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Simultaneous internalization of traffic congestion and noise exposure costs

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Abstract This study elaborates on the interrelation of external effects, in particular road traffic congestion and noise. An agent-based simulation framework is used to compute and internalize user-specific external congestion effects and noise exposures. The resulting user equilibrium corresponds to an approximation of the system optimum. For traffic congestion and noise, single objective optimization is compared with multiple objective optimization. The simulation-based optimization approach is applied to the real-world case study of the Greater Berlin area. The results reveal a negative correlation between congestion and noise. Nevertheless, the multiple objective optimization yields a simultaneous reduction in congestion and noise. During peak times, congestion is the more relevant external effect, whereas, during the evening, night and morning, noise is the more relevant externality. Thus, a key element for policy making is to follow a dynamic approach, i.e. to temporally change the incentives. During off-peak times, noise should be reduced by concentrating traffic flows along main roads, i.e. inner-city motorways. In contrast, during peak times, congestion is reduced by shifting transport users from the inner-city motorway to smaller roads which, however, may have an effect on other externalities.

Keywords Road traffic noise · Traffic congestion · Internalization · Optimal pricing · Dynamic tolling · Activity-based transport modeling

Introduction and problem statement

Transport users do not only invest their own time and money, but impose so-called external costs on others, such as congestion, noise, air pollution, or accidents. If the users had to compensate for their external damages, they might behave differently, e.g. by using other routes, other time slots, switching to environmentally friendlier vehicles or modes, or travel

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less. The economic theory states that correct prices yield an optimal use of transport resources. However, due to the existence of external effects, prices only reflect parts of the full cost. Consequently, the wrong incentives are given which results in a typically too extensive usage of transport resources yielding welfare losses. Following the concept introduced by Pigou (1920), the social welfare optimum can be achieved by correcting the costs payed by the transport users according to the marginal external cost. Thus, external costs are internalized and prices reflect full cost. Hence, pricing can be understood as a decentralized (or market-based) instrument to change individual travel decisions towards an overall improved transport system (see e.g. Maibach et al. 2008; Small and Verhoef 2007).

Many studies find that during peak times, congestion causes the largest part of all transport related external costs (see e.g. Maibach et al. 2008; de Borger et al. 1996; Small and Verhoef 2007; Parry and Small 2009, p. 103). In particular, for heavy goods vehicles (HGV) and during night times, noise is found to be a very important contribution to the total external costs (Maibach et al. 2008; Nash 2003). In this study, the focus is placed on traffic congestion and noise exposures which both differ in many respects. Increased travel times due to traffic congestion mainly affect individuals within the transport system, i.e. the following road users. In contrast, traffic noise primarily affects individuals outside the transport system, for example local residents. Furthermore, traffic congestion and noise differ significantly in their cost structure. Marginal congestion cost are larger than average congestion cost (Maibach et al. 2008; Korzhenevych et al. 2014). In contrast, marginal noise cost are below average noise cost which is explained by the logarithmic characteristic of noise, i.e. that the impact of an additional vehicle is smaller for large traffic volumes compared to small traffic volumes (FGSV 1992; Maibach et al. 2008). Several studies indicate that external effects such as traffic congestion, noise, air pollution and accidents are interrelated with each other (see e.g. Calthrop and Proost 1998 for an analytical study, see e.g. Ghafghazi and Hatzopoulou 2014 for a simulation-based study, see e.g. Barth and Boriboonsomsin 2009 for an empirical study). That is, reducing one externality may increase or decrease other external effects. Noise computation models typically account for a road-specific free-flow speed level in that a higher speed level increases the noise level (see e.g. FGSV 1992). Makarewicz and Galuszka (2011) address the model-based prediction of road traffic noise using the speed-flow diagram and find that traffic congestion and noise are inversely related, i.e. that a reduced speed level due to increased traffic congestion reduces the annual average sound level. The interrelation between speed level and air pollution is empirically found to be "U"-shaped, with lower speeds and higher speeds yielding larger emissions than middle-ranged speed levels (Barth and Boriboonsomsin 2009). This relationship is taken into account by analytical and simulation-based air pollution emission models (see e.g. Wismans et al. 2011; Kickhöfer et al. 2013). For the relation between congestion and accident costs, on the one hand, the number of interactions (and possible collisions) increase with the number of vehicles. On the other hand, for high traffic volumes, studies that are based on empirical data find that a reduced speed level due to congestion may lead to less severe accidents and decreasing accident costs (Shefer and Rietveld 1997; High Level Group on Transport Infrastructure Charging 1999; Maibach et al. 2008). Noland et al. (2008) analyze empirically the impact of the London congestion charge on road casualties and identify an increase in motorcycle casualties which is explained by the incentive to use motorcycles in order to avoid the congestion charge. However, Noland et al. (2008) do not find a significant change in road casualties. Also, the increase in speed levels is found to have no effect on the severity of accidents (Noland et al. 2008). In several studies, the overall benefits are analyzed by measuring changes in

congestion costs as well as other external costs for different transport policies (see e.g. Beamon and Griffin 1999; Daniel and Bekka 2000; Proost and van Dender 2001; Beevers and Carslaw 2005 for model-based approaches, and see e.g. Percoco (2014, 2015) for empirical approaches). Wismans et al. (2011) use an analytical model to separately optimize single external effects and measure the impact on other externalities. For an illustrative case study, Wismans et al. (2011) find congestion and air pollution to be positively correlated, whereas congestion and air pollution are negatively correlated with noise and accidents.

The interrelation of external effects makes it difficult for transport planners to employ the right policy. Ideally, a transport policy should simultaneously reduce all external costs which, however, may not be easy to achieve. In particular, the reduction of one external effect may increase another external effect. This inverse relationship between different external effects puts policy makers in a dilemma. A combined optimization approach in which several external effects are simultaneously minimized provides a way out and may help to resolve the trade-off between different external effects. In a few recent studies, external effects are simultaneously optimized for a simplified network using analytical methods, see for example Chen and Yang (2012) and Wang et al. (2014) who minimize the combined external costs of congestion and air pollutants or Verhoef and Rouwendal (2003) who minimize congestion and accident costs. In Shepherd (2008), a single link model is used to compute optimal tolls for simple and more complex CO_2 and accident models. The author finds the complexity of the external cost model to have a significant impact on the optimal toll level. Because of their rather simplified nature, most analytical approaches are less appropriate to handle complex real-world networks or a more sophisticated representation of the transport demand side, for example multiple origin-destination points, non-deterministic behavior, complex user reactions, or user-user interactions such as dynamic congestion with spill-back. In contrast, Agarwal and Kickhöfer (2015) use an agent-based simulation framework to simultaneously optimize congestion and air pollution levels for a complex real-world scenario of the Munich metropolitan area. The authors find congestion and air pollution emissions to be positively correlated since the internalization of one external effect also reduces the other one.

