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What if Air Quality Dictates Road Pricing? Simulation of an Air Pollution-based Road Charging Scheme☆

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ABSTRACT

Road tolls serve various purposes, such as to refinance the road infrastructure or to regulate traffic. They are typically levied for the use of a freeway or the entire road network of a region or country. Toll charges may depend on the duration of use, the vehicle's emission class, the time of the day, the distance travelled, or the traffic volume. The primary objective of a few recent toll system deployments is to internalize externalities with respect to vehicle-caused air pollution. However, the air quality along the toll roads has so far not been considered to directly influence road usage prices. This article investigated by simulation the expected monetary expenditure for drivers and the traffic impact of applying a new distance and air pollution-based charging scheme in the metropolitan region of Berlin. The road usage charges were determined on a per-trip basis by taking the vehicle's emission class, the distance travelled, and the air pollution levels along the route into consideration. The simulation results indicate that it is beneficial for drivers to avoid areas of high air pollution in order to reduce the trip's total road usage charges. The average additional detour distance is thereby short in comparison to the route's length and the resulting additional emissions do not increase to the same extent as the number of detours, since detours are partly even shorter in terms of distance. The explorative analysis gives initial insights into the traffic effects of a charging scheme in which air pollution dictates road pricing.

Introduction

Urban air pollution originating from the sector of road transport is known to significantly increase the mortality and morbidity rate of the affected population (Künzli et al., 2000). For 2018, 18,400 premature deaths in the U.S. can be attributed to the exposure of traffic-related air pollution (Dedoussi, Eastham, Monier & Barrett, 2020). The situation is further complicated by the fact that the global traffic demand is expected to increase over the next decade (International Transport Forum, 2019). Successfully applied regulatory measures to fight traffic-related air pollution include the promotion of environmentally friendly means of transport (Xia et al., 2015), introduction of traffic control signal systems (Wood & Baker), or the development of more efficient combustion engines and aftertreatment systems. Nevertheless, the air pollution in many metropolitan regions remains to exceed many times the limits recommended by the World Health Organization (2016) or as set by The European Parliament & the Council of the European Union (2008).

In Germany, local authorities of cities particularly affected by urban air pollution are being forced (due to possible penalties) to introduce driving bans for vehicles of particular emission classes (Fensterer et al., 2014) or to tighten speed limits on particular road segments (Vardoulakis et al., 2018). However, depending on how driving restrictions are implemented, they may have little or no effect on the urban air pollution (Davis, 2017), worsen the air quality situation (Zhang, Lin Lawell & Umanskaya, 2017), or even encourage illegal behavior among drivers (Wang, Xu & Qin, 2014). Driving restrictions that proved to significantly reduce air pollution are - among others - the vehicle pollution charge Ecopass in Milan (Rotaris, Danielis, Marcucci & Massiani, 2010), the low emission zones (LEZ) in Germany (Jiang, Boltze, Groer & Scheuvens, 2017; Wolff, 2014), and the driving bans in Quito (Carrillo, Malik & Yoo, 2016). The regulatory measures are different and customized to the local particularities, but the impacts on the air quality are on a similar order of magnitude. In Milan, the European vehicle class dictates whether downtown Milan can be entered for free or by paying a charge that depends upon the vehicle's emission class. In Germany, older and high polluting vehicles are generally prohibited to enter LEZs. In Quito, the last digit of the vehicle plate determines the day a vehicle is prohibited to enter the restricted area during peak hours. These and similar driving restrictions are of intrusive

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nature and are not meant to change over a long period of time. They are set by municipalities and apply no matter how the urban air pollution eventually develops at each day and time of the day. Vehicles may be banned, and drivers be charged although on some days, for example, the fine dust concentration within the air might turn out to lie far below a value that is harmful to health.

To be more flexible, a few municipalities and urban areas started to introduce temporary LEZs that are only active in case high urban air pollution is predicted or happened in the past days. In Geneva, only vehicles with a state-issued vignette can drive within the LEZ during its active period. The last day's level of air pollution determines thereby the type of restrictions that apply for the vehicles. Despite operating in a more flexible manner with respect to changing environmental circumstances, an activation still needs to be announced a few hours in advance and an activation is valid throughout the day or at peak hours. These regulations prevent the system to react spontaneously to an unforeseen change of the air quality at the day of activation. A further drawback of currently deployed systems with temporary LEZs is that the extent of LEZs corresponds to administrative areas or are limited by well recognizable ring-shaped closed transport routes such as city-rings or circular railways. The range of a fixed LEZ roughly corresponds to the extent of the urban area that is affected by urban air pollution, but it does not necessarily represent it accurately on days with exceptional weather and traffic conditions.

Another principal challenge of applying access-based charging schemes to reduce air pollution lies in the fact that the costs of using the road network within an LEZ do not depend upon the real usage. The more a vehicle drives within an LEZ, the more it pollutes, but the costs remain constant in Geneva and for all LEZs deployed around the globe. The Green Activity Zones research project proposed a first-best toll, namely, to charge a driver of heavy-duty vehicles within a LEZ based on the emissions measured within the vehicle (Tretvik, Nordtømme, Bjerkan & Kummeneje, 2013). A similar first-best toll approach simulates vehicles in Munich that are charged based on their modeled emissions (Kickhöfer & Kern, 2015; Kickhöfer & Nagel, 2016). Both approaches propose charging schemes that are closely related to distance-based charging; a charging scheme that has gained more and more popularity in recent years. At toll plazas in France, a driver pays a charge that depends upon the distance travelled on the freeway. In Germany, drivers of heavy goods vehicles are obliged to pay a more fine-grained distance-based toll in case they use the federal highway network (Broaddus & Gertz, 2008). Instead of toll plazas, an on-board unit – as part of an electronic toll system - records the exact route so that a fine-granular charge based on a price per driven kilometer can be applied. But distance-based charging is currently not applied to deal with urban air pollution despite the proportional correlation between the distance travelled and the amount of emissions (Etyemezian et al., 2003).

Yet, the technological progresses of the last decade in the fields of mobile computing, mobile communication, outdoor localization, and electronic road pricing made it possible - today - to determine the route of a vehicle by satellite, accurate to the meter, at low cost, and to transmit it reliably to a central authority for control and accounting purposes (Donath et al., 2009). Hence, with the proven technical and economic feasibilities of distance-based charging schemes, the European Union plans that until 2023, all European toll systems for heavy good vehicles as well as buses must switch to distance-based charging to improve fairness and environmental protection[1].

At the same time, sensors for measuring air quality have become more compact, more reliable, and less expensive (Jovašević-Stojanović et al., 2015). The unit price has even reached a level that allows private households to measure air quality with their own sensor stations and share the results with the community (Muller et al., 2015). Coupled with communication modules, they can now be an integral part of city-wide dense sensor networks, enabling the urban air quality to be measured in real time and across the entire city (Sivaraman, Carrapetta, Hu & Luxan, 2013). It is therefore technically possible to develop an intelligent transport system (ITS) that takes the current air quality distribution within a metropolitan region into account. What role the urban air quality can play in an ITS depends on the primary objectives, local conditions, and political decision-makers. If, for example, air pollution hotspots should be relieved by additional traffic-related emissions, then the spatial and temporal extent of LEZs could be dynamically determined based on the time-dependent spatial distribution of the air pollution across an urban area (Rodriguez Garzon & Küpper, 2019). In other words, the city-wide air quality dictates the shape, size, and location of temporary LEZs. In combination with distance-based charging, a driver could then be charged based on the real distances travelled through dynamically determined LEZs. A temporary LEZ based on high air pollution levels can thereby be associated with high transit prices per kilometer to make a transit through an air pollution hotspot less attractive for a polluter than passing through low polluted area. The charging scheme can also optionally be combined with emission class-dependent pricing. The tariff per kilometer and air pollution level will then - in addition - depend upon the vehicle's emission class. A distance and air pollution-based charging scheme may lead drivers to avoid passing through heavily polluted LEZs, respectively to stop worsening the situation by an additional polluter, and to switch, instead, to more environmentally friendly means of transport.

To the best of our knowledge, a highly dynamic road pricing scheme with spatially and temporally evolving LEZs has not been investigated yet. To do so, a multitude of research questions arise and need to be examined with respect to, among many others, the technical feasibility, usability from the perspective of the road users, the acceptance among road users, the predictability of returns for the toll operators or collectors, its implications on the mobility behavior, its influence on the urban air pollution and its socio-economic effects. This article investigates the implications of such a distance-based and air pollution-aware charging scheme on the mobility behavior by exemplarily simulating road network usage within the city of Berlin. LEZs are hereby modeled based on the spatial distribution of the urban air pollution across the city. The traffic of 10% of the population was simulated for a period of 24 h on three days with significantly different air pollution characteristics. An open data-based transport demand model for Berlin was used in conjunction with real measurements of the particulate matter concentration taken by privately-owned sensors that were located within the limits of Berlin. Although needed to finally evaluate the charging scheme with respect to the objective of improving the overall air quality in an urban area, its influence on the urban air pollution was not determined because of a lack of yet to be developed particulate matter dispersion models, a fine-granular spatiotemporal wind and weather model for the city of Berlin and a comprehensive list of location-specific polluters other than motorized vehicles with their individual contributions to the particulate matter concentrations. However, the results of simulating road usage - with a hypothetical charging scheme being in place and the air pollution being modelled by means of real world measurements - are intended to give first impressions of how parts of the traffic might shift to alternative routes, what daily volume and compositions of toll trips can be expected in Berlin for days with low, medium, and high urban air pollution and how the vehicle-caused emissions might change due to road users intentionally bypassing LEZs with high transit costs.

[1] https://www.europarl.europa.eu/news/en/press-room/20181018IPR16551/reform-of-road-use-charges-to-spur-cleaner-transport-and-ensure-fairness

In the following section, recent approaches to set road, parking facility, and public transport prices based on the predicted or current urban air pollution are discussed. The core concept of the new air quality and distance-based charging scheme is then introduced in Section Concept. In Section Simulation, the simulation setup for Berlin and the simulation results are presented. Assumptions, limitations of the simulations, and the charging scheme in general are summarized and discussed in Section Discussion. The article concludes with the major findings, open research questions, possible applications, and extensions of the charging scheme.

Related work

The pros and cons of applying dynamic road pricing schemes to tackle congestion and air pollution have been discussed extensively over the past decades (Saharan, Bawa & Kumar, 2020; Yang & Huang, 2005). The main property that distinguishes the concept of dynamic road charging from its static counterparts is the fact that either the road usage fee as a whole or only a fraction of it may vary depending on the situational circumstances. Time of the day (Chen, Xiong, He, Zhu & Zhang, 2016), road network load (Supernak, Steffey & Kaschade, 2003), and car occupancy are the most widespread discussed and considered price-influencing situation factors in literature or in real world deployments. Despite the considerable amount of work examining the impact of different charging schemes on the air quality (Beevers & Carslaw, 2005; Cavallaro, Giaretta & Nocera, 2018; Johansson, Burman & Forsberg, 2009; Rotaris et al., 2010), only a few research articles suggest that the urban air quality should be considered, directly or indirectly, through metrological properties, as an additional variable for dynamic road pricing. Coria, Bonilla, Grundström & Pleijel (2015) propose to adjust road prices dynamically so that the sum of traffic-related emissions do not exceed the maximum air pollution capacity of an environment (assimilative capacity). Coria et al. (2015) use the wind speed to estimate the current assimilative capacity and the current traffic load to vary the prices accordingly, instead of measuring the emissions respectively air quality. The location-specific correlations between wind speed, air pollution dispersion, and traffic network load are thereby predetermined based on historical hourly wind speed, air quality, and traffic flow data for the city of Stockholm. The road usage prices do not reflect the current air quality itself but the atmosphere's ability under the current wind and traffic conditions to cope with traffic-related air pollution, without suffering from long-term environmental damage. Further investigations revealed that pollution peaks indeed can be smoothed if road charges take the air pollution dispersion into consideration (Coria & Zhang, 2017). Coria's approach and the approach taken in this article differ in the sense that Coria et al. (2015) examined the impact of a traffic-, weather and environment-aware charging scheme on the air quality while this article deals with the impact of an air quality-based charging scheme on the traffic itself. Despite not dealing with road usage charges, Reddy, Yedavalli, Mohanty, & Nakhat, 2017 sketched the idea to link future public transit prices in general to the predicted urban air pollution. Poorzahedy, Aghababazadeh and Babazadeh (2016) follow a similar idea and propose to determine the next day's cordon access fees and rates for park & ride facilities at public transport hubs based on the current carbon oxide concentrations and the next day's weather forecasts. The objective is to make public transport pricewise more and private vehicle transport less attractive in case high air pollution levels are forecasted. Although lesser flexible with respect to price determination, Costabile and Allegrini (2008) present a prototypical ITS that forecasts air pollution levels for Beijing and automatically imposes driving restrictions in case thresholds will likely be exceeded. Today, similar systems for air quality-dependent driving restrictions are successfully deployed in Geneva, Budapest, Madrid, and Oslo. But road prices remain to be determined or driving restrictions be imposed based on air quality estimations or forecasts. The estimated or forecasted air quality does not only deviate from the actual air quality at the time a car ride is charged but may even not be experienced everywhere in a fixed LEZ or cordon with the same intensity. Rodriguez Garzon and Küpper (2019), in contrary, describe the concept of an air pollution-aware and distance-based charging scheme in which the price per kilometer depends upon the urban air pollution that is measured along the route. It incorporates distance-based charging to fairly price the environmental damage caused by a single car ride and it adjusts the fees dynamically to the urban air pollution to make the worsening of an already critical air pollution situation more costly than the worsening of a non-critical situation. This article adopts this new and highly dynamic concept of road pricing and applies it in a customized way hypothetically to the city of Berlin.

