ACTIVITY-BASED COMPUTATION OF MARGINAL NOISE EXPOSURE COSTS: IMPLICATIONS FOR TRAFFIC MANAGEMENT

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Abstract

In this paper, an innovative simulation-based approach is presented to calculate optimal dynamic, road- and vehicle-specific tolls based on marginal traffic noise exposures. The proposed approach combines the advantages of an activity-based simulation with the economically optimal way of price setting. Temporal and spatial differences of traffic noise levels and population densities are considered. Moreover, noise exposures at work and educational activities are accounted for. The results of the case study for the area of Berlin, Germany, show that transport users avoid marginal noise cost payments by shifting to roads stretches in areas with lower population densities, typically major roads. The simulation experiments indicate that the marginal cost approach can be used to improve the overall system welfare and to derive traffic control strategies.

INTRODUCTION

Environmental noise is found to cause cardiovascular diseases, tinnitus, cognitive impairment and sleep disturbances (see e.g. 1, 2, 3, 4, 5). Noise barriers, quieter road surfaces as well as improved aerodynamics, tires and motor engines aim to reduce noise exposures (see e.g. 6). An alternative approach is to reduce noise by means of intelligent traffic management, i.e. individual changes in travel behavior. Road pricing is one out of a variety of tools to manage traffic. The economic theory provides the answer to the question of how to set road prices. Pigou (*7*) introduced the principle of marginal social cost pricing, where road users are charged a toll that is equal to the marginal cost imposed on other travelers or the society as a whole. That is, external costs are included in decision making processes and people's behavior is changed towards a more efficient use of the transport system (see e.g. 8, 9). Optimal prices may also be understood as cost terms to correct the transport users' generalized travel cost. Increasing the travel time for certain roads may for example result in the same cost correction as a toll having the same effect on the transport users' travel decisions.

In this study, an innovative simulation-based approach is presented which calculates vehicle-specific, dynamic and road-specific marginal noise costs. Based on the marginal cost, differentiated optimal noise tolls are calculated and charged from the transport users. Further external cost components such as congestion, air pollutants and accidents are neglected. The proposed marginal noise cost pricing methodology is based on the noise exposure computation approach presented in Kaddoura et al. (*10*) and summarized in Sec. 2.2. Combining this approach with the economically optimal way of price setting provides new insights into improved traffic management.

Several studies address the improvement or validation of the traffic noise model (see e.g. 11, 12). Simulation allows for a sophisticated noise computation which accounts for acceleration and deceleration behavior (13). However, the focus in the present study is placed on the sophisticated representation of the affected population which allows for a detailed exposure analysis.

Most noise action planning approaches use static resident numbers to investigate population exposures to noise (see e.g. 14, 15, 16). This is plausible for the night (see e.g. 17, pp. 187–189), but not for the day when residents usually leave their homes. Differentiated noise limit values for hospitals, schools, residential areas and commercial areas (*18*) as well as for different work activity types such as a conference room, a single office, an open space office or an industrial workspace (*19*) indicate that noise exposure analysis should go beyond residential noise exposures and additionally account for traffic noise at the workplace or education activities. Also, the Environmental Noise Directive of the European Union 2002/49/EC (*20*) suggests a differentiated noise exposure analysis for specific building types, i.e. schools and hospitals. Lam and Chung (*21*) analyze population exposures to noise with regard to socio-economic characteristics and identify certain population groups that are worst affected by traffic noise. Murphy and King (*22*) mention the importance to account for weekend commuters, whereas, the importance to account for daily commuters when analyzing noise exposures is not addressed. Ruiz-Padillo et al. (*23*) propose an approach to calculate a priority index for noise control action planning. The index prioritizes roads depending on the noise level, the number of exposed residents and the "occurrence of noise sensitive centers", i.e. educational, cultural or health facilities. Tenaileau et al. (*24*) address the size of the neighborhood area to be considered for residential noise exposure analysis. The authors conclude that their approach should be revised to capture the population's within-day activities and that population exposures to noise should ideally be calculated on an individual-based level. The noise exposure analysis proposed by Kaddoura et al. (*10*) goes beyond residential noise exposures, i.e. considers individuals that may be affected at work, university or school and accounts for the temporal and spatial variation of both the noise level and population density.