This study aims to investigate the interrelation of congestion and noise in order to implement effective policies that control both congestion and noise. The inverse relation between congestion and noise raises the question if or how it is possible to simultaneously reduce both externalities by means of intelligent traffic management. Similar to Agarwal and Kickhöfer (2015) who looked at congestion and air pollution, the present study applies an agent-based simulation approach to identify an approximation of the optimal congestion levels and road traffic noise exposures. A market-based optimization approach is applied (see Sec. 2.1) which combines two external cost pricing tools, first a congestion internalization tool which accounts for dynamic queueing and heterogenous users (Kaddoura 2015; Kaddoura and Nagel 2016b, see Sec. 2.3) and, second, a marginal user-specific noise exposure pricing tool in which noise levels and population densities are dynamically computed (Kaddoura and Nagel 2016a, see Sec. 2.4.) The innovative optimization approach is applied to a real-world case study of the Greater Berlin area (see Sec. 3). Several simulation experiments are carried out which are analyzed with regard to the changes in travel behavior, congestion level, noise impact and overall system welfare (see Sec. 4).

Methodology

General approach

The proposed methodology makes use of an iterative simulation of the market mechanism and follows the Pigouvian taxation principle. First, road-, user- and time-specific tolls are set to reflect marginal external costs. Second, the transport users are enabled to adjust their travel behavior to reduce toll payments. Since the prices that are paid by the users reflect full cost, specifically the private cost (own travel time) and the external cost (delays imposed on other travelers, noise exposures), the system changes towards a higher efficiency. That is, transport users adjust their travel behavior to reduce the sum of the private and the external cost. This will lead to a state where all users (approximately) pay for their marginal external costs. The road-, user, and time-specific tolls can also be interpreted as correction terms to be added to the users' generalized cost formulation in order to increase the system efficiency. However, since the approach uses a local search algorithm, it does not necessarily converge to the globally optimal solution. In a related study, we investigate marginal noise cost pricing regarding the existence of different equilibria for different starting points (Kaddoura and Nagel, in preparation). Preliminary results indicate that for illustrative examples, different assumptions regarding the starting point, i.e. the initial network loading, result in different equilibria. In contrast, for large-scale case studies in which real-world traffic conditions are used as a starting point, preliminary results indicate that all considered starting points eventually lead to the same equilibrium.

The proposed approach to approximate optimal toll levels uses the open-source transport model MATSim[1] to compute the external cost and to simulate the market mechanism, i.e. the changes in travel demand as a response to the external cost toll payments (see Sec. 2.2). In this study, the external costs are assumed to be composed of two cost components only, namely traffic congestion, i.e. delays imposed on other transport users (see Sec. 2.3), and noise damages, i.e. population exposures to traffic noise (see Sec. 2.4). However, the proposed market-based approach allows to easily add further cost components (see Sec. 6).

Transport simulation framework MATSim

MATSim is an activity-based transport simulation where traffic is the result of spatially separated activities. The demand for transport is modeled as agents that have an individual mental and physical behavior. Initially, each agent's behavior has to be provided by means of a travel plan which describes the daily activities (e.g. home-work-leisure-home) as well as the transport modes and activity end times. Applying an evolutionary iterative approach, the demand side adapts to the supply side and the initial behavior is modified. Depending on the enabled choice dimensions, those parts of the initial plans are modified that are considered to be endogenous, for example the transport route, the departure time or the mode of transportation. In each iteration, (1) the plans are executed (Traffic flow simulation), (2) evaluated (Evaluation) and (3) new plans are generated (Learning).

1. *Traffic Flow Simulation* All agents simultaneously execute their travel plans. Thereby, they interact in the physical environment. The vehicles are moved along road segments (links) applying a queue model (Gawron 1998). Each link is considered as a *First In First Out* queue with the following attributes: a free-flow speed travel time, a flow

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[1] Multi-Agent Transport Simulation, see www.matsim.org.

capacity c_{flow}, and a storage capacity (causing spill-back). Individual movements of agents can be aggregated to flows that are found to be consistent with the fundamental diagram (see e.g. Agarwal et al. 2015).

2. *Evaluation* Each executed plan is scored based on predefined behavioral parameters. A plan's score is typically composed of two parts, the trip related travel cost (e.g. travel time, monetary payments) and the utility gained from activity performing (see Charypar and Nagel 2005). Depending on the agent-specific travel plans, in particular the number and types of activities, agents are differently pressed for time, resulting in different values of travel time savings (Kaddoura and Nagel 2016b).

3. *Learning* In every iteration, the agents choose a plan to be executed in the next iteration following a multinomial logit model. However, some agents generate new plans by making a copy of an existing plan and modifying parts of the plan, for example the transport route (sequence of links the agent is taking to travel from one activity location to another one).

A consecutive repetition of the above described iteration allows the agents to improve and obtain plausible travel plans. Finally, the simulation outcome stabilizes and the scores of the executed plans do not change significantly from one iteration to the next one. Assuming each agent's travel plan to form a valid choice set, i.e. representing all realistic travel options, the system state is considered as an approximate stochastic user equilibrium (Nagel and Flötteröd 2012). Further details of the applied simulation framework are for example described in Raney and Nagel (2006).

Congestion pricing

In this study, external congestion effects are computed applying the methodology described in Kaddoura and Kickhöfer (2014) and Kaddoura (2015). The computation of external congestion effects is directly linked to the queue model described in Sec. 2.2 (Traffic Flow Simulation). Whenever an agent is delayed at a bottleneck, the causing agents in the queue ahead are identified. Each of the causing agents has previously consumed a fraction of the bottleneck's flow capacity, i.e. $\frac{1}{c_{flow}}$, and is therefore considered to be responsible for the delay equivalent to that amount of time. The delay is converted into monetary units accounting for the delayed transport user's value of travel time savings. Thereby, the pricing approach considers model-inherent heterogeneous values of travel time savings (see Kaddoura and Nagel 2016b). Based on the delay costs imposed on other travelers, the causing agents have to pay a toll which corresponds to an approximation of marginal external congestion cost. Hence, external congestion costs are internalized and transport users are enabled to change their travel behavior in order to avoid these tolls (see Sec. 2.1).

Noise exposure pricing

In this study, noise damages are internalized applying the marginal cost approach presented in Kaddoura and Nagel (2016a). Road-, user- and time-specific tolls are set based on marginal noise exposure cost. For each road segment and time interval, the discretization of marginal noise exposure costs are computed by adding one additional car or heavy goods vehicle (HGV) and computing the difference in noise damages in the surrounding area. The computation of noise damages is mainly based on the German RLS-90 approach ('Richtlinien für den Lärmschutz an Straßen', FGSV 1992) applying the approach 'lange,

gerade Fahrstreifen' ('long, straight lanes'). In a first step, for each time interval and road segment, a basic noise emission level is calculated as a function of traffic volume and HGV share.