Air pollution-aware charging

The road charging concept under investigation comprises of distance-based charging and air pollution and emission class-dependent road usage prices. The principal idea of the concept is that the road usage price per kilometer increases as urban air pollution levels rise along the way, no matter, whether the air pollution originates primarily from traffic or other sources such as wood burning or the industry sector. The concept's main objective is to reduce the urban air pollution at pollution hotspots by encouraging or incentivizing the drivers to reconsider the transport mode and/or the route decision. By changing their route, drivers are supposed to spread the emissions more evenly across the city. The charging happens independently of the traffic load or assimilative capacity of the environment. Even if the environment might be able to cope with a very high air pollution without suffering long term damages, prices per kilometer will be high if air pollutions levels are high. This does not mean that the proposed charging scheme is not able to take the assimilative capacity or traffic load into consideration. However, in this article, it will solely be investigated in an isolated and unbiased manner to simplify the interpretation of the results. In further studies and possible extensions, the assimilative capacity could, for example, be used to support the tariff specification process while the variable traffic load can serve as another dynamic variable for the price calculation.

In general, air pollution caused by traffic is made up of different components. Gas emissions in form of nitrogen dioxide, carbon monoxide, and sulfur dioxide or particulate matter are only some of the well-known waste products of burning fossil fuel in combustion engines (Berkowicz, Winther & Ketzel, 2006). The urban air pollution is usually given in the form of an air quality index (AQI) (Cheng et al., 2007). An AQI groups together different pollutants and maps the combination of pollutant concentrations to a few pollution levels, e.g., low, medium, and high. Instead of progressively linking the road usage price directly to the individual concentrations of pollutants in the air, in the proposed concept, the road usage price at a location depends primarily on the location-specific and discretized AQI level. A current AQI level can either be determined for a whole toll area as applied in Geneva for the air pollution-dependent LEZ, or at each position individually. An individual AQI level per arbitrary position, however, is only possible if the air quality can be determined with high accuracy, at any road within the toll area. Hence, the air quality sensor density across the toll area needs to be sufficiently high to be able to accurately interpolate air pollution levels without significant deviations from the real exposure. Given these requirements are fulfilled, then, at each point in time, a toll area can be spatially segmented into coherent zones with the same AQI level. Fig. 1 illustrates exemplarily the particulate matter-driven AQI zones as determined for the 24th of January 2020 at 9:00 AM in the downtown of Berlin. The charging scheme interprets each blueish AQI zone as a temporary LEZ with a fixed price per kilometer as applied throughout the whole LEZ. AQI zones might contain holes in which different AQI levels are measured or interpolated. The resulting temporary LEZs may therefore contain smaller LEZs that are associated with different road usage prices. Since temporary LEZs are not statically defined by a human instance but being processed based on the urban air pollution distribution,

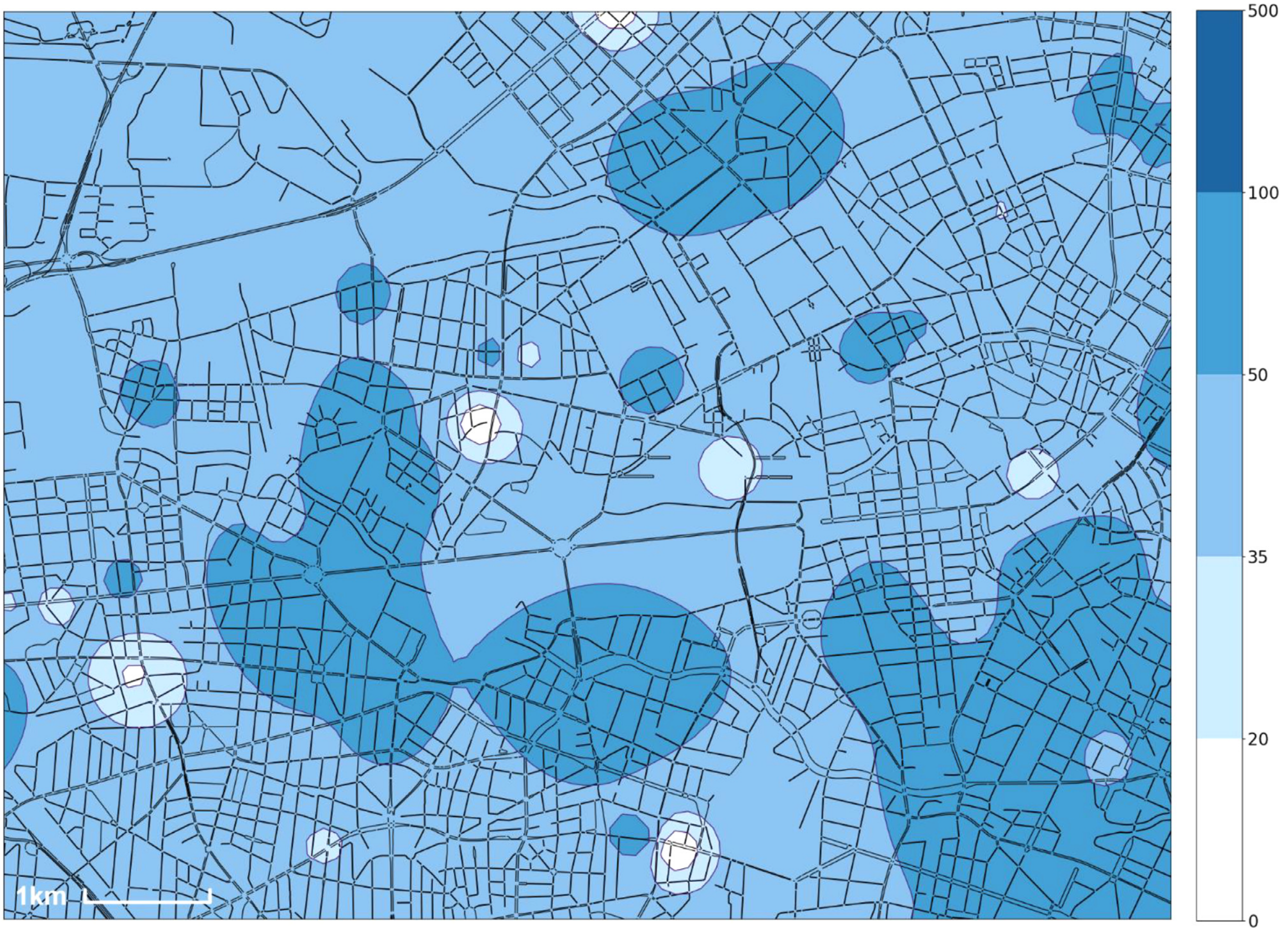

Fig. 1. Particulate matter-driven AQI zones for downtown Berlin on the 24th of January 2020 at 9:00 AM, given in μg/m^3.

city, district limits, or distinctive infrastructures, such as city highways, do not serve as delimiters for the temporary LEZs

As the measured air quality at a given position can vary considerably within a short period of time, e.g., due to a single gust of wind, so can the extent of the temporary LEZs vary significantly or the LEZs even "move" or disappear. To deal with the dynamics of urban air pollution and the operational implications on an air pollution-based charging scheme, two distinct measures are taken. To cope with strong short-term fluctuations at a sensor, the air pollution is measured over a certain period and the sensor readings being averaged using the inverse distance weighting method. The values measured last are thereby given a higher weight to take trends into account. The resulting LEZs thus reflect the geographical distribution of air pollution more accurately, but still change over time. If temporary LEZs were determined in very short time intervals under adverse weather conditions, it would be difficult, if not impossible, to predict the road usage charges for a longer car ride. However, according to the Smeed Report (Ministry of Transport, Great Britain, 1964), price stability and ascertainability by the road user are crucial factors for the success or acceptance of a road charging scheme. To make the price of a journey more predictable, temporary LEZs are active for a certain amount of time by freezing the measurement results (AQI zones) for an activation period. For example, the air quality is measured from 1:45 PM until 2:00 PM and the resulting temporary LEZs are active from 2:00 PM until 3:00 PM. The longer the activation period is, the more predictable are road charges for a car ride. On the other hand, towards the end of an activation period, LEZs may tend to inappropriately represent the air pollution distribution because of changing weather conditions. Hence, there is always a trade-off between the accuracy of the air pollution distribution representation by means of temporary LEZs and the length of the activation period. To find the right balance, local conditions such as average driving time, driver acceptance, and the local dynamics of weather conditions must be considered.

In the proposed concept, the road usage price is not only linked to the temporary LEZ a vehicle is driving through but also to the vehicle's emission class. As it is common in today's ITSs and toll system installations, the higher the emission of a vehicle is, the higher is the base price per kilometer. The total road usage charge c_{total} of a car ride results from the LEZ transits charges for all passed AQI zones 1 to z:

$$c_{total} = \sum_{i=1}^{z} d_i * p\left(l_i, e\right)$$

An LEZ transit charge is determined by multiplying the distance travelled within the LEZ d_i with the price *p()* per emission class e and AQI level l_i of the AQI zone *i*. Thus, road usage charges are determined individually per trip, depending on the distance a vehicle traveled across air polluted zones. In contrast to LEZs in Germany and Switzerland, all vehicle types are permitted to enter temporary LEZs with arbitrary AQI levels.

For an operational deployment of the proposed charging scheme within an ITS, vehicles must be accurately locatable in a continuous fashion and air pollution must be directly measurable by connected sensors on a fine granular manner in a city-wide scale and accurately interpolatable at positions where no air pollution sensors are located. In addition, road users should be able to examine expected road usage fees prior to a trip and be notified of sudden price changes via a sort of connected mobile device such as a smartphone or on-board unit. But the investigations conducted in this article assume the dynamic charging scheme to be hypothetically applied to road network users independent of any concrete technical implementation of it. The reader is referred to the article "Pay-Per-Pollution: Towards an Air Pollution-Aware Toll System for Smart Cities" (Rodriguez Garzon & Küpper, 2019) for a more detailed discussion about the requirements of such a charging scheme like price predictability, the corresponding challenges like user acceptance and its technical feasibility.

Simulations

The traffic in Berlin was simulated with the air pollution-aware charging scheme being applied in order to determine the daily volume of transit journeys through AQI zones exemplarily on days with varying levels of urban air pollution. This makes it not only possible to estimate future revenues for the toll collector and local authorities, but also to examine the impact of the road charging scheme on the traffic and the traffic-induced emissions. The research questions investigated in this article are the following:

- **RQ1**: What is the overall toll volume in terms of expected AQI zone transits per day?
- **RQ2**: How often are tariff changes experienced by the drivers during a trip?
- **RQ3**: To what extent are AQI zones bypassed?
- **RQ4**: What are the characteristics of the detours?
- **RQ5**: To what extent are emissions from motorized vehicles changing?
- **RQ6**: What is the impact of detours on the traffic distribution?

Whether the proposed air pollution-aware charging scheme reduces the overall air pollution or, at least, helps to evenly distribute the emissions across the urban area are not investigated and remain as open questions for further research.

