caruso (2014, 2018) related traffic emission and exposure effects. They compared alternative theoretical urban development patterns, and similar to De Ridder et al. (2008a) and Martins (2012), who worked on real cases, stressed the contradicting effect of urban densification: lower emission concentrations in compact urban developments or close to city centers, but lower population exposure in dispersed developments or in the periphery. This result also matched the empirical investigation of Schweitzer and Zhou (2010) across US metropolitan areas or the intra-urban discrepancies between emission and exposure found by Sider et al. (2015). Sider et al. (2015) also added a social equity dimension since they found that disadvantaged population groups experience highest exposure levels.

Urban externalities and optimum urban interventions

Traffic congestion is probably the externality that is closest in nature to traffic-induced air pollution and where different kinds of interventions have been modeled and compared to a planner's optimum. Except for McConnell and Straszheim (1982) and Currie and Walker (2011), who already considered both congestion and emissions, the congestion effect is mostly considered for the time loss or the additional transportation cost it adds to economic agents, rather than its impact on regional emissions or on residents' exposure to pollution induced by passing traffic. Congestion has been internalized to understand its impact on equilibrium urban structure, and there is a wide literature on how different urban interventions, especially per-km taxes or cordon tolls, compare to optimal strategies (e.g., Mun, Konishi, and Yoshikawa 2003; Verhoef 2005; De Lara et al. 2013; Brueckner 2014) to reduce congestion.

Optimal pricing schemes have been considered in the context of traffic-induced air pollution but rather focus on aggregate emissions than health concerns of localized, spatially differentiated air pollution, and results are mixed depending on the very assumptions of the model. Le Boennec (2014) analyzed the optimal level of an eco-tax (i.e., emission tax) that accounts for the environmental damage of pollution from commuting traffic. He showed that a per-km tax is a good second best intervention by reducing emissions and densifying the city. With pollution externality added to congestion, McConnell and Straszheim (1982) showed that the more serious the pollution is (increased pollution or aversion to it) compared to congestion, the less is a per-km tax a suitable alternative to the optimal tax. Johansson (1997) illustrated how an optimal road charge should increase when speed decreases in a model where extra emissions are due to congestion. Li et al. (2014) studied cordon pricing as a second-best policy in case of congestion and environmental externalities. They presented an analytical model with simultaneous optimization of the cordon location and the level of the toll, but population distribution and travel demand were exogenously defined linear functions of distance. Works investigating the indirect effects of congestion charges on emissions in the city are mostly of empirical nature or without consideration of location decisions or their implications on population exposure (Atkinson et al. 2009). Equity is not considered as such in optimum policies, except in the early work of Robson (1976) who took interest in improving utility for the worst off household but does not considered transport costs in the residential trade-off.

We think that an intra-urban geographical analysis of urban interventions in the context of traffic-induced air pollution is timely. We focus on their effects on the spatial structure of the city and discuss their spatial equity, health, and environmental performance.

The remaining article is structured as follows: Section "The model" presents, solves, and discusses the closed city equilibrium model providing the benchmark urban scenario, that is, a city of fixed population size where households are averse to air pollution induced by traffic depending on everyone's residential location choice without any planner's intervention. Section "Urban interventions" models and discusses urban interventions and their resulting urban structures. Section "Aversion to exposure, spatial patterns of exposure and spatialequity" then compares the different interventions, first against how much information/aversion households have about their exposure to traffic pollution; second against resulting spatial patterns of exposure across residential locations within the city; and third against the spatial equity households might be concerned with, that is their relative assessment of own exposure versus responsibility for exposure of others. We conclude in Section "Discussion and conclusion".

The model

Model framework

We consider a linear monocentric urban system with absentee landowners in the tradition of Alonso (1964). All jobs are located in a spaceless Central Business District (CBD) at the origin of the system, $r = 0$. Obviously this monocentric assumption can be challenged, but given that most of the literature considers pollution as a single aggregate outcome for a city, digging into urban structure with this spatial dimension is already an important step forward. In addition, the commuting interaction is still an essential part of urban structures. Empirical studies provide evidence to think that monocentricity is still a good representation for most cities, while polycentrism is a case for cities when they grow large only (e.g., Louf and Barthelemy 2013; Lemoy and Caruso 2020) and that the Alonso model is actually still a very good candidate for representing densities (e.g., for European cities see Delloye, Lemoy, and Caruso 2020).

All households are homogeneous in characteristics and preferences. The city is closed in the sense that the number of households living in the city is fixed but households can move freely within the city to maximize utility. A closed city with constant population was chosen to facilitate the comparison of various urban interventions, as explained later on. This model framework means that our findings are valid within a large range of city sizes but need to be reconsidered for cities in the highest ranks.

While in the standard model without pollution, households only trade-off accessibility to the CBD and housing consumption, households in our model add exposure to air pollution from passing traffic to this basic trade-off. The utility function is of the Cobb–Douglas type and includes pollution exposure at residential locations across the city (as defined in the open city model in Schindler, Caruso, and Picard (2017)). Each household maximizes their utility defined as

$$U = \kappa Z(r)^{1-\alpha} H(r)^{\alpha} P(r)^{-\beta} \tag{2.1}$$

where $\kappa = (1-\alpha)^{\alpha-1}\alpha^{-\alpha}$ is a simplification constant. Households receive utility from consuming non-housing goods Z and housing space H, for which they have preferences $(1-\alpha)$ and α, respectively, and where $0 \leq \alpha \leq 1$. Households dislike to be exposed to air pollution $P(r)$ from passing traffic at their residential location r by $0 \leq \beta \leq 1$, which varies depending on the population distribution within the city.

Households spend their entire income Y on commuting, as well as on housing space H and non-housing goods Z. The above utility is therefore maximized under the following budget constraint

$$Y = Z(r) + H(r)\,R(r) + t\,r \tag{2.2}$$

where t are the unit transport costs per distance r and $R(r)$ is the land rent paid for housing at location r.

Each household residing at location r endures a negative externality from being exposed to air pollutants generated by commuters living at further distances from the CBD, up to the urban boundary r_f, and passing the location r on their way to work.

The spatial distribution of households within the city is endogenous, and so is the local pollution exposure externality $P(r)$ as it is defined by the location of household commuters (one commuter per household is assumed).

The exposure to local pollution $P(r)$ is increasing with the traffic volume passing at r, and is given by

$$P(r) = \left(1 + a + b\int_r^{r_f} \frac{1}{H(r)}dr\right)^{\gamma} \tag{2.3}$$

A linear relation to technology standards is expressed by the parameter $b > 0$. The larger b, the higher are the emissions per vehicle and unit distance travelled. b is unrelated to monetary costs of fuel consumption (hence transport costs t) such that it only reflects the cleanness of vehicle technology. $\gamma > 0$ reflects the level of risk perception associated with air pollution and addresses potential deviations (e.g., Gatersleben and Uzzell 2000) between households' perception and actual levels of air pollution. At each location, a constant (regional) background air pollution concentration $a > 0$ originating from other sources (Fowler et al. 2013) than traffic is assumed. a is exogenous and not related to the total population or total distance commuted in the city. A unitary term is added to the equation such that in the absence of pollution, exposure $P(r)$ is equal to one and does not affect the utility level.

Equilibrium city and benchmark simulation

In the following, we characterize the equilibrium city that is the laissez-faire without any planner's intervention. We focus on the density and exposure distribution across the city and the city's spatial extent. For more detail on the solution of the equilibrium, the reader is referred to Appendix A. The derived equilibrium benchmark scenario will then be contrasted to characteristics of other urban scenarios with planner's interventions in Section "Urban interventions".

In equilibrium, all households receive the same utility no matter their residential location, such that no household has an incentive to move. No equilibrium exists in case aversion to traffic-induced exposure is too strong compared to the opportunity cost of land offered by farmers, transport costs, and the background pollution prevailing at the city border.