$$E_{r,t}^0 = 37.3 + 10 \cdot \log_{10}\big[M_{r,t} \cdot \big(1 + 0.082 \cdot p_{r,t}\big)\big], \tag{1}$$

where $E_{r,t}^0$ is the basic noise emission level in dB(A) resulting from the initial computation step, r denotes the road segment, t is the time interval, $M_{r,t}$ is the total number of vehicles and $p_{r,t}$ is the HGV share. In further computation steps, the noise level is corrected, in particular to account for the speed level (see e.g. Kaddoura et al. 2017). Next, noise immissions are calculated for each time interval and a predefined set of receiver points accounting for the noise emissions at the surrounding road segments. Finally, for each time interval, noise exposure costs are computed as a function of noise immission level and number of affected people. The number of affected people is computed for each time interval based on the simulated population density, i.e. the agents' activities (locations and activity start and end times). In residential areas, for example, the population density may decrease during the day since people go to work, school or other activities. In contrast, in central business districts, for example, the population density is very high during the day and very low during the night. The conversion into monetary units follows the threshold-based German EWS approach ('Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen' FGSV 1997). Noise exposure costs are computed as

$$C_{j,t} = \begin{cases} c^T \cdot N_{j,t} \cdot 2^{0.1 \cdot (I_{j,t} - I_t^{min})} & I_{j,t} \geq I_t^{min} \\ 0 & I_{j,t} < I_t^{min} \end{cases}, \tag{2}$$

where $C_{j,t}$ is the noise damage costs per receiver point j and time interval t; $N_{j,t}$ denotes the number of exposed individuals; $I_{j,t}$ is the noise immission level in dB(A); I_t^{min} is the threshold immission level[2]; c^T is the cost rate computed as $c^T = c^{annual} \cdot \frac{T}{(365 \cdot 24 \cdot 3600)}$; where T is the duration of the time interval in seconds; and c^{annual} is the annual cost rate per dB(A) that is exposed to one individual. In this study, c^{annual} is set to 63.3 EUR based on value given in the EWS (FGSV 1997) for the year 1995, updated with an annual interest rate of 2% and converted into EUR. A detailed description of the applied noise computation methodology is provided in Kaddoura et al. (2015c) and Kaddoura et al. (2017).

Kaddoura and Nagel (2016a) present some results regarding the model's sensitivity: marginal noise cost pricing is contrasted with much higher average noise cost pricing. Overall, the effects go into the same direction: reduction of traffic on smaller roads and concentration of volumes on already heavily used larger streets. However, while for marginal cost pricing the overall welfare goes up, the average cost pricing approach pushes so hard that the overall welfare goes down again, and ends up lower than the base case.

Extension: Actual speed instead of free-flow speed The RLS-90 noise computation approach ignores actual vehicle speeds. Instead, the RLS-90 only accounts for the maximum speed level in the range of 30 to 130 km/h for passenger cars and 30 to 80 km/h for HGV (FGSV 1992). In this study, the noise computation methodology is modified in order to account for the interplay of noise and traffic congestion, i.e. reduced speed levels resulting in lower noise levels. Other than described in the RLS-90, in this study, noise emissions are computed based on the actual speed level instead of the free-flow speed

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[2] In this study, the threshold immission values are set to 50 dB(A) for during the day (6 a.m.–6 p.m.), 45 dB(A) for during the evening (6 p.m.–10 p.m.) and 40 dB(A) for the night (10 p.m.–6 a.m.).

level. Thus, the extended computation approach additionally requires the average speed level of each road segment and time interval which is provided by the dynamic traffic simulation, specifically the queue model described in Sec. 2.2 (Traffic Flow Simulation). For speeds below 30 km/h, noise levels are computed assuming the minimum speed of 30 km/h (FGSV 1992). For speeds above the valid range, the speed level which is used to compute noise emissions is set to either 130 km/h for passenger cars or 80 km/h for HGV according to the maximum speed values considered by the RLS-90 approach (FGSV 1992).

Simulation experiments

In this study, the following simulation experiments are carried out. The first two experiments investigate both of the above described pricing approaches separately. The third simulation experiment combines the two pricing approaches and traffic congestion and noise exposures are simultaneously optimized. In simulation experiment 4a, 4b and 4c, a cordon pricing scheme is investigated for different toll levels.

1. *Isolated congestion pricing*: External congestion effects are internalized applying the methodology described in Sec.2.3. Road-, user- and time-specific tolls only reflect the congestion cost.
2. *Isolated noise exposure pricing*: Noise exposure costs are internalized applying the methodology described in Sec. 2.4. Road-, user- and time-specific tolls are set equal to the marginal noise exposure cost. In order to properly account for the interplay of congestion and noise, noise emissions are calculated applying the extension, i.e. using the actual speed level instead of the free-flow speed level. Noise exposure costs are computed assuming that noise damages are incurred for individuals that are exposed to noise at *home*, at *work* and *education* activities, i.e. school and university.
3. *Simultaneous congestion and noise exposure pricing*: Prices are simultaneously set based on the external noise and congestion cost applying the methodology described in Sec. 2.3 and 2.4. Road-, user- and time-specific tolls are composed of two additive terms, one reflecting the congestion cost and the other one reflecting the noise exposure cost. For the computation of noise exposure costs, again, noise damages are assumed to be incurred for individuals at *home*, *work* and *education* activities.
4. *Cordon pricing*: Each time a vehicle enters the cordon area a monetary amount has to be payed. The cordon area is defined as the inner-city area of Berlin by setting the cordon line according to the circular urban railway line and the inner-city motorway ring road A100. The inner-city motorway ring road is situated outside the cordon area.

    (a)   The cordon toll is set to 1 EUR.
    (b)   The cordon toll is set to 10 EUR.
    (c)   The cordon toll is set to 100 EUR.

In each pricing experiment, transport users are enabled to adjust their route choice decisions in order to avoid toll payments. In this study, further user reactions such as departure time and mode choice are deactivated. New transport routes are identified based on the least cost path. Vehicle-specific generalized travel costs are discretized and computed for 15 min time bins. To improve the computational performance, noise levels and population densities are computed for a time bin size of 1 h. Each simulation experiment is run for a

total of 100 iterations. During each of the first 80 iterations, 10% of the agents experience new routes. During the final 20 iterations, agents' choice sets are fixed and travel plans are selected based on a multinomial logit model. The utility which is relevant for a travel plan's probability to be chosen is computed as described in Eq. 3. To keep the required amount of memory low, the number travel alternattes per agent is limited to 4 plans.

Real world case study The above described simulation experiments are applied to the real world case study of the greater Berlin region, Germany. The case study was generated by Neumann et al. (2014) who converted a macroscopic and trip-based model into an activity- and agent-based MATSim scenario. Transport demand comprises survey-based "population-representative" agents and "non-population representative" incorporating additional traffic such as freight and tourist traffic. The scenario was calibrated accounting for the mode shares, travel times and travel distances. As input demand for the above described simulation experiments, the agents' executed plans of the relaxed travel demand generated by Neumann et al. (2014) are used. To allow for a better computational performance, a 10% population sample is used. Furthermore, the public transport mode is considered applying a simplified approach in which travel times are computed based on the linear distance. This study focuses on traffic congestion within the road network. Delay effects within the public transport mode or interaction between cars and buses is neglect. The noise computation is limited to noise caused by passenger cars and HGV, other noise sources such as public transit vehicles are not accounted for.