The greater area of Berlin was chosen as the hypothetical toll area because Berlin has sufficient air quality sensors distributed across the city area, only a minor amount of deep urban canyons due to mostly low multi-story or single-family buildings, flat terrain, and city-wide homogenous weather conditions. In addition, there is an open data-based transport demand model for Berlin publicly available (Ziemke, Kaddoura & Nagel, 2019). The synthesized transport demand model was developed by Ziemke et al. (2019) using different open data sources such as, e.g., a nation-wide census of Germany, commuter statistics, and local traffic counts. A comparison of the model's results with those of two independent travel surveys shows that it realistically emulates transport demand in and around Berlin. The reader is referred to the work of Ziemke et al. (2019) for more details about the synthetization and validation of the transport demand model. The investigations of the proposed charging scheme can then be conducted with urban air pollution and transport demand models that represent or, in case of the transport demand model, well approximate real-world conditions.

In the following, the experimental setup of the simulations is described, including the general assumptions and configurations. Afterwards, the simulation results are presented in detail.

Setup

Berlin has an urban area of approx. 891.68 km^2, a population density of approx. 4115 inhabitants per km^2 and a road network of approx. 5437 km length. Berlin is in a moderate climate zone with prevailing continental southwest winds and maritime northwest winds. Due to lesser traffic, flat terrain, weather conditions, and only a small manufacturing industry within the city limits, the air pollution is not as severe as in cities with a similar population of about 3.7 million. Nevertheless, on 27 days in 2018, a state-operated measuring station in Berlin recorded an exceedance of the limits for fine dust pollution with PM_{10}[2] (particulate matter with a diameter of 10 μm or less). However, 6 of the 16 state-operated and connected air quality measuring stations are located especially at major roads and 5 out of 16 are located at the outskirts or forests where a particularly high respectively low air pollution is expected[3]. Measurements taken in urban background roads may significantly vary from the air pollution levels measured along major roads (Boogaard et al., 2011). Hence, measurement stations along major roads are only of limited help to properly interpolate air pollution levels in their surroundings due to their strong bias towards high air pollution. Only a "*well-placed site*" allows to estimate proper air quality values for the surroundings (Williamsand et al., 2014). Privately-owned and operated air pollution sensors are installed at windows, on balconies, walls, or roof-top terraces and are arbitrarily located across a metropolitan region. Community-driven air quality measurement initiatives, in general, gained popularity over the last decade, leading to multiple deployments worldwide. In Berlin and similar metropolitan regions, the amount of privately-owned and operated sensors, as used for crowdsourcing air quality data, exceeds the number of state-operated sensor installations many times. During the first half of 2020, between 375 and 430 private air pollution sensors within the limits of Berlin contributed their sensor readings to the citizen science initiatives Luftdaten.info[4] (Blon, 2017) and OpenSenseMap[5]. Fig. 2 shows the location of Luftdaten.info- and OpenSenseMap-connected sensors across the metropolitan region of Berlin. Nine most probably faulty sensors were not considered because they delivered constantly air quality values that reached far beyond the ones of their closest neighboring sensors. Automatic outlier detection and filtering was deployed as well. The local sensor density correlates in Berlin roughly with the population density (Arandelovic & Bogunovich, 2014). The low sensor density in the northwest, mid-west, south-west, and south-west is attributed to a low population density because lakes and forests predominate the respective outskirts of Berlin.

Table 1
Particulate matter-driven air quality index.

PM_{10} (µg/m^3)	0 - 20	20.1 - 35	35.1 - 50	50.1 - 100	>100
AQI level Air quality	0 very good	1 good	2 moderate	3 poor	4 very poor

Every two to three minutes, the air quality is measured by the privately-owned and operated sensors and the readings being transmitted to a central unit managed by the initiatives. Based on these crowdsourced and publicly available measurements in Q1 and Q2 of 2020, three days were selected to adequately represent days with low, medium, and high PM_{10} concentrations in Berlin. Fig. 3 visualizes the AQI zones for Berlin at each of the selected days at different day times. The discrete mapping of PM_{10} concentrations to AQI levels is based on the air quality index provided by the Federal Environment Agency in Germany[6]. Table 1 shows the mapping from PM_{10} values to AQI levels and air qualities as used throughout this article. AQI level 0 is considered as harmless to health and a transit through an AQI zone of level 0 will therefore not be charged. At the 25.03.2020 (low average PM_{10} concentration), southeast winds with wind speeds of about 7–17 km/h were measured throughout the day. At the 11.06.2020 (medium average PM_{10} concentration), northeast winds of about 6–8 km/h were registered while on the 24.01.2020 (high average PM_{10} concentration), north and east winds of about 2–14 km/h were measured. In general, wind speeds were low which in turn increased the accuracy of interpolations as described in the next paragraph. In this study, gases such

[2] https://www.berlin.de/sen/uvk/presse/pressemitteilungen/2019/pressemitteilung.775788.php

[3] https://www.berlin.de/senuvk/umwelt/luftqualitaet/de/messnetz/blume.shtml

[4] https://www.luftdaten.info

[5] https://www.opensensemap.org

[6] https://www.umweltbundesamt.de/berechnungsgrundlagen-luftqualitaetsindex

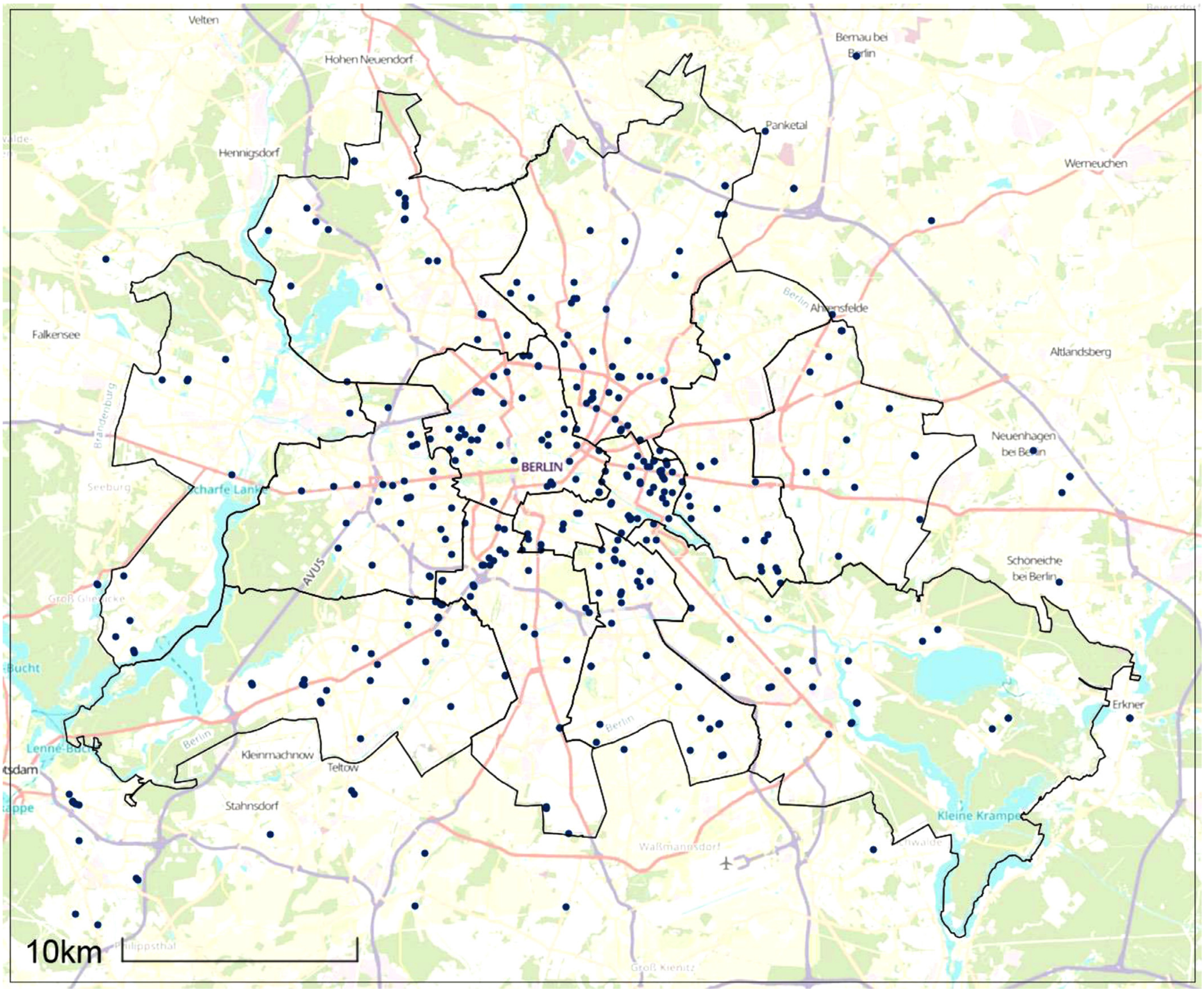

Fig. 2. Privately-owned and operated air quality sensors (blue dots) that are registered at Luftdaten.info and OpenSenseMap within the metropolitan region of Berlin as of January 2020. Background map source: https://www.openstreetmap.org.

as carbon monoxide, carbon dioxide, and nitrogen oxide were not considered since their emissions of motorized vehicles are likely to decline significantly with the introduction of hydrogen or electric vehicles. Particulate matter in the form of $PM_{2.5}$ or PM_{10}, on the other hand, will still be an issue because, for example, about 73% of traffic related PM_{10} concentrations in UK originate from the brake, tire, and road surface wear (Department for Environment, Food and Rural Affairs (Defra), Northern Ireland, 2019). In Berlin, these non-exhaust traffic sources contributed to about 80% of the PM_{10} concentrations in 2019[7].

In between air quality sensors, the air pollution needs to be approximated by interpolation because the charging scheme requires a gapless spatial air pollution distribution. The outcome of an air pollution spatial interpolation process depends significantly on the interpolation method (Wong, Yuan & Perlin, 2004). To simulate with accurate air pollution distributions in the form of AQI zones for the days under investigation, a 7-fold-cross-validation per spatial interpolation method was conducted with ten repetitions each. Berlin's inherent property of having mostly flat terrain and low-rise buildings made it an ideal spot to apply spatial interpolation without the need to take artificial obstacles or uneven terrain into consideration. The three days of investigation were also chosen because of the low wind speeds which otherwise would need to be considered within the interpolation process. The spatial interpolation method Inverse Distance Weighting (IDW) with a power parameter of 2 was finally selected as IDW won the vast majority of validation runs among the twelve test candidate methods Nearest Neighbour, Natural Neighbour, IDW, Linear Radial Basis Function (RBF), Gaussian RBF, Cubic RBF, Quintic RBF, Multiquadratic RBF, Inverse Multiquadratic RBF, Thin-plate RBF, Ordinary and Universal Kriging. The Marching Squares algorithm is then used with a grid size of 100 × 100 m for the contouring, namely, to extract the isolines (forming the AQI zones) for the particulate matter distributions. In the simulations, the activation period for AQI zones was set to ten minutes. Hence, every ten minutes the AQI zones were recalculated, and the results being applied for the next ten minutes. Air quality sensor readings of the last 30 min. contributed thereby to the calculation of the AQI zones, whereby the latest readings received a higher weighting.

