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Implications for Traffic Management

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In this paper, an innovative simulation-based approach is presented to calculate optimal dynamic, road- and vehicle-specific tolls on the basis of 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 a case study for the area of Berlin showed that transport users avoided marginal noise cost payments by shifting to road stretches in areas with lower population densities, typically major roads. The simulation experiments indicated that the marginal cost approach could be used to improve the overall system welfare and to derive traffic control strategies.

Environmental noise is found to cause cardiovascular diseases, tinnitus, cognitive impairment, and sleep disturbances (*1–5*). Noise barriers, quieter road surfaces, as well as improved aerodynamics, tires, and motor engines aim to reduce noise exposure (*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 of a variety of tools to manage traffic. The economic theory provides the answer to the question of how to set road prices. Pigou introduced the principle of marginal social cost pricing in which road users were charged a toll equal to the marginal cost imposed on other travelers or on the society as a whole (*7*). That is, external costs were included in decision-making processes, and people's behavior changed to make more efficient use of the transport system (*8, 9*). Optimal prices may be understood also as cost terms to correct transport users' generalized travel cost. Increases in travel time on certain roads may, for example, result in the same cost correction as a toll that has the same effect on the transport users' travel decisions.

In this paper, an innovative, simulation-based approach is presented, which calculates vehicle-specific, dynamic, and road-specific marginal noise costs. On the basis of the marginal cost, differentiated optimal noise tolls are calculated and collected from transport users. Further external cost components (e.g., congestion, air pollutants, accidents) are excluded. The proposed marginal noise cost pricing methodology has its basis in the noise exposure computation approach presented in Kaddoura et al. and summarized later in this paper (*10*). The combination of this approach with the economically optimal way of price setting provides new insights into improved traffic management.

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

Most noise action planning approaches use static resident numbers to investigate population exposures to noise (*14–16*). This approach is plausible for exposure at night (*17*, pp. 187–189) but not during the day, when residents usually leave their homes. Differentiated noise limit values for hospitals, schools, residential areas, and commercial areas (BGBl. I S. 1036, BGBl I S. 2269) as well as for different work activity types (e.g., conference room, single office, open-space office, industrial workspace) (DIN EN ISO 11690-1; German version EN ISO 11690-1:1996) indicate that noise exposure analysis should go beyond residential noise exposure and account for traffic noise at the workplace or during educational activities. Also, a European Union directive (2002/49/EC) suggests a differentiated noise exposure analysis for specific building types (i.e., schools and hospitals). Lam and Chung analyzed population exposures to noise with respect to socioeconomic characteristics and identified certain population groups as those worst affected by traffic noise (*18*). Murphy and King noted the importance to account for weekend commuters, whereas the importance to account for daily commuters when noise exposures were analyzed was not addressed (*19*). Ruiz-Padillo et al. proposed an approach to calculate a priority index for noise control action planning (*20*). The index prioritizes roads depending on the noise level, the number of exposed residents, and the occurrence of noise-sensitive centers (e.g., educational, cultural, health facilities). Tenaileau et al. addressed the size of the neighborhood area to be considered for residential noise exposure analysis (*21*). They concluded 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 level. The noise exposure analysis proposed by Kaddoura et al. went beyond residential noise exposures (i.e., considered individuals that might have been affected at work, university, school) and accounted for the temporal and spatial variation of the noise level and the population density (*10*).

In Kaddoura et al. (*22*), average noise cost prices per road, time, and vehicle were calculated with the approach used by Gerike et al. (*23*). In a first step, noise damage costs were assigned to the road segments. In a second step, the road segment's total contribution

Technische Universität Berlin, Transport Systems Planning and Transport Telematics, Sekr. SG12, Salzufer 17-19, Berlin 10587, Germany. Corresponding author: I. Kaddoura, kaddoura@vsp.tu-berlin.de.

was 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 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 prices that are too high, which may result in welfare losses.

In the present study, the advantages that come along with the activity-based simulation approach were combined with an economically optimal noise pricing methodology. The proposed innovative optimization approach was applied to a case study of the greater Berlin area.