In Kaddoura et al. (*25*) average noise cost prices per road, time and vehicle are calculated following the approach by Gerike et al. (*26*). In a first step, noise damage costs are assigned to the road segments. In a second step, the road segment's total contribution is allocated to the different vehicle types and vehicles. Average noise cost pricing seems a valid approach to reduce noise exposure costs and to obtain revenues which are sufficient to compensate everybody for incurred damages. However, the economically optimal solution is to charge marginal cost prices. In the case of noise, marginal costs are below average costs (*8*). That is, average noise cost pricing results in too high prices which may result in welfare losses.

In the present paper, the advantages which come along with the activity-based simulation approach are combined with an economically optimal noise pricing methodology. The proposed innovative optimization approach is applied to the case study of the Greater Berlin area.

METHODOLOGY

Simulation framework

The proposed marginal noise cost pricing approach applies the open-source simulation framework MATSim[1] to calculate noise levels and population densities. Optimal exposure tolls are computed for each time bin, road and vehicle and transport users are iteratively enabled to react to these tolls. MATSim is a dynamic and activity-based transport model, thus, it is straightforward to collect time-specific information about the population density for certain activity types, e.g. home, work, school. The demand for transport results from spatially separated activity locations. The demand for transport is modeled as individual agents. Each agent holds one or more travel plans which describe the daily activity schedule as well as transport information such as the transport modes. Initial plans have to be provided that may be modified during the process of demand adaptation to supply. The demand adaptation is based on an evolutionary iterative approach with the following three steps: (1) travel plans are executed (traffic flow simulation), (2) the executed plans are scored (evaluation) and (3) plans are modified (learning).

1. **Traffic Flow Simulation** All travel plans are simultaneously executed and the agents interact in the physical environment. Vehicles are moved along road segments (links) applying the queue model developed by Gawron (*27*). The obtained traffic flows are consistent with the fundamental diagram (see e.g. 28).

2. **Evaluation** Each agent scores the executed plan based on travel-related costs such as the travel time or monetary payments, but also based on the utility gained from performing activities (*29*).

3. **Learning** Based on the previous evaluation, the agents select one travel plan for the next iteration by choosing among their existing plans based on a multinomial logit model. During the phase of choice set generation, in each iteration, some agents generate new plans by copying and modifying and existing plan. In this study, only the transport route can be modified. However, the simulation framework allows for further choice dimensions.

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

An iterative repetition of the above steps enables the agents to improve their scores, obtain plausible travel alternatives and the simulation outcome to relax. Assuming the travel plans to represent valid choice sets, the system state is considered as an approximate stochastic user equilibrium (*30*). A detailed description of the simulation framework is provided in Raney and Nagel (*31*).

Traffic noise exposures

The noise computation methodology is mainly based on the German RLS-90 approach (‘Richtlinien für den Lärmschutz an Straßen’, 32) applying the approach ‘lange, gerade Fahrstreifen’ (‘long, straight lanes’). For each time interval, noise emissions are calculated on the basis of the traffic flow, the share of HGV (heavy goods vehicles) and the speed level. Noise immissions are calculated for a predefined set of receiver points accounting for the noise emissions at the surrounding road segments and considering the decrease in noise due to air absorption. To allow for fast computational performance which is in particular relevant for the iterative optimization approach, in this study, further noise corrections such as ground attenuation, multiple reflections or shielding of buildings are not considered. Instead, the focus is placed on a detailed representation of the affected population. Applying the activity-based simulation methodology allow to track each individuals’ daily activities (locations and activity start and end times) which are then used to compute dynamic population densities. Furthermore, the types of activities such as being at home, at work, school or university are known and can therefore be used for an activity-type specific computation of population densities. Both, the noise immissions and demand activities are required to compute noise exposures. Hence, the computation of noise exposures accounts for the within day dynamics of varying population densities in different areas of the city. Noise is converted into monetary units based on the avoidance costs and willingness to pay applying the threshold-based German EWS approach (‘Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen’ 33) which defines a limit value of 40 dB(A) for the night (6 p.m. to 6 a.m.) and 50 dB(A) for the day (6 a.m. to 6 p.m.). In order to comply with the noise evaluation method defined by the European Union (20, Annex I), in this study, an evening period is introduced. Hence, the threshold immission values are set to 50 dB(A) for during the day (6 a.m. to 6 p.m.), 45 dB(A) for the evening (6 p.m. to 10 p.m.) and 40 dB(A) for the night (10 p.m. to 6 a.m.). A detailed description of the applied computation methodology is provided in Kaddoura et al. (*10*).