In this case study, the utility functions are set as follows:

$$V^{plan} = \sum_{i=1}^{n} (V_i^{act} + V_i^{trip}),$$ (3)

where V^{plan} is the utility of the agent's executed plan, n denotes the total number of daily activities, V_i^{act} is the utility gained from performing activity i and V_i^{trip} is the utility related to the trip to activity i. V_i^{act} is computed following the approach by Charypar and Nagel (2005).

$$V_i^{act} = \beta^{act} \cdot t_i^* \cdot ln\left(\frac{t_i^{act}}{t_i^0}\right),$$ (4)

where t_i^{act} is the time spent performing activity i, t_i^* is activity i's typical duration, β^{act} is the marginal utility of performing an activity at its typical duration and t_i^0 is a scaling parameter linked to the activity's priority which is only relevant if activities can be dropped from the plan which is disabled in this study. V_i^{trip} follows a linear approach:

$$V_i^{trip} = \beta_m^0 + \beta_m^d \cdot d_{m,i} + \beta_m^t \cdot t_{m,i} + \beta^c \cdot c_i,$$ (5)

where m denotes the mode, β_m^0 is the alternative specific constant, $d_{m,i}$ is the travel distance, β_m^d is the marginal utility of the distance, $t_{m,i}$ is the travel time, β_m^t is the marginal utility of the travel time, c_i is the sum of all monetary amounts paid during the trip to activity i and β^c is the marginal utility of monetary costs.

In this case study, an agent's approximate VTTS is

$$VTTS \approx \frac{\beta^{act} - \beta_m^t}{-\beta^c} = 10\,\text{EUR/h}$$ (6)

However, depending on the agent's individual time pressure, actual VTTS may be higher or lower (Kaddoura and Nagel 2016b).

Results

The interplay of congestion and noise

In this section, the extension described in Sec. 2.4 is compared to the previously existing approach. The extended noise computation approach accounts for reduced speed levels due to traffic congestion. Figure 1 depicts the changes in noise immissions for the city center area of Berlin between 3.00 and 4.00 p.m. as a result of the new computation approach.

For certain road segments, actual speed levels are lower compared to the free-flow speed level which directly translates into lower noise emissions. However, for some road segments traffic congestion is very low resulting in very small differences between the model extension and the existing approach. The differences in noise levels are found to be much larger along motorways during peak times. This is explained by the higher free-flow speed level and therefore larger differences between the free-flow speed and the actual speed level in the case of congestion.

Simultaneous versus isolated noise and congestion pricing

Aggregated results

Table 1 provides aggregated results for pricing experiments 1, 2 and 3. In simulation experiment 1, tolls are set based on the external congestion costs, whereas noise damages are neglected (isolated congestion cost pricing). In simulation experiment 2 tolls are set based on marginal external noise exposure costs, whereas external congestion costs are not accounted for (isolated noise cost pricing). In experiment 3, the optimization methodology is simultaneously applied to both congestion and noise. The pricing experiments are compared with the base case in which no pricing scheme is applied.
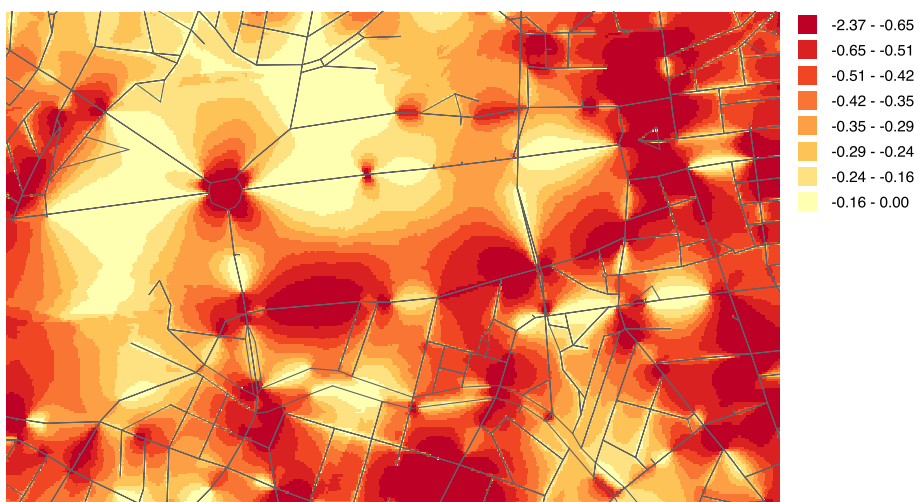

Fig. 1 Change in noise levels in dB(A) as a result of traffic congestion (City center area of Berlin, 3.00–4.00 p.m.)

In all pricing experiments, transport users are enabled to adjust their route choice decisions. In order to avoid highly tolled roads, transport users are even willing to take detours. Consequently, the total travel distance is found to increase for all pricing experiments compared to the base case (no pricing). In the isolated congestion pricing policy (experiment 1), the change in travel behavior results in a congestion relief effect indicated by a decrease in total travel time. In contrast, the isolated noise pricing policy (experiment 2) results in a much larger increase in total travel distance and an increase in total travel time. The noise damage costs are observed to slightly increase in the isolated congestion pricing policy (experiment 1). In contrast, isolated noise pricing (experiment 2) results in a large decrease of noise damage costs.

The system welfare is defined as the sum of the transport users' travel related benefits (including toll payments), the toll revenues and the population's noise damages. Each of the three pricing experiments results in an increase in system welfare compared to the base case (no pricing). In the simultaneous congestion and noise pricing policy (experiment 3), both the total travel time and noise damage costs are found to decrease. Consequently, the increase in system welfare is larger compared to the isolated pricing studies (experiment 1 or 2). However, in all three internalization pricing experiments the change in travel related user benefits is negative. That is, without returning toll revenues to transport users, the population is in total worse off. This is in line with findings from other studies (e.g. Levinson 2010).

A comparison of the aggregated numbers for simulation experiment 1 and 2 reveals that congestion and noise tolling have an opposite effect. Each isolated pricing policy is found to reduce one external effect but to increase the other one. This explains why in the simultaneous congestion and noise pricing policy, the increase in system welfare is below the sum of the increase in welfare in the two isolated pricing policies (see Table 1, last row).

Spatial and temporal analysis

Isolated pricing policies Figure 2 depicts the changes in daily traffic volumes as a result of the different internalization policies. A comparison of Fig. 2a, b illustrates the conflicting route shift effects resulting from congestion and noise tolling.

