Traffic management based on large-scale traffic and high-resolution air pollution simulation

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Short summary

Reducing traffic-related air pollutant concentrations requires the development of suitable traffic management policies. By coupling the mesoscopic traffic and emission model MATSim with the microscopic urban climate model PALM-4U, it becomes possible to calculate traffic emissions and their dispersion for large simulation areas in high resolution. Utilizing both models, an appropriate traffic management strategy using distance-based tolls is implemented to reduce critical air pollutant concentrations throughout the day. The designed traffic management policies are applied to various study areas, and its effectiveness in reducing air pollutant concentrations is evaluated.

Keywords: Activity-based modelling, Traffic management, Air pollution modelling

1 Introduction

Modeling the interplay between environmental impacts and traffic is an important tool when designing suitable policies for reducing traffic emissions. Numerous established traffic emission models are available (Forehead & Huynh, 2018), to estimate environmental impacts of traffic.

To assess these impacts, traditional dispersion models parameterize pollutant transport (Johnson, 2022), while CFD (Computational Fluid Dynamics) models offer a physically accurate representation of the emission dispersion process (Liang et al., 2023). By combining traffic emission and dispersion models, it becomes possible to identify high pollution areas (Forehead & Huynh, 2018), so that traffic management policies can be implemented to mitigate excessive pollutant concentrations (Vosough et al., 2022; Agarwal, 2017).

This study innovates by coupling MATSim (Multi Agent Transport Simulation), a mesoscopic traffic and emissions model, with PALM-4U, a high-resolution CFD and air chemistry model. Using PALM-4U's pollutant concentrations, we design and evaluate a traffic management system to reduce air pollutant hotspots.

2 Technical Prerequisites

MATSim, an open-source traffic simulation, models travelers as synthetic persons (Horni et al., 2016). These synthetic persons have daily schedules with activities that require moving on a simulated road network, where road sections are represented as links. To maximize utility, synthetic persons adapt their behavior using a co-evolutionary algorithm through an iterative process involving mobility simulation, plan evaluation, and behavior adjustment.

MATSim's framework features an extension developed by Hülsmann et al. (2011) and Kickhöfer et al. (2013) for traffic emissions modeling, which uses emission factors from the HBEFA (Handbook Emission Factors for Road Transport) database version 4.1 (Notter et al., 2019). Emissions are computed for each vehicle traversing a link, aligning with MATSim's mobility simulation resolution. After a link was passed, HBEFA emission factors are looked up, then multiplied by the link length and recorded as emission events.

For atmospheric dispersion of traffic emissions, the PALM Model System operating in LES (Large Eddy Simulation) mode is used (Maronga et al., 2020). It resolves obstacles, like buildings and orography, and scales for large urban simulations. The PALM Model System includes a chemistry module developed for urban environments (Khan et al., 2021), offering air chemistry mechanisms and passive tracer simulation. Anthropogenic pollution can be input via a so-called chemistry driver file (Maronga et al., 2020, 1353).

To integrate MATSim with PALM-4U, traffic emissions from MATSim are converted into PALM-4U's chemistry driver format (Laudan et al., 2023; Laudan, 2023a). MATSim and PALM-4U employ different data models for spatial and temporal resolution. MATSim uses vector representation for space, while PALM-4U divides space into a grid, with each grid cell representing a discrete volume. Time resolution in MATSim is in seconds, while PALM-4U's chemistry driver requires emissions in uniform intervals. Thus, transformation of second-by-second traffic emissions into time-interval-based and gridded emission flows is necessary. The study presented in section 3 uses an hourly interval, altering emission flow into the PALM-4U simulation every hour.

3 Methodology

The case study uses the MATSim *Open Berlin Scenario* (Ziemke et al., 2019; Leich et al., 2023), representing travel demand of Berlin's and Brandenburg's population. The synthetic population can adapt behavior by altering routes, modes, or departure times. For emission dispersion calculations, an existing PALM-4U setup for Berlin's city center is employed (Khan et al., 2021; Khan, 2020). It covers the red square in Figure 1, with a 10 m grid resolution. The setup simulates July 17, 2017, representing a typical summer day. The original PALM-4U setup is adjusted for this study, assuming a constant 1 m/s westerly wind instead of dynamic conditions, and employs MATSim-generated traffic emissions (NO (Nitrogen Monoxide), NO_2 (Nitrogen Dioxide), PM_{10} (Particulate Matter)) instead of emissions obtained from historic data.