For the traffic simulation, the microscopic traffic simulator Eclipse SUMO (called shortly SUMO hereafter) (Lopez et al., 2018) was used

[7] https://www.berlin.de/sen/uvk/presse/pressemitteilungen/2020/pressemitteilung.881368.php

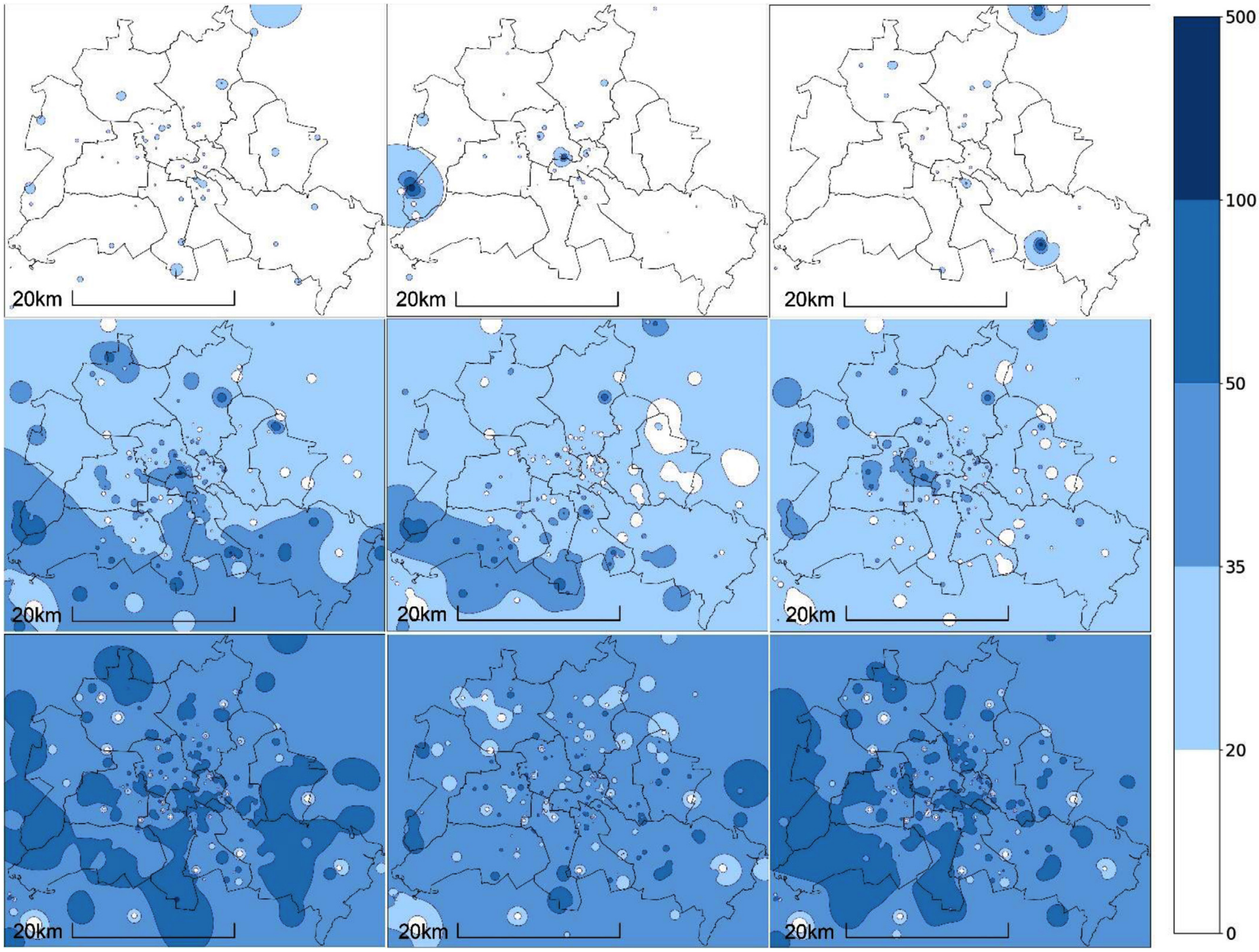

Fig. 3. AQI zones in Berlin. First row: 25.03. (low air pollution), second row: 11.06. (medium air pollution) and third row: 24.01.2020 (high air pollution). From left to right: AQI zones at 9:AM, 12:00PM and 5:00PM. AQI zones are given in μg/m^3 (PM_{10}).

because individual routes and their transit passages through AQI zones needed to be determined at each step of the simulation. In contrast to large-scale microscopic traffic simulators such as MATSim, streets are modeled in SUMO with their real-world shapes instead of direct connections between two endpoints. This is an important feature that makes it possible to determine precise routes and their exact trajectories through AQI zones. One second was chosen as the timestep length respectively time resolution of the simulation. At each timestep of the simulation, the positions of all vehicles are calculated by SUMO and the corresponding AQI zones are determined and logged for each vehicle. The road network was extracted from publicly available map data provided by the OpenStreetMap[8] project. As a transport demand model, the publicly available MATSim Open Berlin Scenario (Ziemke et al., 2019) for the multi-agent transport simulator MATSim[9] was used. Since MATSim creates individual activity plans to model the network load, the planned car trips of all synthetized individuals needed to be converted into a single origin-destination (O/D) matrix with annotated trip start times that is suitable for SUMO.

To make the road fees also dependent on the level of emissions of a vehicle, a Euro emission class was randomly assigned to each origin-destination pair (of the O/D matrix) based on the vehicle emission class distribution for Berlin (Kraftfahrt-Bundesamt, 2020). Table 2 shows the fuel and emission class distribution in Berlin for 2020 as used within the simulation. Since no information was available on emission class-dependent driving behavior, the possible differences, particularly regarding the frequency of vehicle use, could not be considered in the simulated trips. Although the total shares of hybrid and gas vehicles and vehicles with other alternative propulsion systems are rather small (hybrid 2.0%, gas 1.2% and other 0.03%), they were considered during the simulation, in particular, because of their non-negligible emission contribution. Electric (0.4%) vehicles were simulated (contributing to simulated traffic) as well, but due to the lack of appropriate emission models, they did not contribute to the simulated emissions.

The enhanced O/D matrix was then used throughout the evaluation in the simulation runs for each of the days under investigation. It incorporates 289,207 trips (with 63,554 distinct drivers) characterized by the origin, the departure time at origin, the destination, the Euro emission class, and the driver ID. The distribution of trip departure times across the day is shown in Fig. 4. The set of trips corresponds to about 10% of the daily traffic volume in Berlin and its close surroundings.

One of the main goals of the simulation is to determine how many AQI zone transits can be expected in Berlin on days with different air pollution characteristics under the assumption that all vehicles follow the shortest route in terms of trip duration. Other objectives are to deter-

8 https://www.openstreetmap.org

9 https://www.matsim.org/

Table 2
Vehicle type distribution for Berlin (as of 2020) in% as used in the simulations.

Fuel	Total Share	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Gasoline	72.62%	0.71	1.74	7.86	7.16	30.27	21.35	30.90
Diesel	23.63%	0.40	0.46	3.67	9.56	15.76	30.05	40.10

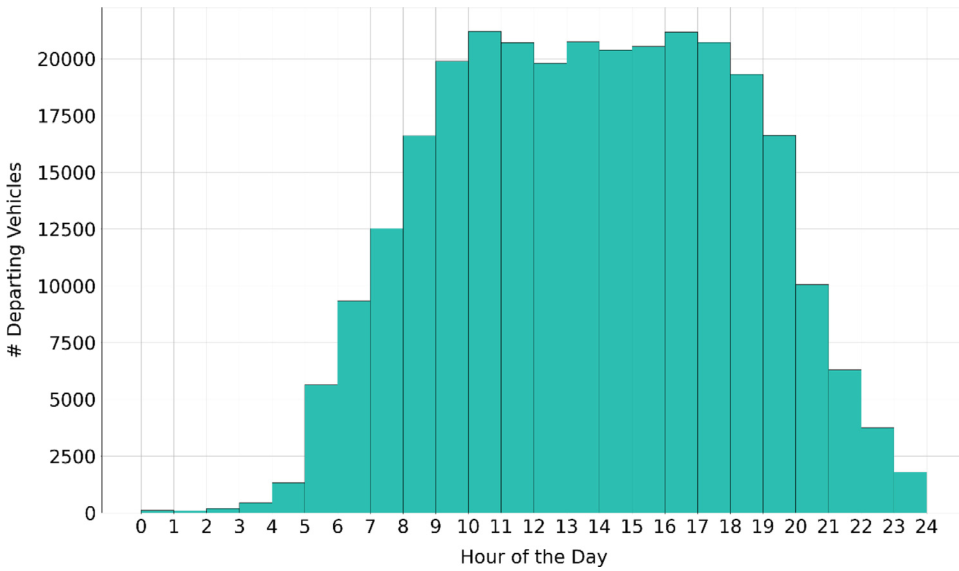

Fig. 4. Departure time distribution across the day.

mine how the traffic, AQI zone transits, and emissions of the motorized vehicles evolve if drivers decide to circumvent costly AQI zones, under the assumptions that all drivers evaluate their route with respect to road usage costs and no driver switches to public transport. Hence, this is an investigation of an edge scenario in which every driver evaluates the route before departure. It is intended to give first insights into the consequences of applying the proposed dynamic charging scheme in Berlin under the assumption that drivers are well-informed about the current AQI zones.

Results

To reveal the baseline first, vehicles were simulated to travel from their origins to their destinations with given vehicle-specific departure times and without intervening into the routing decisions made by SUMO. In SUMO, routing decisions are made based on weights at the edges of the transport network. The edge's current travel time, resulting from the fixed distance and speed limits, and the dynamic road occupancy, serve as the edge's weight in SUMO. The situation-specific aspect of the edge's weight leads to a proportional increase of an edge's current travel time with increased traffic along the edge. The Dijkstra algorithm is then applied in SUMO at the start of a trip to determine the fasted route to the destination in terms of trip duration. Every five simulated minutes, SUMO reevaluates the remaining portion of the route for a simulated vehicle based on the current travel times. After the reevaluation, SUMO adjusts the vehicle's driving speed at each remaining edge or even reroutes the vehicle. As a result of the simulation, all detailed routes, including the distances and the trip durations, were determined for each O/D pair. Fig. 5 shows the resulting distributions of the trip distances and trip durations. The average distance of a trip is 8.27 km with a 25%-quantile of 2.73 km, a 50%-quantile of 5.68 km, and a 75%-quantile of 11.30 km. The average trip duration is 11:30 min. with a 25%-quantile of 4:40 min., a 50%-quantile of 8:51 min., and a 75%-quantile of 15:45 min.. All vehicles covered a total distance of 2391,993.08 km with a total duration of 55,421.39 hrs..

Table 3
Accumulated AQI zone transit kilometer per day with low, medium, and high air pollution.

Day with	AQI Levels Level 1	Level 2	Level 3	Level 4
low air pollution	294,968	2650	1068	161
medium air pollution	1577,691	475,688	26,551	907
high air pollution	160,227	1374,271	811,445	3283

At the next step, the detailed routes were compared with the AQI zones for each day under investigation to tackle **RQ1**. The primary objective was to reveal the amount of AQI zone transits under the assumption that the charging scheme does not influence driving decisions. In other words, it was determined how many km in total were driven within an AQI zone with levels 1, 2, 3, and 4, without the drivers changing their route due to the existence of the road charging scheme. This information is particularly relevant for toll operators and collectors or, more generally, for the economic viability of a toll system and indicates the orders of magnitude with which environmental compensation measures could be implemented.

Since AQI zones are updated every ten minutes, it was required to map the 24-hour day's PM_{10} concentrations to 144 AQI zone snapshots. An AQI zone snapshot contains all AQI zones that are active within the toll area for 10 min.. Fig. 3 shows exemplary AQI zone snapshots at 9 AM, 12 AM and 5 PM. Table 3 shows the accumulated transit kilometer per AQI zone for each of the days under investigation. The total road charges per day for 10% of the population can then be calculated by breaking down the accumulated AQI zone transits into transits per emission class (given the emission class distribution in Berlin in Subsection Setup) and by applying concrete tariffs per AQI zone level and emission class. For example, if approx. 30% of the gasoline vehicles in Berlin (gasoline vehicle's total share in Berlin is approx. 72%) are Euro 4 gasoline vehicles and if they are hypothetically charged 5 Cent per kilometer in AQI zone level 1, then the total road charges for Euro 4 gasoline vehicles in AQI zone level 1 at a day with low air pollution results in

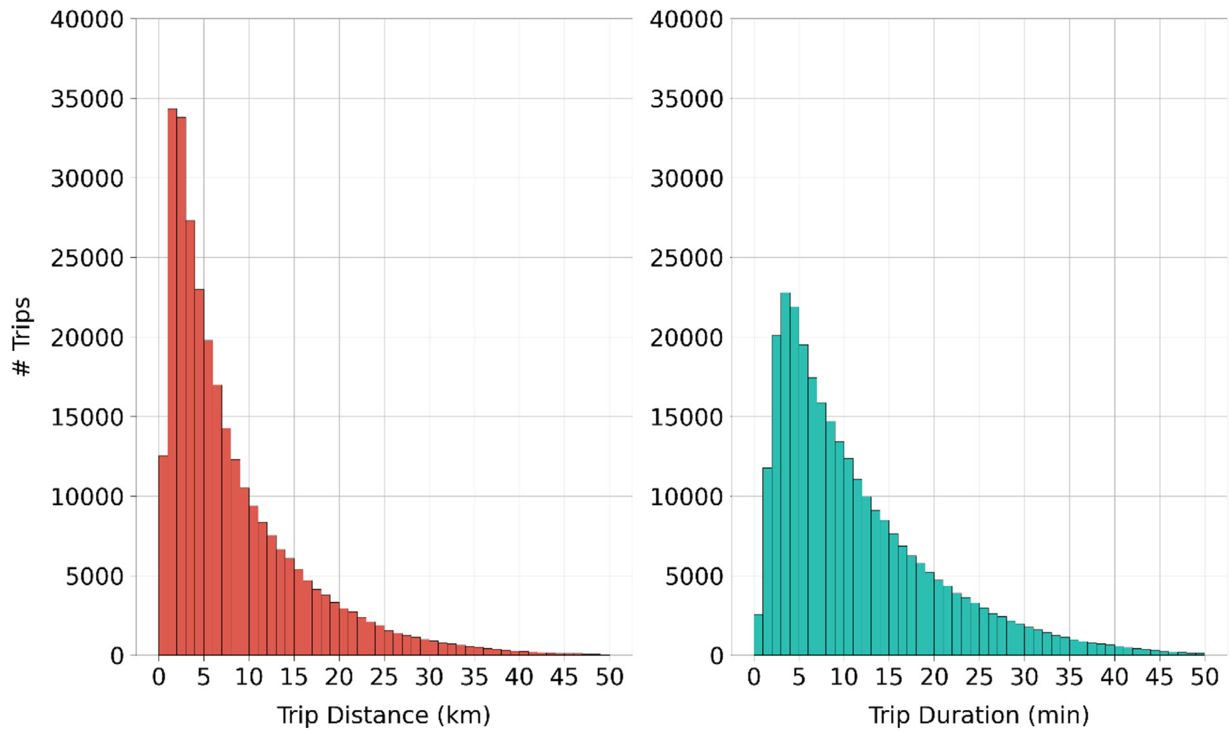

Fig. 5. Distribution of trip distances and trip durations for the baseline.