Marginal noise cost

For each receiver point and time interval, the superposition of noise from the surrounding links is computed applying the principle of energetic addition; the final noise immission level is

$$I_{j,t} := 10 \cdot \log_{10} \sum_{i} 10^{0.1 \cdot I_{i,j,t}(n_i^{car}, n_i^{hgv})} \quad \{I_{i,j,t} > 0\} \tag{1}$$

where $I_{j,t}$ is the noise immission level in dB(A) at receiver point j during the time interval t; $I_{i,j,t}$ denotes the immission level in dB(A) at receiver point j resulting from link i; n_i^{car} is the number of cars; and n_i^{hgv} is the number of HGV. To improve the computational performance, in this study, only the links within a maximum radius of 500 meters around each receiver point are taken into account.

The change in noise immission for an additional vehicle is computed as depicted in Eq. 2 and 3. For computational reasons the terms are rearranged to avoid the repeated summation over the surrounding links of each receiver point and to use $I_{j,t}$ instead, which is computed in a previous step. The noise immission level for an additional car on link k is

$$\begin{aligned} I_{j,t}^{car,k} &:= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}(n_k^{car}+1, n_k^{hgv})} + \sum_{i \neq k} 10^{0.1 \cdot I_{i,j,t}(n_i^{car}, n_i^{hgv})}\right) \\ &= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}(n_k^{car}+1, n_k^{hgv})} - 10^{0.1 \cdot I_{k,j,t}(n_k^{car}, n_k^{hgv})} + 10^{0.1 \cdot I_{j,t}}\right) \\ &\{I_{i,j,t} > 0, I_{k,j,t}(n_k^{car}, n_k^{hgv}) > 0, I_{k,j,t}(n_k^{car}+1, n_k^{hgv}) > 0\} \end{aligned} \tag{2}$$

where $I_{j,t}^{car,k}$ is the noise immission level for one additional car on link k in dB(A). The noise immission level for an additional HGV on link k is

$$\begin{aligned} I_{j,t}^{hgv,k} &:= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}(n_k^{car}, n_k^{hgv}+1)} + \sum_{i \neq k} 10^{0.1 \cdot I_{i,j,t}(n_i^{car}, n_i^{hgv})}\right) \\ &= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}(n_k^{car}, n_k^{hgv}+1)} - 10^{0.1 \cdot I_{k,j,t}(n_k^{car}, n_k^{hgv})} + 10^{0.1 \cdot I_{j,t}}\right) \\ &\{I_{i,j,t} > 0, I_{k,j,t}(n_k^{car}, n_k^{hgv}) > 0, I_{k,j,t}(n_k^{car}, n_k^{hgv}+1) > 0\} \end{aligned} \tag{3}$$

where $I_{j,t}^{hgv,k}$ is the noise immission level for one additional HGV on link k in dB(A). Marginal noise exposure costs are

$$\begin{aligned} mc_t^{car,k} &:= \sum_j \left(C_{j,t}(I_{j,t}^{car,k}) - C_{j,t}(I_{j,t})\right) \\ mc_t^{hgv,k} &:= \sum_j \left(C_{j,t}(I_{j,t}^{hgv,k}) - C_{j,t}(I_{j,t})\right) \end{aligned} \tag{4}$$

where $mc_t^{car,k}$ are the marginal cost of an additional car on link k; $mc_t^{hgv,k}$ are the marginal cost of an additional HGV on link k; and $C_{j,t}$ are the cost as a function of a time-dependent threshold value, the number of exposed individuals and the noise immission level (*10*).

APPLICATION

Berlin case study

The marginal noise cost pricing approach is applied to a real-world case study of Berlin, Germany, generated by Neumann et al. (*34*). The transport network consists of all major and minor roads of the Greater Berlin area. The transport demand side is modeled as "population-representative" agents and "non-population representative" agents to account for additional traffic such as freight, airport and tourist traffic. The model was calibrated against mode shares, travel times and travel distances. A comparison of the model with survey data (35) shows that the differences in mode shares per distance are below 5% (34). The executed plans of the relaxed system state by Neumann et al. (*34*) are used as initial demand for the simulation experiments in this study. For a faster computation, a 10% population sample is used and the traffic flow model only accounts for cars and HGV. For other transport modes, i.e. public transport, bike and walking, travel times are computed based on the beeline distance and the noise impact is neglected. The 10% sample size comprises a total of 598,891 agents performing a total of 1,411,910 trips. Of this number, 476,198 trips are performed by car or HGV.