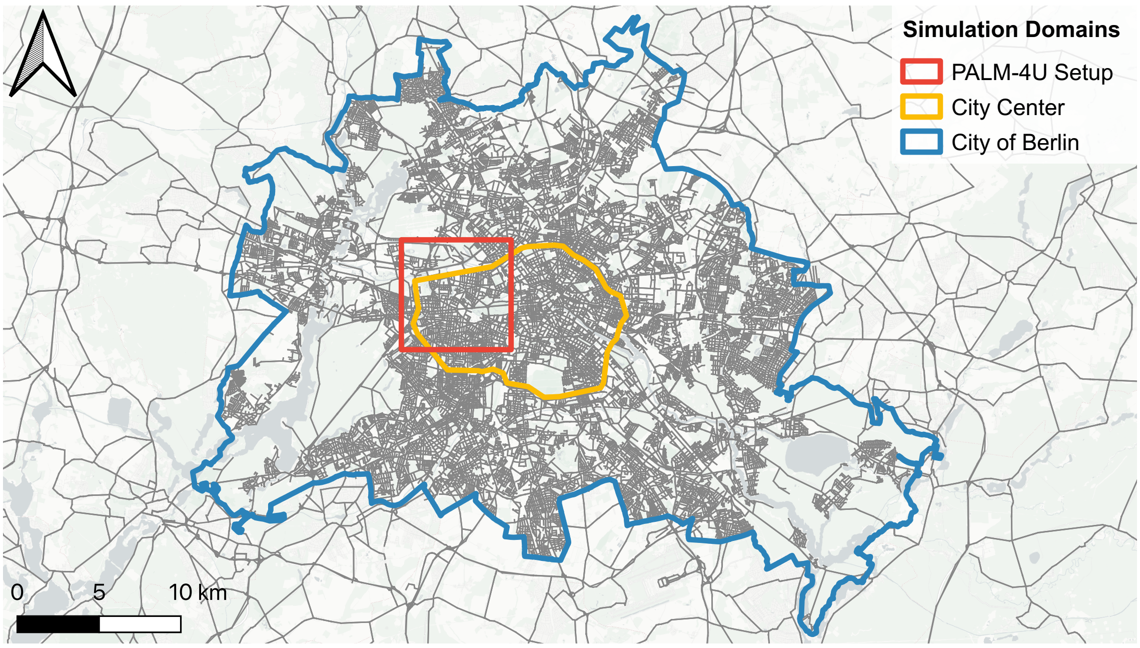
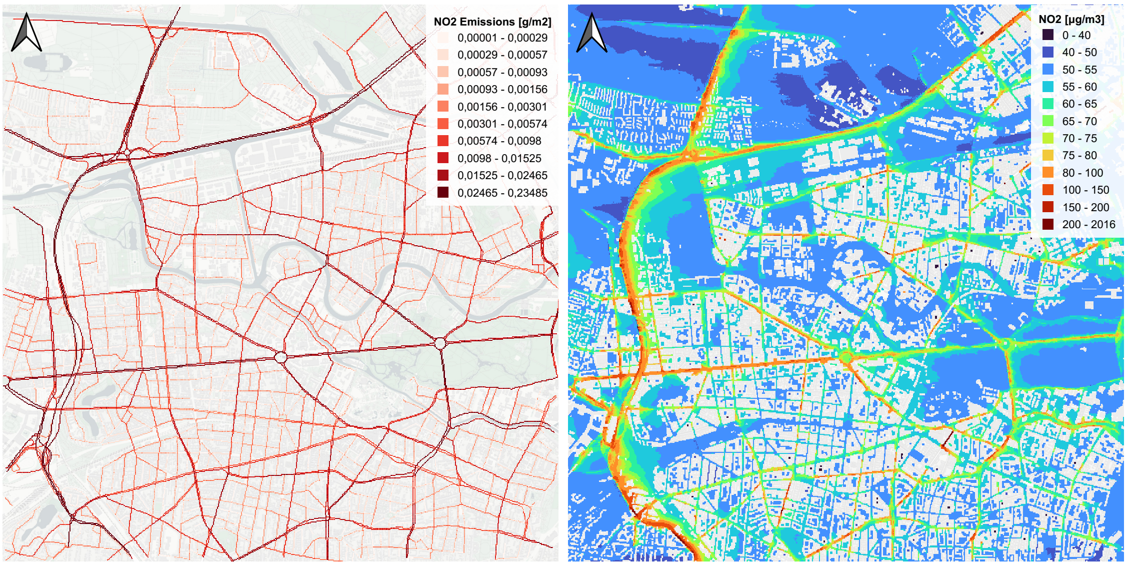