Table 4
Average number of times a tariff change is experienced per trip at a day with low, medium, and high air pollution.

Air Pollution	Tariff changes	25%-Quantile	50%-Quantile	75%-Quantile
low	0.58	0	0	1
medium	3.05	1	2	4
high	4.07	1	3	5

approx. 294,968 km * 0.72 * 0.30 * 0.05 Euro/km = 3185.65 Euro for 10% of the population. The higher the average air pollution in Berlin, the higher are the total road usage charges under the assumption that no driver switches to alternative transport means or adjusts the route to minimize the trip's road charges. Fig. 6 shows the relative distribution of AQI zone transits per time of the day. It illustrates that the likelihood of passing through an AQI zone of level 3 at a day with high air pollution is higher at rush hours between 6 and 10 AM and between 4 and 10 PM. This corresponds to the clearly visible higher air pollution at 9 AM and 5 PM compared to 12 PM at the day of high air pollution in Fig. 3. An indicator that car rides during the rush hours will be significantly more costly than car rides during off-peak hours, at least at a day with high air pollution.

To tackle **RQ2**, it was investigated how often a driver experiences a tariff change per trip. The tariff is defined as the current toll price per kilometer for a motorized vehicle of a particular emission class. Table 4 shows the results for days with low, medium, and high air pollution. A tariff change during a trip can be triggered in two ways: (1) the vehicle actively leaves an AQI zone and enters a new AQI zone or (2) the vehicle suddenly drives in a new AQI zone because the activation period of the current AQI zone snapshot expires and the new valid AQI zone snapshot with a new AQI level at the vehicle's location becomes active. This metric is an indicator of how dynamic the charging scheme will be experienced by the drivers in case the activation period is set to ten minutes. The price stability is an important criterion to evaluate the practicability and acceptability of a dynamic road charging scheme (Ministry of Transport, Great Britain, 1964).

At the next step, cost-conscious drivers were introduced. A cost-conscious driver evaluates at the start of a trip whether an alternative route, possibly circumventing an AQI zone with high transit costs or detouring through an AQI zone with low transit costs, should be taken to reduce the total trip charges. In SUMO, this can be simulated by switching a cost-conscious driver to effort-based routing instead of routing by travel time. The edge's effort (previously referred to as weight) can be customized individually per edge to suit the needs of the scenario under investigation. For cost-conscious routing, the edge's effort does not only consider the actual travel time but also the transit costs. The effort associated with an edge for cost-conscious routing is therefore defined by

$$effort_{edge} = \begin{cases} \Delta t \; if \; l = 0 \\ \Delta t \; + \left(\frac{d}{s} * c(e) * p(l)\right) \; if \; l \neq 0 \end{cases}$$

with actual travel time Δt, edge distance d, edge speed limit s, emission class factor function $c()$, vehicles emission class e, pollution factor function $p()$ and AQI zone level $l \in \{0, 1, 2, 3, 4\}$. The additional costs caused by the charging scheme are thereby represented by a pollution level- and emission class-dependent percentual increase of the actual travel time. In other words, the monetary additional expenses are translated into additional travel time per edge. The magnitude of Values of Travel Time Savings (VTTS) is thereby assumed to be similar for all drivers. The additional travel time is given by the time it takes for a vehicle to pass the edge ($\frac{d}{s}$) without considering the current traffic situation, an emission class factor representing the percentage increase for the given emission class ($c(e)$) and a pollution factor representing the percentage increase for the given AQI level ($p(l)$). Hence, the additional transit costs in terms of hypothetical additional edge travel time do not depend upon the current traffic situation (as already considered by Δt) because the charging happens only in a distance and not time-based manner. A vehicle is charged the edge's transit costs no matter how long it needed to pass the edge.

The taxation of the various pollutant classes for vehicles in Germany served as the basis for determining the percentage differences among the emission class-dependent factors. For example, if a Euro 2 diesel is

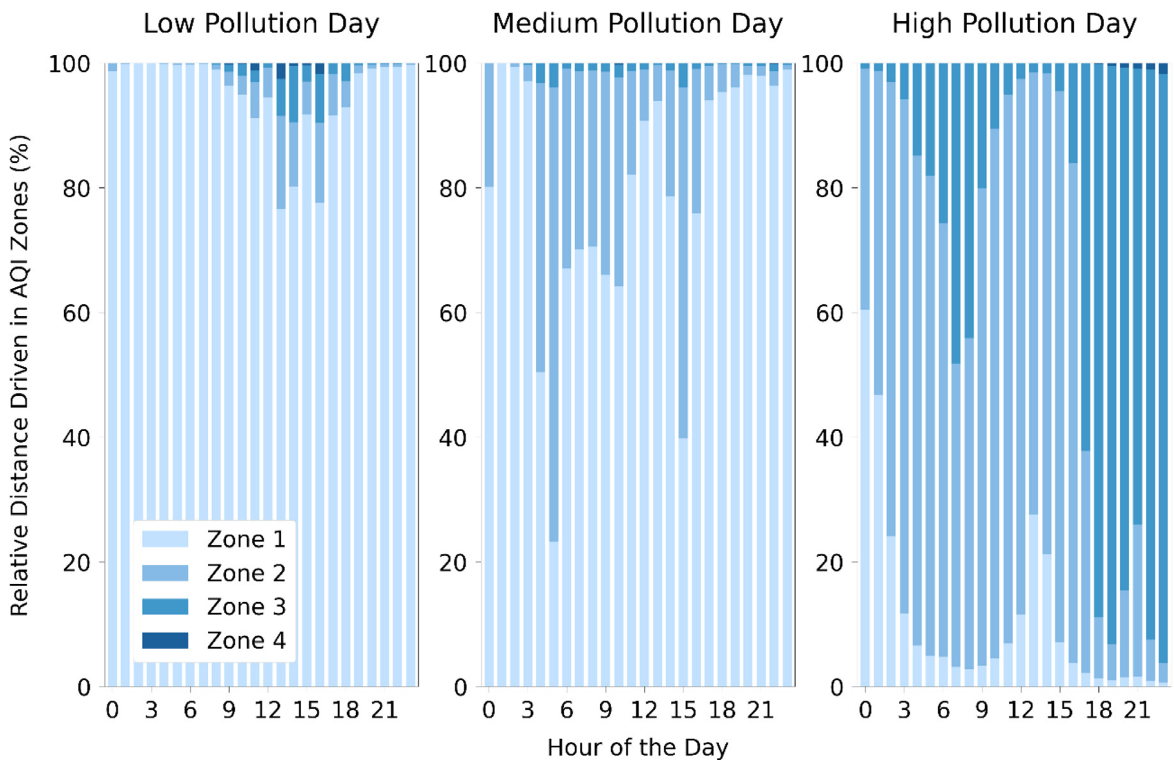

Fig. 6. Relative AQI zone transit distance per day with low, medium, and high air pollution.

Table 5
Differences of emission class taxation in comparison to Euro 6 gasoline in Germany as of August 2020 given in%.

	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Gasoline	376	224	109	100	100	100	100
Diesel	557	405	238	229	229	229	229

taxed 3.9% more than a Euro 3 diesel, then c ("*Euro* 2 *diesel*") is 3.9% higher than c ("*Euro* 3 *diesel*"). The percentage differences in relation to the taxation of a Euro 6 petrol vehicle are given in Table 5. Electric, gas and hybrid vehicles have a discount of 10% on the Euro 6 taxation. If one $c(e)$ is fixed, then the other emission class-dependent values for the emission class factor can be inferred from the percentage differences.

The pollution factor function $p(l)$ maps an AQI level to a concrete pollution factor. It increases with the amount of air pollution. The actual design of the function depends on various factors. It is, for example, possible to make the form of price increase with higher air pollution dependent on the increasing health hazards to correlate the probability of a related disease with the price per kilometer. However, the causal relationship between particulate matter concentration and morbidity rate was examined to be of linear (Liu et al., 2014) or non-linear (Szyszkowicz, 2018) nature. Some results indicate even no statistically significant relationship at all (Ren et al., 2017). But at first, the type of price increase depends upon the air pollution quantization used to infer the AQI level. For the simulations, which made use of the air quality index provided by the Federal Environment Agency in Germany, the pollution factor function is exemplarily defined as

$$p(l) = s * l^2$$

The factor increases exponentially with the AQI level. The slope is controlled by the parameter s. The higher the slope parameter, the faster grows the pollution factor with the AQI level. An exponential increase was chosen to better study the effects of bypasses because it was assumed that the higher the transit price for an AQI zone (given as additional edge pass time) is, the more likely it is expected that an AQI zone will be bypassed. A linear increase of the price is possible as well and would most probably reduce the simulated number of bypasses. At the border of a zone, it is possible that an edge may cross two or more zones. In this case, the highest zone level of all zones concerned is used to calculate the individual effort for the edge.

The number of drivers that are considered cost-conscious within a toll area depends upon several factors such as potential road charges, driver's educational background, income, and trip urgency. Due to the related complexity to model a region-specific decision finding process it was decided to simulate an edge case in which all drivers are considered cost-conscious. During the simulations, a driver evaluates possible bypasses at the start of the trip, chooses the best route with respect to the edge efforts and keeps following the route to the destination.

The primary objectives of the simulations with cost-conscious drivers are to investigate the extent of bypassing (**RQ3**), the characteristic of detours (**RQ4**), the change of vehicle emissions (**RQ5**) because of bypassing, and the impact of rerouting on the traffic (**RQ6**). Since cost-conscious drivers are highly price-sensitive, simulations were conducted with different tariffs. Instead of simulating with different concrete prices per kilometer (for emission class and AQI level), the slope parameter of the pollution function was varied. It was increased from 0.2 to 1.4 with a step length of 0.2 while c ("*Euro* 6 *gasoline*") was fixed to 0.1 for all simulations. According to the effort function, the percentual increase of travel time for a Euro 6 gasoline vehicle in an AQI zone with level 1 at slope parameter of 0.2 is 2%. At the other end, for a Euro 0 diesel vehicle the additional travel time results in 11%. A maximum slope parameter of 1.4 was selected because the percentual increase for a Euro 6 diesel vehicle in AQI zones with level 4 is very high at 1247.00%. With such an additional travel time, Euro 6 diesel vehicles were expected to bypass - by all means - AQI zones with high associated road charges.