METHODOLOGY

Simulation Framework

The proposed marginal noise cost pricing approach applies the open-source simulation framework MATSim (i.e., multiagent transport simulation) 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 in certain locales (e.g., home, work, school). The demand for transport results from spatially separated activity locations. Demands for transport are modeled as individual agents. Each agent holds one or more travel plans, which describe the daily activity schedule as well as transport information (e.g., transport modes). Initial plans have to be provided that may be modified during the process of demand adaptation to supply. The demand adaptation has its basis in an evolutionary iterative approach with the following three steps: (*a*) travel plans are executed (traffic flow simulation), (*b*) the executed plans are scored (evaluation), and (*c*) plans are modified (learning).

- Traffic flow simulation. All travel plans are simultaneously executed, and the agents interact in the physical environment. Vehicles are moved along road segments (links) with application of the queue model developed by Gawron (24). The obtained traffic flows are consistent with the fundamental diagram (25).
- Evaluation. Each agent scores the executed plan on the basis of travel-related costs (e.g., the travel time or monetary payments) but also on the basis of the utility gained from performance of the activities (26).
- Learning. On the basis of the previous evaluation, the agents select one travel plan for the next iteration by choosing among their existing plans on the basis of a multinomial logit model. During the phase of choice set generation, in each iteration, some agents generate new plans by copying and modifying an existing plan. In this study, only the transport route could be modified. However, the simulation framework allows for further choice dimensions.

An iterative repetition of these steps enables the agents to improve their scores, obtain plausible travel alternatives, and relax the simulation outcome. If it is assumed that the travel plans represent valid choice sets, the system state is considered an approximate stochastic user equilibrium (27). A detailed description of the simulation framework is provided in Raney and Nagel (28).

Traffic Noise Exposures

The noise computation methodology has its basis mainly in the German RLS-90 approach Richtlinien für den Lärmschutz an Straßen and application of the approach of *lange, gerade Fahrstreifen* (i.e., long, straight lanes) (29). For each time interval, noise emissions are calculated on the basis of the traffic flow, the share of heavy goods vehicles (HGVs), and the speed level. Noise immissions are calculated for a predefined set of receiver points that account for the noise immissions at the surrounding road segments and consider the decrease in noise from air absorption. To allow in this study for fast computational performance, which was particularly relevant for the iterative optimization approach, further noise corrections (e.g., ground attenuation, multiple reflections, shielding of buildings) were not considered. Instead, the focus was on a detailed representation of the affected population. Application of the activity-based simulation methodology made it possible to track each individual's daily activities (locations and activity start and end times), which then were used to compute dynamic population densities. Furthermore, the location of activities (e.g., home, work, school, university) were known and could therefore be used for an activity-type–specific computation of population densities. Noise immissions and demand activities are both required to compute noise exposures. Hence the computation of noise exposures accounted for the within-day dynamics of varying population densities in different areas of the city. Noise was converted into monetary units on the basis of the avoidance costs and willingness to pay with the application of the threshold-based German EWS approach (i.e., Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen), 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.) (30). To comply in this study with the noise evaluation method defined by the European Union (2002/49/EC, Annex 1), an evening period was introduced. Hence the threshold immission values were set to 50 dB(A) during the day (6 a.m. to 6 p.m.), 45 dB(A) during the evening (6 to 10 p.m.), and 40 dB(A) during 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 was computed with the application of the principle of energetic addition; the final noise immission level was

$$I_{j,t} := 10 \cdot \log_{10} \sum_i 10^{0.1 \cdot I_{i,j,t}\left(n_i^{\text{car}}, n_i^{\text{hgv}}\right)} \qquad \{I_{i,j,t} > 0\} \qquad (1)$$

where

$I_{j,t}$ = noise immission level in dB(A) at receiver point *j* during the time interval *t*,
$I_{i,j,t}$ = immission level in dB(A) at receiver point *j* that results from link *i*,
n_i^{car} = number of cars, and
n_i^{hgv} = number of HGVs.