Table 1 Comparison of simulation experiment 1 (isolated congestion cost pricing), 2 (isolated noise cost pricing) and 3 (simultaneous congestion and noise pricing) with the base case

	Experiment 1	Experiment 2	Experiment 3
Changes in travel distance	+22,899 km	+633,070 km	+667,146 km
Changes in travel time	−17,012 h	+4486 h	−9971 h
Benefits from changes in noise damage costs	−1147 EUR	+110,867 EUR	+110,413 EUR
Changes in travel related user benefits (including toll payments)	−1,033,819 EUR	−373,970 EUR	−1,507,082 EUR
Changes in toll revenues	+1,484,971 EUR	+367,007 EUR	+1,883,735 EUR
Changes in system welfare	+450,006 EUR	+103,903 EUR	+487,066 EUR

Isolated congestion pricing results in route shifts from major to minor roads. In particular, transport users avoid the heavily congested and tolled inner-city motorway and use alternative routes along smaller roads (see Fig. 2a). Thereby, the simulation captures the following effects on the noise level:

- Because of the logarithmic computation of noise, a shift from a busy road to a less busy road translates into higher noise levels.
- Overall, the population density along the motorway is rather low, whereas the population density is much higher along smaller roads. Thus, shifting from less densely populated areas to very densely populated areas increases the level of noise exposures.
- Reduced traffic congestion is linked to a higher speed level which in turn increases the noise level (see Sec. 4.1).

In contrast, isolated noise pricing results in an increase in traffic volume on the inner-city motorway and on main corridors in less densely populated areas. In return, the traffic volume decreases on smaller inner-city roads (see Fig. 2b). This has the following impact on traffic congestion:

- Transport users avoid densely populated areas by taking detours (longer travel distances and travel times) which increases the traffic volume and the congestion level.
- Due to the logarithmic structure of noise, marginal noise cost tolls are lower on very busy roads. As a result, transport users are concentrated along major roads resulting in a higher level of congestion.

Figure 3 depicts the resulting change in L_{den}, the day-evening-night noise index proposed by the Environmental Noise Directive of the European Union 2002/49/EC. As indicated by Table 1, in the isolated congestion pricing policy (experiment 1), the increase in noise damages is rather small. Figure 3a reveals a small decrease in noise along certain corridors and a small increase in noise in a wider area. That is, the increase in noise damages is due to the larger number of exposed people rather than an overall increase in noise levels. In contrast, in the isolated noise pricing policy (experiment 2), overall noise damages are found to decrease significantly. Figure 3b reveals that in a very wide area, noise levels are significantly reduced, whereas along certain corridors with few exposed individuals, noise levels significantly increase. A detailed investigation of spatial equity is provided in Kaddoura et al. (2017) for a noise pricing scheme and in Kaddoura (2015) for a congestion pricing scheme.

Simultaneous pricing policy In the simultaneous congestion and noise pricing policy (experiment 3), the changes in daily traffic volume depicted in Fig. 2c seem to correspond to the overlay of Fig. 2a, b. Moreover, in the simultaneous pricing policy, the change in noise levels is similar to the isolated noise pricing policy (Fig. 3b).

Figures 4 and 5 depict the relevance of congestion and noise for the overall toll level in simulation experiment 3 depending on the time of the day.[3]

Figure 4 shows the average delay imposed on other travelers which increases during the peak periods, in particular during the afternoon-peak. In contrast, Fig. 5 shows the opposite effect: Marginal noise cost are observed to increase during off-peak times, in particular during the early morning and late evening when noise threshold values are higher and overall traffic volumes are on a lower level. Consequently, the congestion externality results in high toll levels during the day and low toll levels during early morning and late

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[3] The analysis only refers to the "population-representative" agents. "Non-population-representative" agents such as HGV, commercial traffic and tourists are excluded from the analysis.
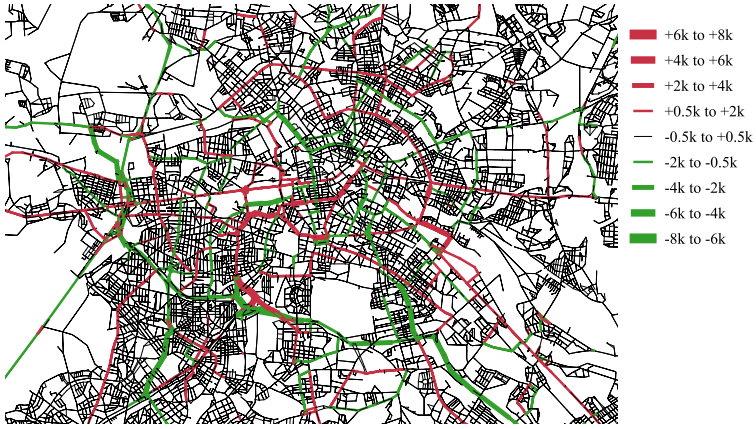
(a)

(b)

(c)

◄Fig. 2 Changes in daily traffic volume. **a** Isolated congestion pricing (experiment 1). **b** Isolated noise pricing (experiment 2)]. **c** Simultaneous congestion and noise pricing (experiment 3)
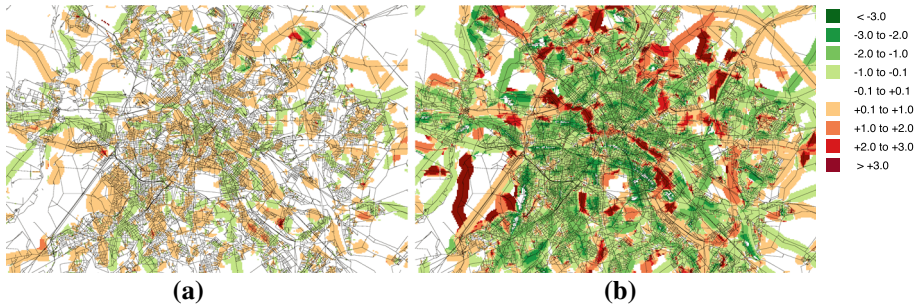

(a)   (b)

Fig. 3 Change in noise levels in dB(A) as a result of the pricing policy (L_{den}: day-evening-night noise index, see Environmental Noise Directive of the European Union 2002/49/EC). **a** Isolated congestion pricing (experiment 1). **b** Isolated noise pricing (experiment 2)
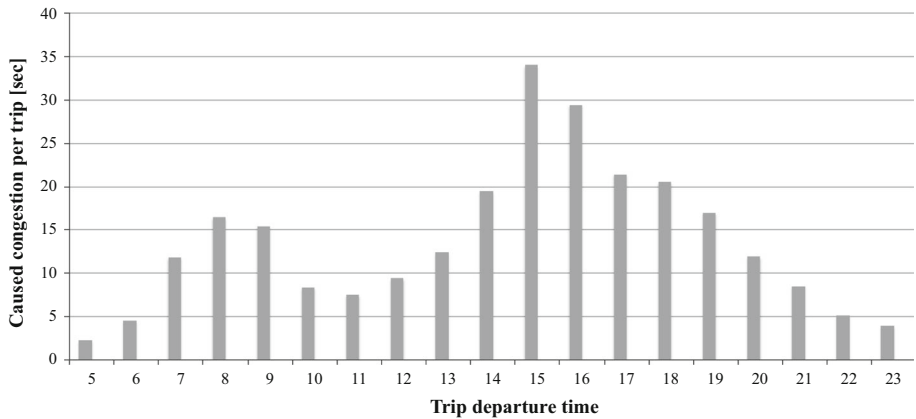
Fig. 4 Caused congestion effect per trip departure time (experiment 3, population representative agents)

evening. In contrast, the noise externality results in high toll levels during the early morning and late evening and low toll levels during the peak periods. That is, in the simultaneous congestion and noise pricing study (experiment 3), depending on the time of the day, road prices result from different effects. During the day, in particular during peak times, travel behavior is dominated by the reaction to avoid congestion prices. In contrast, during the early morning and late evening, travel behavior is dominated by the reaction to avoid noise prices.