Figure 1: Simulation Domains: Blue - City of Berlin; Red - PALM-4U Setup; Yellow - Berlin City Center

With the adjusted PALM-4U setup, a base case is simulated using emission flows generated with MATSim (cf. Figure 2a), resulting in corresponding pollution concentrations as shown in Figure 2b. Pollution concentrations in Figure 2b align with input emission flows in Figure 2a, with high NO_2 concentrations near links with heavy traffic volumes.



(a) (b)

Figure 2: (a) Rastered emission flows for the period between 8 and 9 a.m.; (b) corresponding PALM-4U NO2 concentrations after dispersion.

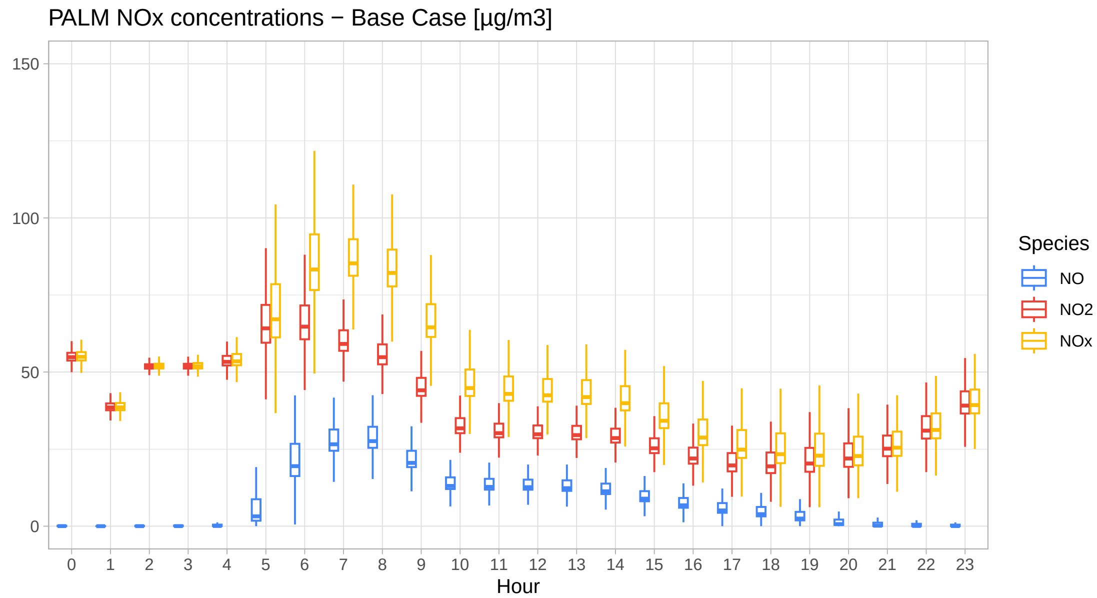


Figure 3: Simulated PALM-4U pollutant concentrations

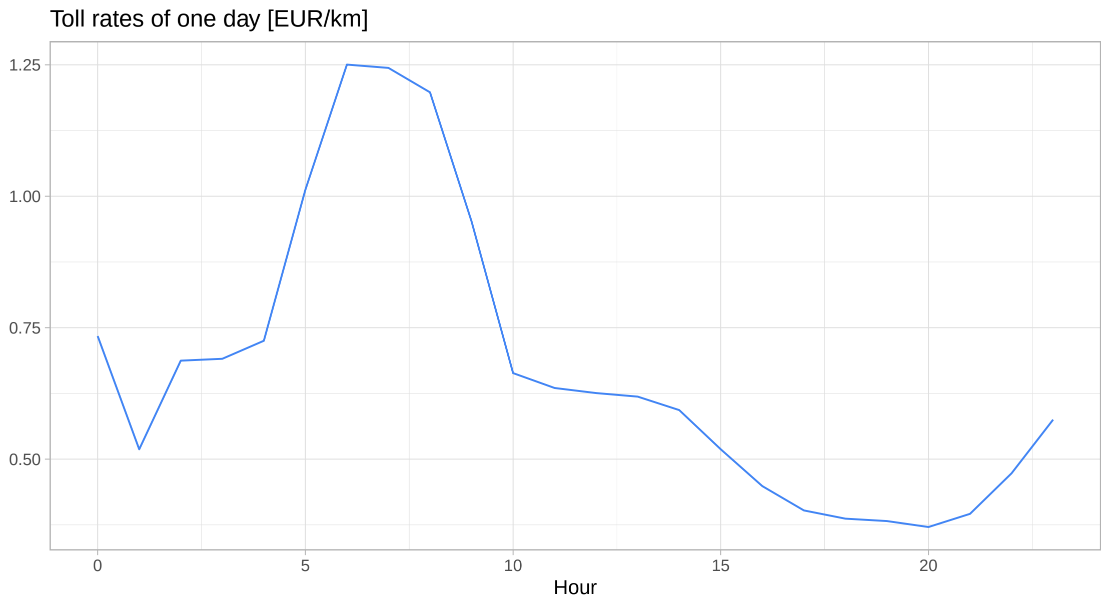


Figure 4: Time-varying distance toll scaled by a factor of 100

To mitigate pollutant concentration peaks, a time-varying distance toll is implemented into the simulation. Initially, it was attempted to determine all vehicles contributing to high concentrations and to charge a toll exactly to them. However, our investigations showed that there is no simple relation between concentrations in PALM-4U and tailpipe emissions – evidently, the dispersion dynamics is more complex than that even with the simplified constant wind assumed in our study. Instead, it became clear that concentrations are much higher in the morning than in the evening (Figure 3), although levels of traffic are quite similar. This is because emissions are mixed into the atmospheric boundary layer, which, as turbulence is related to solar heating, is thinnest at the end of the night and thickest at the end of the day. In consequence, the same amount of emissions leads to much larger concentrations.