To improve the computational performance in this study, only the links within a maximum 500-m radius of each receiver point were taken into account.

The change in noise immission for an additional vehicle was computed as depicted in Equations 2 and 3. For computational reasons

the terms were rearranged to avoid the repeated summation over the surrounding links of each receiver point and to use $I_{j,t}$ instead, which was computed in a previous step. The noise immission level for an additional car on link k was

$$I_{j,t}^{\mathrm{car},k} := 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}+1, n_k^{\mathrm{hgv}}\right)} + \sum_{i \neq k} 10^{0.1 \cdot I_{i,j,t}\left(n_i^{\mathrm{car}}, n_i^{\mathrm{hgv}}\right)}\right)$$

$$= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}+1, n_k^{\mathrm{hgv}}\right)} - 10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}\right)} + 10^{0.1 \cdot I_{j,t}}\right)$$

$$\left\{I_{i,j,t} > 0,\ I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}\right) > 0,\ I_{k,j,t}\left(n_k^{\mathrm{car}}+1, n_k^{\mathrm{hgv}}\right) > 0\right\} \quad (2)$$

where $I_{j,t}^{\mathrm{car},k}$ was 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 was

$$I_{j,t}^{\mathrm{hgv},k} := 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}+1\right)} + \sum_{i \neq k} 10^{0.1 \cdot I_{i,j,t}\left(n_i^{\mathrm{car}}, n_i^{\mathrm{hgv}}\right)}\right)$$

$$= 10 \cdot \log_{10}\left(10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}+1\right)} - 10^{0.1 \cdot I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}\right)} + 10^{0.1 \cdot I_{j,t}}\right)$$

$$\left\{I_{i,j,t} > 0,\ I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}\right) > 0,\ I_{k,j,t}\left(n_k^{\mathrm{car}}, n_k^{\mathrm{hgv}}+1\right) > 0\right\} \quad (3)$$

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

$$\mathrm{mc}_t^{\mathrm{car},k} := \sum_j \left(C_{j,t}\left(I_{j,t}^{\mathrm{car},k}\right) - C_{j,t}\left(I_{j,t}\right)\right)$$

$$\mathrm{mc}_t^{\mathrm{hgv},k} := \sum_j \left(C_{j,t}\left(I_{j,t}^{\mathrm{hgv},k}\right) - C_{j,t}\left(I_{j,t}\right)\right) \quad (4)$$

where

$\mathrm{mc}_t^{\mathrm{car},k}$ = the marginal cost of an additional car on link k,
$\mathrm{mc}_t^{\mathrm{hgv},k}$ = the marginal cost of an additional HGV on link k, and
$C_{j,t}$ = 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 was applied to a real-world case study of Berlin, generated by Neumann et al. (31). The transport network consisted of all major and minor roads of the greater Berlin area. The transport demand side was modeled as population-representative agents and nonpopulation-representative agents to account for additional traffic (e.g., freight, airport, tourist traffic). The model was calibrated against mode shares, travel times, and travel distances. A comparison of the model with survey data (32) showed that the differences in mode shares per distance were below 5% (31). The executed plans of the relaxed system state by Neumann et al. were used as the initial demand for the simulation experiments in this study (31). For a faster computation, a 10% population sample was used, and the traffic flow model accounted only for cars and HGVs. For other transport modes (e.g., public transport, biking, walking) travel times were computed on the basis of the beeline distance, and the noise impact was ignored.

The 10% sample size comprised 598,891 agents who performed 1,411,910 trips. Of this number, 476,198 trips were made by car or HGV.

In this study, two noise pricing experiments were carried out on the basis of two assumptions. Marginal noise cost prices were computed on the basis of the following:

Assumption A. Noise exposure costs were incurred only by residents exposed to traffic noise at their home location.
Assumption B. Noise exposure costs were incurred by individuals exposed to noise at their home location, and at work, school, or university.