In this study, two noise pricing experiments are carried out for two assumptions:

- **Assumption *A*:** Marginal noise cost prices are computed based on the assumption that noise exposure costs are only incurred for residents that are exposed to traffic noise at their **home** location.
- **Assumption *B*:** Marginal noise cost prices are computed based on the assumption that noise exposure costs are incurred for individuals that are exposed to noise at their **home** location, and additionally at **work**, **school** or **university**.

In both experiments, marginal noise cost are computed as described in Sec. 2.3. Each simulation experiment is run for a total of 100 iterations. During each of the first 80 iterations, 10% of the transport users are allowed to experience new routes (choice set generation) and for the final 20 iterations, travel alternatives are selected based on a multinomial logit model (fixed choice sets). Each agent's choice set comprises a maximum of 4 travel alternatives. The traffic flow model only accounts for road users, i.e. cars and HGV.

Results

In the following, the marginal noise cost pricing approach is compared with the average noise cost pricing approach applied to the same case study in Kaddoura et al. (*25*). For both pricing approaches welfare relevant parameters are compared with the base case situation in which the simulation is run for 100 iterations without pricing.

In Table 1 the changes in welfare relevant parameters are provided for assumption *A* and *B* and both average and marginal noise cost pricing. All noise pricing experiments result in higher

TABLE 1 Daily changes welfare relevant parameters as a result of noise pricing: Average cost pricing (ACP) vs. Marginal cost pricing (MCP)

	Assumption *A*		Assumption *B*	
	ACP	MCP	ACP	MCP
Benefits from changes in noise exposures [EUR]	+51,436	+91,492	+63,925	+104,369
Benefits from changes in travel related cost (including toll payments) [EUR]	−852,026	−375,620	−1,156,701	−396,513
Changes in toll revenues [EUR]	+801,853	+287,945	+1,044,888	+371,775
Changes in system welfare [EUR]	+1,263	+3,817	−47,889	+79,632

benefits from reductions in noise exposures. Furthermore, noise pricing decreases travel related user benefits. This is explained by (i) toll payments and (ii) the reaction to avoid these toll payments, for example making a detour. For assumption *A*, the daily changes in social welfare are minimal (+1,263 EUR, +3,817 EUR), whereas, for assumption *B*, the changes in social welfare are on a much higher level. For assumption *B*, the average cost pricing approach results in lower daily system welfare compared to the base case (−47,889 EUR), whereas, marginal noise cost pricing strongly increases daily system welfare (+79,632 EUR). The reduction in noise exposures is considerably larger despite an overall lower level of toll payments when applying marginal noise cost prices compared to the average cost approach. Therefore, the overall price reaction is weaker, resulting in a slighter decrease of travel related user benefits.

Figure 1 depicts the daily traffic volumes for the inner-city area of Berlin. Clearly visible is the inner-city highway in the south-western area as well as the main inner-city roads. A second layer depicts the aggregated daily population units for assumption *B*, with darker red tones indicating a higher population density. Areas with very low population densities such as green areas are displayed in white. Figure 2 depicts the absolute daily changes in traffic volume for the inner-city area of Berlin as a result of the marginal noise cost pricing approach for assumption *B*. For comparison, Figure 3 depicts the absolute daily changes in traffic volume for the inner-city area of Berlin as a result of the average noise cost pricing approach. Green-colored road segments indicate a decrease in traffic, red-colored road segments indicate an increase in traffic volume.