Intra-urban distribution of population and exposure

Households take the exposure level at a location as a given and choose the consumption of housing space accordingly. Population density n across the city is a result of people's spatially differentiated housing consumption since land availability at each residential location is normalized to $n = 1/H$.

$$n = \alpha^{-1} u^{*\,-\frac{1}{\alpha}} P^{-\frac{\beta\gamma}{\alpha}} (Y - t\,r)^{\frac{1}{\alpha}-1} \tag{2.4}$$

Thus, households consume more housing space (i.e., lower density) where exposure and transport costs are higher, in order to receive the same utility level u^* as all other households elsewhere in the city.

The exposure profile across the city is then

$$P = P_0 u^{* - \frac{1}{\alpha+\beta\gamma}} \left[(Y - t\,r)^{\frac{1}{\alpha}} - (Y - t\,r_f)^{\frac{1}{\alpha}} + a_0 \right]^{\frac{\alpha}{\alpha+\beta\gamma}} \tag{2.5}$$

where

$$P_0 = \left(\frac{b}{t} \alpha^{-1} (\alpha + \beta\gamma) \right)^{\frac{\alpha}{\alpha+\beta\gamma}} > 0 \quad \text{and} \quad a_0 = \left(\frac{a+1}{P_0} \right)^{\frac{\alpha+\beta\gamma}{\alpha}} > 0$$

P_0 is a base pollution exposure level generated by commuting traffic within the city for given economic and technology frameworks. Additionally, there is a spatially differentiated exposure level at each location, respectively (the term in brackets in (2.5)). a_0 expresses the relative importance of both pollution sources by relating the base traffic pollution to the background pollution level. Equation (2.5) highlights the negative interrelation between local pollution and the endogenous utility level u^* all households gain in the city.

Spatial extent of the city

Households locate inside the city boundary r_f and farmers beyond r_f. The equilibrium spatial extent of the city r_f can then be determined as the location where rents offered by residents and farmers equalized, which yields

$$r_f = \frac{Y}{t} - \frac{R_A^{\alpha}(1+a)^{\beta\gamma}}{t\,u^*} \tag{2.6}$$

The city's spatial extent increases with larger household income Y and endogenous utility level u^* and, thus, as we will see the emission factor b and total population N. In other words, higher pollution due to higher emissions per distance driven results in a spatially expanded city to accommodate the same number of households N. The spatial extent decreases with higher opportunity costs of land R_A, level of background pollution a and transport costs t.

Simulated example

In Fig. 1, we provide simulated equilibrium population density distributions in a city with and without households being concerned about exposure to traffic-induced air pollution (i.e., exposure externality) to explore spatial effects of the externality.[1] Equilibrium household distributions in a city with exposure externalities (solid black line in Fig. 1) show a flat negative density gradient with the mid-distances and outer locations being attractive location choices even at comparably high densities. Compared to an equilibrium city without exposure externalities (dashed blue line in Fig. 1), the urban fringe distance is extended in the closed city equilibrium and more households live in suburban locations. From urban economic theory (Fujita 1989), we know that in a city without externalities, density monotonously decreases with distance to the CBD. In comparison, exposure externalities let residents to choose to crowd less in central city areas and instead form a slower density decrease with distance to the center further extended into the

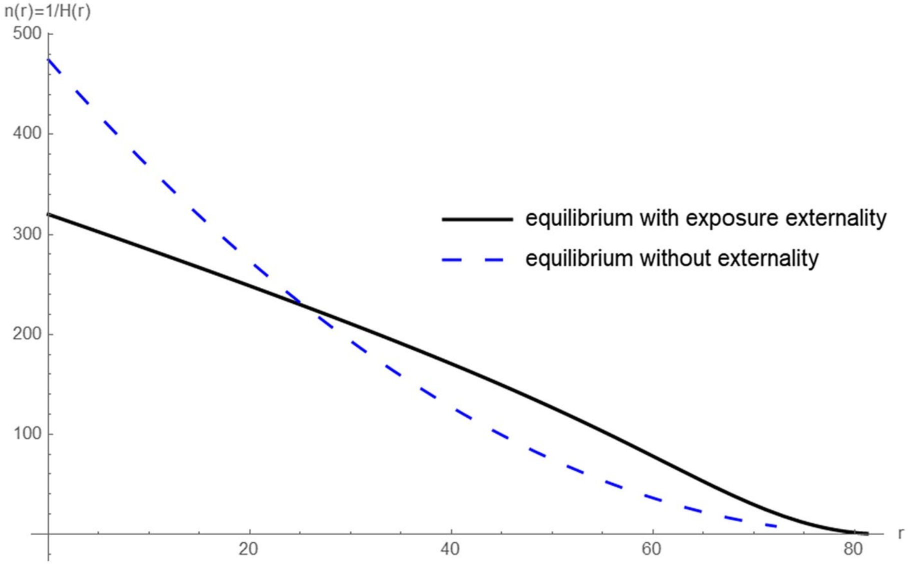

Figure 1. Equilibrium population densities as a function of distance to the city center for two urban scenarios: (a) households are not concerned about exposure to traffic-induced air pollution (standard urban model); (b) households are averse to exposure to traffic-induced air pollution. [Colour figure can be viewed at wileyonlinelibrary.com]

suburbs. This results in a visible drop in population exposure in central locations that is the number of people living at a location multiplied by the exposure at that location (Fig. 2). Hence, the number of people exposed to maximum air pollution levels prevailing at central city locations is reduced. Since total population is fixed in the closed city, utility is reduced in case of households being concerned about exposure to localized pollution compared to the standard urban model. Using Fig. 1 as a base point, we look in the next section at effects of various urban interventions.

Urban interventions

Urban and transport planners and decision makers can choose from a pool of interventions aimed at tackling health concerns from traffic-induced air pollution. How these various interventions affect urban structures and subsequently population exposure to traffic-induced air pollution is, however, not clear a priori. Thus, we set out to analyze how planners' interventions impact the relationship between residential location choice, urban structure, and exposure, and compare common urban interventions: we analyze the effects of a flat commuting tax (3.1), derive a planner's optimal policy (that is as we will learn a distance-based tax) (3.2), simulate an urban growth boundary (UGB) (3.3), and derive a cordon toll as second-best, easier to implement policy (3.4). Fig. 3 summarizes the analyzed interventions and their derived urban structures, and Fig. 4 gives a more detailed illustration of the different policies at suburban locations near the urban fringe.[2] Each intervention and its impacts are in turn explained in the following subsections. Note that we conducted sensitivity analyses of the chosen parameter values on the simulations but found that the results did not change qualitatively.