In both experiments, marginal noise cost was computed as described earlier in this paper. Each simulation experiment was run for 100 iterations. During each of the first 80 iterations, 10% of the transport users were allowed to use new routes (i.e., choice set generation) and for the final 20 iterations, travel alternatives were selected on the basis of a multinomial logit model (i.e., fixed choice sets). Each agent's choice set comprised a maximum of four travel alternatives. The traffic flow model accounted only for road users (i.e., cars, HGVs).

Results

The marginal noise cost pricing approach was compared with the average noise cost pricing approach applied to the same case study in Kaddoura et al. (22). For both pricing approaches, welfare-relevant parameters were compared with the base case situation in which the simulation was run for 100 iterations without pricing.

In Table 1, the changes in welfare-relevant parameters are provided for Assumption A and Assumption B and their respective average and marginal noise cost pricing. All noise pricing experiments resulted in higher benefits from reductions in noise exposures. Furthermore, noise pricing decreased travel-related user benefits. This finding was explained by (a) toll charges and (b) actions taken to avoid toll payments (e.g., detour). For Assumption A, the

TABLE 1 Daily Changes in Welfare-Relevant Parameters Resulting from Noise Pricing: Average Cost Pricing Versus Marginal Cost Pricing

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

Note: ACP = average cost pricing; MCP = marginal cost pricing.
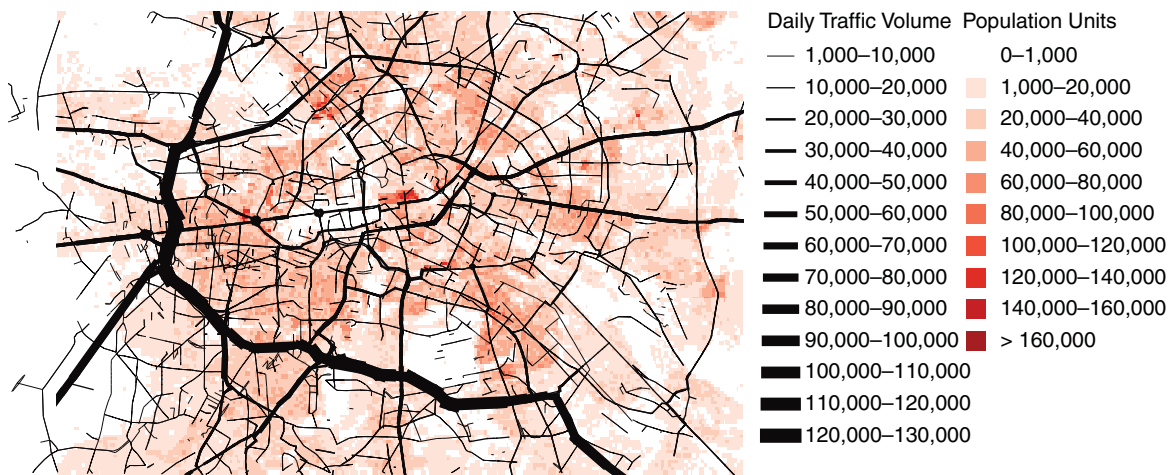
FIGURE 1 Base case: daily traffic volume and population units (Assumption B).