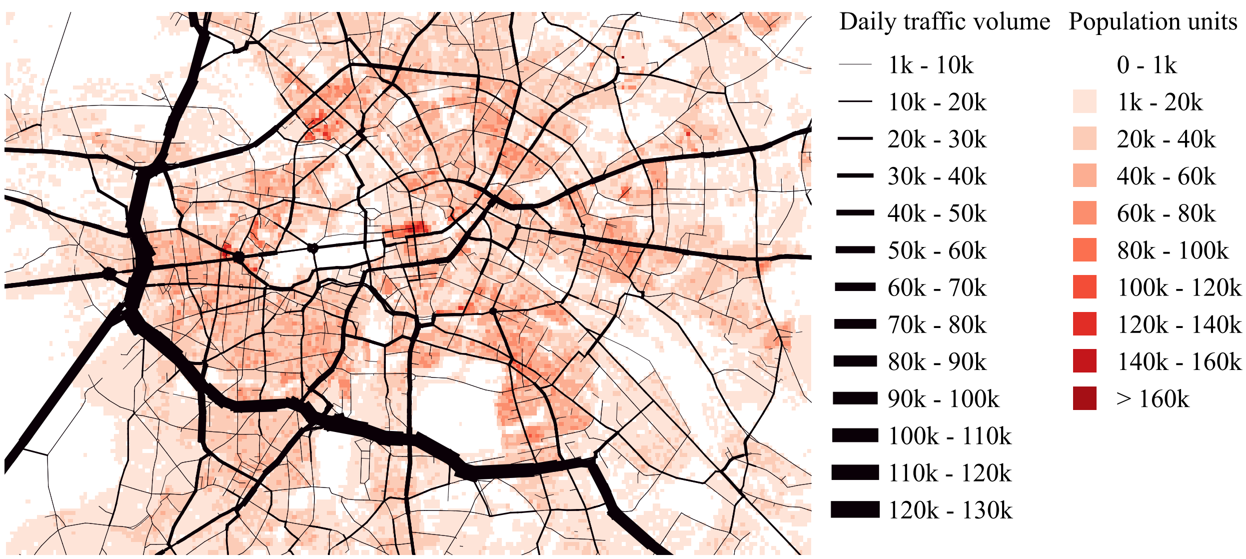

FIGURE 1 Base case: Daily traffic volume and population units (assumption B)

Overall, the structural changes in traffic volumes are similar for both the average and the marginal noise cost pricing approach. Transport users avoid noise tolls by shifting to roads in areas with lower population densities. For most minor roads the traffic volume decreases, whereas on major road segments, such as the inner-city highway, the traffic volume typically increases. A comparison of both pricing approaches reveals that marginal noise cost pricing results in overall smaller changes in traffic volumes. Due to lower marginal noise cost prices, the changes in traffic volume are substantially smaller. By contrast, average noise cost pricing provokes a stronger reaction as exemplified by elevated traffic volume variations for a larger number of road segments. For assumption *A*, the considered population units appear differently, seeing as work and educational activities are neglected. As a consequence, both noise pricing approaches result in different traffic flows, i.e. higher traffic volumes in areas with a large number of work and educational activities such as the central business districts. Due to the smaller number of population units, optimal tolls