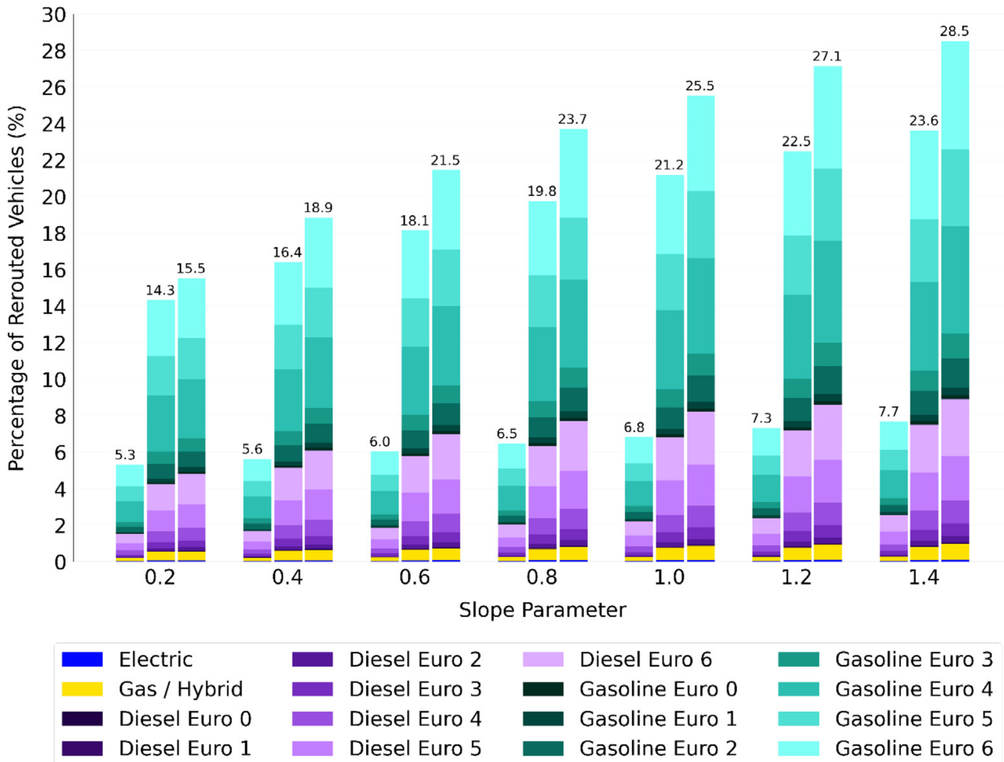

Fig. 7. Share of rerouted vehicles of all trips for days with low (left bars), medium (middle bars), and high (right bars) air pollution and increasing slope.

Hence, in this investigation, the slope parameter was used to vary the road charges (represented by additional travel time) and to observe how the cost-conscious drivers influence the traffic, the amount of AQI zone transits, and the emissions of the vehicles.

The first subject investigated here is to what extent cost-conscious drivers bypass AQI zones, depending on the vehicle emission classes (**RQ3**). Fig. 7 shows the relative number of vehicles that take a detour out of all trips broken down by emissions classes and days under investigation. Fig. 8 supplements this information by illustrating the share of rerouted vehicles among each emission class. Since Euro 1 diesel vehicles are more affected by higher road charges it is more worthwhile for them to take a detour at all days under investigation. At the day of medium air pollution, the numbers of detours for all emissions classes are at similar order of magnitudes as the ones at the day with high air pollution. The reasons can be manifold, ranging from detour roads reaching maximum capacity over the shape and size of AQI zones until the location of AQI zones at major roads with more attractive detour possibilities in general. However, the distribution of air pollution during the day with medium levels of pollution has many small AQI zones with level 0 that are worth passing through, even in a detour. On the other hand, the AQI zones with level 3 during the day with high pollution are more extensive and therefore less attractive to circumvent. The short drops, e.g., for rerouted Euro 1 diesel vehicles at slope 1.2 at the day of low air pollution, indicate that detour roads were already busy and thus less attractive. They become attractive again - even if busy – after the slope increases even more.

The next step of investigation dealt with the characteristics of the detours (**RQ4**). Table 6 lists the average trip distance differences of the rerouted vehicles in comparison to the baseline. The detours remain rather short in distance, culminating at days with a medium air pollution of about 220 m for slope 1.4. However, a few outliers were identified for long distance trips of more than 30 km. Fig. 9 shows exemplarily the distribution of detour distance differences for the days under investigation for a slope of 1.4. It illustrates how many detour trips are longer or shorter in distance, in comparison to the baseline. As a result, a trip with price-guided detours can even be shorter in distance. In some cases, driving directly through the notoriously crowded downtown area instead of using the bypassing city-circle helps to avoid passing through highly polluted areas as well as to decrease the trip distance. But it leads to an increase of the trip duration. Nevertheless, on average, rerouted vehicles cover a longer distance compared to the baseline. Fig. 10 shows the relative amount of the trips rerouted, grouped by trip distance. The longer the trip distance is, the higher is the chance that road charges can be avoided by detouring. Towards trips with longer distances, the trend can no longer be clearly identified. The reason lies in the number of total trips which gets smaller with increasing distance up to a point where small changes have too much influence on the overall result. Higher distance results should therefore be interpreted with due care. See the baseline results in Fig. 5 for more details about the trip distance distribution. However, at the day of medium and high air pollution, the shares of rerouting vehicles reach their peaks already for trips with medium distances (>20 km) while on the day with low air pollution, the peak is reached for trips with longer distances (>35 km). The very sporadic and relatively small zones with level 1 within a city-wide clean air in Berlin lead to the result that the probability of choosing a favorable bypass on a route increases more slowly than on days with medium and high air pollution.

Table 6
Distance differences of rerouted vehicles (* in km).

	Low Pollution Day		Medium Pollution Day		High Pollution Day	
Slope	0.2	1.4	0.2	1.4	0.2	0.4
Mean*	0.01	0.09	0.03	0.22	0.02	0.17
σ*	0.92	1.11	0.90	1.37	0.91	1.23

The more cost-conscious drivers are bypassing zones with high air pollution or detouring through zones with less air pollution, the higher are the average distances travelled. This leads inevitably to an increase of the overall vehicle emissions during the day. Since not every rerouted

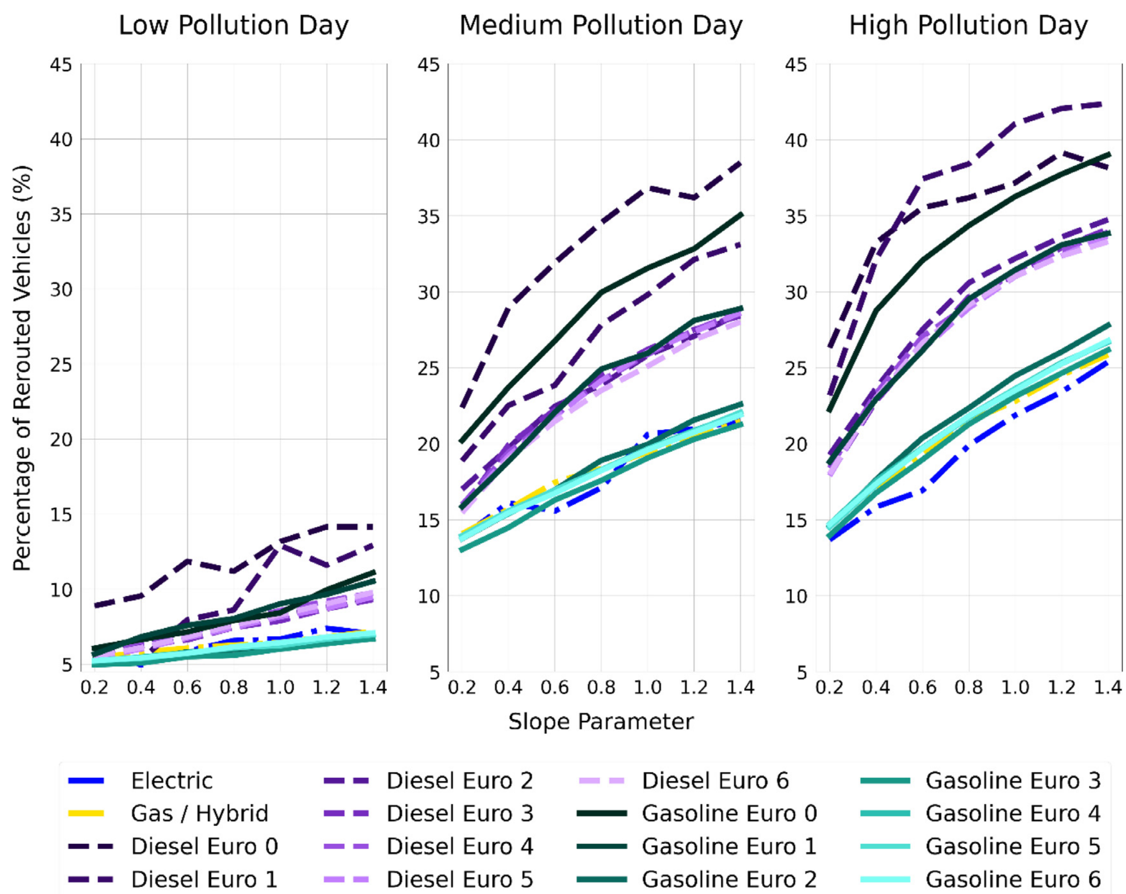

Fig. 8. Share of rerouted vehicles within each emission class for days with low, medium, and high air pollution.

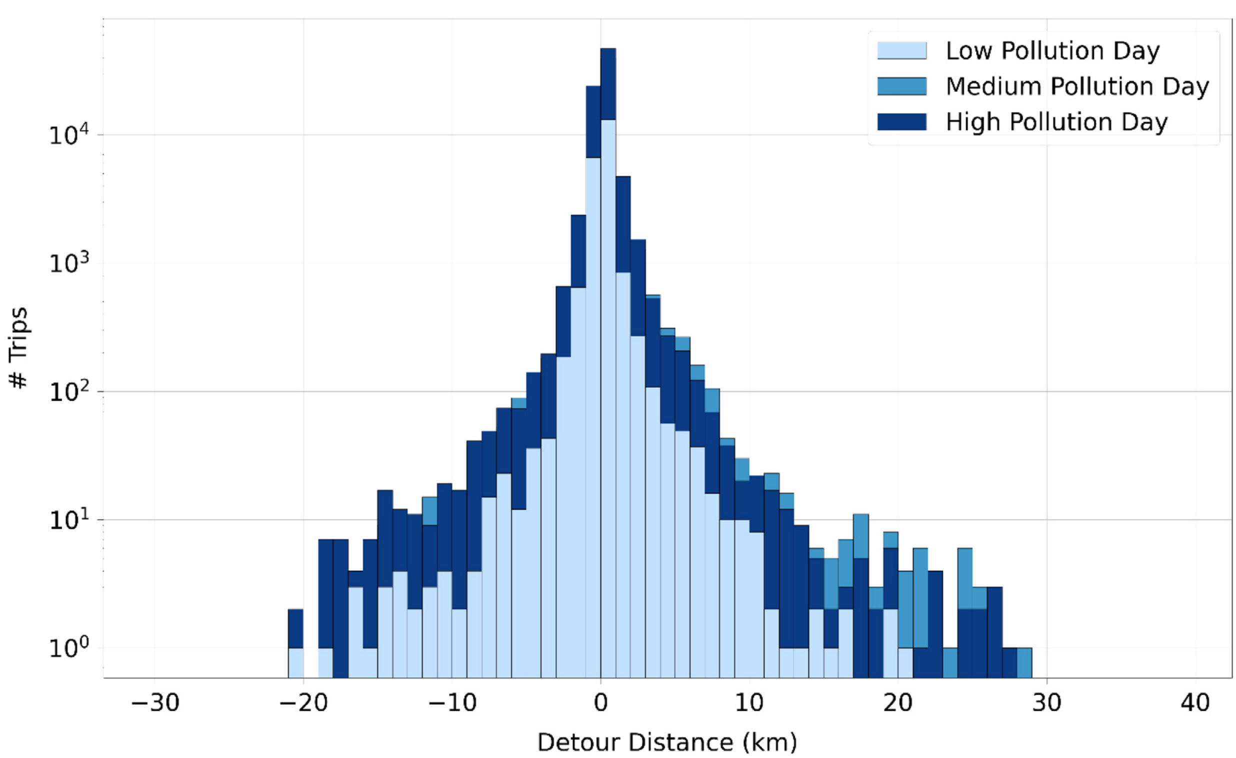

Fig. 9. Distribution of detour distance differences in comparison to the baseline. L1.4: Low pollution day, M1.4: Medium pollution day, and H1.4: High pollution day.