daily changes in social welfare were minimal (+€1,263, +€3,817), whereas, for Assumption B, the changes in social welfare were on a much higher level. For Assumption B, the average cost pricing approach resulted in lower daily system welfare compared with the base case (−€47,889), whereas marginal noise cost pricing strongly increased daily system welfare (+€79,632). The reduction in noise exposures was considerably larger despite an overall lower level of toll payments when marginal noise cost prices were applied and compared with the average cost approach. Therefore, the overall price reaction was weaker, which resulted in a slighter decrease in 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 southwestern 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 that indicate a higher population density. Areas with low population densities (e.g., 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, and red-colored road segments indicate an increase in traffic volume. Overall, the structural changes in traffic volumes are similar for 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 (e.g., inner-city highway), the traffic volume typically increases. A comparison of both pricing approaches revealed that marginal noise cost pricing resulted in overall smaller changes in traffic volumes. Given the lower marginal noise cost prices, the changes in traffic volume were substantially smaller. By contrast, average noise cost pricing provoked a stronger reaction, as exemplified by elevated traffic volume variations for a larger number of
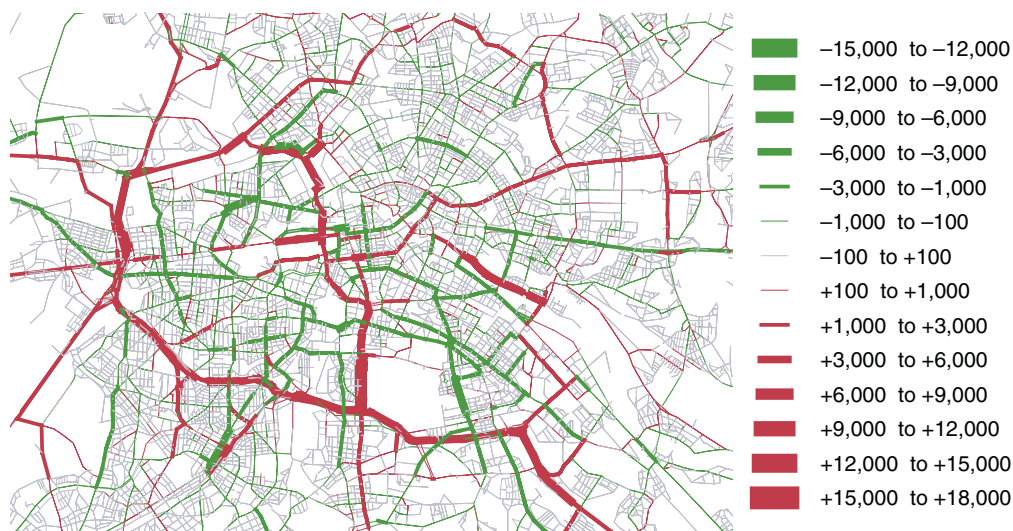

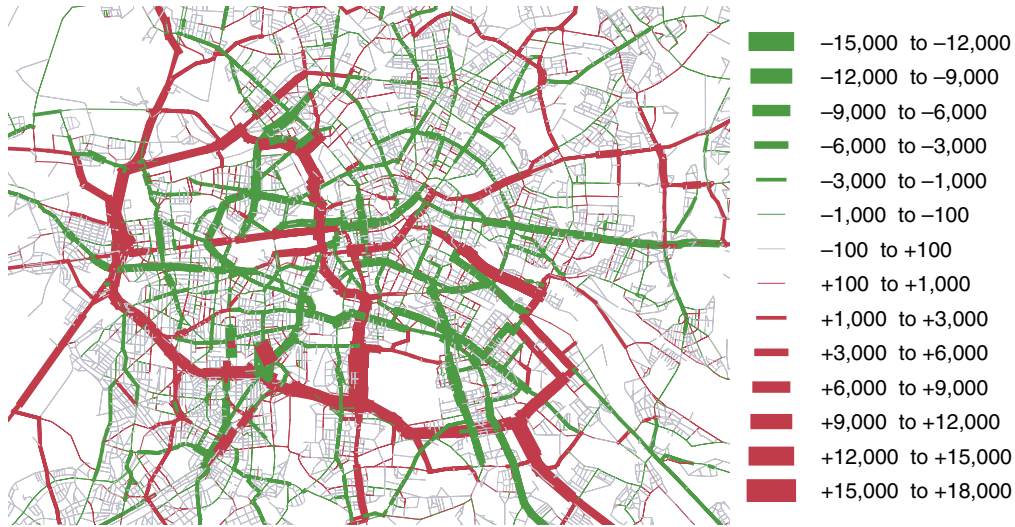**FIGURE 2** Marginal noise cost pricing: changes in daily traffic volume (Assumption B).

FIGURE 3 Average noise cost pricing: changes in daily traffic volume (Assumption B).

road segments. For Assumption A, the considered population units appeared differently, given that work and educational activities were not addressed. As a consequence, both noise pricing approaches resulted 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). Given the smaller number of population units, optimal tolls were considerably less under Assumption A than under 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 were lower than average cost prices. During the daytime, the difference between average and marginal noise cost tolls was minimal, whereas in the morning, evening, and night, given lower traffic volumes, average noise cost prices were demonstratively higher than marginal noise cost tolls.