In consequence, and in an attempt to come up with a reasonably simple scheme, it was decided to use a time-dependent distance toll. Hourly toll rates, per kilometer, are determined based on simulated NO_x (Nitrogen Oxides) and PM_{10} concentrations as depicted in Figure 3. As the resulting toll during the peak hour is only 0.0125 €/km, scaling factors of 1, 10 and 100 are tested in a preliminary study. It is found that a scaling factor of 100 for the implemented toll results in pronounced behavioral changes, resulting in 1.25 €/km during peak hour.

An open question was across which area such a toll should be plausibly implemented – we investigated a toll only within the inner city (**Scenario 2**; Figure 1 yellow), one everywhere within the federal state of Berlin (**Scenario 1**; Figure 1 blue), and one everywhere in the simulation area, i.e. also extending into the rural areas of Brandenburg. The following discussion concentrates on Scenario 1.

All scenarios are first simulated and evaluated in MATSim. Afterward, PALM-4U runs are performed to assess the effectiveness of the implemented tolls regarding pollution concentrations.

4 Results and Discussion

Figure 5 presents the NO_x concentration values calculated with PALM-4U for the base case, as well as for Scenarios 1 and 2. It is evident that the introduction of a toll throughout the entire city leads to a significant reduction in pollutant concentrations levels, especially in the morning hours. For Scenario 1, a halving of the average pollutant concentration is observed.