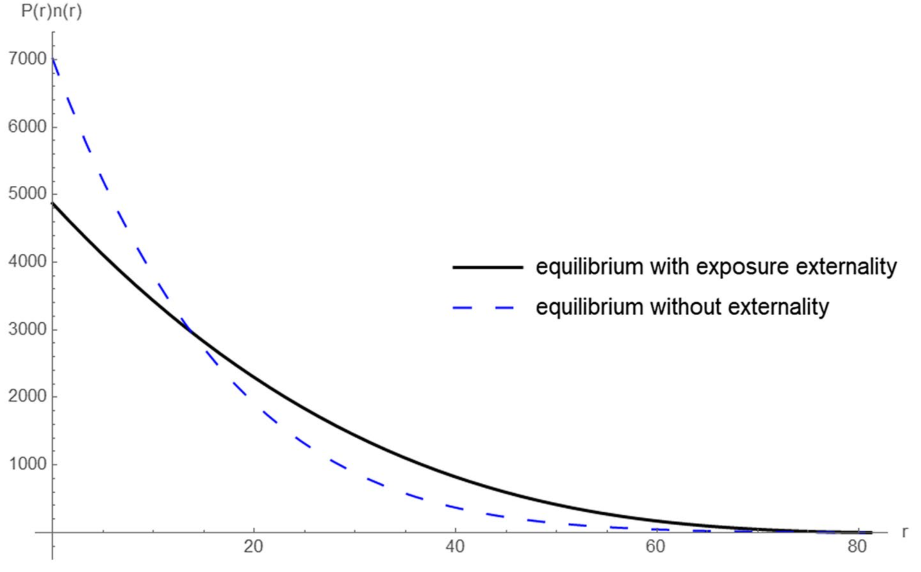

Figure 2. Equilibrium population exposure (i.e., exposure multiplied by population density at each location) as a function of distance to the city center for two urban scenarios: (a) households are not concerned about exposure to traffic-induced air pollution (standard urban model); (b) households are averse to exposure to traffic-induced air pollution. [Colour figure can be viewed at wileyonlinelibrary.com]

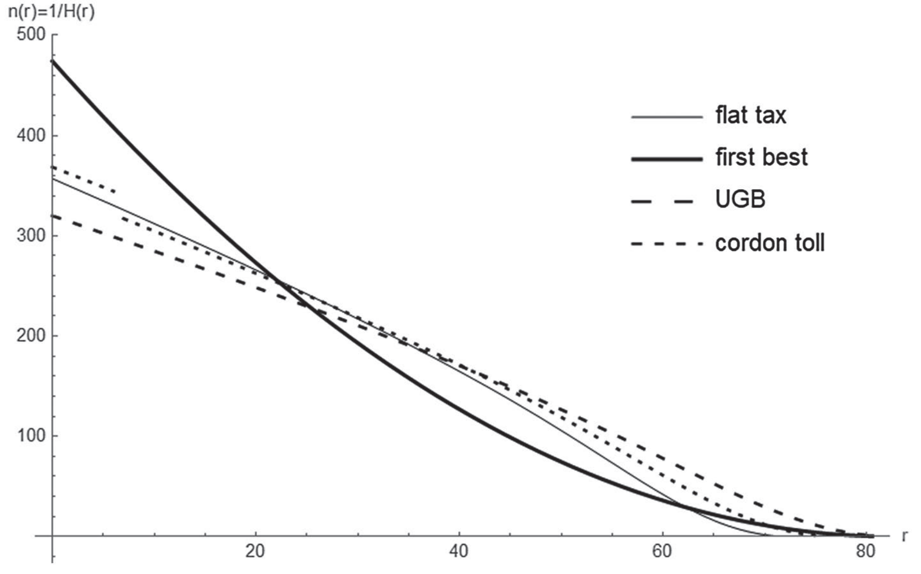

Figure 3. Population densities as a function of distance to the city center in case of the four analyzed policies.

Flat commuting tax

A common and easy to implement policy measure to disincentivize car commuting and distances traveled is a flat commuting tax. Such a tax increases the costs of commuting per distance in a lump-sum fashion, for instance, collected through increased fuel prices. Yet, it is a policy which is implemented uniformly across the city. As simulated for a reasonable example tax level comparable in relation to the other urban intervention scenarios in Fig. 3 (thin solid line), such a uniform tax reduces the size of the urban area and fosters a population shift toward central locations. Density gradients are thus steeper, with more people locating in central locations, while population densities at mid-distances are still high. Compared to equilibrium in Fig. 1, the urban area is spatially reduced due to the higher commuting costs. Yet, utility is reduced since households incur higher transport costs, while population size is fixed.

First-best intervention: distance-based tax

City-wide interventions, such as a flat commuting tax, however, do not differentiate between households living at different distances from the CBD and the respective spatial heterogeneity of their contribution to pollution concerns. To account for the spatiality of the pollution issue, we now develop the optimal planner's intervention to endogenize this heterogeneity (see Appendix B) and compare it to the other urban scenarios.

First-best planner's intervention

$\mu(r)$ expresses the optimum intervention which a planner should impose in order to achieve an optimal distribution of households in the city. μ solves condition (B.10) and writes as

$$\mu(r) = \beta\gamma\alpha^{\frac{\alpha}{1-\alpha}} u^{*\frac{1}{1-\alpha}} \int_0^r (H(s))^{-\frac{1}{1-\alpha}} (P(s))^{\frac{\beta\gamma+\alpha-1}{1-\alpha}} \mathrm{d}s \tag{3.1}$$

which is nil at the center and positive at all other locations. Since n and P are positive functions, we can show that μ is increasing with distance to the CBD and that a planner can decentralize the first-best by levying a localized lump-sum tax of value $b\mu$. The tax affects the city structure as described in the following.

First-best city structure

As simulated in Fig. 3, a first-best policy increases population densities at central locations since the pricing policies provide an incentive to reduce both commuting distances and the number of households to go past on the commute to work (Fig. 3, thick solid line). Interesting are the lower densities at mid-distances in the first-best urban scenario. Households there benefit neither as much from accessibility to the CBD nor from reduced local exposure levels and are therefore compensated by larger housing lots. As also Brueckner (2014) finds in the discrete spatial set-up with traffic-congested bridges, population concentrates at central and outer locations rather than mid-distances. The first-best policy, however, mostly acts on density distributions. The city boundary is slightly brought closer to the center (reduced city extent) educed compared to the equilibrium spatial extent due to the extra spatially differentiated charges. The utility level is highest in the first-best urban scenario compared to the other policy scenarios.

Urban growth boundary

As the optimal intervention (i.e., distance-based tax) requires intensive knowledge of location-differentiated marginal disutility of exposure and resources for implementation by the planner, second-best alternatives are commonly considered by planners. An example is urban growth boundaries (UGB). As we have seen, if households consider pollution exposure in their residential choice, they escape exposure by moving to fringe locations without a planner's intervention.

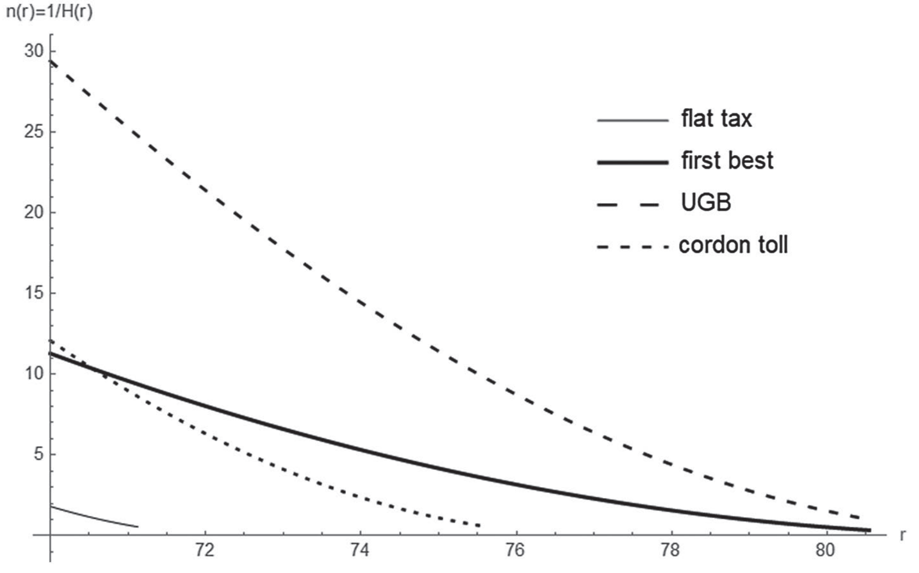

Figure 4. Zoom-in to outer urban locations close to the fringe: population densities as a function of distance to the city center in case of the four analyzed policies.