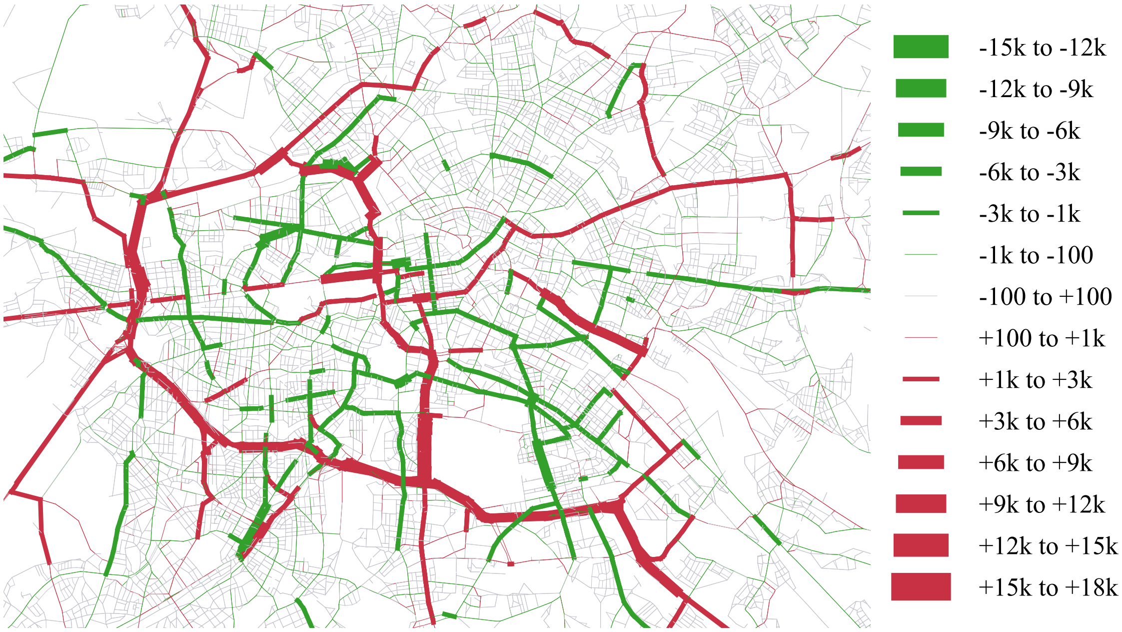

FIGURE 2 Marginal noise cost pricing: Changes in daily traffic volume (assumption B)

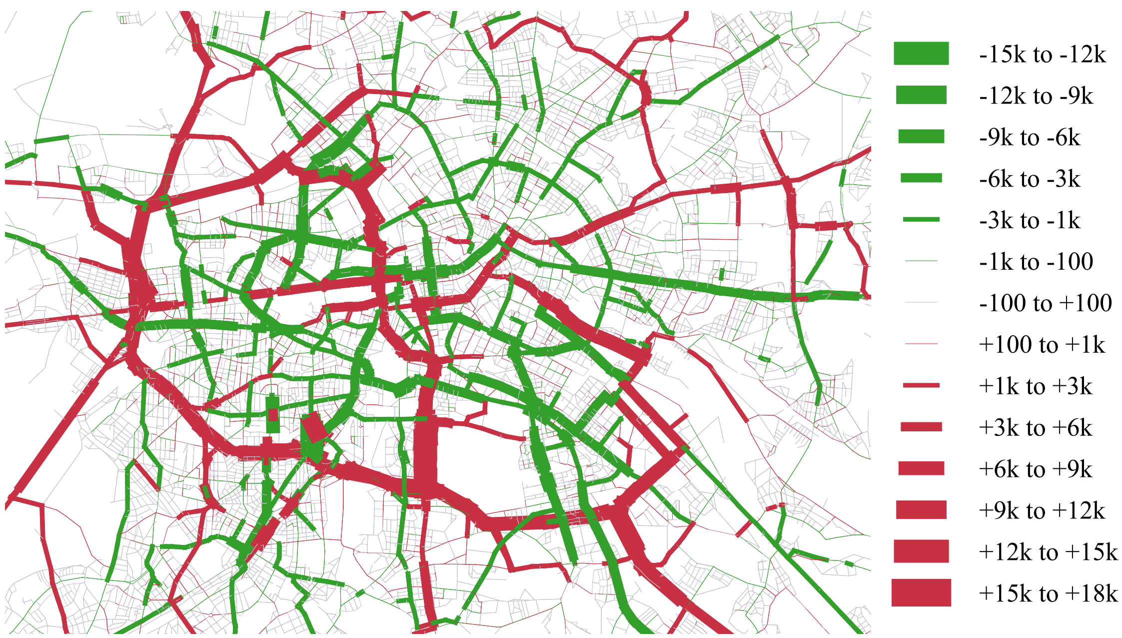

FIGURE 3 Average noise cost pricing: Changes in daily traffic volume (assumption B)

are considerably less for assumption *A* compared to assumption *B*.

Figure 4 depicts the temporal distribution of the average toll per car trip for the average and marginal noise cost pricing experiments (Assumption *B*). Overall, marginal noise cost prices are lower than average cost prices. During daytime, the difference between average and marginal