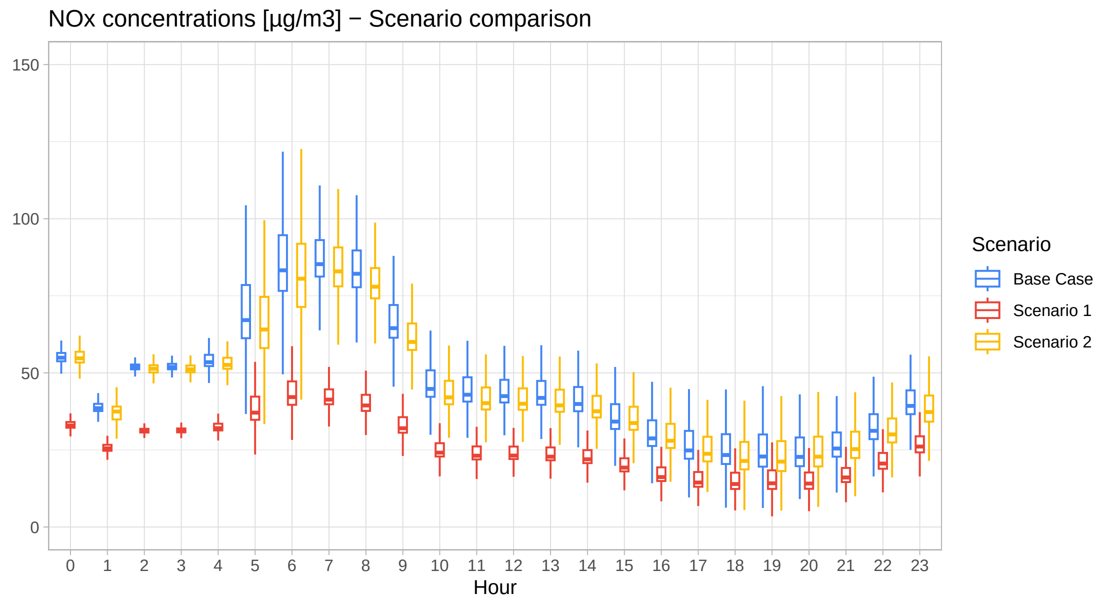
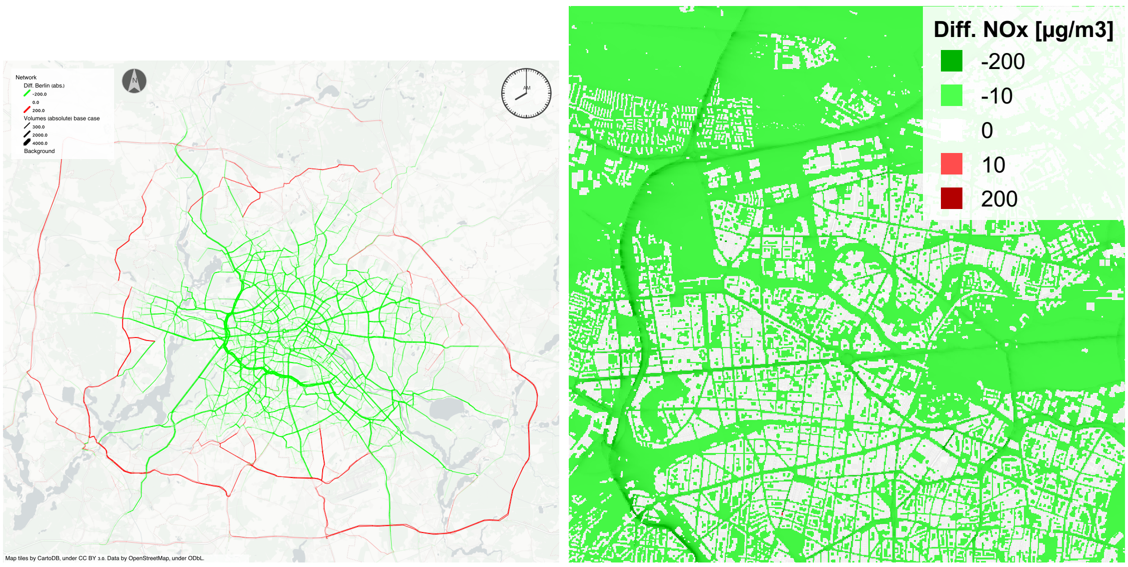


Figure 5: Comparison of aggregated NOx concentrations; median values, 25th and 75th percentiles, and 1.58 IQR whiskers are shown

Scenario 1 — City-wide Toll

The spatial analysis of traffic volumes for Scenario 1 in Figure 6a shows how the synthetic population adapts its behavior to the introduced toll. Car trips starting and/or ending within the toll area are replaced by other means of transportation, mainly public transit and bicycles. For trips passing through the toll area, the affected synthetic persons choose alternative routes to bypass it. This leads to increased traffic on the motorways surrounding Berlin.

For the entire area of the PALM-4U model setup, a decrease in concentration levels can be observed as shown in Figure 6b. Corresponding to the reductions in car traffic, a more significant decrease in pollutant concentrations is recorded in the morning compared to the evening. The strongest decrease in pollutant concentrations occurs along the motorway and major roads, as these are the largest emitters of traffic emissions in the base case.