A common easy to implement planning policy to countervail household's flight toward the fringe, especially with the aim to stop urban sprawl, is the restriction of the spatial extent of the city with an urban growth boundary (e.g., Brueckner 2000). We test whether an UGB is indirectly beneficial in the air pollution context as UGBs not only restrict the boundary of built-up areas, but also affect the internal city structure.

Simulations (Fig. 3) show that restricting the city's spatial extent at the fringe distance from the first-best (tax) scenario particularly increases densities at outer locations and may result in non-monotonic density gradients. Households still escape from pollution by moving away from the center and accept higher densities at locations close to the UGB as the valuation of local air quality increases. The segment of positive density gradients depends on the level of valuation of local air quality, background air pollution, transport costs and the stringency of the UGB. Thus, while urban structures resulting from an optimal tax are characterized by dense central locations (Fig. 3), an UGB instead densifies locations near the UGB, also following Brueckner (2007). Utility in the city is lower due to the exogenous restriction of the city's spatial extent.

Cordon toll

A cordon toll is a common second-best alternative that has been analyzed mainly in the context of traffic congestion and as to its efficiency to indirectly reduce emissions. A cordon toll charges only commuters who live beyond a certain distance a fixed amount. In the context of local pollution, this policy design accounts for the increased emissions generated per capita and responsibility for exposure induced on others by households who live further away from the CBD. The analysis of such a flat pricing scheme for outer locations also originates from the properties of an optimal tax, which increases strongly with distance at central locations while changes at outer locations are small.

The level of the cordon toll

A cordon toll charges households who live beyond the location of a cordon r_c a fixed toll τ, while households within the cordon area are exempted. We call those who have to pay the toll n_o, and the ones exempt from it n_i. We find (details in Appendix C) that the level of the cordon toll is then

$$\tau = b\beta\gamma\,(1-\alpha)^{-1}u^{*\,\frac{1}{1-\alpha}}\int_0^{r_c} n_i^{\frac{1}{1-\alpha}}\,P_i^{\frac{\beta\gamma}{1-\alpha}-1}\,dr(r_f - r_c) \tag{3.2}$$

which reflects the shadow costs related to exposure of households living inside the cordon area. It is either nil in the cordon area or equal to τ at any location beyond the cordon station on $]rc, rf]$. It depends on the population and pollution distribution within the cordon area, aversion to exposure, utility and the distance between the city fringe r_f and the cordon station r_c. A stronger aversion and a larger distance between r_f and r_c require a higher cordon toll.

Allocating an additional household inside the cordon area has only direct implications for locations inside the cordon area (C.8). The population density inside the cordon area n_i decreased with increased exposure impacts on others, local pollution, level of the composite good, preference for housing space, agricultural rent, transport costs, and distance to the CBD; and increases with income and stronger household preferences for non-housing goods.

In contrast, locating an additional household at locations beyond the cordon location has direct (private) and indirect (social) effects on welfare and other households (C.9). The population density outside the cordon area is positively related to the preference for non-housing goods and income, but negatively to the level of exposure, the toll level, the distance between r_f and r_c, the preference for housing space, transport costs, agricultural rent and distance to the CBD.

Urban structure under a cordon toll scenario

The cordon toll densifies central areas more than a scenario without any planner's intervention (equilibrium), as in case of congestion externalities in work by De Lara et al. (2013), while locations at mid-distances away from the CBD still yield higher population densities than in the first-best tax scenario (Fig. 3, small dashed line). The cordon toll makes living beyond the cordon station more expensive such that locating just before the cordon is beneficial for more households since it reduces exposure at minimum costs. Thus, a relocation of households from the periphery into the cordon area occurs. Densities drop just after the cordon station since when paying the toll, an allocation at larger distances is more beneficial.

The cordon toll reduces households' available budget and, therefore, also brings the city boundary closer to the CBD (Fig. 4, small dashed line). This explains the spatial discontinuity introduced by the cordon station and thereby densified mid-distances. Yet, a cordon toll fails to densify central areas as much as advised by the planner's optimum, while acting more on the spatial extent of the city.

Aversion to exposure, spatial patterns of exposure and spatial equity

Exposure aversion and pollution information

Information about air pollution is becoming more and more readily available to residents and reporting of concerns related to urban air pollution raises peoples' awareness of the health threat. Increased information available to residents can be considered an alternative measure to act on peoples' behavior in the hope to mitigate health effects from traffic-induced air pollution. Therefore, we analyze how an increased aversion to traffic-induced air pollution exposure,

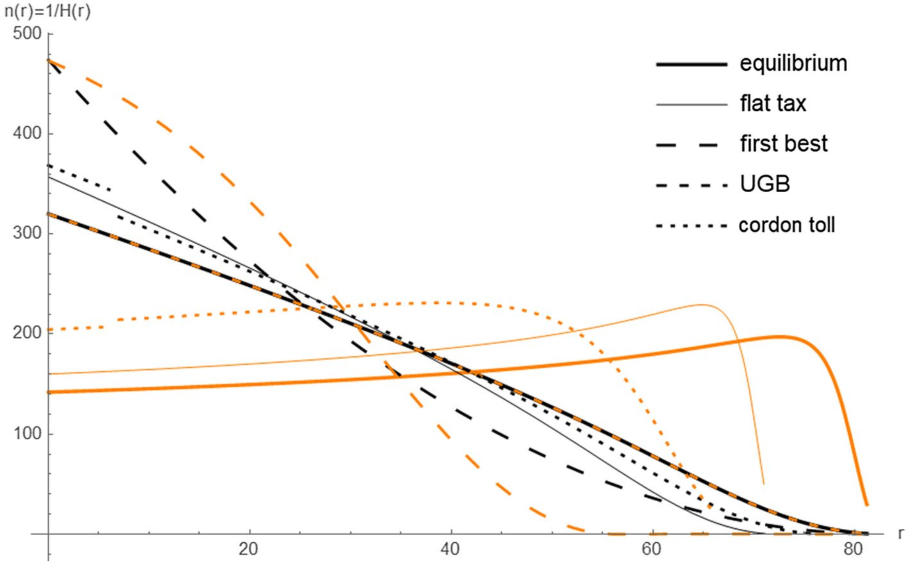

Figure 5. Distance-related effects of an increase in aversion to traffic-induced air pollution exposure on population density for the different urban regimes: weak aversion (β = 0.2)—black lines; strong aversion (β = 0.9)—orange/lighter lines. [Colour figure can be viewed at wileyonlinelibrary.com]

potentially triggered through increased information availability and raised societal awareness, impacts urban structures.

Raising societal awareness of health concerns of air pollution is reflected in households' stronger aversion to being exposed to local air pollution (β). Fig. 5 shows the change in population density as a function of distance to the CBD for an increase in aversion to traffic-induced pollution exposure for the different scenarios analyzed in this article.[3] Effects vary greatly per urban scenario.

In a scenario without planner's intervention (equilibrium), increased societal awareness results in a population shift from central locations to suburban locations with potential for non-monotonous density gradients (Fig. 5, solid thick line). Suburban locations are much more attractive as exposure to traffic-induced air pollution is much lower there. Density gradients may increase near the fringe in case of a strong aversion. Densities in this simulation increase as we get closer to the urban fringe since there is no traffic-induced pollution which causes a tension on the land market which can only be resolved with higher densities. The spatial extent of the urban area is increased since households escape high exposure levels at central locations.

In case of a flat commuting tax (Fig. 5, thin solid line), increased societal awareness also results in a population shift from central locations to suburban locations with potential for non-monotonous density gradients (thin solid orange/lighter line). Yet, population densities increase in all locations since the spatial extent of the city is reduced due to the additional per-distance charges incurred by residents.