Figure 6 depicts the changes in traffic volume as a result of the simultaneous congestion and noise pricing policy for a time period during the day (3 p.m.–4 p.m.) and for an off-peak time period (8 p.m.–9 p.m.). As indicated by Figs. 4 and 5, a comparison of Fig. 6a, b reveals different route shift effects for different times of the day. During the afternoon
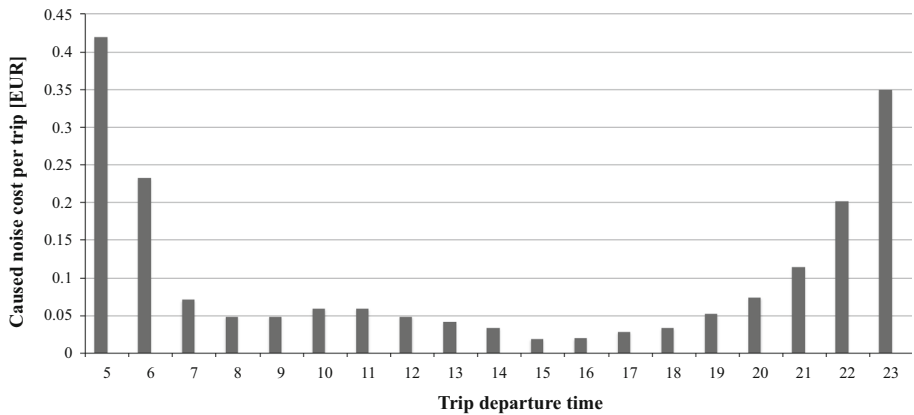
Fig. 5 Caused noise cost per trip departure time (experiment 3, population representative agents)

peak, the changes in traffic volume are similar to the isolated congestion pricing policy, i.e. transport users are observed to shift from major to minor roads. In contrast, in the evening, the demand changes are similar to the isolated noise pricing, i.e. transport users are observed to shift from minor to major roads.

Sensitivity analysis

To investigate the model sensitivity, the toll levels are systematically varied. In the simultaneous congestion and noise pricing experiment (experiment 3), the road-, user- and time-specific toll is composed of two cost components: a monetary amount which approximates marginal external congestion costs (congestion toll) and a monetary amount which approximates marginal external noise damage costs (noise toll). In different simulation experiments, the congestion and the noise toll level are increased by 10 and +30%.

Figure 7 depicts the changes in total travel distance, travel time and noise damages of the simultaneous pricing scheme (experiment 3) compared to the base case (no pricing) for different congestion and noise toll levels.

The results of the sensitivity analysis show that for all toll levels, the simultaneous congestion and noise pricing experiment results in an increase in travel distance, a reduction in car travel time and a reduction in noise damages. The comparison with the base case (no pricing) reveals that a higher congestion toll level yields a larger reduction in total travel time compared to the base case (no pricing). Furthermore, the results show that increasing the congestion toll component reduces the benefits from changes in noise damages. This is explained by the change in the weighting of the different cost components. The noise cost component becomes more and more irrelevant for the transport users' routing decisions compared to the congestion cost component. Increasing the noise toll level reveals the opposite effect: The noise cost component becomes more and more relevant and dominates the transport users' behavior, i.e. the agents take long detours indicated by the large increase in changes in total travel distance compared to the base case (no pricing). Consequently, for higher noise toll levels, the benefits from changes in noise damage costs increase.
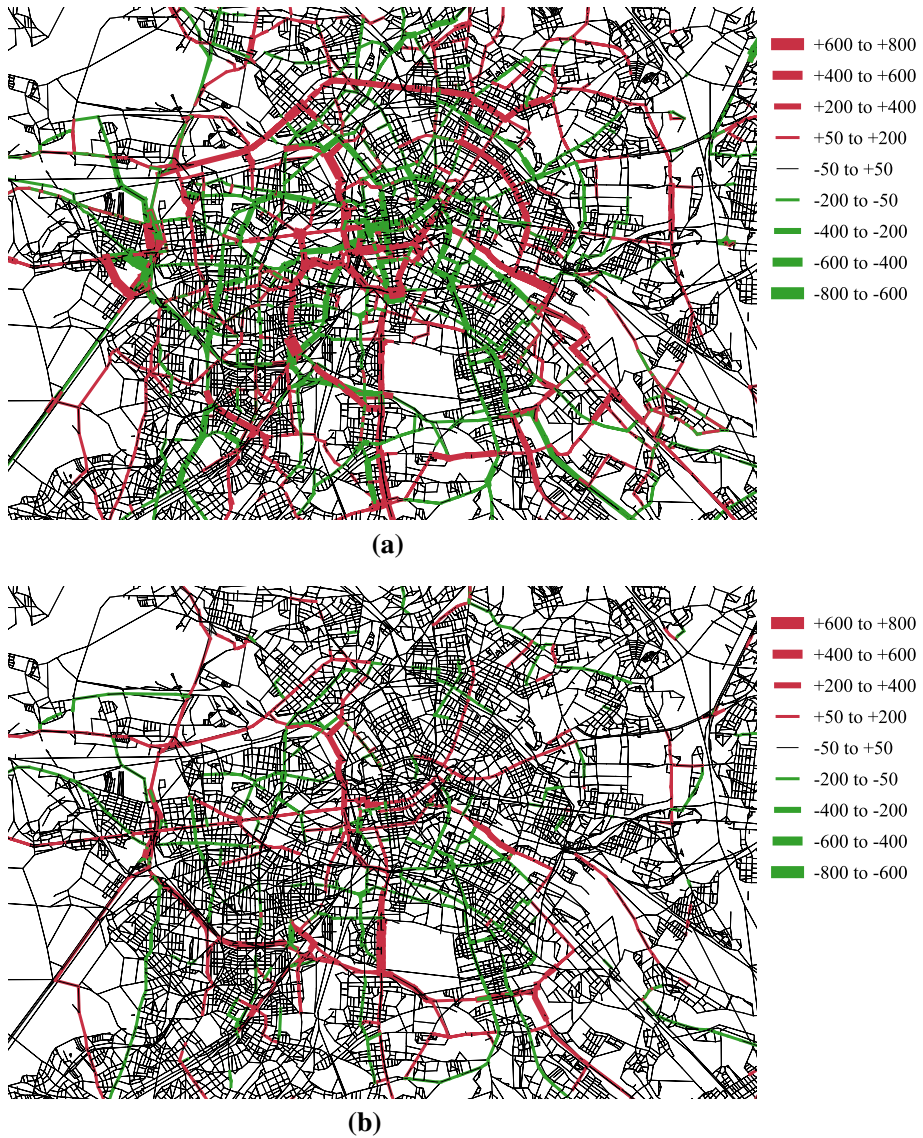
Fig. 6 Changes in traffic volume: Simultaneous congestion and noise pricing (experiment 3). **a** Peak: 3 p.m.–4 p.m. **b** Off-peak: 8 p.m.–9 p.m

Analyzing the effects of a cordon toll

This section provides the results of the cordon pricing scheme described in Sec. 3 (simulation experiment 4a, 4b and 4c). Table 2 provides the aggregated parameters for the different cordon toll levels (1, 10 and 100 EUR). Transport users are only enabled to avoid the toll payments by adjusting their route choice decisions, i.e. not crossing the cordon.