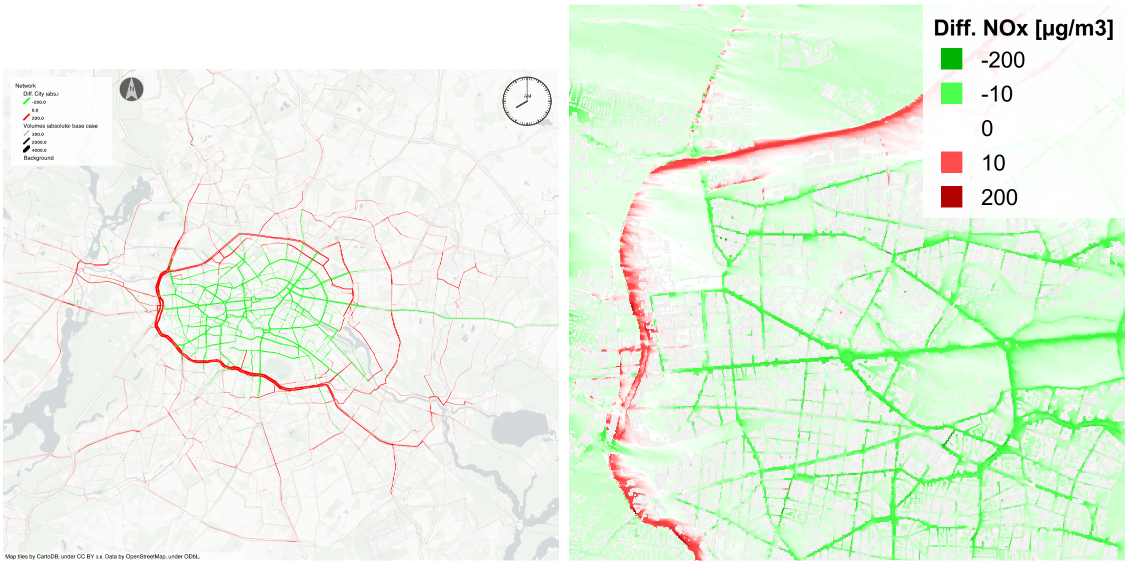
(a) (b)

Figure 6: (a) Difference in traffic volumes at 8 a.m.; (b) Differences in pollutant concentrations at 8 a.m. for Scenario 1.

Scenario 2 — Toll only in City Center

For scenario 2, only a slight decrease in aggregated emission concentrations can be observed in Figure 5. However, Figure 7a shows that traffic volumes within the toll area decrease. This effect is more pronounced during the morning hours with higher prices than in the evening hours. As in Scenario 1, there is an adaptation in behavior by selecting routes leading around the toll area. The main bypass route in Scenario 2 is the A100 city motorway, which runs just outside the toll area and offers a high-capacity alternative for car trips to avoid the toll.

Unlike the case of the citywide toll system in Scenario 1, the border of the toll area in Scenario 2 runs through the PALM-4U simulation area. Figure 7b shows changes in NO_x concentrations in Scenario 2 compared to the base case and reflects the changes in traffic patterns from Figure 7a. Within the toll area, a general decrease in NO_x concentrations can be observed in the morning (Figure 7b). However, increased traffic volumes result in increased NO_x concentrations near the A100 motorway, located outside the toll area. This effect is most pronounced on sections within densely built-up areas.



(a) (b)

Figure 7: (a) Difference in traffic volumes at 8 a.m.; (b) Differences in NO_x concentrations at 8 a.m. in Scenario 2

5 Conclusion & Outlook

This study explores the application of traffic management measures using detailed air pollutant concentrations obtained from simulations. By coupling traffic emissions from the MATSim model with the high-resolution air pollution dispersion model PALM-4U, including air chemical reactions, the consequences of emission tolls can be explored.

A simple “first-best” allocation of localized concentrations to tailpipe emissions was not possible, since no simple correlation between them could be found. Instead, it was found that emissions in the morning lead to much larger concentrations than emissions in the afternoon, since in the afternoon the height of the atmospheric boundary layer is larger and thus the same emissions are mixed into a larger amount of air. In consequence, we investigate tolling schemes that predominantly suppress morning traffic.

Only tolling the city center leads to adverse effects at the borders of the toll area, in some cases even leading to larger concentrations than without tolling. Tolling the entire federal state of Berlin suppresses high concentrations effectively. Tolling also the rural areas around Berlin is unnecessary if reducing high concentrations is the goal.

A question from here is what is to be achieved regarding emissions. Regulations presumably point to a scheme where certain concentration levels are not to be exceeded. From a public health perspective, schemes that reduce average doses might be more efficient. The coupled simulation system can now address the consequences of such decisions.

6 Open Access & Funding

Open Access: Simulation data (Laudan, 2023b), source code of the conversion tool (Laudan, 2023a), and the OpenBerlinScenario (Leich et al., 2023) are publicly available.

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