In the scenario with an optimal, per-distance tax (Fig. 5, large dashed line), it results in steeper density gradients at outer locations, while density gradients near the CBD become flatter. Thus, densities increase mostly some distance away from the CBD but decrease sharply at locations near the city boundary. A stronger aversion to exposure reduces the city extent and pulls population from outer locations toward mid-distances. Yet, densities mainly increase at some distance away from the center and a strong enough aversion to exposure may result in non-monotonic density curves. Thus, compared to the open city framework in Schindler, Caruso, and Picard (2017)—where densities drop mostly at central locations—we observe a population shift toward mid-distances. A planner flattens the density gradient near the center but steepens it at outer locations.

In an urban system with an UGB, a stronger aversion to exposure increases densities throughout the city slightly, while densifying mostly locations near the UGB.

In contrast, a cordon toll (small dashed line in Fig. 5) reduces densities markedly in central locations but increases densities at mid-distances with potential non-monotonous density gradients.

Thus, depending on the scenario, a stronger aversion to exposure steers densification processes at different distances within the city; hence at different spatial locations.

Spatial patterns of exposure across residential locations within the city

So far we have mostly discussed the effects of the various urban interventions on urban structures, that is, on the intra-urban distribution of the population and the spatial extent of the city. Here we focus on how each intervention impacts exposure to pollution across residential locations within the city.

Fig. 6 displays population exposure to traffic-induced air pollution as a function of distance to the CBD as a result of the various intervention scenarios. We see that the optimal tax markedly reduces exposure in all locations. Note that exposure in the first-best scenario is still decreasing with distance to the CBD although not well observable in Fig. 6 due to its relatively low values. Other interventions yield more spatially differentiated exposure patterns. Notably, the cordon toll

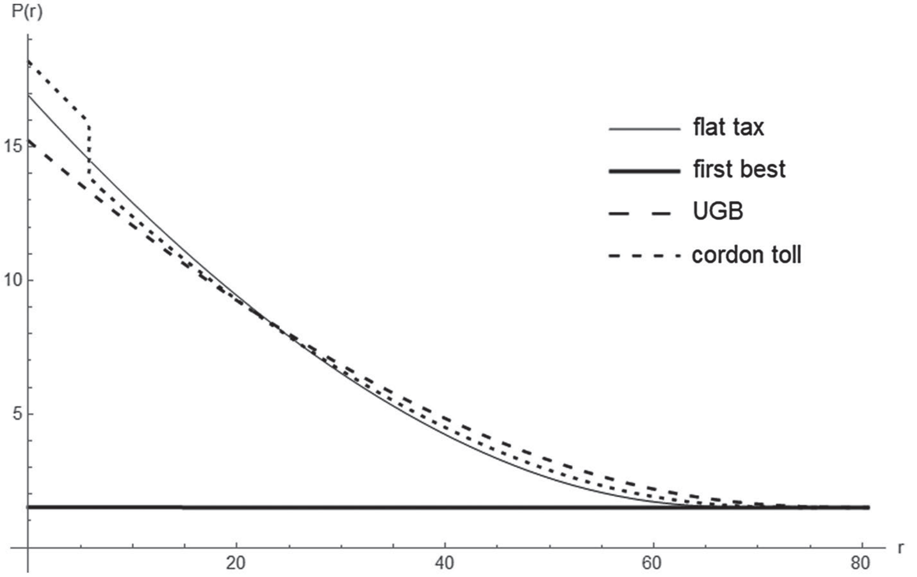

Figure 6. Exposure to traffic-induced air pollution as a function of distance to the CBD under different urban regimes.

still causes central city residents to be exposed more than all the other interventions. The cordon toll results in the steepest drop of exposure with distance, while levels at central locations are comparably high. In contrast, an UGB shifts population exposure from central locations toward suburban locations.

Spatial equity—a relative spatial assessment of households' exposure versus responsibility

In addition to studying how homogeneous households are exposed to different levels depending on where they live within the city and the location choice of others, we now discuss another perspective of equity: We evaluate the different urban scenarios as to the relative spatial assessment of responsibility for and exposure to air pollution by households at different locations within the city. The focus is set on distributional aspects, which explains our notion of equity. We consider spatial equity, where the focus lies on geographical and place-based contexts (as for example done by Sider et al. (2015) and Day (2007)), rather than on socio-economic factors of households as often done in environmental justice literature (e.g., Buzzelli et al. 2003; Pearce, Kingham, and Zawar-Reza, 2006; Kingham, Pearce, and Zawar-Reza 2007; Clark, Millet, and Marshall 2014; Moreno-Jiménez et al., 2016). Taking a geographical perspective, Sider et al. (2015) address effects of households' location linked to socio-economic characteristics on spatial equity by contrasting emission generation and exposure. Marshall (2008)'s study on California indicates environmental inequality for air pollution exposures for different sub-populations influenced by population density.

We also take a geographical perspective but look at equity within the urban area among homogeneous households, only differentiated by residential location, and focus on exposure to traffic-induced air pollution. We understand equity as the ratio between the exposure households incur by living at location r caused by the number of residents living further away from the CBD and the exposure these residents at r cause themselves for residents living closer to the CBD (hence, on their commute to work). It is, thus, a relative assessment of who incurs and who causes how much exposure within the city based on geographical location. This is depicted in Fig. 7 and expressed by

$$\varepsilon(r) = \frac{\int_r^{r_f} n(r)dr}{\int_0^r n(r)dr} \tag{4.1}$$

Such relative assessment among homogeneous households, differentiated only by the location of residence, might in turn influence households' perception of air pollution concerns (Gatersleben and Uzzell 2000). A household might perceive its own exposure less negatively if it causes others to be additionally exposed or vice versa. This local perception influenced by lived experience (Bickerstaff and Walker 2001), in turn, can influence residential choice and therefore policy makers benefit from including this information in their evaluation of different urban interventions.

With this distributional spatial definition of equity, central households are multiple times more exposed to air pollution than they generate emissions themselves and cause exposure of others. One question then is up to which distance from the CBD households are more exposed than they are responsible for the exposure of others. This knowledge can inform policy makers on equity concerns related to the various urban interventions and help in determining the design

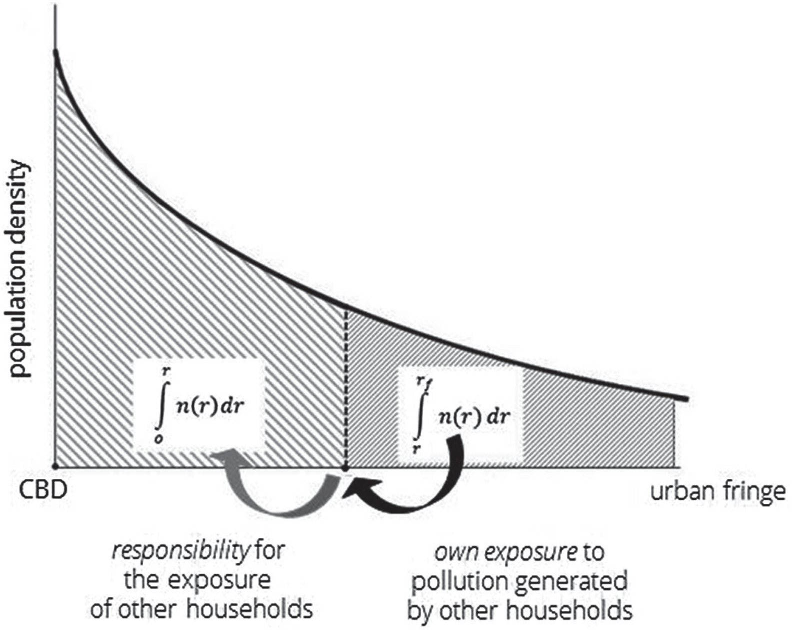

Figure 7. Illustration of the notion of spatial equity: exposure at location *r* caused by the number of residents living further away from the CBD versus the exposure induced by a household living at location *r* on residents living closer to the CBD.

of measures which make peripheral households accountable for their responsibility to population exposure.