For all cordon toll levels, the travel time and travel distance are found to increase. For the 1 EUR cordon toll (experiment 4a), the changes on the demand side are rather small.
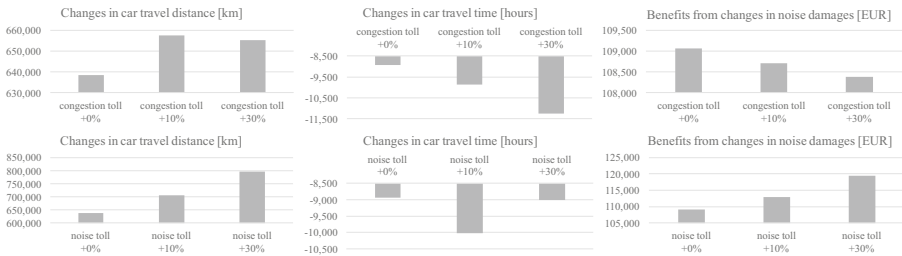
Fig. 7 Sensitivity analysis: variation of the congestion and noise toll level; comparison of the simultaneous congestion and noise pricing experiment with the base case (no pricing)

For higher cordon toll levels (experiment 4b and 4c), the user reactions are stronger, indicated by a larger increase in travel time and travel distance. The benefits from changes in noise damages are rather small in all cases. A comparison of the cordon toll with experiment 2 and 3 (see Table 1), reveals that both of these schemes result in a much larger reduction of noise damages than the cordon toll. Additionally, while experiments 1, 2 and 3 the overall welfare effect is positive, the cordon pricing scheme (experiment 4a, 4b and 4c) decreases the system welfare. This is related to the assumption that transport users are only enabled to adjust their transport routes. That is, the simulation experiments neglects additional possible user reactions such as switching to alternative modes.

A spatial plot of the changes in daily traffic volume due to the cordon toll of 10 EUR compared to the base case is provided in Fig. 8. Since the inner-city motorway ring road is located outside of the cordon area, transport users rather take the motorway than driving through the city center. The overall effect of the cordon pricing scheme is that transport demand decreases in the inner-city area and increases outside the cordon area. However, along a few inner-city road stretches travel demand slightly increases compared to the base case. This can be explained by transport users that avoid to exit and reenter the cordon area for trips starting and ending within the cordon area. Figure 9 shows the change in noise day-evening-night index (L_{den}) resulting from the cordon pricing scheme (cordon toll = 10 EUR; experiment 4b). Along the inner-city motorway ring road and outside of the cordon area, noise levels are observed to increase. In contrast, along most roads in the inner-city area, noise levels are observed to decrease. Overall, the changes in noise levels resulting from the cordon tolling scheme are at a lower level compared to the noise internalization approach.

Table 2 Comparison of simulation experiment 4a, 4b and 4c (cordon pricing) with the base case

|	Experiment 4a	Experiment 4b	Experiment 4c
Cordon toll	1 EUR	10 EUR	100 EUR
Changes in travel distance	+82,476 km	+382,609 km	+432,386 km
Changes in travel time	+1828 h	+7883 h	+8687 h
Benefits from changes in noise damage costs	+312 EUR	+3349 EUR	+3481 EUR
Changes in travel related user benefits (including toll payments)	−730,179 EUR	−6,046,062 EUR	−58,065,791 EUR
Changes in toll revenues	+683,150 EUR	+5,876,100 EUR	+57,782,000 EUR
Changes in system welfare	−46,718 EUR	−166,613 EUR	−280,311 EUR
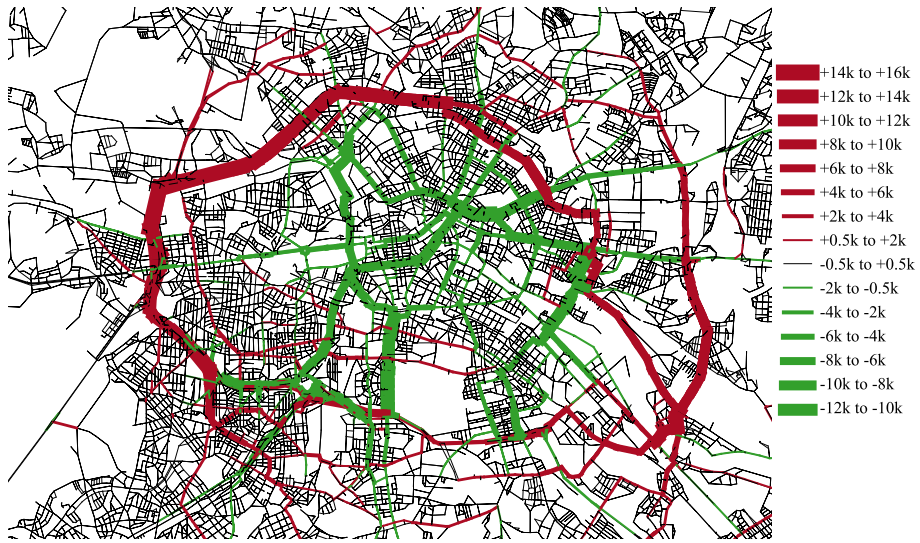
Fig. 8 Changes in daily traffic volume: Cordon toll = 10 EUR

Discussion

This study evaluates the trade-offs between traffic congestion and noise reduction strategies. Taking into account further external cost components in the price setting may have a considerable effect on the observed results. Including the cost of greenhouse gases such as CO_2 presumably pushes towards shorter travel distances to reduce global emission cost (see e.g. Kickhöfer and Nagel 2016). In contrast, accounting for local air pollutants such as particulates and nitrogen oxides, may have an effect similar to noise since damages depend
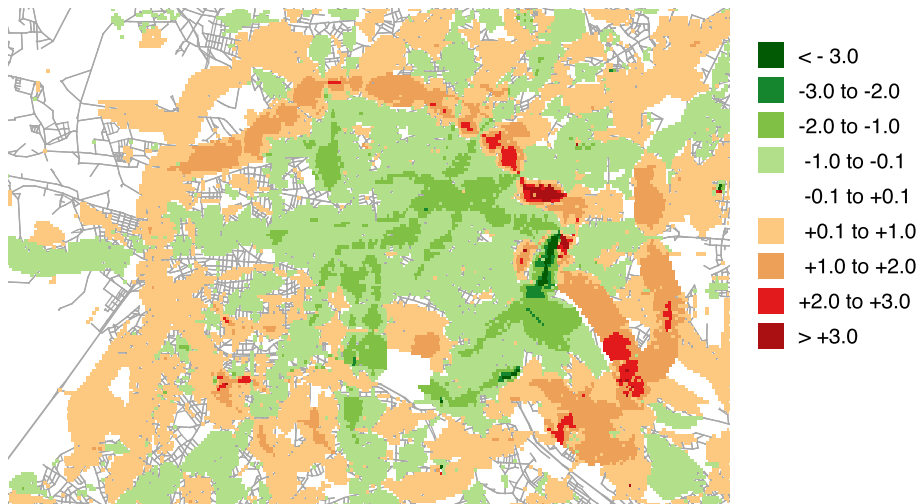