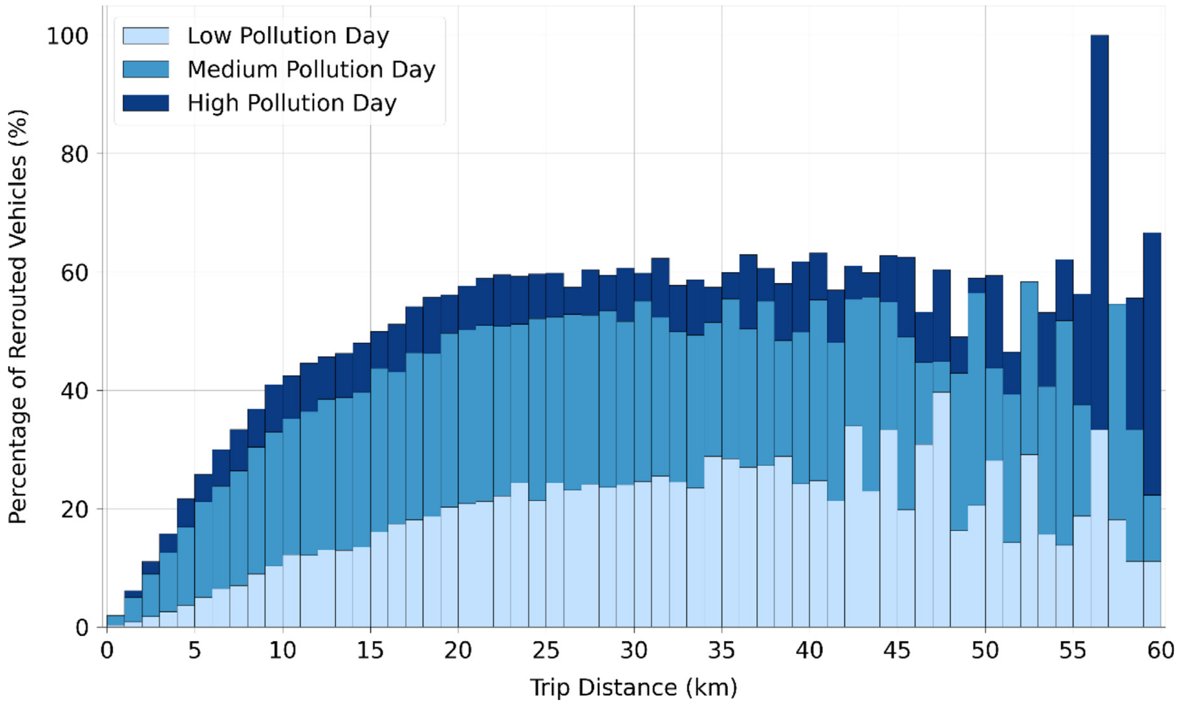

Fig. 10. Share of rerouted trips with slope 1.4 at days with low, medium, and high air pollution and grouped by trip distances.

vehicle covers the same or a longer distance, but a shorter one instead, it is necessary to investigate which additional vehicle emissions can be expected (**RQ5**). SUMO uses the databases provided by the Handbook Emission Factors for Road Transport (HBEFA)[10] in version 3.1 to model the exhaust emissions of passenger and light delivery emission classes. Non-exhaust emissions such as particulate matter caused by brake, tire, and road surface wear are not supported in HBEFA version 3.1. The simulated emissions depend upon the kilometers driven, the vehicle speed and the vehicle emission class. Fig. 11 shows the relative increase of vehicle emissions with an increasing slope with respect to all trips, including trips without rerouting. The relative increase due to detouring remains below 1.5% even with a high slope on the day with medium air pollution. Surprisingly, on days with high air pollution, there is only a 1.3% increase in fine dust pollution, although about 28.5% of drivers choose to bypass. These are the additional emissions from vehicles only and it does not even consider wind and weather conditions. Since detouring causes additional emissions in zones with lower air pollution and relieves zones with high air pollution from further emissions, the overall air pollution should get more evenly distributed across a toll area. Unfortunately, this may lead side roads to experience a higher traffic load with additional negative consequences such as increased noise and air pollution and traffic risks.

So, if the road charging scheme would be deployed, how would the road network utilization in Berlin change (**RQ6**)? Fig. 12 plots the absolute traffic increase and decrease (additional and lesser number of vehicles per edge) at a slope of 1.4 in contrast to the baseline for each day under investigation. It shows, contrary to the assumption above, that main roads are mostly affected by the detours through an increase or decrease of the traffic, even at the day with high air pollution. Roads used for detours and their counterparts are clearly visible for all days because the increase at an alternative main road of a detour with similar distance leads to a decrease at the main road at the original route. The traffic at a few notoriously overcrowded sections of the inner-city freeway (clearly visible as a semicircular red line in the baseline plot) gets even worse at days with medium and high air pollution while most of the sections experience either no effect or lesser traffic. Some detours are frequently used detours even without the hypothetical charging scheme in place. It remains to be investigated which situation factor contributed most to the decision of the driver to detour: actual travel time based on traffic load or upcoming road charges for the rest of the original route?

A change of the traffic behavior has also an effect on the amount of AQI zone transits since cost-conscious drivers try to avoid costly routes. Hence, this leads to a change of the overall toll volume to be expected by a toll operator or collector, as investigated with respect to **RQ1**. Fig. 13 shows the absolute increases and decreases of the amount of AQI zone transits with an increasing slope for the days under investigation. On the day with high air pollution, cost-conscious drivers cause a significant decrease of transits through AQI zones of level 3 and at the same time an increase of transits through AQI zones of level 1 and 2. The overall effect culminates at a difference of approx. 52,000 km for transits of AQI zones with level 3. Drivers at a day with high air pollution have no options to avoid tolled zones. At the day with low air pollution, in contrary, detours are conducted to avoid tolled zones in general and to drive through non-polluted areas (AQI zone with level 0). The decreases of transits through AQI zones of levels 1 to 3 are thus not compensated by tolled trips.

Discussion

For a proper interpretation of the results, it is necessary to summarize the assumptions and limitations of the conducted simulations and put them in relation to the findings. A major limitation is to simulate only 10% of trips that Berlin usually experiences during a weekday. The traffic for weekends were not simulated at all. With only 10% of traffic, a traffic network (not scaled) that is designed to cope with order of magnitudes higher traffic demand will hardly present any sections where traffic congestions occur. The actual travel time, as used in the determination of the effort, thus might play only a minor role for the routing decision. This would mean, on the other hand, that the rerouting happened mostly to reduce the overall road charges for a trip. A non-scaled network allows therefore to investigate the effects in an isolated manner. If even alternative main roads would get congested, vehicles might

[10] https://www.hbefa.net/e/index.html

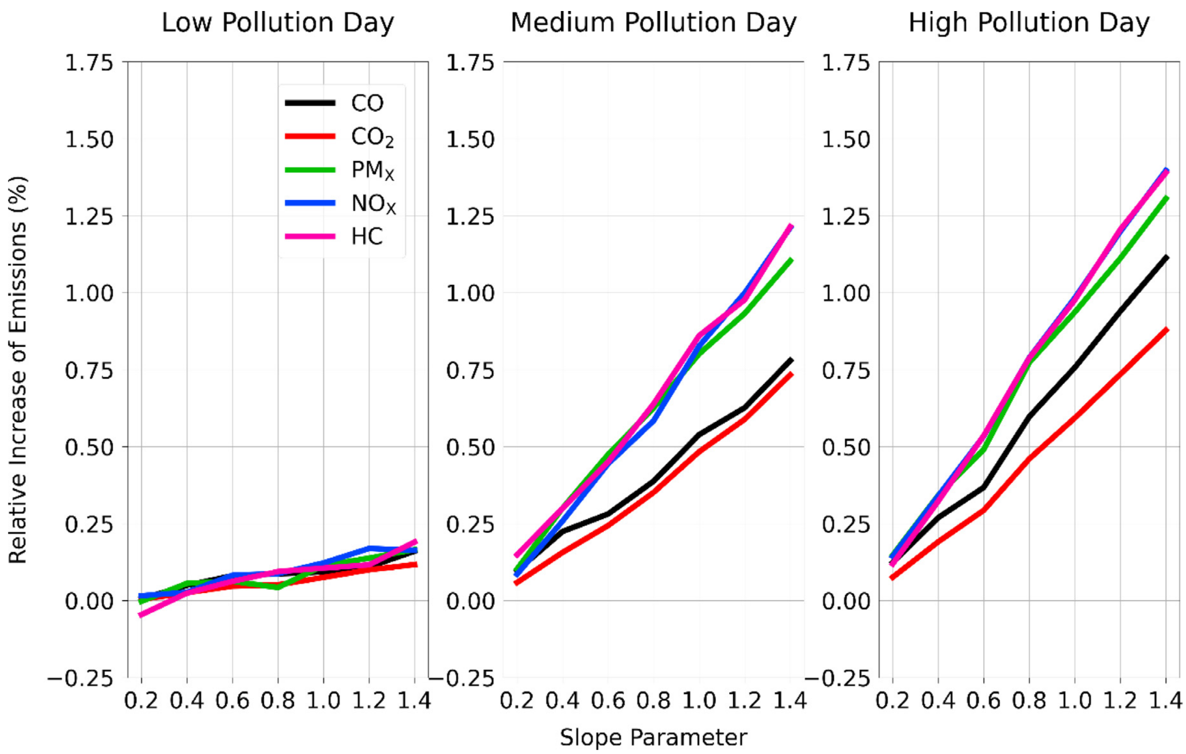

Fig. 11. Relative increase of vehicle emissions depending on the slope parameter. CO: Carbon Monoxide, CO_2: Carbon Dioxide, PM_x: Particulate Matter, NO: Nitrogen monoxide, HC: Hydrocarbons.

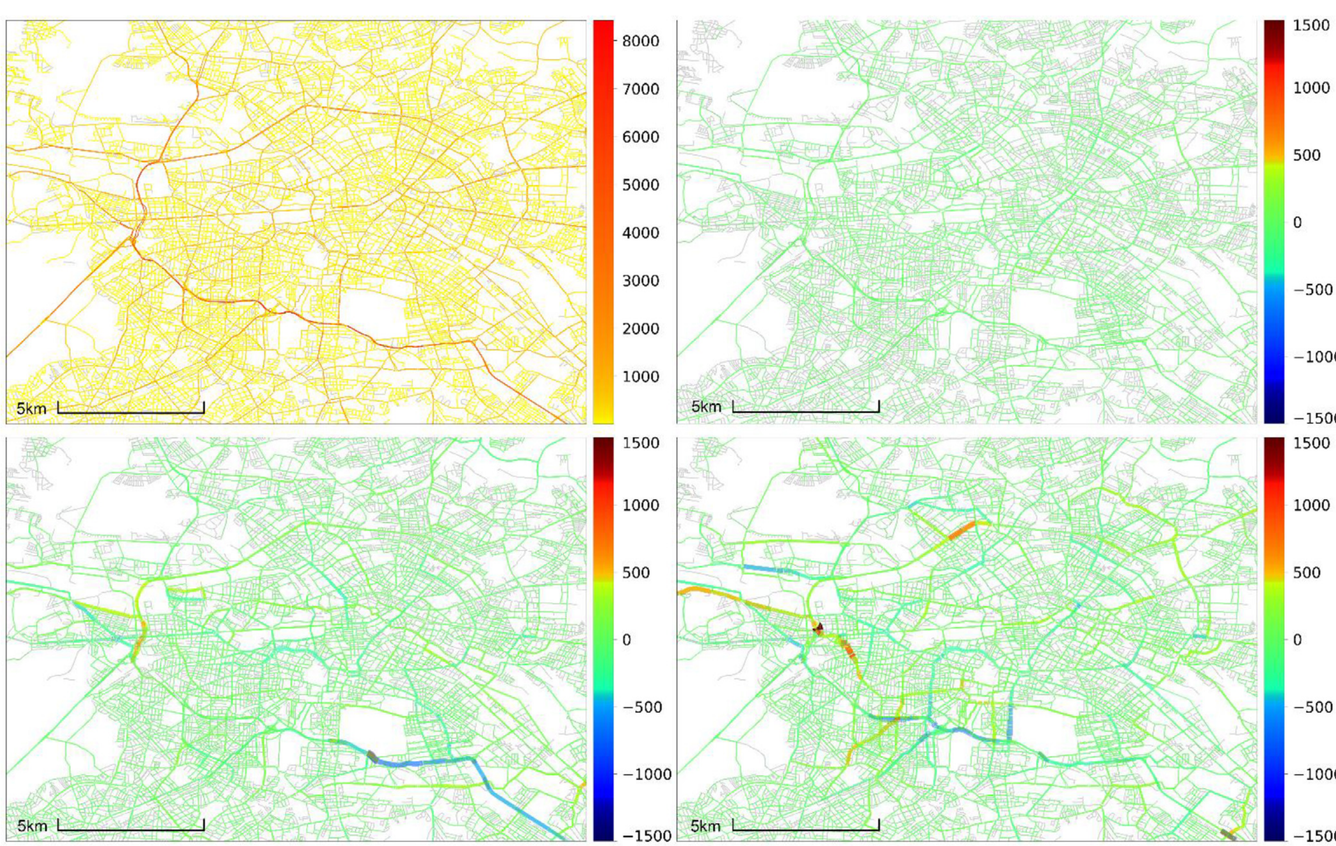

Fig. 12. Absolute increase and decrease of trips per edge of the traffic network within the downtown of Berlin at slope 1.4. Top left: baseline; top right: low pollution day; bottom left: medium pollution day; bottom right: high pollution day.