We define this spatial turning point as $\tilde{r}$, that is, the distance where $\epsilon(r) = 1$: Closer to the CBD than $\tilde{r}$, households are more exposed than they contribute themselves; Beyond $\tilde{r}$, households contribute more through their commute to work than they are exposed themselves. Table 1 shows that the urban scenarios shift $\tilde{r}$ (second column) as well as how many households are responsible for more exposure than they are exposed themselves (last column), the maximum of ϵ (first column), and the equity measure at the urban fringe (third column).

Taking a spatial equity perspective, the simulations show that the planner's optimal intervention scheme holds the potential to reduce the mismatch between responsibility for and own exposure to air pollution within the city. The cordon toll improves equity within the city similarly to the per-distance tax as the pollution burden is partly shifted toward locations further away from the CBD and households at larger distances are to some extent held responsible for their location

Table 1. Perspectives of Spatial Equity in the Different Urban Regimes

Urban regime	Max (ϵ)	$\tilde{r}$	$\epsilon(\boldsymbol{r_f})$	$\int_0^{\tilde{r}} n(r)dr$
Equilibrium	468	18	0.0141	5,187.47
Flat tax	465	17	0.0141	5,419.68
First-best tax	816	18	0.0122	6,817.96
UGB	468	18	0.0143	5,187.51
Cordon toll	485	18	0.0153	5,376.35

choice. The choice of the cordon location and toll level, however, strongly impacts on the spatial distribution of responsibility and exposure. A cordon set wider than optimal, for instance, easily causes households to be multiple times more affected than they are responsible for health effects themselves.

Thus, we argue that in addition to evaluating urban interventions as to their effects on urban structures and population exposure, a distributional equity view adds another valuable perspective to consider for policy makers, as it might have re-enforcing effects on residential choices in case of exposure concerns among the population.

Discussion and conclusion

We have performed a spatial impact analysis of various urban interventions in a city with households concerned about exposure to localized traffic-induced air pollution based on an extended urban equilibrium model. In contrast to Li et al. (2014), the spatial distribution of the population in the city is endogenous in our model. Compared to Schindler, Caruso, and Picard (2017), a fixed population size allowed us to analyze a city's internal structure and welfare while keeping a constant population for comparative purpose rather than letting households flee out of the city because of the pollution. We have modeled a city with a planner's optimum intervention where local pollution externalities are internalized through spatially differentiated tax levels and a city with a cordon toll. These were contrasted to simulations of other urban interventions: a flat commuting tax and an UGB.

First, our analysis highlights the importance of understanding households' preferences and their effect on urban structures in order to optimally design interventions that balance health, environmental awareness, social and equity concerns arising from local traffic-induced air pollution, an externality that directly derives from the distribution of the population. From an individual perspective, dispersed development evolving without any planner's intervention leaves many households less exposed as they avoid central locations. From a public perspective, a planner's intervention can benefit both average welfare and spatial equity.

Second, we show that increased awareness of health concerns due to local urban air pollution (e.g., triggered through increased information availability) yields distinct population distributions per intervention scenario: an optimal planner's intervention advises a relocation from suburban areas to locations some distance away from the center, though not to the most central locations. That is, a flat density gradient near the center, but steep near the fringe. In contrast, in a city without intervention a population shift occurs toward the city border with high densities at mid-distances. A cordon toll provides incentives for the densification of central areas and a steep density gradient toward the fringe, while mid-distances remain attractive locations. Furthermore, our simulations show that a cordon toll might be preferable over an UGB in order to approximate optimum city structures and in particular to ensure high levels of utility. A similar finding was obtained by Brueckner (2007) in the traffic-congestion context, where urban structures as outcome of UGBs and first-best policies were contrasted. Additional in-depth analytical analysis is required to further substantiate our simulation findings.

Third, we find that the cordon scenario provides a balance between health and environmental equity concerns. It provides incentives for the densification of central areas and relocations from mid-distances toward the fringe while limiting a city's spatial extent, which lowers emissions to the benefit of the health of many while also addressing spatial distributional equity concerns. This is in line with the previous point that a center-periphery dichotomy is not sufficient. A cordon toll provides incentives for the densification of central areas and a steep density gradient toward the fringe, while mid-distances remain attractive locations. This adds to findings by Li et al. (2014) who find that a cordon toll reduces traffic congestion and therefore total vehicle emissions in a city with a linear population density function. We further show that a cordon toll is preferable over another standard planning instrument, that is, an urban growth boundary since it better approximates the optimum city structures thus ensuring higher utility levels. A similar finding was obtained by Brueckner (2007) in the traffic-congestion context, where urban structures as outcome of UGBs and first-best policies were contrasted.

More generally, beyond the interventions themselves, our results suggest that tackling health concerns require compensatory policies that demand efforts from the least exposed households, that is, the peripheral households, while tackling both via a reduction in emissions and spatial inequities requires a further focus on mid-distances. Additional in-depth analyses are required to further substantiate this as a general finding.

Our framework surely encounters limitations due to its theoretical nature and simplification assumptions. Residential trade-off effects are potentially influenced by household's environmental consciousness and pollution related processes, like diffusion processes of pollutants. Similarly adapting the model framework to include a redistribution of toll revenues is also a next important step for dealing with equity. Obviously relaxing the homogeneity of households' conditions by allowing income or preferences to vary would then open our framework to larger equity, segregation and environmental justice questions. Population groups differ in their vulnerability to health effects from exposure, with the elderly and children particularly at risk. Better understanding of more differentiated location choices could inform future policy design on further equity concerns. Furthermore, we have studied a partial equilibrium setting with a focus on residential locations. A general equilibrium model could relax the assumption of a spaceless CBD and consider location choices of firms, which are concerned about their employers being exposed to air pollution. This might result in polycentric urban structures or increased commuting distances if employees consider remote working options or altered office hours. Lastly, increasing the spatial complexity of the model, as for instance done in 2D by Schindler and Caruso (2018), would allow for advanced discussion of neighborhood effects in addition to distance-related effects and policies. For example, they found that setting back houses from main networks or adequately located green space is an effective policy to reduce exposure. The optimality though cannot be retrieved so clearly in a 2D environment where numerous spatial parameters are to be varied.

Notes

1 Parameter values are: $a = .000001$, $\beta = .2$, $N = 13070$, $t = 350$, $\alpha = 1/3$, $c = .5$, $Y = 29000$, $R_A = 100$ and $u^* = 115.4$; no externality - $u^* = 174.5$.

2 Parameter values are: flat tax - $u^* = 109$, $t = 400$; first-best - $u^* = 160.7$; UGB - $u^* = 115.4$ 5; cordon toll - u^*=106.3, τ=2,000.

3 Parameter values for u^* for $\beta = 0.9$ are: equilibrium 22.5; flat tax - 19.4; first-best - 69; UGB - 22.25; cordon toll - 44.5.

APPENDIX A

EQUILIBRIUM

In the following, we drop the reference to r (spatial reference) for conciseness whenever it causes no confusion.