Fig. 9 Change in L_{den} in dB(A) as a result of the cordon pricing scheme (experiment 4b, cordon toll = 10 EUR)

on the number of locally affected people. Hence, accounting for local air pollution cost will presumably shift transport users to even longer distances to avoid trips through densely populated areas (e.g. Kickhöfer and Kern 2015). The external effects' cost structure is of major importance. As described above, marginal noise costs are very low for busy roads during peak times which is found to result in traffic concentration effects. In contrast, in the case of air pollution and human health, the dose response function is linear and marginal costs are similar to average costs (Maibach et al. 2008) which is expected to result in cost levels that are more likely decision-relevant for travelers on busy roads during peak times. Additionally, emissions of air pollutants increase for high speed levels and low speed levels compared to medium speed levels (Barth and Boriboonsomsin 2009; Maibach et al. 2008) which provides an additional incentive to avoid heavily congested roads during peak times.

In the applied case study of the Greater Berlin area, transport users are only enabled to adjust their transport routes. Hence, the simulation experiments may underestimate the real-world effects, i.e. the aggregate increase in system welfare. Indeed, the presented methodology allows for more complex user reactions; transport users may for example be enabled to adjust their mode of transportation. In this context, the presented methodology may also be combined with existing optimization approaches for the public transport mode (Kaddoura et al. 2015a, b).

Our results confirm the well-known result that toll revenue redistribution is important in order to generate overall positive benefits for road users (e.g. Levinson 2010). On the damages side, our approach is equitable by design: Each person-hour spent at an activity is valued equally when negatively affected by noise. The present paper does not look at, say, income-differentiated reactions to the tolls. The approach itself is capable to do this (Kickhöfer et al. 2011); we wanted, however, to investigate the interaction between congestion and noise tolls without having to disentangle the results from additional effects. Still, the present study is an important milestone on the way to a simulation package that is able to both model behavior and to assess benefits and damages by individual synthetic person.

Conclusion

This study elaborates on the interrelation of external effects. For congestion and noise, single objective optimization is compared with multiple objective optimization. The optimization methodology follows an iterative market-based approach. An agent-based simulation framework is used to compute and internalize external congestion effects and noise exposures. The applied internalization approach accounts for dynamic congestion and heterogeneous values of travel time savings. Tolls are computed for each transport user, road segment and time interval. For the case study of the Greater Berlin area, several simulation experiments are carried out, (1) isolated congestion pricing, (2) isolated noise pricing, (3) simultaneous congestion and noise pricing and (4) cordon pricing. In each pricing experiment, transport users are enabled to adjust their route choice decisions in order to avoid toll payments.

The results reveal a negative correlation between congestion and noise since the internalization of one effect increases the other one. This interrelation of congestion and noise is consistent with the findings of other studies (Wismans et al. 2011; Makarewicz and Galuszka 2011, see Sec. 1). Nevertheless, the multiple objective optimization shows that it

is possible to simultaneously reduce congestion costs and noise damages. Going beyond the scope of most existing studies, the results are analyzed for a large-scale network and a detailed representation of the population. A detailed investigation of temporal and spatial effects reveals that the interrelation of congestion and noise is very low. Depending on the time of day, travel behavior primarily results from avoiding either one externality or the other one. During peak times, congestion is the more relevant external effect, whereas during off-peak times, in particular during the night, noise is the more relevant externality. During peak times, transport users are observed to shift from the inner-city motorway to smaller roads. In contrast, during off-peak times, transport users shift from minor to main roads, in particular to the inner-city motorway. The comparison with different cordon pricing schemes reveals that the simultaneous congestion and noise pricing methodology is more effective in terms of welfare maximization, i.e. reduction of noise damages and congestion costs.

The presented methodology provides important implications for policy makers. The results of the Berlin case study indicate that it is possible to simultaneously reduce congestion and noise. The key factor is to follow a dynamic traffic management approach and temporally change the incentives during the course of the day:

- During the evening, night and morning, transport policies should aim at reducing noise exposures in residential areas. This objective may be achieved by concentrating traffic flows or providing incentives to use roads in less densely populated areas. The through traffic may for example be banned in residential areas inducing transport users to take detours. The resulting increase in traffic congestion is minor compared to the reduction in noise exposures.
- During the day, the results of the simulation experiments indicate that system welfare is increased by reducing congestion, i.e. by motivating a shift from congested motorways to smaller roads and spreading the demand within the network. Due to higher noise threshold values during the day compared to the morning, evening and night, as well as due to the logarithmic scale of noise and the overall high demand levels during the day, the increase in noise damages is minor compared to the reduction in congestion costs.

This neglects the impact of further external effects. Considering additional external cost components, the policy recommendations for the evening, night and morning presumably hold. In contrast, the results observed during the day, in particular the shift from motorways to minor roads in more densely populated areas is presumably associated with an increase in air pollution exposure and accident costs yielding a decrease in system welfare.

A major task for the future is to make the model more useful for practitioners and decision makers. This includes the following tasks:

- The proposed market-based optimization approach will be extended to simultaneously account for further external effects, in particular, air pollution (Kickhöfer and Nagel 2016; Kickhöfer and Kern 2015) and accidents. Additional external effects will be taken into account by extending the computation of road-, user- and time-specific tolls and introducing further additive terms that correspond to the marginal cost of other external effects. The existing methodology for air pollution pricing by Kickhöfer and Nagel (2016) and Kickhöfer and Kern (2015) builds on the same transport simulation framework and therefore allows for an easy integration of road-, user- and time-specific air pollution cost terms.
- The simulation experiments will account for more complex user reactions. As discussed in Sec. 5, the applied simulation framework allows for additional choice

dimensions such as the mode of transportation and the departure time. However, this requires that the model calibration accounts for endogenous mode and departure time choice. The presented pricing methodology may be applied to further case studies, i.e. other models for specific regions, to investigate whether the policy recommendations hold for a different spatial and temporal structure of the transport system and the population. It is also possible to apply the presented pricing approach only to a predefined area, e.g. the city center area. The code is open source and publicly available which allows for an easy application by traffic modelers once the case study is set up. Current research work focuses on easy and fast processes of generating such case studies (see e.g. Ziemke et al. 2015). An overview of the currently existing MATSim case studies including the considered choice dimensions is provided by Horni et al. (2016, Part IV: Scenarios).

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