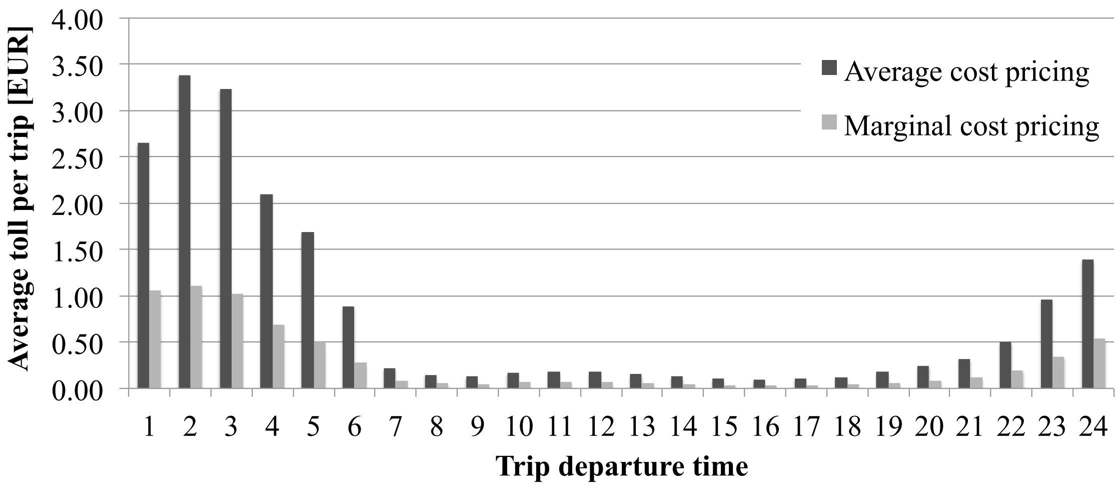

FIGURE 4 Average noise price per car trip over departure time

noise cost tolls is minimal, whereas in the morning, evening and night, due to lower traffic volumes, average noise cost prices are demonstratively higher than marginal noise cost tolls.

Marginal and average noise cost tolls are found to increase with the trip distance. However, for longer travel distances the toll level increases at a lesser degree. This can be explained by long stretches of travel routes which go through less densely populated areas. For assumption *B* with regard to all vehicle types, marginal noise cost tolls increase from 0.01 EUR for trips shorter than 1 km up until 0.10 EUR for trip distances between 19 and 20 km. In contrast, average noise cost tolls are on a higher level, ranging from 0.03 EUR (<1 km) until 0.28 EUR (19-20 km).

CONCLUSION AND OUTLOOK

In this study, an innovative simulation-based approach was presented to calculate marginal noise costs. The approach makes use of an existing simulation-based methodology to compute noise exposures by Kaddoura et al. (*10*). By making use of an activity-based transport simulation, the computation of noise exposures accounts for temporal and spatial differences of noise levels and population densities. Furthermore, the approach allows to account for individuals that are exposed to traffic noise at work or educational activities. Marginal noise cost can be converted into optimal time-, road- and vehicle-specific tolls to optimize the transport system - provided the transport users are enabled to adjust their travel behavior. The contribution of the proposed approach is that the economically optimal way of price setting is combined with the advantages of the activity-based simulation. The proposed optimization approach was applied to the large-scale case study of Berlin, Germany, in which transport users were enabled to change their transport route. The results were compared with a similar approach in which tolls are set based on average noise cost (*25*).

The results of the case study have shown that the proposed marginal noise cost pricing approach increases the overall system welfare. Transport users are found to avoid marginal noise cost payments by shifting to roads stretches in areas with lower population densities. For most minor roads the traffic volume decreases, whereas on most major road segments, such as the inner-city highway, the traffic volume increases. The assumption regarding which activity types are accounted for (assumption *A* vs. *B*) results in different optimal traffic flows. For road segments where the optimal traffic volume is lower than the existing one, instead of a toll, for example, the speed level can be reduced while having the same effect on the transport users' travel decisions. For the marginal cost approach, the reduction in noise exposures is found to be larger than applying the average cost approach despite the fact that toll payments are lower. This indicates that the marginal cost approach works quite well for traffic noise. By contrast, the average noise cost approach results in smaller noise exposure reductions. Moreover, the average cost approach overprices the transport system. As a consequence, the transport users' changes in travel behavior is too strong which, for assumption *B*, leads to a substantial welfare loss.

Overall, the presented approach can be used to obtain optimal traffic flows which may be used to derive traffic control strategies. Definitely, in some cases, traffic management will not achieve the desired objectives and other noise control measures are more suitable. However, it is worth considering the rearrangement of traffic flows as one of the tools to control noise.

In future studies, the presented noise pricing approach will be combined with existing pricing approaches within the same simulation framework that address other external effects such as congestion (36) and exhaust emissions (37). Further case studies are required to investigate under which conditions, i.e. for which network and population structures, pricing or traffic management in general is a suitable tool to decrease noise exposure costs and increase social welfare.

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