Consumptions of housing space and the non-housing good at residential locations across the city

Using the maximization problem (2.1) subject to (2.2), we can derive how much households consume of non-housing goods Z and how much housing space H they demand per residential location in relation to the distance to the CBD to receive the endogenous utility level u^* reached by all households in equilibrium.

$$Z = (1-\alpha)(Y - t\,r) \tag{A.1}$$

$$H = u^{*\frac{1}{\alpha}}\,\alpha\,P^{\frac{\beta\gamma}{\alpha}}\,(Y - t\,r)^{1-\frac{1}{\alpha}} \tag{A.2}$$

Intra-urban distribution of exposure and population

(A.2) reflects the dependence of housing consumption (i.e., inverse density population) on the pollution exposure distribution within the city. Since P is differentiable, we can replace (2.3) with $\dot{P} = -b/H$ and $P\left(r_{rf}\right) = 1 + a$, where $\dot{P}$ refers to the derivative of P with respect to r, $\dot{P} = dP/dr$, and with (A.2) the dependence can be resolved to see Schindler, Caruso, and Picard (2017))

$$P = P_0\,u^{*-\frac{1}{\alpha+\beta\gamma}}\left[(Y - t\,r)^{\frac{1}{\alpha}} - (Y - t\,r_f)^{\frac{1}{\alpha}} + a_0\right]^{\frac{\alpha}{\alpha+\beta\gamma}} \tag{A.3}$$

where

$$P_0 = \left(\frac{b}{t}\alpha^{-1}(\alpha+\beta\gamma)\right)^{\frac{\alpha}{\alpha+\beta\gamma}} > 0 \quad \text{and} \quad a_0 = \left(\frac{a+1}{P_0}\right)^{\frac{\alpha+\beta\gamma}{\alpha}} > 0$$

P_0 is a base pollution exposure level generated by commuting traffic within the city for given economic and technology frameworks. Additionally, there is a spatially differentiated exposure level at each location respectively (the term in brackets in (A.3)) a_0 expresses the relative importance of both pollution sources by relating the base traffic pollution to the background pollution level.

Households take the exposure level at a location as a given and choose the consumption of housing space accordingly. Since land availability at each location is normalized such that $n = 1/H$, population density n across the city is then a result of people's spatially differentiated housing consumption:

$$n = \alpha^{-1}u^{*-\frac{1}{\alpha}}P^{-\frac{\beta\gamma}{\alpha}}(Y - t\,r)^{\frac{1}{\alpha}-1} \tag{A.4}$$

The housing demand and supply in the city require the population constraint $N = \int_0^{r_f} n(r)dr$ to hold. All households N pass at the central location $r = 0$. The exposure externality at the center ($r = 0$) is then defined by population size N, the emission factor b and the background pollution level a as

$$P(0) = (bN + a + 1)^{\gamma} \tag{A.5}$$

Spatial profile of land rent and location of the urban fringe

Households locate inside the city boundary r_f and farmers beyond r_f. Farmers pay an exogenously given agricultural rent R_A, which is constant throughout the agricultural area. The boundary of the city r_f is determined by the location where the bids of farmers (R_A) and the maximum land rent households are willing to pay ($\Psi(r)$) equalize, that is, where $\Psi(r) = R_A$. Thus, the urban equilibrium must satisfy $R(r_f) = R_A$ and $R(r) > R_A$ for all $r \le r_f$, which gives with $R(r) = \max\left\{\Psi(r),\ R_A\right\}$

$$R = u^{*-\frac{1}{\alpha}}(Y - t\,r)^{\frac{1}{\alpha}}P^{-\frac{\beta\gamma}{\alpha}} \tag{A.6}$$

Land rents R increase with household income Y and the share of income spent on housing α, but decrease with the endogenous level of utility u^*, transport costs t and exposure P.

An urban equilibrium exists with land rents falling throughout the city with distance from the center. No equilibrium exists in case aversion to traffic-induced exposure would be too strong compared to the opportunity cost of land (R_A), transport costs and the background pollution prevailing at the city border. Conditions for the existence of equilibrium are equivalent to the open city framework as derived and discussed in Schindler, Caruso, and Picard (2017).

The equilibrium spatial extent of the city r_f can then be defined by solving $R(r_f) = R_A$ for r_f as

$$r_f = \frac{Y}{t} - \frac{R_A^{\alpha}(1+a)^{\beta\gamma}}{t\,u^*} \tag{A.7}$$

Utility in the city

We can use the value for P from (A.3) in (A.5) and solve for the endogenous utility level u^*. Since all households in the city have to obtain the same utility level, the endogenous equilibrium utility in the city is then given by (with A.7)

$$u^* = \left[\frac{b\,(\alpha+\beta\gamma)\left(Y-(Y-t\,r_f)^{\frac{1}{\alpha}}\right)}{t\,\alpha\,(b\,N+a+1)^{\frac{\alpha+\beta\gamma}{\alpha}}}\right]^{\alpha} \tag{A.8}$$

From (A.8) we see that utility in the city decreases as the pollution effect from traffic increases, due to a larger emission factor b. A larger population N also reduces utility in the city but a resulting spatially extended city (r_f) increases utility. An analysis of the endogeneity effect of utility will be presented in the policy discussions in the next sections.

APPENDIX B

FIRST-BEST OPTIMUM

A planner maximizes social welfare W in the city subject to the density constraint (B.2),the population constraint (B.3), trafic-induced pollution exposure (B.4) and the resource constraint (B.5). The planner's maximization problem can then be expressed as

$$\max_{\{u^*,H(\cdot),Z(\cdot),n(\cdot),P(\cdot),r_f\}} W = \int_0^{r_f} U(H(r), Z(r), P(r))n(r)\mathrm{d}r \tag{B.1}$$

$$\text{s.t.} \quad n(r) = \frac{1}{H(r)} \tag{B.2}$$

$$N = \int_0^{r_f} n(r)dr \tag{B.3}$$

$$P(r) = \left(1 + a + b\int_0^{r_f} n(r)dr\right)^{\gamma} \tag{B.4}$$

$$0 = \int_0^{r_f} (Y - t\,r - H(r)R_A - Z(r))n(r)dr \tag{B.5}$$

This is an optimal control problem to which we apply Pontryagin's maximization principle where the variable of motion is given by differentiating and replacing the integral equality (B.4) by $P(r) = -b\ n(r)$ similar to the solution proof shown in Schindler, Caruso, and Picard (2017) for an open city framework.

The Hamiltonian is then defined as

$$\mathscr{H}(P,n,r,\mu)=\int_0^{r_f}\left(U(P,n,\mu,r)+\lambda(Y-Z-tr-R_AH)-b\,\mu\right)\,n\,dr \tag{B.6}$$

where λ and μ are functions of r. Then, necessary conditions for the optimal control problem with free final location r_f are

$$\frac{\partial\mathscr{H}}{\partial n}=0\Leftrightarrow n\left(U'_n+\lambda C'_n\right)+U+\lambda C=b\mu \tag{B.7}$$

$$\frac{\partial\mathscr{H}}{\partial Z}=0\Leftrightarrow n\left(U'_Z-\lambda\right)=0 \tag{B.8}$$

$$\cdot\mu=-\frac{\partial\mathscr{H}}{\partial P}\Leftrightarrow-\dot{\mu}=nU'_P \tag{B.9}$$

$$\mu(0)=0 \tag{B.10}$$

$$R_A=n(r_f)[Y-tr_f-Z(r_f)-b\mu(r_f)] \tag{B.11}$$

with $C=(Y-t\,r-R_AH-Z)$. The first term of (B.7) expresses the effect on utility of an additional household in the city on all other households at the same location. The second term indicates additional utility gained, the third term is the income effect and on the RHS the term $\mu(r)$ expresses the marginal indirect effect due to additional local pollution exposure, multiplied by the emission factor b. The co-state variable $\mu(r)$, thus, reflects the shadow cost of traffic-induced pollution exposure to residents in the interval [0, r). With free final location the constraint (B.11) becomes

$$0=n(r_f)\lambda\left[Y-t\,r_f-Z(r_f)\right]-R_A+\frac{Z(r_f)^{1-\alpha}}{n(r_f)^{\alpha}a^{\beta}}-n(r_f)\mu(r_f)$$

where $\mathscr{H}(P,n,r,\mu)$ is evaluated at (P,n,Z,λ,μ,r). For $Z>0$ and $P>0$ an interior solution is found with the budget constraint $C=(Y-t\,r-R_AH-Z)$ and $\cdot P=-bn$ and $P(r_f)=a$. The household allocation is only optimal if all effects equal to zero, which is the objective of a planner. (B.8) defines that λ expresses exactly the utility gained from an additional unit of composite good Z in case of optimal resource allocation.