Marginal and average noise cost tolls were found to increase with the trip distance. However, for longer travel distances, the toll level increased to a lesser degree. The explanation was the long stretches of travel routes that passed through less densely populated areas. For Assumption B with regard to all vehicle types, marginal noise

cost tolls increased from €.01 for trips shorter than 1 km up to €.10 for trip distances between 19 and 20 km. In contrast, average noise cost tolls were on a higher level, and ranged from €.03 (<1 km) to €.28 (19 to 20 km).

CONCLUSION AND OUTLOOK

In this paper, an innovative, simulation-based approach is presented to calculate marginal noise costs. The approach makes use of an existing simulation-based methodology by Kaddoura et al. to compute noise exposures (10). Through the use of an activity-based transport simulation, the computation of noise exposures accounts for the temporal and spatial differences of noise levels and population densities. Furthermore, the approach makes it possible to account for individuals exposed to traffic noise at work or in educational activities. Marginal noise cost can be converted into optimal time-, road- and vehicle-specific tolls to optimize the transport system, provided that transport users are able to adjust their travel behavior. The contribution of the proposed approach is that the economically optimal way of price setting is
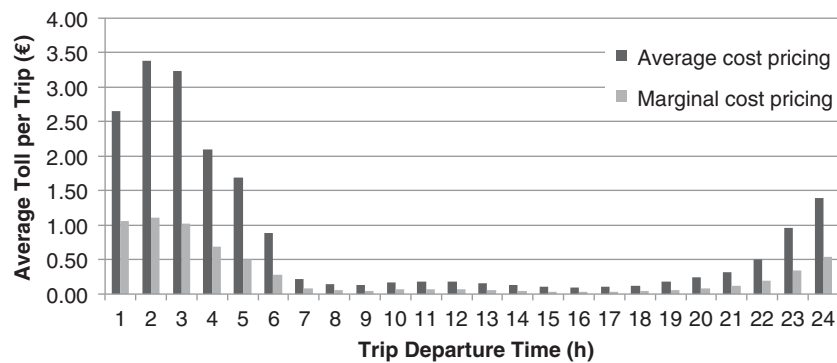

FIGURE 4 Average noise price per car trip over departure time.

combined with the advantages of the activity-based simulation. The proposed optimization approach was applied to a large-scale case study of Berlin, in which transport users were able to change their transport routes. The results were compared with a similar approach in which tolls were set on the basis of the average noise cost (*22*).

The results of the case study showed that the proposed marginal noise cost pricing approach increased the overall system welfare. Transport users were found to avoid marginal noise cost payments by shifting to roads stretches in areas with lower population densities. On most minor roads, the traffic volume decreased, whereas on most major road segments (e.g., inner-city highway) the traffic volume increased. The assumption as to which activity types were accounted for (Assumption A versus Assumption B) resulted in different optimal traffic flows. On road segments on which the optimal traffic volume was lower than the existing volume, instead of a toll, for example, the speed level could be reduced and have the same effect on transport user travel decisions. For the marginal cost approach, the reduction in noise exposures was found to be larger than it was for the application of the average cost approach despite the fact that toll payments were lower. This finding indicated that the marginal cost approach worked quite well for traffic noise. By contrast, the average noise cost approach resulted in smaller noise exposure reductions. Moreover, the average cost approach overpriced the transport system. As a consequence, the changes that transport users made in their travel behavior were excessive, which, under Assumption B, led to a substantial welfare loss.

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

In future studies, the noise pricing approach presented here will be combined with existing pricing approaches within the same simulation framework that addresses other external effects such as congestion (*33*) and exhaust emissions (*34*). Further case studies are required to investigate under which conditions in general (i.e., for which network and population structures) the approach is a suitable tool to decrease noise exposure costs and increase social welfare.

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