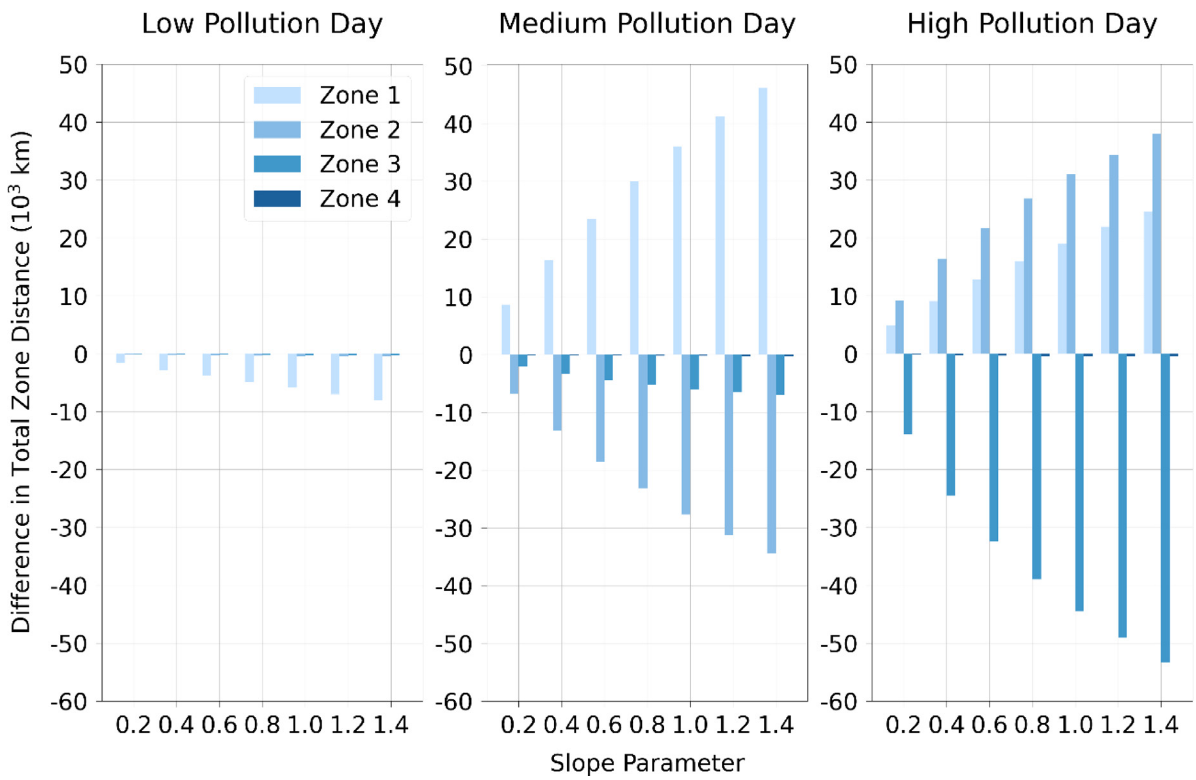

Fig. 13. Absolute difference of AQI zone transits depending on the slope and day of investigation.

switch onto side roads. Which side road to switch to, might then be as well influenced by the road charges. A closely related assumption is to take the rerouting decision only at the beginning of the trip. During a trip, as can be inferred from the tariff changes per trip, AQI zones might change. A routing decision taken at the start of a trip might turn out to be not optimal with respect to road charges. For proper investigation it needs to be empirically determined how often drivers are willing to change their route based on, for example, recommendations by an air pollution-aware navigation system. In general, the decision process to take a detour is quite complex and depends on several context factors such as day of the week, time of the day, personal preferences, etc. (Ziebart, Maas, Dey & Bagnell, 2008). For the simulations, the driver was assumed to reroute only based on travel time. The travel time encompasses the actual travel time and the additional travel time resulting from the road charges. A driver might even decide to leave the car and take the public transport or to change the destination instead. Another option would be to advance or postpone the trip in order to avoid the rush hours with their longer trip durations and higher road charges. However, this requires forecast mechanisms to be in place or decision making based on experience. Hence, another limitation is the focus on a few factors in decision making and the limited number of choices. Especially, because taking alternative means of transport or rescheduling the trip will most probably have a significant impact on the resulting amount of AQI zone transits and overall emissions. But not every driver evaluates the route to the destination. Some might follow their preferred routes independent of hypothetical road charges. In this work, 100% of the drivers were simulated to evaluate their route at the start of the trip to investigate an edge case. If the share of cost-conscious drivers among all drivers would be lower, then the amount of AQI zone transits would most probably rise. The results with respect to the AQI zone transits should therefore be interpreted as a lower bound while the amount or rerouted trips should be considered as the upper bound. It would also be possible to restrict access to AQI zones with particular AQI levels for vehicles with specific emissions classes as done within today's LEZs in Germany. This would probably have a significant impact on the lower bound of AQI transits and upper bound for the amount or rerouted vehicles. However, adjusting the extent of restricted zones in a temporal and spatial manner makes it, on the one hand, difficult for drivers to predict whether an envisioned route is permitted and, on the other hand, likely to accidentally drive in a zone that is not supposed to be crossed due to rather spontaneous tariff changes.

It was not intended to define a concrete price per kilometer, AQI zone and emission class and to investigate the effects, but only to observe the development of traffic with increasing relative prices per emission class. Mapping the relative prices to additional virtual driving time without defining a budget limit or upper limit for the expected driving duration bears the justified risk of taking detours that take many times longer, but in reality, are not driven due to higher fuel costs or lack of time. Due to the limited extent of the investigated area, only a few alternative trips were identified, whose tracks proved to be unrealistic. 50 out of 289,207 trips experienced a trip duration increase of over 50% and 2 trips over 100% on a day with medium air pollution and slope 1.4.

To model the air pollution in Berlin, crowdsourced air quality measurements were taken. Privately-owned and operated air quality sensors integrate mostly low-cost sensors. Low-cost sensors, such as the one mainly used in the Luftdaten.info initiative, bear the risk of unprecise measurements (Budde et al., 2018). Moreover, they can be placed at arbitrary locations, for example, in the garden, on the roof top, or close to windows. Without considerable expert knowledge, it cannot be guaranteed that they will be placed at locations that allow representative measurements of the urban air quality. Their measurements might be biased by cooking or heating smoke or emissions at highly frequented roads. Community-operated sensors might also be faulty or broken (Wan et al., 2016). . Despite the conducted removal of outliers prior to the modeling of the urban air quality, the measurements should always be interpreted as approximations. For the urban air pollution modeling it is assumed that the density of sensors in Berlin is sufficiently high to properly interpolate the traffic-related air pollution at places lacking a sensor. However, an arbitrarily distributed air quality sensor network, such as the one in Berlin, should - in general - be thoroughly investigated with respect to its suitability to properly represent traffic emissions (Sun, Li, Lam & Leslie, 2019). Hence, not only the microscopic placement at a building but also the placement out of a macroscopic perspective within an urban environment needs to be considered.

Whether AQI zone snapshots should be determined based on the measurement of the last 30 min. and updated every 10 min. as done within the simulation must be decided upon by the toll operator or collector. An activation interval of 10 min. was chosen to keep a fair balance between the accuracy of representing the current air pollution distribution and the price stability for the driver. A lower interval might not increase the accuracy significantly because the air quality must be measured anyhow by taking multiple sensor readings into consideration. Since air pollution might even arise at places without air pollution sources (Dedoussi et al., 2020), cross-street, cross-quarter, or cross-district air movements needs to be taken into consideration for a proper interpretation of sensor readings (Taseiko, Mikhailuta, Pitt, Lezhenin & Zakharov, 2009). As weather conditions play a major role for the urban air pollution dispersion (Holzworth, 1969), days with similar weather conditions were compared to each other. It remains to be investigated how the air pollution dispersion characteristics in Berlin evolve under different weather conditions, for example, with heavy rain and higher wind speeds.

The major risk of the proposed charging scheme is that drivers will take detours to save costs. Detours can cause additional emissions, pollute residential side streets, and lead to congestions on alternative routes. As can be seen in the results, emissions are in fact rising, but not with the same amount as the number of rerouted vehicles. This can be attributed to detours which are short on average compared to the length of the route and which sometimes even lead more directly to the destination and are therefore shorter in total. Since rerouted vehicles take alternative routes, the overall vehicle-caused emissions get more evenly distributed across the toll area. Side roads are hardly or only marginally used for detours, while some sections of alternative main roads show an increase of a maximum of 1000 vehicles per day at the day with medium air pollution. However, it is not possible to determine whether there may even be a reduction in overall emissions with the simulation setup because the drivers' scope for deciding whether to advance or postpone the start of the trip or to switch to alternative means of transport was not modeled. Another important finding is that the number of detours depends not only on the average pollution levels along the route, but also on the spatial distribution of the air pollution. The smaller the zones with higher or lower air pollution along or close to the route are, the more detours are beneficial for the driver. Due to the different characteristics of the distributions, it is difficult to compare the results between the day with the medium and the days with the low and high air pollution. To achieve a general applicability of the findings, the specific characteristics of spatial distributions of urban air pollution must be identified and their impact on driving behavior be investigated, together with a concrete pricing model.

Conclusion

This article presented an explorative analysis of an air quality and distance-based charging scheme for the metropolitan region of Berlin. As the first of its kind, it investigated the effects of adjusting the extend of LEZs dynamically without human interaction, according to the spatial and temporal distribution of the urban air pollution. By simulating 10% of the daily traffic volume on a working day in Berlin for days with different particulate matter concentrations, it was examined, how many trips are likely to be eligible for road usage charges and how the trip charges are composed of transit costs through LEZs with different PM_{10} concentrations. The impact of the charging scheme on the traffic and vehicle emissions was investigated by varying the relative price tag per temporary LEZ and by allowing cost-conscious drivers to decide on the preferred route before departure. A key finding, beside others, is the moderate increase of the overall emissions with the increasing number of rerouted vehicles. Detours are on average short compared to the trip length and sometimes even shorter than the original route. Major roads are affected mostly by an increase or decrease of traffic while side streets experience no significant changes in traffic volume. It turned out that the spatial characteristics of the PM_{10} concentrations within a toll area - besides the price tags - had a significant impact on the number of drivers that decided to take an alternative route. Hence, not only the AQI level and the associated price per kilometer but also the sizes, shapes, and placements of AQI zones influence the characteristics and number of detours with their additional emissions. Further investigations are necessary to identify recurring air pollution patterns, generalize their distribution characteristics, and examine their impact on the mobility behavior of motorized drivers. Although particulate matter was considered only in this investigation, further considerations, for short to medium term solutions, could also include emission gasses such as carbon dioxide.

However, the results of the simulations gave first valuable insights into the expected overall road usage charges per day and the potential consequences for the road network infrastructure. Whether the main objectives of the charging scheme have been achieved, namely, to better distribute or even reduce the overall emissions and to relieve critical areas in the city from further traffic and thus emissions, remains to be examined. To do so, transport mode switches, rescheduled departure times, local air dispersion models, and a scaled transport network need to be considered as well within the simulations. But the insights can at least be used as a starting point for toll collectors and municipalities to further investigate whether it's worthwhile to control the urban air pollution through temporarily and spatially varying LEZs. This also raises the crucial question of whether citizens would accept a toll system in which the price for the passage of a road section can change after each activation period. Road usage costs for trips become, therefore, difficult to predict although the average number of tariff changes per trip is rather low with 0 to 3 for 50% of the simulated trips.

Although the dynamic charging scheme was considered in isolation, it could also be part of a more complex charging scheme that also considers other context parameters, e.g., such as current traffic volume, road type, time of day, vehicle occupancy, and assimilative capacity of the environment. The latter could help to set the price range for the dynamic air pollution-dependent portion of the total charges, while the prices per time of day, road type, and vehicle occupancy are fixed by tariffs similar to the emission class. Electric vehicles could also be considered to contribute to additional emissions due to their comparable or even higher particulate matter emissions. The flexible air pollution-based LEZs could - besides road charging - also be used by hybrid vehicles to automatically switch between combustion and electric engines to directly influence vehicle emissions within the toll area. Overall, ITSs with the proposed charging scheme put in place are excellent applications of the new monitoring and control mechanisms for urban traffic and the associated urban air pollution that can be used in modern smart cities, due to the technical possibilities such as distributed city-wide sensor networks and precisely localizable and connected vehicles, to meet the growing demand for mobility while raising the awareness for sustainable urban living.

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