We can readily see that $P>0$ and $\lambda\geq 0$ such that it must be that $\mu(r)\geq 0$ and $\mu(r)>0$. Thus, there is pollution everywhere in the city and a policy rule reflected by $\mu(r)$ must increase with distance to the CBD.

APPENDIX C

CORDON TOLL

$$\begin{aligned}\max_{r_f,r_c,\tau}W=&\int_0^{r_c}U\left(H_i(r),Z_i(r),P_i(r)\right)n_i(r)dr\\&+\int_{r_c}^{r_f}U\left(H_o(r),Z_o(r),P_o(r)\right)n_o(r)dr\end{aligned} \tag{C.1}$$

$$\text{s.t.}\,u^*=\kappa Z_i(r)^{1-\alpha}H_i(r)^{\alpha}P_i(r)^{-\beta\gamma}=\kappa Z_o(r)^{1-\alpha}H_o(r)^{\alpha}P_p(r)^{-\beta\gamma} \tag{C.2}$$

$$0=\left(Y-Z_i-tr-R_AH_i\right)=\left(Y-Z_o-t\,r-R_AH_o-\tau\right) \tag{C.3}$$

$$P_i = \left(b \int_r^{r_c} n_i dr + b \int_{r_c}^{r_f} n_o dr + a + 1 \right)^{\gamma}$$

$$P_o = \left(b \int_r^{r_f} n_o dr + a + 1 \right)^{\gamma} \tag{C.4}$$

$$r_f \geq r_c \tag{C.5}$$

$$0 = Y - Z_o(r_f) - t\, r_f - R_A\, H_o(r_f) \tag{C.6}$$

$$Y - Z_i(r_c) - tr_c - R_i(r_c)H_i(r_c) = Y - Z_o(r_c) - t\, r_c - R_o(r_c)H_o(r_c) \tag{C.7}$$

where subscript i indicates locations inside the cordon area and subscript o locations outside and τ is the cordon toll paid by households outside the cordon area. Again, we drop the reference to r where it causes no confusion. Density is normalized to n = 1/H, all households receive the same utility u^* no matter their location, (C.6) gives the fringe distance r_f and (C.7) needs to hold at the cordon station r_c.

The first-order conditions in the case of a cordon toll are as follows.

Allocating an additional household inside the cordon area has only direct economic implications for locations inside the cordon area as observable from C.8.

$$\underset{n_i}{\text{FOC}} \equiv \int_0^{r_c} Y - t\,r - \frac{b\,\beta\gamma\, n_i^{\frac{1}{1-\alpha}}\, P_i^{\frac{\beta\gamma}{1-\alpha}-1} \left(r_c - r\right)\, u^{*\frac{1}{1-\alpha}}}{1-\alpha} - \frac{n_i^{\frac{1}{1-\alpha}-1}\, P_i^{\frac{\beta\gamma}{1-\alpha}}\, u^{*\frac{1}{1-\alpha}}}{1-\alpha}\, dr = 0 \tag{C.8}$$

The first terms of (C.8) express the effect of commuting costs on net available income. The third term reflects the effect of exposure at location r on the land rent and the last term the effect of population density.

In contrast, locating an additional household at locations beyond the cordon location has direct (private) and indirect (social) effects on welfare and other households as observable from C.9.

$$\underset{n_o}{\text{FOC}} \equiv \int_{r_c}^{r_f} Y - \tau - r\,t - \frac{b\,\beta\gamma\, n_o^{\frac{1}{1-\alpha}}\, P_o^{\frac{\beta\gamma}{1-\alpha}-1} \left(r_f - r_c\right)\, u^{*\frac{1}{1-\alpha}}}{1-\alpha} - \frac{n_o^{\frac{1}{1-\alpha}-1}\, P_o^{\frac{\beta\gamma}{1-\alpha}}\, u^{*\frac{1}{1-\alpha}}}{1-\alpha}\, dr - \frac{b\,\beta\gamma \int_0^{r_c} n_i^{\frac{1}{1-\alpha}}\, P_i^{\frac{\beta\gamma}{1-\alpha}-1} dr \left(r_f - r_c\right)\, u^{*\frac{1}{1-\alpha}}}{1-\alpha} = 0 \tag{C.9}$$

(C.9) reflects the interrelations between pollution exposure, the distance between the location of the cordon and the fringe and the pollution externality that is induced on others (last term).

The last term of (C.9) reflects the shadow costs related to exposure of households living inside the cordon area and defines the level of the cordon toll:

$$\tau = b\,\beta\gamma\,(1-\alpha)^{-1} u^{*\frac{1}{1-\alpha}} \int_0^{r_c} n_i^{\frac{1}{1-\alpha}} P_i^{\frac{\beta\gamma}{1-\alpha}-1} dr (r_f - r_c) \tag{C.10}$$

Locating the cordon station a marginal distance further away from the CBD has exposure and monetary (cordon toll) effects on households close to the cordon station. The optimal location of the cordon station is where these effects are offset.

$$\begin{aligned}\underset{r_c}{\text{FOC}} \equiv & -n_o\left(r_c\right)\ \left(Y-\tau-r_c\, t\right)+n_i\left(r_c\right)\ \left(Y-r_c\, t\right) \\ & +n_o\left(r_c\right)^{\frac{1}{1-\alpha}}\ P\left(r_c\right)^{\frac{\beta\gamma}{1-\alpha}}\ u^{*\frac{1}{1-\alpha}}-n_i\left(r_c\right)^{\frac{1}{1-\alpha}}\ P\left(r_c\right)^{\frac{\beta\gamma}{1-\alpha}}\ u^{*\frac{1}{1-\alpha}} \\ & +\frac{b\,\beta\gamma\int_{r_c}^{r_f} n_o^{\frac{1}{1-\alpha}}\ P_o^{\frac{\beta\gamma}{1-\alpha}-1} dr\, n_o\left(r_c\right)\ u^{*\frac{1}{1-\alpha}}}{1-\alpha} \\ & -\frac{b\,\beta\gamma\int_{0}^{r_c} n_i^{\frac{1}{1-\alpha}}\ P_i^{\frac{\beta\gamma}{1-\alpha}-1} dr\ \left(n_i\left(r_c\right)-n_o\left(r_c\right)\right)\ u^{*\frac{1}{1-\alpha}}}{1-\alpha}=0\end{aligned} \tag{C.11}$$

The fringe distance satisfies (C.12). Given the level of the cordon toll and exposure effects of moving the fringe marginally further away from the CBD, the rent at the fringe is then equal to the agricultural rent.

$$\begin{aligned}\underset{r_f}{\text{FOC}} \equiv & \ n_o\left(r_f\right)\ \left(Y-\tau-r_f\, t\right)-R_A-(a+1)^{\frac{\beta\gamma}{1-\alpha}}\ n_o\left(r_f\right)^{\frac{1}{1-\alpha}}\ u^{*\frac{1}{1-\alpha}} \\ & -\frac{b\,\beta\gamma\int_{r_c}^{r_f} n_o^{\frac{1}{1-\alpha}}\ P_o^{\frac{\beta\gamma}{1-\alpha}-1} dr\, n_o\left(r_f\right)\ u^{*\frac{1}{1-\alpha}}}{1-\alpha} \\ & -\frac{b\,\beta\gamma\int_{0}^{r_c} n_i^{\frac{1}{1-\alpha}}\ P_i^{\frac{\beta\gamma}{1-\alpha}-1} dr\, n_o\left(r_f\right)\ u^{*\frac{1}{1-\alpha}}}{1-\alpha}=0\end{aligned} \tag{C.12}$$

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